Emerging Sites of HCI Innovation: Hackerspaces, Hardware Startups & Incubators

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ABSTRACT

In this paper, we discuss how a flourishing scene of DIY makers is turning visions of tangible and ubiquitous computing into products. Drawing on long-term multi-sited ethnographic research and active participation in DIY making, we provide insights into the social, material, and economic processes that undergird this transition from prototypes to products. The contribution of this paper is three-fold. First, we show how DIY maker practice is illustrative of a broader "return to" and interest in physical materials. This has implications for HCI research that investigates questions of materiality. Second, we shed light on how hackerspaces and hardware start-ups are experimenting with new models of manufacturing and entrepreneurship. We argue that we have to take seriously these maker practices, not just as hobbyist or leisure practice, but as a professionalizing field functioning in parallel to research and industry labs. Finally, we end with reflections on the role of HCI researchers and designers as DIY making emerges as a site of HCI innovation. We argue that HCI is positioned to provide critical reflection, paired with a sensibility for materials, tools and design methods.

Author Keywords

Make; making cultures; DIY, hackerspace; materiality; critical making; China; manufacturing; IoT.

ACM Classification Keywords

H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION

Throughout its history, HCI has employed radical envisionment of future technologies as part of its research program. Many of the resulting visions have become landmarks in both research and industry, and have set directions for major research and industry programs [11]. Amongst them, we might count Alan Kay's writings on the Dynabook [19], Apple's "Knowledge Navigator" video, Sun's "Starfire" envisionment, Weiser's Scientific American article on ubiquitous computing [42], and Ishii and Ullmer's CHI paper on "tangible bits" [17].

These visions largely arose during a period when interaction design and the user interface were somewhat neglected topics in system design. Indeed, HCI as a discipline and a professional field developed not only a systematic body of knowledge around user interface design and evaluation, but also advocated for the importance of the user within the design process [8]. Today, HCI conceptions of user experience and interaction design are at the heart of product development and the technology transfer process. HCI, then, has been remarkably successful in shaping technological innovation. However, because of this greater prominence of interaction design and user experience in the technology industry and popular consciousness, HCI is no longer the only place where new interactional visions arise.

Take, for instance, Weiser's vision of a world of seamless, embodied experience of digital devices embedded into the fabric of everyday life. While this vision originally might have been devised in the corridors and meeting rooms of Xerox PARC several decades ago, it is a vision that is being extended and developed not just by other companies, but by tinkerers, hackers, and hobbyists. In particular, a flourishing DIY (do-it-yourself) or "maker" community is expanding HCI visions and methods into commercial products. A quick glance at the crowd-sourced funding website Kickstarter makes this clear: it shows products like the Spark Core, an Arduino-compatible Wifi-enabled prototyping platform that raised over 500,000 USD in crowd-sourced funding on Kickstarter earlier this year. What the Spark Core does is seemingly simple: it turns a standard household appliance into a "smart" one. Once embedded, it brings to life what has long been the vision of ubiquitous computing: the coffee machine that brews the morning coffee when your alarm clock on your mobile rings, the refrigerator that emails you the missing ingredient for dinner right when you leave the office, and the lamp that welcomes you with a warmly-lit living room when you arrive at home after a long day of work. Efforts like the

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Spark Core mark an important shift in the way that a DIY maker ethos and new interactive products are connected.

DIY making is no longer just a hobbyist movement driven by a loose collective of computer enthusiasts, artists, designers, and developers. Central to this development is the confluence of crowd-funding websites, the proliferation of hackerspaces [1] on a global scale, open hardware platforms such as the Arduino[2] and publications such as Make magazine. The combination of new funding models, physical spaces, new platforms, tools, and publications is crucial here. For instance, while Make helps spread an understanding of making as a form of "tech-influenced DIY[3]," innovation and popular engagement with science and technology, hackerspaces provide the physical space and tools to bring people together in implementing these ideas. These developments suggest taking DIY making seriously as a site of technology innovation that emerges alongside professional fields and disciplines like HCI.

In this paper, we examine open hardware products like the Spark Core as emerging sites of HCI innovation. Our particular interest is in the ways in which DIY making has extended beyond hobbyist practice and become a site of industrial innovation. Drawing from long-term ethnographic research and participation in DIY maker communities, we examine the role hackerspaces, hardware incubators, and hardware startups play in this transition.

The Spark Core is illustrative of a whole series of hardware startups committed to embedding into products aspects of the 1960/70s hacker ethos*, i.e.* the commitment to designing technologies that are modifiable by others, the open sharing of knowledge, and peer production. When DIY makers turn ideas into products, do they still practice "DIY" technology production? What concessions have to be made in regards to the openness of a product that is aimed at reaching a mass market? We analyze in this paper both the opportunities and tensions that lie in this transplantation of the hacker ethos into a commercial endeavor.

The rest of the paper is structured as follows: first, we discuss related HCI literature on making cultures. After describing our methods, we delve into discussing the findings from our research, with a particular focus on the role of hackerspaces, hardware startups and hardware incubators in contemporary DIY maker practice. In the discussion, we examine, in light of our empirical cases, the changing relationship between DIY making and HCI through the lenses of amateur expertise, critical making, and materiality.

[1] Hackerspaces are shared spaces that bring together people engaged in building creative technical projects through the sharing of equipment, tools, software and hardware.

[2] The Arduino is an easy-to-use microcontroller that supports the design of hardware-software-material interaction. It has popularized DIY making by simplifying the process and reducing costs. http://arduino.cc/

[3] http://makerfaire.com/maker-movement/

RELATED WORK: DIY MAKING & HACKING

Over the last half decade, there has been a growing interest in DIY making and hacking cultures within HCI. This prior work has explored DIY making as site of 1) novel forms of engagement with diverse materials including electronics as much as fabrics, wood, plastic, paper, etc. [5, 32, 35, 36 38], 2) community formation around lay expertise and open sharing [24, 31, 35, 41], and 3) in terms of its impact for research, design and teaching [15, 16, 22, 23, 24, 36, 40]. Taken together, these works show that DIY making is a productive site for HCI research, design, and teaching.

Hartman *et al.* [16], for instance, illustrate that practices such as mashing, hacking, and gluing can be understood as "opportunistic design." By this, they refer to a practice of design that integrates existing artifacts and site-specific tools to target a particular user or community. The authors suggest that this development approach changes the relationship between prototyping and product design, accompanied by an increase in a sense of fulfillment for the designer. DIY maker practice has also been explored as a productive site for teaching and learning. Kolko *et al.* demonstrate that DIY hacking is useful in teaching especially non-STEM students science and engineering skills, because of its hands-on and interdisciplinary engagements [23]. Across these works, DIY making is often understood as taking place mostly outside of professional design and development. Tanenbaum *et al.* [36], for instance, show that HCI researchers tend to portray DIY making as a recreational or hobbyist practice, *e.g.* [41].

In this paper, we are extending from these works by focusing on ongoing efforts from within making cultures toward entrepreneurialism and professionalization. DIY making is more than just a novel form of material engagement. It is an emerging site, where technological visions are crafted into tangible products and alternate models for industrial development and design. In our fieldwork, makers did not just utilize 3D printers and laser cutters in hackerspaces; they started up businesses and collaborated with manufacturers to scale up prototypes and reach mass markets. They worked with governments to set up educational programs, and partnered with venture capitalists to develop models of R&D. These developments call upon us to take into account how DIY making is extending into product design and industrial development.

METHODS: WORKING WITH AND AS MAKERS

The work presented here is based on ethnographic research with makers over the last 4 years and active participation in the maker scene through hands-on projects over the last 10 years. We have conducted participant observation as well as formal and informal interviews at over twenty maker-related events such Maker Faires, Maker Carnivals, Dorkbots, Start-up Weekends, Arduino workshops, and BarCamps throughout North America, Europe, Asia and

South America. We have also conducted participant observation at four hackerspaces in China, two in the United States and at a hardware incubator [26, 27].

This distributed nature of our inquiry is a key element of our research and of this community. DIY making and start-up culture have traveled beyond innovation hubs such as Silicon Valley or New York City. This global context makes it increasingly important to ethnographically examine the mobilization of DIY making in relation to varied political and cultural processes. This paper draws on our long-term engagement with makers across regions.

Participant observation at hackerspaces included joining daily affairs such as space management, member meet-ups, open houses, and the organization of events. The research at the hardware incubator took place throughout the duration of the program and included daily observations at the office space as well as accompanying start-ups to factory visits. In total, we conducted over 60 formal interviews with relevant stakeholders including members of hackerspaces, start-ups, urban planners, policy makers, entrepreneurs, investors, and media representatives. These formal interviews are accompanied by informal conversations with a wide range of people at maker-related events.

We also organized and gathered data at eight workshops that investigated projects and ideologies of contemporary maker culture[4]. Each event brought together scholars and practitioners concerned with making and from diverse backgrounds, including but not limited to: HCI, the arts, design, engineering, and manufacturing. These workshops proved to be productive to distill themes or questions that had remained unclear throughout the ethnographic research [14]. Workshop topics included educational aspects of making, global questions of maker culture, and the role of future visions in the professionalization of maker practice.

We draw upon this long-term engagement with making cultures to trace the ongoing transformation from hobby to entrepreneurial practice and manufacturing. We begin by briefly discussing some of the origins of the hacker ethos and how makers are reworking it into product design. We uncover this development as part of a broader transition from hacking to making.

FROM HACKING TO MAKING

Our contemporary landscape of information technology production has been profoundly influenced by the emergence of so-called "hacker culture" in the 1960/70s. Its members were committed to peer production and to designing technologies that were open and modifiable by users [18, 25]. From Mac OS X to Android, from Amazon.com to Google Chrome, the technology landscape is full of products that depend upon this alternative model of technology production, variously known as "open source," "peer production," "open innovation," and the like.

Fifty years later, we find ourselves in the middle of a new hacker movement that both draws from this history and departs from it in significant ways. It is rooted in a growing network of hackerspaces that expand the ideas of the Web generation into hardware. A typical hackerspace is equipped with computing tools that allow for experimenting with the physical/digital boundary—computer controlled laser cutters, 3D printers, and open microcontroller platforms such as the Arduino. The origins of the hackerspace movement developed in Europe, where the first hackerspace *C-base* opened in 1995 [2]. Today, with an estimated 1,100 active spaces in existence worldwide, hackerspaces are a significant global phenomenon [26].

The contemporary movement extends and in part remakes earlier hacker practice. While earlier generations invented the production and use of digital things and software, makers today are shaping the production and use of physical things and hardware. Makers identify with an open hardware approach, which builds on open source software. Open hardware, in this sense, refers to "tangible artifacts – machines, devices or other physical things—whose design has been released to the public in such a way that anyone can make, modify, distribute, and use those things."[5] More importantly though, just as Web startups and the Bay Area counterculture drove aspects of new technologies and IT culture, so is the contemporary culture reinventing manufacturing and innovation in hardware. In other words, we are witnessing a parallel between the developments in the 80s, when the counterculture turned into the software industrial complex of Silicon Valley we know today [37].

Hackerspaces are crucial sites in this contemporary movement as physical spaces that provide social and technological resources for people to collaborate on the production of new technologies. Across the hackerspaces we visited, many people drew inspiration from the earlier hacker movement and its impact on IT culture. They were driven to bring the hacker ethos of earlier generations to the masses by designing and developing open hardware products. They believed that this has the potential to lead to a significant transformation in current economic, social and political processes of industrial production. One maker, for instance, put this as follows: "*if you look back into time, you see what's happening in the 60s. The 60s brought advances in computing. Its pioneers were people like Wozniak and Steve Jobs. They were makers, hackers, academics, and entrepreneurs. But this time around it's different. You have Kickstarter and VCs… Hardware startups today can really make anything possible. Everyday startups build new products, from biotech all the way to video games, new shoes, clothing, toys, vehicles, you name*

[4] http://www.hackedmatter.com, http://www.conceptlab.com

[5] http://www.oshwa.org/definition/

it. It's an exciting time to be in. Because of this the meaning of DIY changed. Today, DIY means that anyone can take a product to the market, with the support from the crowd."

This idea that the very essence of what DIY making means has changed is crucial here. It describes what many makers are strongly committed to: the democratization of technology production, enabled by the concerted effort of startups that develop products that are modifiable by their users, new educational programs and funding infrastructures such as Kickstarter. The ultimate goal for many is to enable others – in particular those less tech-savvy – to become producers of technologies.

Attitudes and reasons for participation in a hackerspace and making, however, are undoubtedly diverse. While some individuals are strongly endorsing a countercultural ethos, others actively participate in start-up initiatives in their regions, collaborate with government officials, or even large corporations. Despite often heated debates about these differing approaches, what many nevertheless agree upon is the belief that "making" technology leads to individual empowerment, perceived as essential in times of increased global economic uncertainty and social upheaval. Making, here, is conceived of as a new form of citizen engagement. It is seen as a path to turn passive consumers into active participants in state affairs and the market; or as a maker told us: *"Our society renders us as customers. The maker movement is really about making us citizens again, so that we can truly own something – truly understanding how a thing works. I am thinking what computer to get my nine-year-old son for his birthday. First I was thinking tablet, but it's too passive. Then I thought Linux, and how it's really about this idea of turning customers into citizens. So I want to give my sun a Linux PC. I want him to open the console and understand what's going on inside. I know it will be hard at first, but I want him to understand it."*

Hackerspaces are perceived by many in a similar vein; as spaces that encourage people to experiment with alternative modes of citizenship. A hackerspace "evangelist" that has been central in spreading such beliefs across different hackerspaces is Mitch Altman, the co-founder of the San Francisco Hackerspace Noisebridge. Over the last half decade, Altman has toured around the world to visit hackerspaces, share his own insights and experiences of working in and making a living off of DIY making. In a public lecture at the Maker Carnival in Beijing in 2012, he described his take on hackerspaces as follows: *"Hackerspaces are a fantastic way for people to explore their creativity in a supported environment… You might find that if you love what you are doing, you can make a living off of it.,, the Internet is all fine, it's a great tool, but it's not real community. When people come together in hackerspaces and share what they love, magical things happen."*

Altman's articulation of hackerspaces as providing a relatively safe environment to explore an alternative life- and work-style is something we found to be shared amongst many makers. Indeed, over the last years, several successful startups have spun out of this environment; Altman himself, for instance, invented "TV-B-Gone," a device of the size of a TV remote control that allows the user to turn on and off public televisions in vicinity. Embedded in the device is a countercultural ethos that critiques the passivity of devices such as the TV. Altman stressed that building such a disruptive device does not entail that he can't or shouldn't make a profit by selling it to others. That the commitment to countercultural ethics was not perceived as antithetical to structures of the market economy is what we would like to emphasize here. Many, similar to Altman, did not see a contradiction in critiquing the status quo and sustaining one's livelihood through fruitfully merging social critique, industrial production, and product design. On the contrary, many considered such alignments essential in order to move DIY making beyond a hobbyist practice. Many believe that making works from within the system and alter what they considered problematic aspects of contemporary capitalist structures such as passive consumption, top-down and test-oriented education systems, and hierarchical politics.

"Making is going Mainstream"

One of the most powerful supporters of this idea that individual makers can reposition themselves in a world dominated by large and powerful corporations is Make magazine, a key publication in the field of DIY making. Make magazine is a compilation of electronic hobby projects and tutorials that use clever physical construction, open source microcontrollers, robotics, and physical computing. Launched by O'Reilly Media in 2005, Make spun off into its own company in 2013. Make also organizes and operates Maker Faire, an outlet for individuals and companies to exhibit their projects. Make magazine marks a broader transition from "hacking" to "making." For instance the magazine's founder Dale Dougherty had initially proposed to title the magazine "Hacks." Reflecting on these earlier days, Dougherty described how when he proposed the name "Hacks," his children were not convinced and suggested: *"why don't call it Make? Everyone likes to make things."* He goes on: *"So, I started using the word makerspaces, because I was interested in getting them into schools, and I didn't want to get into the semantics of hacking versus making."*

Make magazine is aimed at signaling inclusivity to the wider public, schools, and potential sponsors as well as an active distancing from "hacking" as a practice to subvert computer security systems for malicious or criminal purposes, also known as "cracking" [10, 25]. Make, in this way, has transformed a principle at the heart of HCI – that technology production can or even should be the site of user participation – into a profitable undertaking [26]. Or in other words, user participation has become a powerful marketing rhetoric that brands an emerging industry of hardware design as technoscientific expertise shared with families, children and other tech novices [29] – or in

Dougherty's words at a 2013 keynote[6]: *"making is going mainstream and is positioned to impact culture, innovation, and education."*

Not just Make magazine, but also hackerspaces are deliberating carefully how to position their work in ways that wouldn't render their work in association with illegal or "black hat" hacking. For instance, as stories of Chinese hackers breaking into Google servers circulated widely in national and international mass media outlets in 2010, the Chinese term *heike* 黑客 became the widely used term to describe this illegal practice of hacking into a system. Makers working in China were anxious to come up with a term that did not have any immediate associations with *heike* or hacker. It was during the planning stages of the first international maker event, the Beijing Maker Carnival, when China's makers settled on an alternative term: 创客 (c*huangke* , creative professional). *Chuangke* has the advantage of connoting *chuangyi* (creativity) and *chuangxin* (innovation), which are employed in positive terms in political and public discourse, as a way to foster social change and technological innovation [26, 26]. *Chuangke* subsequently became the term widely used in China's DIY maker scene. Similar to the decisions made at Make, a central focus, here, was on spreading the word of make by rebranding hacking and softening the tone of its language.

FROM MAKING TO MANUFACTURING

We will now discuss how such efforts to turn making into a mainstream practice have been accompanied by new partnerships between makers, manufacturers, VCs, as well as educational and state-run initiatives. We zoom in on hackerspaces and hardware incubators that seed and support the growth of startups, bringing maker ideas to the market.

Hackerspaces: drivers of economic & societal change

Maxigas has traced three waves of hackerspaces [30]; the first wave constituent of hackerspaces like *L0pht* that were started covertly in the 1990s and provided access only to a selected few; second of hackerspaces like *C-base* in Berlin, that started with a more public profile and a strong commitment to Internet freedom; and the third wave of hackerspaces like *Noisebridge* in the Bay area, committed to a global hackerspace movement. We add a fourth wave, here; the hackerspace as incubation of startups and as functioning in the realm of research and development.

Several of the hackerspaces we worked with functioned – even if informally – as incubator programs for hardware startups. Prominent examples of companies that emerged from such hackerspaces are the Pebble Watch (a programmable watch whose team is the recipient of the largest Kickstarter campaign in history) and MakerBot (a low-cost 3D printer that has become a key symbol for an industrial revolution via DIY making). Many of the founders and members of hackerspaces we interviewed considered hackerspaces as emerging sites of innovation, research and development. They stressed that this was because hackerspaces experiment with different materials, open collaboration, and rapid prototyping. The hackerspace, many stressed, was innovative in ways different from established R&D labs, which many considered slow moving and caught up in patent wars.

While many makers stressed that a hackerspace shouldn't be reduced to its potential for entrepreneurial practice, they were nevertheless instrumental movers and shapers in local or international start-up scenes. For instance, members of a hackerspace in Shanghai, which did not house any startups per se, actively participated in the organization of events such as Startup Weekends, BarCamps, and Hackathons. The underlying motivation was that these events introduced others in China through a hands-on manner to concepts and practices of technology production less common in China.

Other hackerspaces centrally incorporated incubating practices and/or industrial production. The founder of the hackerspace in Shenzhen, for instance, described this as follows: *"We have a maker concept here that a hackerspace can also be the place where people exhibit and even sell their products. As you can see, there are a lot of maker products, and we also provide 3D printing services… It's a very good entry point: people don't need to own a printer. They can come over and print it by grams. We also sell the printed objects. We have memberships, we have routine workshops and meet-ups. I foresee there will be many more people – not only engineers but everybody – to come up with great ideas and make them reality."*

The hackerspace in Shenzhen is ideally located for this endeavor to enable "more people" turn great ideas into reality. In the heart of a former manufacturing site turned into a trendy loft area of art boutiques, design studios, bars and cafes, the Shenzhen hackerspace functions as an interface between China's emerging creative industry and the region's long-term expertise in manufacturing. Just a subway ride away, hackerspace members can access China's enormous industrial fabrication industry, ranging from small craft workshops all the way to large-scale contract manufacturers. Shenzhen has long been a particularly unique environment in China: declared a Special Economic Zone (SEZ) upon its inception, it was designed and built with the goal to encourage foreign investment and economic growth. Foreign corporations, for instance, receive tax reductions and other benefits when they open a production site in the regions. According to Zhang – the founder of a startup housed in the hackerspace – this is a strong motivator to startup a company in Shenzhen over other places in China or abroad. The 28-year-old designer originally registered his company in Shanghai. He now debates to move registrars. Since March 2013, the local government has released a new regulation

[6] http://www.youtube.com/watch?v=ckpXAuxEuOI&feature=youtu.be&t=6m2s, last accessed January 5, 2014.

that significantly lowers barriers to start up a business in the Shenzhen region. *"Shenzhen feels much more open than any other city in China,"* Zhang explained, *"it's a place where lots of people begin to think about starting up a business. That's why we like to be here."*

This alignment between making and other spheres of economic and social development is also visible in a recent government initiative: in 2011, the Shanghai government endorsed hackerspaces as so-called "innovation houses" to be supported by government funding. The official document described this initiative as part of a larger effort to build a citywide platform for supporting widespread science work and innovation. This support of DIY making by the Chinese government contributes to a larger nation-wide effort of moving China's economy away from its image of copying products or manufacturing for others towards a hub of creativity and innovation [26]. In other words, the Chinese government sees hackerspaces as pivotal in transitioning the economy from a "Made in China" model to a "Created in China" model.

One year later, the first of these innovation houses was built and is today in active use as a Junior makerspace, *i.e.* a 100-square-meter room located in a public community building, equipped with miniature machines for children to learn how to solder, CNC, and 3D print. Members of China's hackerspaces are not opposed to this. On the contrary, one of the co-founders of China's first hackerspace, for instance, works with the government to host educational workshops to introduce DIY making to a wider public. Such collaborations between makers and official institutions are certainly not unique to China.

Take for instance the announcement by O'Reilly Media that they received significant funding by DARPA (Defense Advanced Research Projects Agency) for an educational program aimed at bringing *"the practices of making into education and* [to] *extend the maker movement into schools"* with a target of reaching 1,000 schools by the school year of 2012-13. The announcement lead to a considerable controversy in maker circles over the official support for what many still wanted to see characterized as a grassroots and countercultural movement. Mitch Altman, for instance, had publicly criticized O'Reilly for tying the maker movement to the goals of the defense industry and US military.

Broadly, we observed that many makers strongly believed that the work of hackerspaces and hardware startups could support the development of their respective local economies. The euphoric rhetoric of making as an industrial revolution has spread far beyond such efforts. For instance, in the US, making is tied to economic recovery, rendered as providing the grounds for a return to a "made in America" brand. President Barack Obama, in a State of the Union Address, lauded a manufacturing innovation institute in Ohio for its work in open-source 3D printing as *"carrying the potential to revolutionize the way we make almost everything."* He also announced plans for building new manufacturing hubs, where businesses will partner with the departments of Defense and Energy *"to help create a network of 15 of these hubs and guarantee that the next revolution in manufacturing is made in America."* Obama, here, echoes the former Wired Editor-in-Chief Chris Anderson, who suggested in his prominent book publication 'Makers" that today's makers are driving forward the "third industrial revolution" – a generation of technology producers that expands from the earlier Web 2.0 techniques to innovate industrial production.

To sum up, hackerspaces are sites where people actively explore new approaches to what constitutes a tech organization, research and development. We suggest that this development requires attention from HCI researchers, not just as a new subject for research or as an engagement with novel materials, but as a model of interaction design and technology production that evolved in parallel to research labs and design studios.

Hardware Incubators: from prototype to product

From January through April of 2013, Lindtner conducted ethnographic research at a hardware incubator in Shenzhen, China. The 15-week-long program, backed by a European Venture Capital firm, has taken place twice a year since 2011, each time investing in 10 selected open hardware startups. The aforementioned Spark Devices, for instance, was amongst the selected to turn their ideas into products by taking advantage of Shenzhen's manufacturing expertise. While each startup focused on developing a unique product, they shared a strong commitment to making products that allowed others, in particular lay experts and novices, to become themselves makers. They envisioned liberating individuals from the confines of capitalist modes of production that render citizens as mere consumers of technologies.

On the marketing slides of the incubator one could read: *"we are a new kind of accelerator program. For people who hack hardware and make things."* DIY making, here, is rendered as a new take on Silicon Valley tech production. The program manager described DIY as a business approach to bringing a product to the market. He stressed that what was before shaped by only a couple of "professional" designers or privileged few is now in the hands of the masses. DIY making, here, is the marketing spin of mass production. What lurks underneath is the promise that today's kludge can be tomorrow's million dollar start-up company. Quite in contrast to the language of openness that typically pervades rhetoric in Make magazine, the language takes another turn. Makers are rendered as risk takers who are willing to quit their daytime jobs. Others, the program manager made clear, do not necessarily fit: *"If you have a product or if you have a project and it doesn't look like it can be turned into a product, it gets filtered out. Ultimately, it is a commercial*

endeavor so we are looking for people that want to do a business around some marketable product."

The hardware accelerator is illustrative of a broader trend we observed in our research: a drive toward mass production accompanied by a degree of black-boxing, *i.e.* the concealing of the inner mechanics of technologies to make them easier to use or more modular. For instance, the startups that participated in the incubator had to make a series of trade-offs. While committed to the production of open technology, they soon realized that the requirements of a consumer product differed significantly from a prototype. Working with factories in China, they learned about specific affordances and limitations of the machines used for mass production including mills, drills, lasers, and molds. Their original designs often changed after having gone through long and involved interactions and material tests with their manufacturers.

This process made many of the startups revisit the concept of openness when merged with industrial product manufacturing. They debated if it was even possible to remain "truly" open source, if this entailed sharing with the consumer the source of each and every single component, from LEDs and PCBs to the physical materials used for the product enclosures. Many agreed that when moving into product design, it came down to a selective form of openness, rather than "all time" openness. One of the program managers for the hardware accelerator put it as follows: ***"****I think that's the dirty secret in open-source hardware: everybody has something that they keep closed, or secret, whether it's their suppliers, or whether it's their testing, or things that they just haven't released yet."*

What we observed across such processes of spreading DIY making beyond a hobbyist practice was also a move away from what was at the heart of some of the original hacker ethos. We see this perhaps best exemplified by one of the earliest and most successful open hardware startups: MakerBot Industries. In 2012, MakerBot announced that they went closed-source with their new printer models of the Replicator 2 and 2X, in addition to changing the terms of use in the website Thingiverse, their 3D model repository. Many of their fellow makers and even one of their own co-founders heavily critiqued this decision as "decidedly moves away from the openness that MakerBot was evangelizing in the past." Bre Pettis, one of the co-founders, characterized the closing of Replicator 2's source as motivated by the challenge of building a sustainable business with more than 150 employees, and being *"as open as we possibly can"* instead of retaining a strict adherence to open source. Pettis characterized open hardware as sustainable for small educationally-oriented businesses such as Evil Mad Science and projects funded by Kickstarter, but incompatible with industrial production.

While the developments at MakerBot lead to significant controversy, it is nevertheless often celebrated as one of THE success stories of the maker movement; i.e. a project that began as a small start-up in a New York City based hackerspace and that is today changing the conversation and practice around industrial production. The recent merger between MakerBot Industries and the professional 3D printing company Stratasys for several hundred million USD further fuels visions of make as a new tech revolution. The efforts of such innovation models in hackerspaces and incubator programs, as discussed in this section, have generated a broader imaginary of DIY making as simultaneously the savior of the American economy by rebuilding a "made in America" brand and the driver of new economies in so-called developing regions.

DISCUSSION

The relevance of DIY making to HCI has been articulated to date in terms of four broad trends: the call for more open and participative forms of design, *e.g.* [21], the relevance of tinkering and experimentation to engagement with digital tools, *e.g.* [5, 15, 27, 32], the emergence of new material as interaction sites [5, 35] and the move towards a more critically engaged HCI practice [32]. However, as we have documented here, DIY making is at a moment of transition, which in turn motivates a new framing and engagement in HCI. We will consider three aspects here: amateur expertise, critical making, and materiality.

Beyond Amateur Expertise

DIY making has extended beyond a practice of nerds hacking away on the weekend. It rests on a range of expertise levels, bridging across a multitude of genres and disciplines, and is aimed at reaching beyond the hobbyist market. We have shown in this paper that hackerspaces, hardware start-ups and incubators are turning the computational visions of ubiquitous computing and user participation into products; and one might begin to ponder, then, whose vision it is anyway. In the move from vision to product, hardware startups largely sidestep the traditional pipeline of HCI R&D that follows the path of academic or industry research labs. In doing so, they introduce a model of open innovation not dissimilar from earlier generations of open source software developers.

Open source software has long been absorbed by corporations, *e.g.* as an "open innovation" strategy that treats open source as a form of external knowledge source [6, 39, 43]. Chesborough [6] illustrates how, in contrast to the more traditional innovation models that house research and development internally as is common in well-known labs such as Bell AT&T and Xerox PARC, open innovation refers to a firm's endorsement of external channels such as spin offs, ventures, licensing, but also individual inventors and startups. Large corporations such as IBM, Intel and Procter and Gamble utilize open source development as "test site" to assess their direction in R&D [6]. Seen in this light of both entrepreneurial practice and open innovation, DIY making also shifts the ground on which HCI's own technical legitimacy rests. Just as open source software

production was at the heart of shaping the technological and social means of Internet technology today [18, 20, 37], so are open hardware efforts enabling a shift in HCI innovation and research practice.

HCI has long argued that information technology should support the creativity of end users and allow people to be productively engaged with digital tools. However, distinctions are still maintained between different spheres of expertise; for instance, that of the HCI professional and that of the end-user who, while expert in their own domain, depend upon the HCI professional for intercession and guidance [9]. Prior work has tackled this question of the relationship between "expertise" on the one hand and "legitimacy" on the other [8]. Collins and Evans, for instance, argued that expertise (as a matter of practical knowledge) and "expert-ness" (as a matter of power and influence) are tightly linked. Or in others words, when people demonstrate expertise, they also exert claims of authority. For instance, they present particular forms of knowledge and practices as central to the discipline or domain. It is in this context that the transformation of DIY practice documented here becomes especially relevant and problematic for HCI, because it is embedded in a similar shift of legitimacy – what we might loosely frame as the legitimacy of the laboratory and the legitimacy of the marketplace. That is, one source of legitimacy of HCI work lies in scientific inquiry, theoretical elaboration, and academic deliberation; another in commercial production, engineering practice, and marketplace valuation.

When we examine new models of manufacturing, and consider alternative forms of industrial practice, we also shift the grounds on which HCI's own technical legitimacy rests. If the relationship between theory and design has long been a source of tension within HCI, then the relationship between design and manufacturing, or between design and entrepreneurship, might also become a site of contests of authority and a place for new forms of authority to arise. In what follows, we outline how prior work in HCI on critical making can be applied to begin tackle such tensions, rather than putting them aside as mere political meanderings.

Critical Making

As we have shown in this paper, DIY making is the site of a highly politicized discourse around economic recovery and innovative development. What do these contemporary developments mean for our engagement with DIY making in HCI? While governments and media have mostly taken up the overtly enthusiastic tone behind publications such as Make, we believe that HCI has something valuable to offer: a repertoire of deep engagement and critical reflectiveness toward technological design.

Our research indicates that many makers believe that acting outside of traditional institutional frames such as the large corporation allows alter contemporary modes of capitalist production. While certainly not all DIY maker products are aimed at cultivating critical awareness amongst users, critical reflection is nevertheless central to the practice: think, for instance, of the ongoing debate around MakerBot Industries going partially closed source or around the announcement of O'Reilly Media to accept funding from the US military agency DARPA. Or, Altman's TV-B-Gone discussed earlier can be seen as an interventionist design not divorced from production.

Such projects and ongoing debate in the maker scene provide new models for critical reflection. As Bardzell and Bardzell have shown, HCI tends to render critical approaches in design in opposition to "affirmative" or "opportunistic" design [3]. We propose a form of critical making that doesn't oppose production and product design. This is in line with and simultaneously extends Ratto's work on critical making, intended to bridge the gap between creative physical and conceptual exploration [32]. With a focus on a process of making prototypes to expand the social study of technology, Ratto's critical making comes from a perspective of injecting DIY making into the process of critical thinking. We see value in extending Ratto's criticality into manufactured products. While Ratto's emphasis is not on what is produced through the process of critical making, we argue to include the releasing of built devices and its implications into critical practice.

Materiality of Making

An interest in the materials of design has been central to HCI for several years. Buechley's work with the Lilypad Arduino – a prototyping platform for responsive systems in fabric and clothing – is a salient example [5]. This has in turn prompted recent discussions at venues like CHI about the topic of "materiality" – not just of new materials but of modes of analysis that proceed from a material foundation [4, 11, 33, 34]. These efforts tend to focus on the small-scale making of craft practice or the research lab.

Our investigations into the entwining of DIY making, professionalization, and commercial endeavors points to another critically important consideration in HCI's study of materiality, which is the materiality of manufacturing. That is, manufacturing and its own materialities shape the kinds of interactive devices that might be produced through DIY practice in a number of ways. We have shown that materials and material forms of production that are effective for prototyping are frequently not effective for larger-scale production. The shift from building something in a 3D printer of a research lab to producing a version on a milling machine on a factory floor tests material limits in different ways. However, HCI has explored DIY making foremost as a method to scale-up and speed-up prototyping [15, 16].

We stress, here, the importance to take into account how hardware startups are already scaling into manufacturing. This requires revisit the concept of "openness" as it is traditionally defined – meaning access to schematics, designs, and electronic formats such as source code or 3D models. Such aspects are only part of the equation when considering manufacturing, at which point suppliers and

supplier relationships and manufacturing partnerships also matter. As we have shown in this paper, the realization of an open hardware product in Shenzhen involved in various capacities diverse actors, sites, values and machines, ranging from new funding websites such as Kickstarter, the affordances of manufacturing machines, the workings of venture capitalist firms alongside those of hackerspaces. The question of materiality pertains not only to the making of an object, but to social, economic, and material infrastructures enlisted in its production.

CONCLUSION

It is a measure of HCI's success that user experience and the importance of interaction design are now central parts of new technological visions. One consequence of this is that HCI concerns are so foundationally entwined with new models of technological innovation, and new fields are involved in developing, designing, and prosecuting visions of interaction. HCI is no longer simply happening in interaction-oriented research labs and HCI-centered academic programs, in user experience groups or at HCI conferences. It is also happening at emerging sites of technical invention – at hardware incubators, at hackathons, and in hackerspaces.

Our goal in this paper has been to document the design and innovation practices arising at some of these sites, with an eye towards understanding the implications for HCI. Our work suggests that we need to understand the broader contexts within which these emerging sites of HCI innovation are embedded. To draw an analogy with open source software, open source is both a form of collaborative programming and a new institutional form, with all its regional, technological, organizational, and political consequences. Similarly, when we turn our attention to hackerspaces, we see not only a space experimenting with new sorts of fabrication tools, but also a community that reshapes the very meaning of innovation. Our research suggests that we need to see the hackerspace not just as a place that amortizes the cost of a laser cutter and a 3D printer across hundreds of people. It is a place where people are experimenting with new ideas about the relationships amongst corporations, designers, and consumers. It is from this perspective that we approach questions of expertise, materiality, and criticality – topics which increasingly also define the relationship between HCI as a discipline and other cultural groups with which HCI interacts.

HCI can serve as a source of knowledge in the DIY era by establishing partnerships with these cultural groups, hackerspaces and hardware startups alike. For instance, as hackerspaces and maker initiatives are receiving not only substantial interest from a wider public, but also funding from government agencies, HCI researchers and designers can productively work with makers to build new research initiatives, summer school programs, and curricula.

HCI will continue to produce radical visions of the future of human engagement with information technologies. What we need to do beyond this is to be equally visionary about what our relationships might be to other sites of tech innovation involved in bringing these visions to fruition.

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