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Materials-to-develop-with: The making of a makerspace

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Abstract

Celebrating hands-on making and technological inventiveness, the Maker Movement promotes the popularity of new makerspaces: learning environments filled with diverse materials for youth's creative projects. Described as "constructionist learning environments," makerspaces can be challenging to design because materials require substantial budgetary investments. Because the practical demands of space and cost often dominate decisions concerning a new makerspace, less attention is paid to how the choice of materials inadvertently limits who uses the space, how learning happens, or how materials in a space will interact and intra-act over time. Building on theories of constructionism and relational materialism to analyze and theorize learning in makerspaces, we take a case-based approach to illustrate the co-development of 3D printing materials, youth and educational programs at an out-of-school makerspace. In the process, we demonstrate the need to rethink the role of materials in human development and educational design. We introduce the concept of *materials-to-develop-with* to explain how objects can be internalized *and* drive the development of spaces, people and learning opportunities.

Across from the makerspace entrance, stacked against the blue-and-white-painted wall, sits the 3D printer queue, consisting of 4 double-stacked tables and 12 3D printers. Connected by network cables, microcomputers and custom-made software, the printers automatically queue prints. Youth and staff can upload files, and the software checks the status of each printer before distributing the files. The printers are almost evenly spaced, suggesting a finished installation, though their visible wiring toppling over the tables makes the workstation appear in-progress. When no 3D printing workshops are being facilitated, some printers run at their own speed, slowly squirting filament across the plane, filling the air with a mellow cacophony of high- and low-pitched sounds while slowly rotating filament spools. Perhaps fastened too loosely, one of the spools bounces onto the floor, unwinding the dark blue filament. As the printer marches on, a former youth and now staff member, Darnel (pseudonym), picks up the spool and winds it back into place. The 3D printer queue as described here has not always had this form. In fact, Darnel joined the makerspace when the first 3D printer kit arrived and the space focused on facilitating

Practitioner Notes

What is already known about this topic

- Makerspace design requires deciding which materials to purchase to support learning.
- Maker-educational spaces have been characterized as constructionist learning environments where materials mediate presupposed learning through the creation of personally meaningful projects.
- This focuses design on maintaining possibilities and controlling materials in makerspaces, which can threaten to limit who used the space, what can be learned, and how we theorize learning in relation to materials.

What this paper adds

- Practically, we share characteristics of materials that can bring about unintended, entangled and desired development of people and materials to support the selection of materials for possibility-rich makerspaces design.
- Theoretically, we advance the idea of materials-to-develop-with to account for the power of materials to internalize ideas *and* to drive the development of spaces and people.

Implication for practice and/or policy

- Materials-to-develop-with rethinks the role of material in the development of educational spaces and learners.
- Makerspace design should consider the development of possible encounters between people and things to support unforeseen transformations.
- Institutional space policies that consider the power of materials-to-develop-with can foster infrastructure for possibility-rich space design.

web-design workshops for youth. Assembling the first 3D printer kit and being part of the development of the workstation from scattered printers, to a row of 3D printers, and finally to the elaborate 3D printer queue, Darnel and the makerspace programs changed, too. Darnel got to know 3D printer technology, established a 3D printing business that he presented at the White House, and became the first African-American staff member at the makerspace. Programs shifted from web design to 3D printing workshops and finally to pathway programs for youth to become members of the makerspace staff, like Darnel.

This paper highlights the materialized co-development of a makerspace, its people, and learning opportunities happening there over a 24-month period. Makerspaces are often physical locations where youth use tangible materials to create personally meaningful projects alongside others (Sheridan *et al.*, 2014). Over the last decade, youth-serving makerspaces have been established in a host of learning spaces, including schools, libraries, museums and out-of-school centers, expanding in number with the rise of the growing Maker Movement (Peppler, Halverson, & Kafai, 2016). Offering materials from 3D printers to sewing machines, these spaces can take different forms and offer pluralistic approaches to learning (Halverson & Sheridan, 2014).

This view of making is grounded in constructionism (Papert, 1993), an approach to learning in which design experiences result in “objects-to-think-with” that are at once material objects and internalized mental structures. Learning happens through cooperation of material environments with embedded ideas (Papert, 1980). Not every material facilitates the same knowledge to assimilate; hence, building constructionist environments means designing particular materials to intentionally serve youths’ learning (Vossoughi, Hooper, & Escudé, 2016). Objects-to-think-with provide opportunities to study moments of material engagement, how these moments support learning, and how learning intensifies as people carry ideas across materials. This approach considers the materials to be stable mediators that stand between an idea and person.

The cognitive idea of objects-to-think-with focuses on the *cognitive development* of youth engaged in production and how to design materials to serve them. However, in the rich material world of makerspaces, objects-to-think-with cannot explain the longer-term co-development of materials and people, which are subject to changing arrangements of tools, participants and programs. Looking at makerspaces from the perspective of objects-to-think-with alone may run the risk of designing makerspaces and developmental possibilities without considering how material changes in designated spaces may drive learning and how these developing materials continue to be useful and grow together with the learner. Wondering what the materials do to the development of makerspaces, youth and educational programs, we asked: *What material developments are produced in makerspaces, and in what ways do these drive possible human development?*

This paper takes a case-based approach (Bassey, 1999) to capture a fine-grained representation of how youth develop in terms of their academic, career and social opportunity, alongside increasing sophistication in the makerspace's programming and technical capabilities. Building on constructionist theoretical foundations and adding to emerging scholarship of makerspaces, we take a relational materialist approach to learning and development (Hultman & Lenz Taguchi, 2010) to capture, analyze and theorize how the coming-together of materials prompts human development and learning opportunities, and how makerspace educators can enact (and understand) similar development through the material design of a space. As part of a longer-term qualitative study that focused on capturing evidence of learning in makerspaces which included the investigation of 10 youth-serving makerspaces Keune & Peppler (2017), this paper presents a fine-grained analysis of the entangled and simultaneous development of a 3D printer queue and a youth member, Darnel, over 42 months and shows how material changes led to the construction of the 3D printer queue and drove the development of Darnel into the first African-American staff member at the makerspace. While similar to other cases at the makerspace, we chose an acclaimed technological tool (the 3D printer) that is frequently found in makerspaces (3D printers) yet has been critiqued as less transformational (Blikstein, 2013). We analyzed a time-lapse video of Darnel building the first 3D printer at the makerspace, retrospective field notes, photographic and written observations, focus-group discussions with youth and educators, and interviews with educators to show how the workstation changed over time and how these changes corresponded with Darnel's development as well as the creation of learning opportunities for other youth. Expanding the concept of "objects-to-think-with," we identified a material-based developmental pattern. To explain this pattern, we share the idea of *materials-to-develop-with (MTDW)*, which acknowledges the role of physical objects to foster the development of internal structures *and* in functioning as drivers of the co-development of people and learning opportunities over longer periods of time. MTDW new avenues for materials in human development and learning and has implications for the design of learning environments.

Theoretical framework

Constructionist views of learning focus on inherent properties of materials that mediate knowing. Learning happens in cooperation with materials as learners internalize formalized structures and discover how materials can drive future actions (Duckworth, 1972). Papert (1980) theorized materials as "objects-to-think-with" that allow learners to discover formal systems while designing personally meaningful projects. Objects-to-think-with exhibit three main characteristics: (1) they are part of children's socio-material environment, (2) they are used in disciplinary domains and (3) they allow children to explore complex ideas through bodily engagement (Papert, 1980). This understanding of materials rests on the idea that seemingly abstract concepts, including disciplinary constructs, can become more concrete through design. It also means that objects-to-think-with, from hand-held construction kits to place-based learning environments, can be intentionally designed.

In place-based learning environments, constructionist design leads youth to take ownership of space (Kafai, Peppler, & Chapman, 2009). Building on this foundation, scholars have drawn on constructionist learning approaches to theorize design and learning in youth-serving makerspaces (Sheridan *et al.*, 2014). Constructionist design principles for material-based interventions suggest considering material affordances and constraints while maintaining people as active agents (Resnick & Rosenbaum, 2013). This echoes the maker educational movement, where in particular the idea of objects-to-think-with foregrounds the intentional inclusion and exclusion of materials based on pedagogical approaches (Litts, 2015; Vossoughi *et al.*, 2016). Therefore, objects-to-think-with is productive for directing and maintaining the design of makerspaces and learning activities that are aimed towards fostering specific constructs.

However, in makerspaces, where material reconfiguration happens frequently yet understanding of possible learning trajectories is still emerging (Keune & Peppler, 2018), looking at human development predominantly as a cognitive change of individuals obscures the impact that material reconfiguration may have on the development of people and learning opportunities. Thus there is a need to broaden the theoretical conception of learning in order to seriously consider the observable and re-configurative material development of makerspaces when studying human development and to intentionally foster it through design.

The relational materialist approach to learning (Hultman & Lenz Taguchi, 2010) presents an expansion of the idea of objects-to-think-with as a productive starting point for understanding the materiality of learning within makerspaces, because it flattens hierarchies between people and materials so that people are no longer superior to materials. The aim is to capture "non-human forces" (Hultman & Lenz Taguchi, 2010, p. 539) in the production of people and learning possibilities. This means that the learner is no longer regarded as superior to materials but becomes part of and is produced by a relational field among things that come into contact (Lenz Taguchi, 2010). A relational field can be considered a unit of analysis, and two questions emerge as particularly salient: What is part of a unit and how do we recognize it?

From a constructionist perspective, a unit (eg, individual learner, particular material) can be clearly defined because subject and object boundaries are considered stable. By contrast, from a relational materialist perspective, a unit consists of unspecified yet entangled parts (Hultman & Lenz Taguchi, 2010). A change in a unit is produced through a repeated and varied real-time coming together of materials and people. This action is referred to as an *encounter*, and the change in the range of possible encounters is considered *learning* (Lenz Taguchi, 2010). In turn, development is a physical result of encounters with materials that have non-neutral histories, where action can be traced, questioned and transformed (eg, Buchholz, Shively, Peppler, & Wohlwend, 2014).

These definitions of learning and development then imply that the change of relationships among component parts can shape the possibilities of what humans can become in terms of the actions they can perform (Lenz Taguchi, 2011). Thus material change becomes evidence for circumventing what is and what is not part of a unit while at the same time indicating development and learning possibilities. Empirically, recognizing changing patterns of arrangements (Barad, 2003; Lenz Taguchi, 2012), capturing what produces these changes, and analyzing what they produce

Figure 1: Digital harbor foundation tech center with the 3D printer queue (left)

becomes a way to identify development (ie, physical change) and possible learning (ie, encounters). Depending on the size and type of material, repeated and varied meetings of materials and people may result in slow changes. This points to a need for continued analysis over longer time periods.

This is relevant to the study of makerspace design as it can explain how materials can continue to develop with people in ways that produce increasingly advanced learning opportunities. For example, the opening vignette of this paper takes place at the point of several historical and opportunistic moments for development, including the arrival of the first 3D printers at a time when these machines were considered cutting-edge and inaccessible technologies. It became advantageous for youth like Darnel to gain early access to this tool at this point in time. While moments like these are not easily replicable, spaces that privilege new technologies are prone to such moments over the course of their development.

Methods

The qualitative study was guided by a constructionist (Papert, 1993) and a relational materialist (Lenz Taguchi, 2011) approach to learning in order to investigate what constituted a material unit, how the unit was reconfigured over time, and how that reconfiguration played a role in the development of the youth and the learning opportunities at the makerspace. We selected a single-case educational study (Bassey, 1999) from four similar cases, because as one builds on materials common to makerspaces and indicates how other makerspaces could support developmental changes of youth through spatial arrangement over time.

Setting, participants and case selection

The research site was the Digital Harbor Foundation Tech Center (Figure 1), an out-of-school youth-serving makerspace founded in 2013 in a working-class neighborhood in Baltimore, MD. At the entrance of the red brick building, stairs lead to a corridor with a door to the Megalab, a large open space housing the makerspace we engaged with. At the time of the research, the makerspace offered programs for 66 youth (11–18 years old; 35% female and 65% male), including 55% Black, 37% White, 3% Asian and 5% Latino (a) youth. By contrast, the 16 adult staff members were predominantly White (76%). The programs included guided maker sessions, such as creating musical instruments with microcontrollers and open-ended member programs with uninterrupted time to explore new materials.

We began engaging with the makerspace as part of the Open Portfolios Project (For more information on the Open Portfolios Project: https://makered.org/opp/) funded by the Gordon and Betty Moore Foundation in 2014. We selected to work with this space due to its continuously developing space design, in an effort to consider materials within assessment of learning in makerspaces. Here, we centered our focus on workstations that youth co-constructed and youth projects that were prominently positioned. While youth projects are discussed elsewhere (Keune & Peppler, 2018), this paper focuses on the workstations. Among the workstations, we analyzed four cases that presented longer-term development of material arrangements, including the design of mobile tables, tool-libraries, ceiling electricity and a 3D printer queue. We chose to focus on the 3D printer queue for an in-depth analysis for two reasons. First, a makerspace survey we conducted in 2014 showed that 3D printers were common in many youth-serving makerspaces (Peppler, Maltese, Keune, Chang, & Regalla, 2015) yet have been critiqued for fostering trinket creation rather than educational transformation (Blikstein, 2013). Second, the reconfiguration of the 3D printing workstation coincided with the development of a youth into the makerspace's first African-American staff member, an important development in a field where we found that educator demographics are significantly less diverse than youth demographics.

Data collection

We facilitated focus groups with makerspace educators and youth, conducted interviews with makerspace educators, and captured photographic and written observations and video data. Data were intended to support the identification of component parts of the workstation, how it was reconfigured over time, and how this drove youth development and learning opportunities.

Focus groups and interviews

Separate audio-recorded focus groups were facilitated with seven staff and four youth. We asked participants to recall how changes to workstations, people and programs were made of in the makerspace. We conducted two audio-recorded interviews with staff, including questions about workstations that focus groups had highlighted as significantly changing and connected to youth development. The recordings were transcribed for analysis.

Photographic and written observations

To surface the makerspace's material development, we captured 640 photographic observations, of which 174 included Darnel and the 3D printer queue. The photographs served to create detailed reflective field notes of 56 hours of observations, including a 3D printing camp and workstation maintenance. The observations provided evidence of material changes to the workstation over time as well as depictions of Darnel's position. We also collected panoramic photographs taken by makerspace educators when first occupying the space and captured 27 panoramic photographs at 10 time points, of which 17 showed the 3D printer queue.

Video data

We downloaded a 4-minute video that the makerspace published showing a time-lapse recording of Darnel assembling the makerspace's first 3D printer. The video provided evidence of the first youth engagement with 3D printers. It was recorded before our engagement with the site.

Data analysis

Cluttered with high- and low-tech materials, the Megalab promted us to take a flattened approach (Lenz Taguchi, 2011) towards understanding what changed or held the spatial arrangements together. We traced the material unit of component parts—in our case the 3D printing queue—and how the unit developed over time in order to understand how long-term material development produced learning opportunities for youth. We looked at how the workstation changed forms, how Darnel's physical position changed within the makerspace, how this connected to shifts in his social position, and emergent learning opportunities for other youth.

Analysis of focus groups and interviews

We turned to the focus groups to identify workstation units that youth and adults mentioned as presenting material developments and connected to the development of youth (eg, professional opportunities). We examined the focus group transcripts and identified cases of longer-term developments for extended case studies. One of these was linked to Darnel, whose development was connected to the development of the 3D printer queue that also spurred makerspace program development. We selected the case of 3D printer/Darnel/programs for further analysis because the case illustrates: (1) how one 3D printer drove the development of an elaborate workstation; (2) Darnel, as the makerspace's first African-American staff member and (3) the instantiation of a youth employment program. Our analysis of the educator interviews focused on creating a workstation development timeline from its inception to the end of the data collection.

Analysis of photographic and written observations

Our analysis of photographic and written observations focused on routines and variations of material compositions to identify material changes that presented significant workstation development, patterns that held things in place or produced encounters and youth learning opportunities. This included an analysis of the youth's position in relation to the workstation. We used the photographic observations to reconstruct a floor plan to show the density of the workstation at different times, how it consolidated and how this consolidation was supported by Darnel's physical position. Photographic observations presented evidence of how materials were held in place, and written observations showed how youth, especially Darnel, became a part of that. We then mapped changes in the material composition of the 3D printer queue to the created timeline to show how the youth's development coincided with and was driven by the development of the workstations.

Analysis of video data

The analysis of the video focused on the components of the first 3D printer and how Darnel engaged in its assemblage. As the first instance of 3D printing at the makerspace, the video included visual information about the process of how the makerspace, 3D printing and Darnel began to form relationships and to co-develop. This further supported timeline instances with evidence before the 24 months of our data collection.

Findings

The Megalab, as experienced through verbal elaborations and observations, was a product of routine encounters among people and materials that produced reconfigurations of workstation setups, which, in turn, drove the development of programs and people. While not the only case like this in the space, we highlight the 3D printer queue and Darnel's encounters with it here as an example of how materials acted beyond tools for internalizing ideas to become growing drivers of learning and development. We show this by (1) presenting the setup of the 3D printer workstation at the end of our field site engagement, (2) tracking key workstation reconfigurations from that elaborated setup to the introduction of the first 3D printer at the makerspace and (3) mapping these material developments to encounters among people and things that the reconfigurations produced. In our analysis, we recognized that the material changes of the workstation drove changes in Darnel's physical and social position as well as new learning opportunities for all youth at the makerspace. We theorize this longer-term materially driven phenomenon of making a makerspace (ie, its workstations, people and programs) as *materials-to-develop-with* (MTDW) and discuss the implications of this notion for further research and makerspace design.

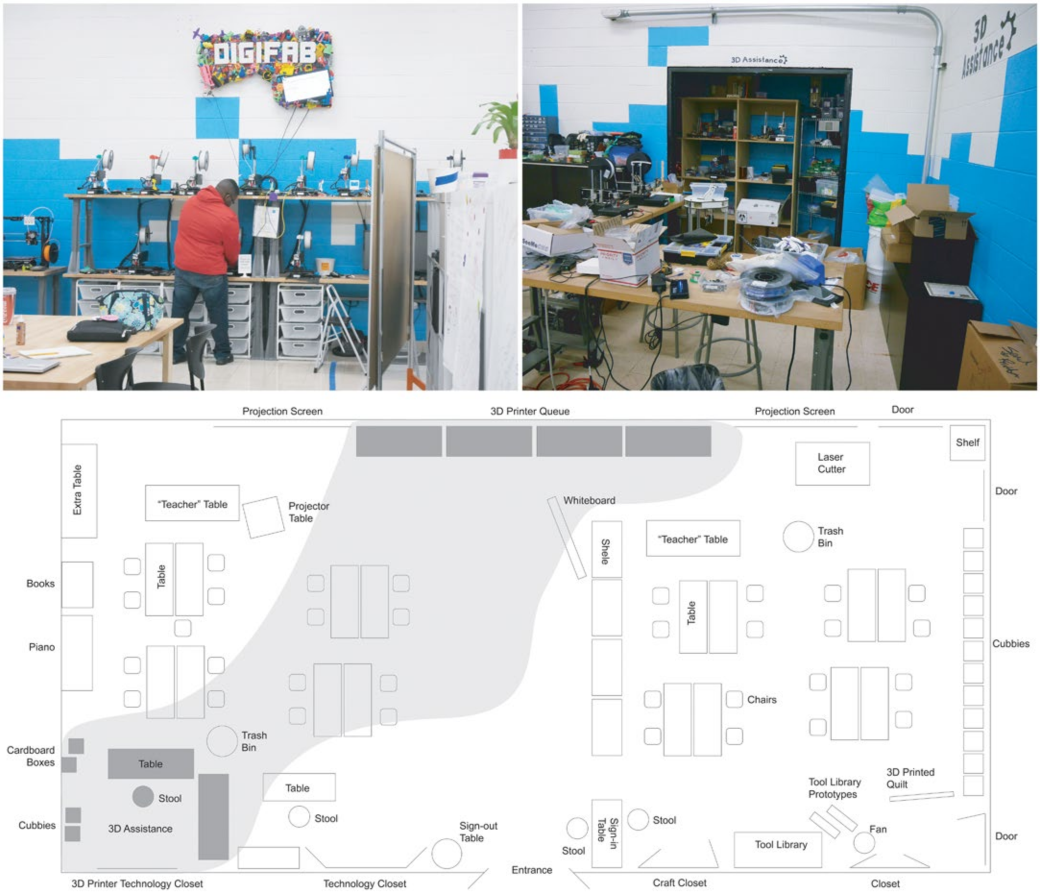

Figure 2: 3D printer queue with Darnel (top left), 3D assistance area (top right) and Megalab setup highlighting the connections across the workstations (bottom)

Assemblage of the 3D printer queue and 3D assistance

The high- and low-tech installation, precariously connected through cables, nuts and bolts, reflected the construction of the printers, which transparently displayed their inner workings. This contrasted to setups we would have expected with expensive technological equipment as discrete units.

3D printers required regular calibration and, on busier days, we observed Darnel pacing between the 3D printer queue (Figure 2, top left) and an area across from it, the 3D assistance area (Figure 2, top right) where, non-functioning printers were repaired. The related materials in both places and the human pacing formed a link across the space, connecting the areas to form one expanded workstation (Figure 2, bottom). The setup was a work-in-progress that developed over 42 months. Starting with courses on web design and the purchasing of one build-it-yourself 3D printer kit, 3D printing was not something that the educators imagined would become a flagship program or would support youth to become staff members. According to the adult staff, the makerspace members "oddly wandered unknowingly into becoming 3D printing experts."

Encounters that produced materialized development
3D printing developed into the elaborate workstation through three key material reconfigurations that spurred new encounters among people and things, producing new learning opportunities for Darnel and other makerspace youth and driving further material changes. Each iteration drove the next as each changed Darnel's position at the makerspace and produced new educational programs (Figure 3). Together, we theorize this as a new notion of the role of materials in development.

The first material development that drove possibilities for encounters of Darnel and the 3D printers started with the assemblage of a build-it-yourself 3D printer kit. Staff members recalled that the makerspace purchased the kit to explore the emergent technology and asked Darnel, a youth member, to assemble it: "It took eight weeks of muddling through terrible documentation trying to figure out what nuts and bolts are, (…) not having a lot of experience with that stuff." The online video of the assemblage process shows Darnel seated among 3D printer parts, consulting online resources on a tablet and laptop computer simultaneously, and makerspace educators occasionally assisting the youth in identifying and holding parts for assemblage. Honoring Darnel's role in the construction of the first 3D printer, the video's last frame features Darnel and a makerspace educator posing in front of the finished product. The 3D printers and projects were visible throughout the space, and curious youth wanted to try 3D printing, producing a need to facilitate *3D printing workshops,* learning opportunities for all youth at the makerspace. Staff said: "to meet that increased demand we scaled up our printers." They ordered *many 3D printers* of the same kind because "they're one of the most reliable and most affordable printers on the market" for establishing a 1-to-1 experience, and could be self-assembled for in-house repair. That potential for self-assembly of the printers encouraged further wrestling among screwdrivers, printer pieces and Darnel. Within four months, the single 3D printer workstation expanded into several printers that were positioned on wheeled tables throughout the room. The expansion of the 3D printers produced a *technology-savvy youth*, who, according to staff, was "able to get the printers to respond."

The second material development occurred from months 4–21, when the 3D printers gathered into a row, breaking the preceding material form. Staff recalled: "We set it up as its own corner so we could manage the materials related to that [in one location]." They wheeled together the

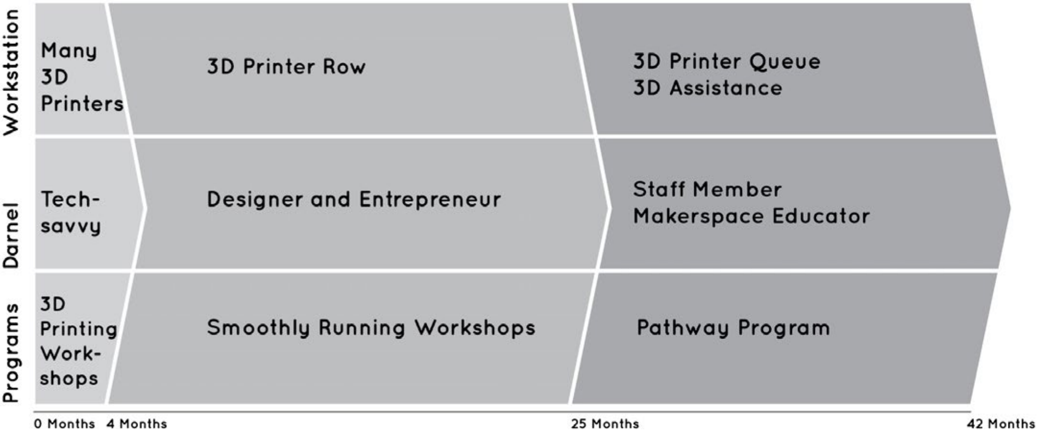

Figure 3: The material development of the 3D printer workstation and the learning possibilities it produced for Darnel and other youth over 42 months

printer tables, producing the *3D printer row* (Figure 4). During a site visit, we observed that some 3D printers remained scattered as if leaving the possibility open to return to the prior setup.

We also observed Darnel designing with 3D printers, creating 3D models and watching them materialize. Educators explained that Darnel initiated a 3D printing business for fabricating and selling phone cases. The business emerged in response to the abundance of 3D printers, Darnel's engagement with them, and the possibility of printing in larger volumes. As workstations and youth formed relationships, Darnel's business provided an opportunity for him to become a 3D printing *designer and entrepreneur.* The makerspace staff welcomed this development, posing for pictures on Darnel's business website and providing the opportunity for Darnel to present his work at a TEDxYouth event as well as the first White House Maker Faire as an example of the possibilities afforded by new fabrication technologies.

On regular days, we observed that 3D printing workshops called youth to design 3D models and to carry their designs to the 3D printer row on flash-drives. Here, manual file management produced file mix-ups and prolonged waiting as busy printers clogged and required repairing. Simultaneously, the demand for 3D printing skyrocketed, and staff commented: "I'm not sure if we always made a choice about wanting to do it as much (as) it's our most in-demand topic. (…) We needed (…) to print 30 or 20 key-chains in two hours, and you can't do that with just 3D printers." This required them to automate the steps of the process and to produce more *smoothly running workshops* so that more youth could follow Darnel's lead.

The third material development was marked by the expansion of the 3D printer row into the 3D printer queue as well as assistance service, across 17 months. The staff created a queuing-software that physically connected the printers and distributed prints across them all. Staff explained what the workstation expansion produced: "The kids work on [a file] and then drag it into a website and it uploads to the printer queue and then there's a queuing system that's managing all of that." On a material level, staff removed wheels from the tables and double stacked and stocked them with 3D printers. This was a point of stabilization as staff transformed a potentially moveable workstation into a stationary one and further tied 3D printing to a specific location. Staff explained that, from this point forward, 3D printing reached an ultimate high: "We were having groups of 25 youth come in (for) 3D printing field trips. And we were having up to three or four field trips a week (…) and [all participants left] with a 3D-printed keychain." The 360°

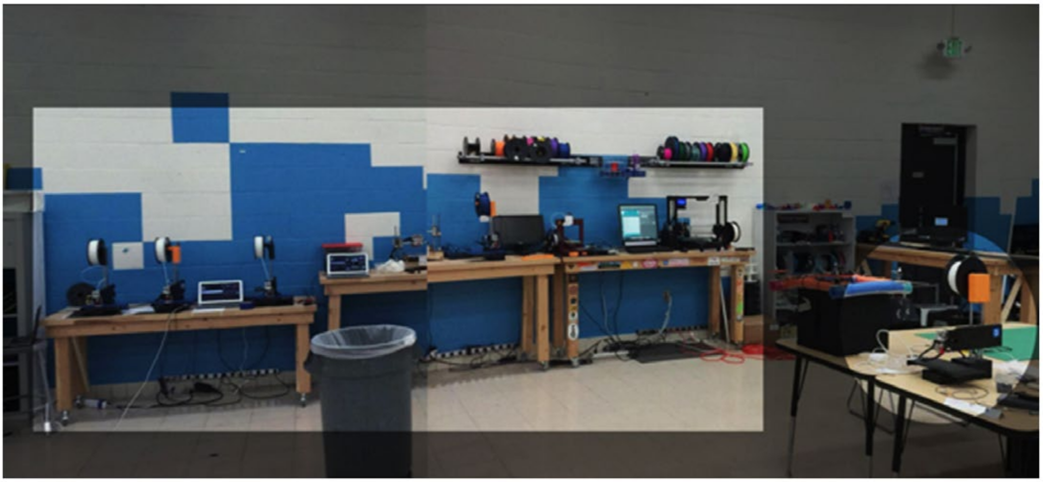

Figure 4: The 3D printer row (rectangle) and a scattered 3D printer (circle)

photographs corroborated the staff's report about increased 3D printing, showing many more 3D prints throughout the space. To accommodate maintenance needs, the workstation expanded further with the 3D assistance service. This setup required a technician who walked between both stations, creating a living link. At this time, Darnel had started college and no longer tended to his printing business instead focusing on new hardware assemblage projects, including 3D scanners. The new need for additional staff produced by the 3D assistance service, combined with Darnel's personal relationship to the 3D printers and his need to pay college tuition, drove the opportunity for Darnel to join the makerspace as its first African-American staff member. He became the person in charge of 3D printing. The evolution of the youth from user to staff member changed who had a say in the space and Darnel's physical and social position at the makerspace. Darnel became a link that tied the 3D printer queue and the 3D assistance service together. Staff recalled: "He came to us and said 'my team is okay but I think I need more.' (…) So, he put together a job description for five interns. He did a casting call for his interns." Encounters of Darnel and the reconfigured 3D printing workstation produced new learning opportunities for Darnel and other youth. Darnel experienced responsibility of leading a team and other youth could join the team. The makerspace administration highlighted the entanglement between the workstation and Darnel as a marker of organizational growth: "now we are working to build out (…) pathways so more of our kids can have opportunities like that." Establishing a *pathway program* would offer experiences for other youth to take on responsibilities and to encourage similar encounters in relation to other emerging technologies, such as laser cutting.

The expanded 3D printer queue plus assistance, Darnel's change to staff member, and the pathways program were consequences that were galvanized by one 3D printer over 42 months. This represents a materially driven longer-term development that had significant consequences for possible youth learning. The expanding workstation drove emergent programmatic goals of the makerspace (eg, pathway programs) that could become crucial to the space's functioning and made room for youth to have a voice in the makerspace administration.

Materials-to-develop-with

The long-term development of the material produced changing encounters and learning possibilities that drove the development of youth and programs, which, in turn, drove the further material reconfiguration of the workstation, and that co-developed with the youth. The presented case of the makerspace and Darnel's development did not contradict the underlying assumptions of objects-to-think-with about learning, designing and capturing; instead, it revealed additional aspects that warrant an extension of the concept. The materials that the workstation was composed of acted as "materials-to-develop-with," physical objects that fostered the development of internal structures *and* co-develop with people over longer periods of time. The idea of MTDW expands the theoretical notion of objects-to-think-with to encompass reconfiguring materials in the development of people, the design of reconfigurable makerspaces and the capturing of learning in technology-rich environments.

Darnel formed a personal relationship with 3D printers and shifted this understanding into the building of other technological tools and entrepreneurial opportunities. In addition to seeing Darnel as an agentic designer and learning as the cognitive internalization of mental structures that are mediated through materials, what kept learning going was the opportunity to reconfigure the workstation. The youth did not outgrow a single 3D printer, rather the continued development of the workstation prompted new opportunities for the development of the youth and its own re-configuration. Material changes were a developmental product that was part of and continued to drive human development. Development happened across the spectrum of people, material and programs rather than only to humans.

The reconfigurable workstation, made possible through the crucial purchase of self-assembly 3D printer models, continued to produce new encounters and with them new possibilities for development of itself (ie, 3D printer queue), the youth (ie, Darnel becoming a staff member), and the educational initiatives (ie, pathway programs). MTDW calls to broaden design from a practice of learning with materials that have been purposefully selected to guide the internalization of particular ideas (ie, the design approach that follows from the notion of objects-to-think-with) to making room for materials to act over longer periods of time. In practical terms, the new notion reminds designers to work towards keeping the emergence of new learning possibilities going.

Materially driven development at the makerspace was slow and recognizing that development required seeing materials as active. While the idea of objects-to-think-with directs the researcher's attention to the acting youth and how design serves the youth at the level of the activity, MTDW calls for tracing changes over longer time periods and across learning spaces in order to identify traces of material re-configurations (ie, development) over time. MTDW suggests that capturing learning in evolving technological environments requires taking a broader look at what can be understood as learning in relation to time and space because individual learning is entangled with material and spatial development.

Discussion and implications

This paper captured the materialized development of an out-of-school makerspace, its programs, and one youth in relation to the physical change of a 3D printer workstation from a single printer into an elaborate workstation that expanded who made decisions and how learning was practiced. Our analysis identified the notion of material-to-develop-with, which encompasses the co-development of people and materials over longer periods of time. This builds on and extends constructionist notions of objects-to-think-with (Papert, 1980) and the idea of material manipulation as medium for internalizing thinking. Where such constructionist notions, particularly the idea of objects-to-think-with, have been productively taken up in the maker movement to direct the design of makerspaces that foster specific constructs, MTDW represents a step towards a theoretical understanding of the unique possibilities that the maker movement contributes to education.

MTDW has implications for the design of makerspaces and extends earlier constructionist approaches for theorizing and designing learning in youth-serving makerspaces that highlight intentional inclusion and maintenance of particular materials (Litts, 2015; Vossoughi *et al.*, 2016) by suggesting a flattened and slow approach that embraces material reconfiguration as a way to sustain learning. Being aware of the power of MTDW can help foster the design of possibility-rich spaces and track the co-development of materials and people without choosing particular educational agendas from the start and investing resources into maintaining them. This is of particular importance for makerspaces, given that they are often intended to be at the forefront of new technologies and innovation, presenting unique opportunities for this type of youth development. Specifically, the theoretical notion of MTDW may stir makerspace educators to choose materials that encourage emergent changes in spatial set-ups, such as tables on wheels, and furniture and technologies that require assembly, and to make room for projects and materials to linger. Further, the notion suggests that new makerspaces should cultivate the placement and use of materials alongside existing and emergent local needs in order to lay the groundwork for potential leaps in the co-development of the makerspace and its youth participants.

Further work is needed to strengthen our understanding of this expanded role of materials in the development of people that considers the notion of MTDW in other makerspace settings (eg, museums, libraries, schools), disciplinary contexts, and a broader range of workstations (eg, laser cutters, sewing stations), including materially controlled setups (ie, without much change). This includes work that considers challenges of re-configurative material set-ups (eg, possible safety hazards) and examples of emergent possibilities that might conceal diversity.

Further work is also needed to identify methods for listening to materials and the educational possibilities they produce. As image-capturing technologies continue to evolve, including 360° still and moving images of spatial arrangements, these technologies could point towards methodological innovations for educators and researchers to capture and analyze developmental phenomena around MTDW in order to design spaces that co-develop with humans and that broaden diversity in makerspace leadership. Theoretical conceptions like MTDW are imperative to understanding the developmental effects that new and emerging technologies may have on humans as we continue to introduce such technologies into educational settings.

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Statements on open data, ethics and conflict of interest

The data of this study can be made available upon request. The Institutional Review Board at Indiana University approved this study. Informed consent was obtained from all adult and youth participants and youth guardians. Pseudonyms were used for individuals. The authors have no conflict of interest.

References

Barad, K. (2003). Posthumanist performativity: Toward an understanding of how matter comes to matter. *Signs*, *40*(1), 801–831.

Bassey, M. (1999). *Case study research in educational settings*. London, UK: McGraw-Hill Education.

Blikstein, P. (2013). Digital fabrication and 'making' in education: The democratization of invention. *FabLabs: Of Machines, Makers and Inventors*, *4*, 1–21.

Buchholz, B., Shively, K., Peppler, K., & Wohlwend, K. (2014). Hands on, hands off: Gendered access in crafting and electronics practices. *Mind, Culture, and Activity*, *21*(4), 278–297.

Duckworth, E. (1972). The having of wonderful ideas. *Harvard Educational Review*, *42*(2), 217–231.

Halverson, E. R., & Sheridan, K. (2014). The maker movement in education. *Harvard Educational Review*, *84*(4), 495–504.

Hultman, K., & Lenz Taguchi, H. (2010). Challenging anthropocentric analysis of visual data: A relational materialist methodological approach to educational research. *International Journal of Qualitative Studies in Education*, *23*(5), 525–542.

Kafai, Y. B., Peppler, K. A., & Chapman, R. N. (2009). *The computer clubhouse: Constructionism and creativity in youth communities*. New York, NY: Teachers College Press.

Keune, A., & Peppler, K. (2017). Maker portfolios as learning and community building tools inside and outside makerspaces. In B. K. Smith, M. Borge, E. Mercier, & K. Lim (Eds.) *Making a difference: Prioritizing equity and access in CSCL: The International Conference on Computer Supported Collaborative Learning (CSCL) 2017, Volume 2* (pp. 545–548). Pittsburgh: International Society of the Learning Sciences.

Keune, A., & Peppler, K. (2018). A self-made woman: Materiality of maker portfolio practices for STEM Identity Development. SIG-Learning Sciences. Paper presented at the Annual Meeting of the American Educational Research Association (AERA), Annual Meeting, New York, NY.

Lenz Taguchi, H. (2010). *Going beyond the theory/practice divide in early childhood education: Introducing an intra-active pedagogy*. New York, NY: Routledge.

Lenz Taguchi, H. (2011). Investigating learning, participation and becoming in early childhood practices with a relational materialist approach. *Global studies of childhood*, *1*(1), 36–50.

Lenz Taguchi, H. (2012). A diffractive and Deleuzian approach to analyzing interview data. *Feminist theory*, *13*(3), 265–281.

Litts, B. K. (2015). *Making learning: Makerspaces as learning environments* (Doctoral dissertation). The University of Wisconsin-Madison.

Papert, S. (1980). *Mindstorms: Children, computers, and powerful ideas*. New York, NY: Basic Books.

Papert, S. (1993). *The children's machine: Rethinking school in the age of the computer*. New York, NY: Basic Books.

Peppler, K., Maltese, A., Keune, A., Chang, S., & Regalla, L. (2015). The maker ed open portfolio project: Survey of makerspaces, Part II. *Open Portfolios Research Brief Series 1*. Oakland, CA: *Maker Education Initiative*.

Peppler, K., Halverson, E., & Kafai, Y. B. (2016). *Makeology: Makerspaces as learning environments*. New York, NY: Routledge.

Resnick, M., & Rosenbaum, E. (2013). Designing for tinkerability. In M. Honey & D. E. Kanter (Eds.), *Design, make, play: Growing the next generation of STEM innovators* (pp. 163–181). New York, NY: Routledge.

Sheridan, K., Halverson, E. R., Litts, B., Brahms, L., Jacobs-Priebe, L., & Owens, T. (2014). Learning in the making: A comparative case study of three makerspaces. *Harvard Educational Review*, *84*(4), 505–531.

Vossoughi, S., Hooper, P. K., & Escudé, M. (2016). Making through the lens of culture and power: Toward transformative visions for educational equity. *Harvard Educational Review*, *86*(2), 206–232.