Professional Statement: Stefanie Mueller (MIT EECS)

Research Area: Advancing Personal Fabrication by Drawing a Parallel to the Evolution of Computing
I advance the field of personal fabrication by drawing a parallel to the evolution of computing over the last decades. Computing has revolutionized how we process and interact with data today, unfortunately, these capabilities are constraint to the digital realm and cannot yet be applied to physical matter. Being able to manipulate physical matter similar to digital content is a difficult problem and requires interdisciplinary solutions in algorithms, hardware, and materials. I address these challenges with my research team along the following dimensions:

Prior to starting at MIT, I demonstrated how interaction principles from computing, such as direct manipulation, can be applied to the design of physical objects by reshaping physical matter continuously while users gesture a desired shape [1, 2, 5, 6, 7, 8, 9]. I’m now broadening this research agenda to other areas of computing, including: (1) how we can update the appearance of physical objects similar to how we can update digital content [3, 10], (2) how we can add computing capabilities to objects by enhancing them with seamlessly integrated sensors and displays [12], (3) how we can enable the download of not only music and video but also functional objects that work right off the fabrication bed, and (4) how we can use principles from WYSIWYG (what-you-see-is-what-you-get) to create unified prototyping environments for objects [13, 14].

#1 Updating Physical Objects: Reprogrammable Color Textures
I envision a future in which physical objects can be “updated” as easily as digital content can be changed today. Consider the ease at which a digital photo can change its appearance by applying a digital filter or adding/removing visual elements. Now imagine the same principle applied to physical objects, i.e. that our clothing can change its color on a daily basis and that product shops are able to showcase different visual designs to customers without the need to have all versions on stock. To enable this vision, my research team developed a method to reprogram the appearance of objects using photochromic dyes. Photochromic dyes are programmable materials that can switch their appearance from transparent to colored when exposed to UV light and switch back to transparent when exposed to visible light, such as from a regular office projector. Since the dyes are bi-stable, they remain in their colored state even when removed from the light source. While prior work had investigated single color textures of either fully saturated or desaturate state, my research team is the first to develop a multi-color method with fine control over each color-channel. For our work, we received the ACM UIST 2019 Best Paper Award [3]. Below, I detail the major development steps to create the reprogrammable multi-color textures.

Figure 1. (a) 3D printed voxel pattern with one color per voxel (ColorMod [10]), (b) A single CMY mixture that deactivates color channels using different absorption spectra of each dye, which enables high-resolution multi-color textures (PhotoChromeleon [3] ACM UIST 2019 Best Paper).
Our first approach to achieve a reprogrammable multi-color texture was to 3D print cyan, magenta, and yellow photochromic dyes as individual voxels across the surface of an object (Figure 1a, ColorMod [10] ACM CHI 2018). To change the appearance of the object after 3D printing finished, we first saturated each voxel with UV light and then selectively desaturated the voxels that were not part of the final appearance using a projector. While this allowed us to demonstrate the concept, the method was low-resolution, limited to a few discrete colors, and required a specialized 3D printer with 4+ materials.

Our second approach solved these issues by mixing cyan, magenta, and yellow (CMY) photochromic dyes into a single solution and leveraging the different absorption spectra of each dye to control each color channel in the solution separately using the different wavelengths from the projector (PhotoChromeleon [3] ACM UIST 2019 Best Paper Award). For instance, red light from the projector desaturates cyan and as a result, only magenta and yellow remain visible to the human eye, resulting in red. Using this principle as the underlying mechanism of our optimization algorithm, we were able to create high-resolution textures from only a single material (Figure 1b), eliminating the limitations from our prior work. Moving forward, we are investigating how to improve our approach concerning two key aspects:

Updating Individual Pixels Rather than Erasing Entire Texture: Our current approach has to erase the entire texture before applying a new one since it uses a single UV light that cannot address individual pixels. We are currently solving this issue with a new hardware setup that uses a UV projector instead of a UV light and a new optimization algorithm that transitions pixels directly from one color to a new target color (ChromoUpdate, planned for ACM CHI 2021).

Eliminating the External Light Source by Using Integrated LEDs: Our current approach requires an external light source (UV/visible light projector), which has been a limitation for real-world applicability. We are currently working with Advanced Functional Fabrics of America (AFFOA) to build a solution in the application domain of fibers. By integrating UV+RGB LEDs inside a fiber during the fiber drawing process and then coating the fiber with the photochromic CMY mixture, we can create textiles that have the ability to change their color without the need for an external projector (ChromoFiber, planned for ACM CHI 2021).

### Integrating Computing Capabilities into Physical Objects

One of the largest open challenges is how to seamlessly integrate computing into the physical environment that surrounds us until the two are indistinguishable from one another [11]. If solved, our physical environments, such as furniture, rooms and entire buildings, are able to sense our interaction with them and react by adjusting their appearance using seamlessly integrated displays. However, to date it is unclear how to best fabricate such seamlessly integrated sensors and displays, which require the materials to be both applicable to large scale surfaces and to adhere to different surface materials and onto irregular surface geometries.

Spraying User Interfaces: To address these challenges, my research team developed a new fabrication technique that is not bound to a particular fabrication volume and that is non-contact and thus can adhere the materials to various surface textures and
surface geometries, such as those with strong curvatures and sharp angles. Our new fabrication technique is based on spraying of functional inks (Sprayable User Interfaces [12] ACM CHI 2020), i.e. by airbrushing conductive, dielectric, and phosphor inks, we are able to seamlessly integrate input elements, such as buttons and sliders, as well as displays across entire rooms. Moving forward, we are investigating how to extend the repertoire of functional inks that we can use to create a larger variety of sensor and display elements and how to automate the process to speed up the integration of computing capabilities into large-scale environments.

#3 Download and Print: Fabricating Fully Self-Deploying Devices
Today, users can already download images, video, and music, and with the increasing distribution of 3D printers they can also download and print simple decorative objects. However, to date, users are not able to download fully functional objects with electronics and computing on board that work right off the fabrication bed. A lamp made with such a technology would be able to turn on right after fabrication and a quadrotor would be able to fly itself off the fabrication platform.

![Image of LaserFactory](image)

**Figure 3. LaserFactory: Once the last trace is cured, devices are functional and self-deploy.**

*Self-Deploying Devices:* To enable the fabrication of self-deploying devices, my research team augmented a laser cutter with the ability to create circuit traces, pick-and-place components, and solder them in place, all using a single add-on that attaches to the laser head (LaserFactory, submission planned for ACM CHI 2021). Users only have to download the design file and load it into the laser cutter software, our fabrication technique then creates the device by cutting the geometry, dispensing silver traces, picking and placing components, and curing the traces with the laser. Once the last wire connection is cured, the devices are functional, i.e. the lamp turns on and the quadcopter lifts off the fabrication platform. Moving forward, we are extending our approach to create self-improving devices that after fabrication finished, can sense their own performance in the world and subsequently instruct the fabrication machine to adjust their own geometry and electronic circuitry as needed.

#4 WYSIWYG: Creating Unified Prototyping Environments
In computing, the what-you-see-is-what-you-get (WYSIWYG) paradigm refers to editing environments that allow content to be edited in a form that mirrors its final appearance. For instance, a web editor with WYSIWYG allows users to edit a website by dragging around its images and text rather than by modifying the underlying code. In physical prototyping, however, users are rarely designing on a representation that mirrors the final appearance of the fabricated object, instead users have to use many low-level and disjoint tools. In addition, current editors do not provide feedback if a design is feasible given the available materials and components. To address this issue, my research team developed several editing tools that integrate steps of the fabrication pipeline into one unified editor to provide the user with a better preview of their final fabricated design.
Previewing Fabrication Constraints: When creating laser-cut objects, users must often consider whether their design can be made with the materials they have available. While tools exist for helping users with preparing their design for fabrication once it is complete, tools that do so while the design is in progress are unexplored. To demonstrate the potential of such an integrated design tool, we developed Fabricaide (planned for submission to ACM CHI 2021). Fabricaide continuously analyzes the user’s design as it is being drawn, and decides how shapes should be placed on existing material sheets. It also provides substitute materials if users run out of material.

Previewing Sensor Fit with Object Geometry: To date, it is difficult for designers to consider how electronic components can be integrated with the shape of a physical design. To address this issue, we developed MorphSensor [14] (ACM UIST 2020), a 3D electronics editing environment that allows designers to morph sensor modules of pre-defined shape into freeform modules that better integrate with the shape of a prototype. Since MorphSensor builds onto existing schematics that define which electronic components are required and how they need to be connected, it reduces the task of creating a freeform sensor arrangement to simple translate and rotate operations for placing the components.

Previewing Electronic Component Layouts on Physical Prototypes: Finally, to allow designers to prototype the layout of electronic components directly on a physical object, we developed a fabrication method that integrates breadboards directly into the surface of physical prototypes. CurveBoards [13] (ACM CHI 2020) allow designers to exchange and reposition electronic components while being able to evaluate the outcome of their design decisions directly in the context of the physical prototype. Since CurveBoards are functional, i.e., the displays are showing content and the buttons take user input, designers can test interactive scenarios and log interaction data on the physical prototype while still being able to make changes to the component layout as needed.

Moving forward, we are investigating how to further integrate information on the fabrication process into the modeling environments, including editing tools that are fabrication-aware, and modeling environments that are augmented with fabrication data based on prior fabricated objects.
Impact: For my research, I have received an ACM UIST 2019 Best Paper Award, a Microsoft Research Faculty Fellowship, a Sloan Fellowship, and an NSF CAREER Award. I was also named a Forbes 30 under 30 in Science. My work has resulted in more than 100 press articles in news outlets such as MIT News, the New Scientist, The Atlantic, CNN, BBC, The Tech Times, Engadget, Gizmodo, Make Magazine, and Wired. I have given more than 50 invited talks about my research at universities and research labs. Finally, my work has attracted many industry partners with whom I’m working closely together to transfer my research into real-world applications, including Ford-Automotive to develop a re-programmable coating for cars, with Benjamin Moore to develop a re-programmable wall paint for color-changing rooms, with New Balance on a fabrication process for re-programmable shoes, and with AFFOA on color-changing yarns for use in clothing and textiles.

Teaching: At MIT, I developed a new undergraduate course “6.810 Engineering Interactive Technologies”, which was first offered as a special subject in fall 2017 and which is now a permanent subject annually offered in the fall semester. In the spring semester, I co-instruct “6.08 Interconnected Embedded Systems” with 200-400 students per offering. For my teaching, I was recognized with MIT EECS’s Outstanding Educator Award and received a Teaching with Digital Technologies Honorable Mention Award. My teaching and research activities are tightly integrated, i.e. after taking my classes many undergraduates and master students join my lab. Out of the 30 undergraduate and master students I advised, 18 students co-authored research papers and 5 students received MIT EECS research awards (MIT EECS SuperUROP Outstanding Research Award for Yunyi Zhu, MIT EECS Licklider Best UROP Award for Xin Wen and Carlos Castillo, MIT EECS Morais & Rosenblum Best UROP Award for Aradhana Adhikari, and MIT EECS Charles and Jennifer Johnson Best MEng Thesis Award for Kenneth Friedman).

Service: Within the Human-Computer Interaction research community, I have held many leadership roles for the premier conferences ACM CHI and ACM UIST. I have been an ACM CHI Subcommittee Co-Chair in 2019/2020 leading a program committee of 60 faculty and coordinating the review process of more than 400 papers. In a similar role, I served as the Technical Program Co-Chair for ACM UIST 2020, leading a program committee of 68 faculty and overseeing 450 paper submissions. In the field of fabrication, I served as the General Co-Chair for the “ACM Symposium of Computational Fabrication” (ACM SCF), an event founded in 2016 and now annually held with around 150 attendees. As the second General Co-Chair in 2017, I worked with ACM to convert the non-affiliated conference into an ACM conference with a new technical papers program and archival proceedings in the ACM Digital Library (see “1st Proceedings of ACM SCF” [4]). To further help the field of fabrication grow, I created a proposal for a new ACM CHI Subcommittee called ‘Interactive Hardware: Devices, Materials, and Fabrication’, which is currently under approval by the ACM CHI Steering committee. At MIT CSAIL, I’m serving as the Head of the “Human Computer Interaction Communities of Research” (HCI CoR). The HCI CoR consists of nine HCI faculty members and 25 postdocs and PhD students. Within the HCI CoR, my responsibility is to ensure that the CoR’s central activities, such as graduate student admission, graduate student review and mentoring, curriculum building, the seminar series, and other shared research and community-building activities, are carried out according to the goals of the CoR. For MIT’s EECS Department, I organized the ‘Rising Stars in EECS’ workshop in 2018, an academic career workshop for women pursuing PhD degrees who will be on the job market the following year. Together with my co-chairs, we reviewed more than 350 applications across all areas of Computer Science and curated a program consisting of more than 35 female panelists and keynote speakers with 70 PhD students attending the sessions.
References


