Anna Vallgårda, IT University of Copenhagen
Laurens Boer, IT University of Copenhagen
Vasiliki Tsaknaki, KTH Royal Institute of Technology
Dag Svanæs, University of Copenhagen and
Norwegian University of Science and Technology

Material Programming

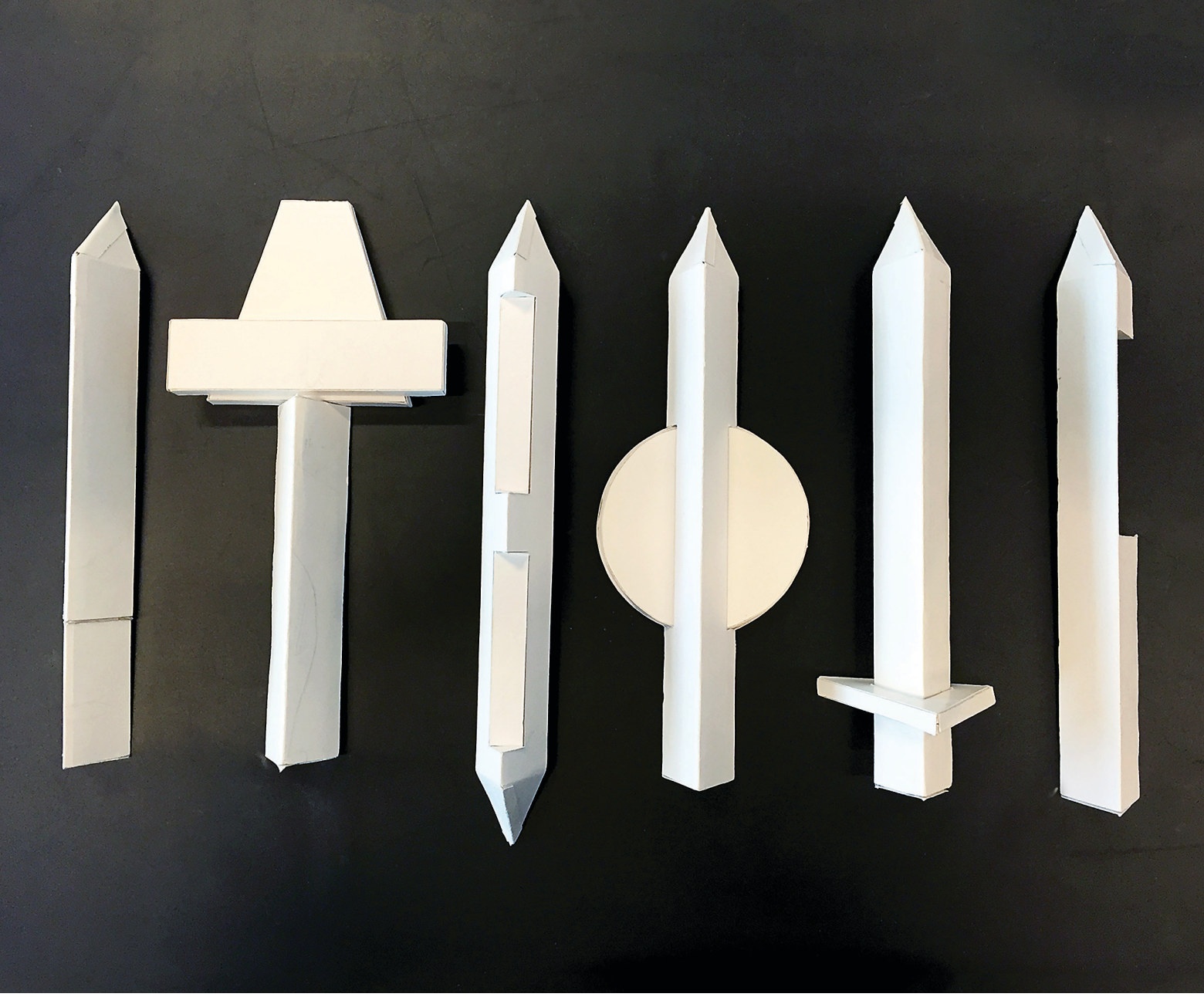
Insights

- Material programming is a proposal for how we are going to practice interaction design in the future, when graphene transistors make genuine computational composites possible.
- Material programming is an embodied form of programming that supports kinesthetic creative practices.

In the near future, smart materials will have computational power embedded in the form of graphene transistors or nanotubes [1]. These will be the ultimate *computational composites*: materials that hold classic material qualities, such as structural durability, flexibility, texture, weight, and color, but that are also capable of sensing, actuating, and computing [2]. Indeed, computers will not be things in and of themselves, but rather will be embedded into the materials that make up our surroundings. This also means that the way we interact with computers, and the way we program them, will change. Consequently, we ask what the practice of programming and giving form to such materials would be like. How would we be able to familiarize ourselves with the dynamics of these materials and their different combinations of cause and effect? Which tools would we need, and what would they look like? Would we program these computational composites through external computers and then transfer the code to them, or would the programming happen closer to the materials? In this article, we outline a new research program that floats between imagined futures and the development of a material programming practice [1].

ENVISIONING A MATERIAL PROGRAMMING PRACTICE

Central to the practice of interaction design is crafting the couplings and relations between user actions and artifact functions. To design interactive artifacts therefore requires



an understanding of the potential dynamics between sensory and actuating mechanisms in the materials with which we design. It is a matter of getting a feel for the potential compositions of cause and effect. Gaining such embodied understanding, however, is really possible only through explorations with the materials we are using for design. As the variety and complexity of computational composites rise over the coming decade, it will become pertinent to develop a design practice that enables the designer to maintain this level of exploration. We envision material programming becoming such a practice [1].

Supporting kinesthetic creative practice. Material programming would complement traditional crafting of physical form with the crafting of temporal form; together they would make up the future practice of interaction design [2]. Indeed, material programming would be a programming practice that enables the designer to stay in the material realm. The designer would program directly on the material and thus have first-hand access to explore and experience the outcome of different interactive compositions. It would minimize the distance between programming and execution, and provide the designer (programmer) access to real-time situated experiences of causes and effects. This immediacy would bridge the intellectual and physical gap we know from other detached programming practices and offer an opportunity for kinesthetic thinking [3].

Tools for material programming. A material programming practice would be a programming practice using physical tools. With tools in hand, working directly with the material, the designer would be able to achieve an embodied sense of its interactive and expressive properties. Such tools would each have a specific function designed from the designer's point of view, rather than from a programming-logic point of view. By limiting the scope for each tool's action space, it would also be possible to create rather sophisticated tools. Such tools might require some learning and expertise, but we assume that professional interaction designers would be willing to invest the necessary time and effort. These tools would not demand highly technical skills from the designer, however, only interaction

design skills. Essentially, we imagine a future design practice in which we use traditional material tools and machines to develop the physical form of the designs, and material-programming tools to develop the temporal form of the interactive artifacts.

Situated and real time. Material programming would happen on-site instead of through a detached desktop computer, with physical tools working directly on the materials. This would lower the threshold for designers to truly explore the potential of a new material in context and thus give them a better sense of the design space. Such expanded support of kinesthetic creative practice and bespoke designs would likely result in more sophisticated expressions, fitted to their context of use. Material programming would, however, be limiting if it were the only means of programming interactive artifacts. Therefore, we envision integration with more complex back-end algorithmic programming and access to databases when needed. In that sense, material programming can be seen as a kind of interface programming. Yet in some cases there may not be any back-end at all, and the interactive artifacts could be designed from working with these computational composites alone.

SKETCHING A MATERIAL PROGRAMMING PRACTICE

To give a better sense of what we mean by tools for material programming, we present here some sketches of physical tools for programming computational composites. In order to convey the functionality of these tool sketches, we assume the existence of a very particular computational composite: a shape-changing material that can respond to airflow. We imagine this computational composite to be used in interior design and architecture, for instance in interactive facades or in furniture (Figure 1). Through speculating and enacting the practice of shaping the behavior of this composite, we discuss qualities of what material programming for interaction designers could look like.

For instance, we suggest that the tools needed for programming shape changes are a Select tool and a Force tool (Figure 2). The Select tool is used to indicate which area of the material is activated for programming by brushing over it. The Select tool can also be used for copying and pasting a programmed area to other areas. The Force tool is used to program the shape-changing behavior with respect to when, where, and how force should be applied in the material by simulating a pulling motion. Both tools are inspired by known techniques for manipulating materials, such as brushing (selecting) and pulling (moving). To minimize the distance between programming and execution, the tools work on the material by wirelessly connecting to its embedded computational power. The material is activated when the tools come into close proximity with it. This allows for the exchanging of information between the tool and the material. Similarly, moving the tool away from the material will "disconnect" the embedded computers and the tool.

Where this particular material is concerned, we are interested in

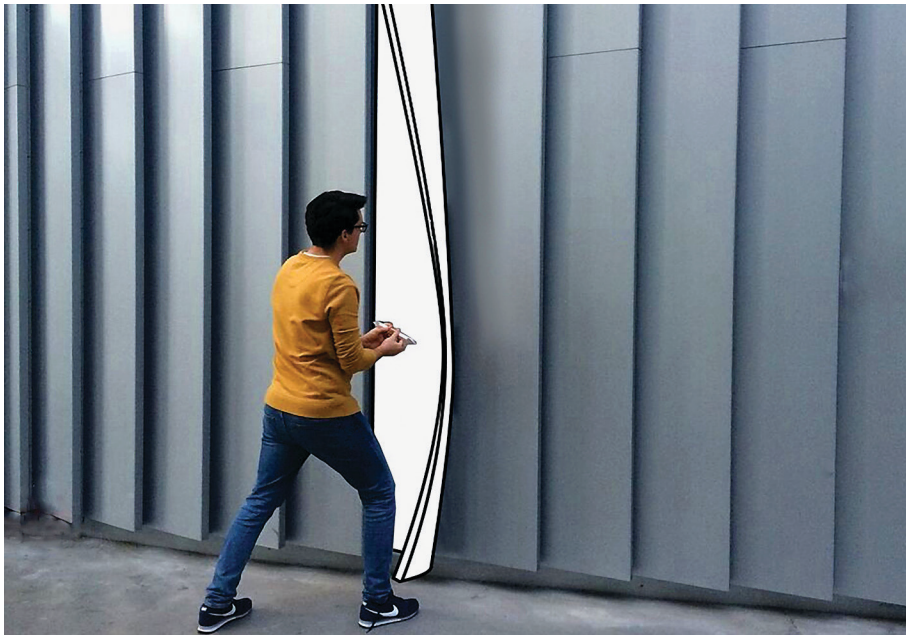


Figure 1. Illustration of the embodied practice of programming a shape-changing material.

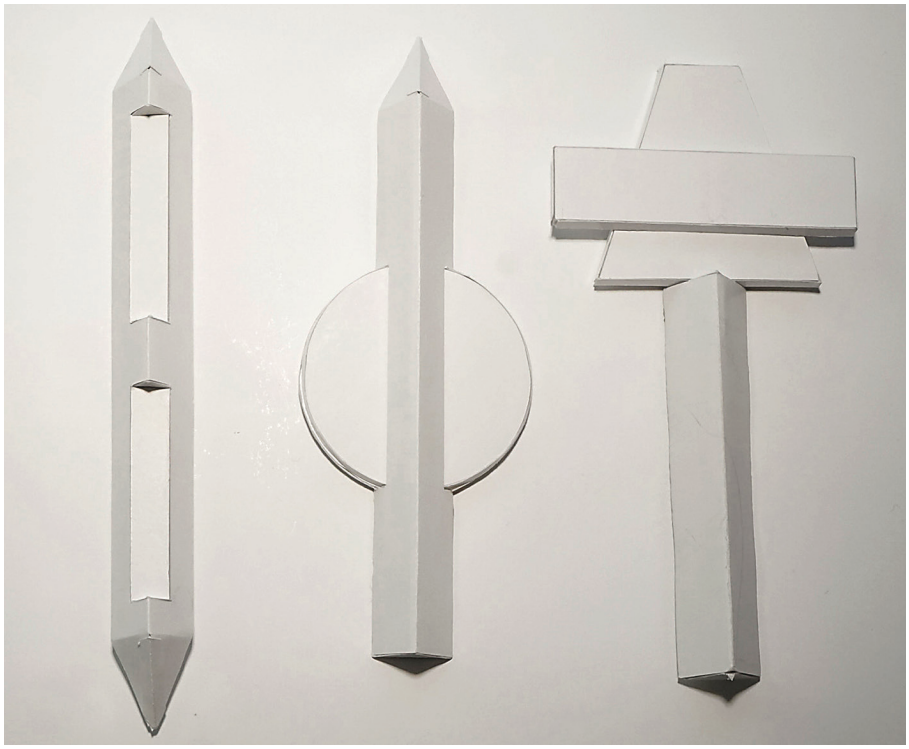


Figure 2. Sketches of three tools for material programming. From left: the Force tool, the Color tool, and the Select tool.

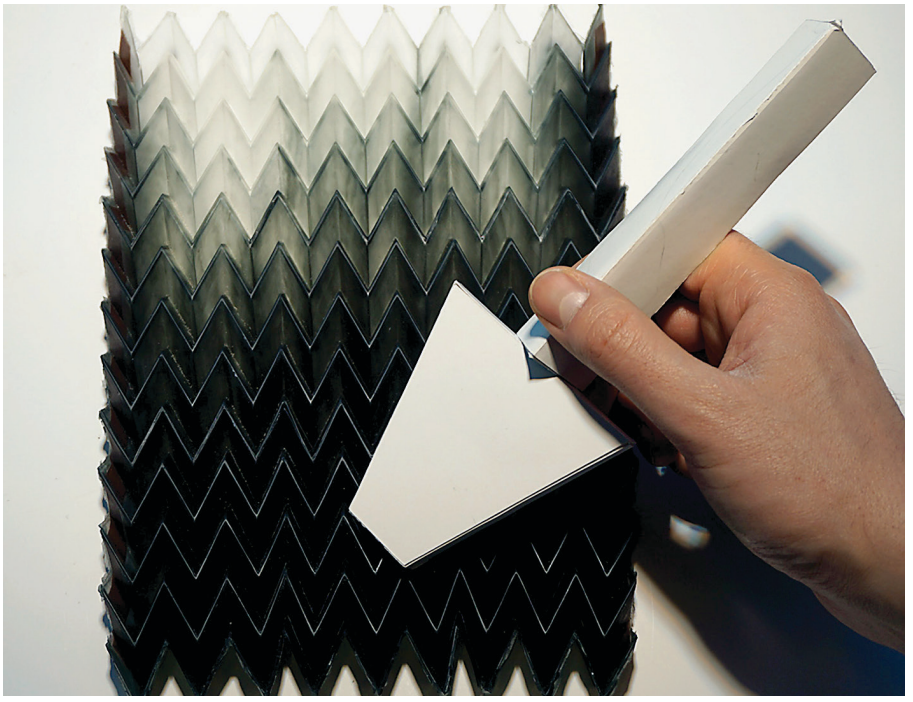


Figure 3. Sketch of the Select tool used on a shape-changing material.

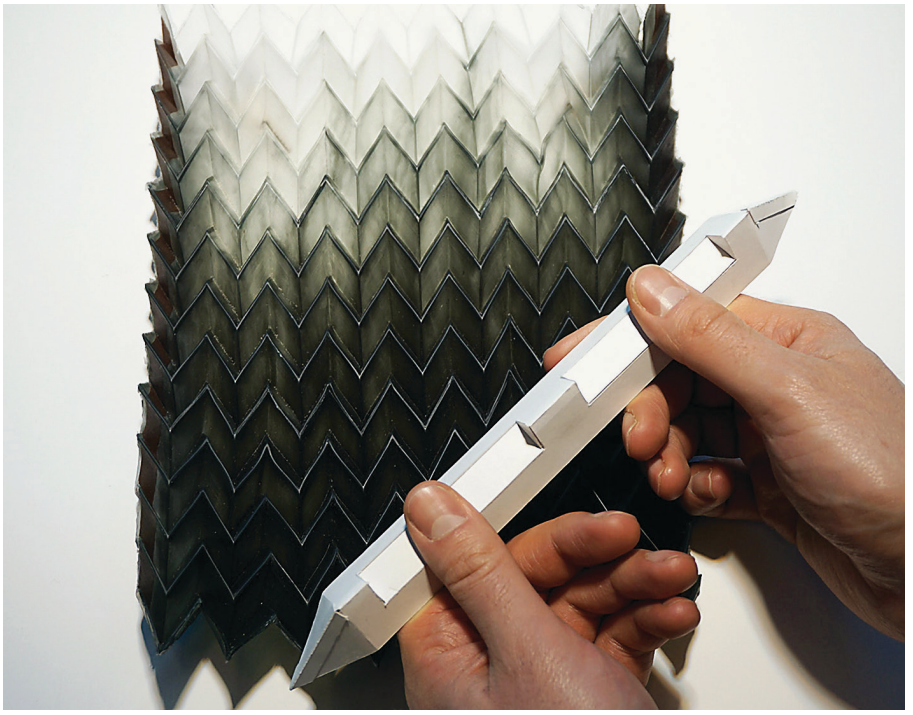


Figure 4. Sketch of the Force tool used for programming a shape-changing material.

programming the relationship between the airflow and a resulting shape change in the material. The first step is therefore to select the area that should change its shape by brushing over it with the Select tool (Figure 3). By adjusting the distance measure on the tool, areas of the material larger than the range of one's arms can be easily selected. This would be needed if the design demanded a large material surface. Using the Select tool allows the designer to program different behaviors into different parts of the material. The next step is to connect the Force tool to the material. Independently of input, the designer can begin exploring the expression space of the shape changes and become familiar with the expressive properties of the particular computational composite (Figure 4). When the designer pulls or pushes the sliders on the Force tool, the material responds with protrusions in the corresponding direction. The sliders are operated directly with the hands, and the tool is responsive to the pressure applied (pace of the fingers), which is then translated into the strength of the force in the material (pace of shape change). Playing around with different forces applied to the selected area, the designer is able to get a feel for the shape-changing qualities of the material and the relationship between the actions on the Force tool and the material's response. Since one continuous swipe on the Force tool results in only one continuous movement in the material, the tool also allows for layers of forces, making it possible to compose more intricate forms of shape change.

Afterward, the designer can use the same tool concurrently with increasing the airflow (input) at the desired areas of the material (Figure 1). Again, the designer can play around with different reaction patterns—whether it should be a simple action-reaction, or if an increase in airflow should result in more elaborate shape-changing patterns. Finally, when the designer has found a desired relationship between expression and airflow, the Select tool can be used to copy and paste this to other parts of the material—or to another piece of the material, if needed.

Programming materials can thus be akin to enacting a composed dance or gradually shaping forms in clay. Depending on the designer's experience, it can be a craft-like explorative practice or a meticulously composed design practice. The more experience, the more intricate expressions the designer will be able to compose. The key to this is the open-endedness of the tools and the real-time reaction to input.

BUILDING ON RELATED PROGRAMMING PRACTICES

In most cases the default mode of programming computers is textual. There are, however, alternatives to textual programming languages that are relevant to discuss in relation to material programming. Visual programming, tangible programming, and programming by example, for instance, all support explorative design practices by minimizing the distance (mentally as well as physically) between programming and execution. Here we will discuss the relationship between the qualities

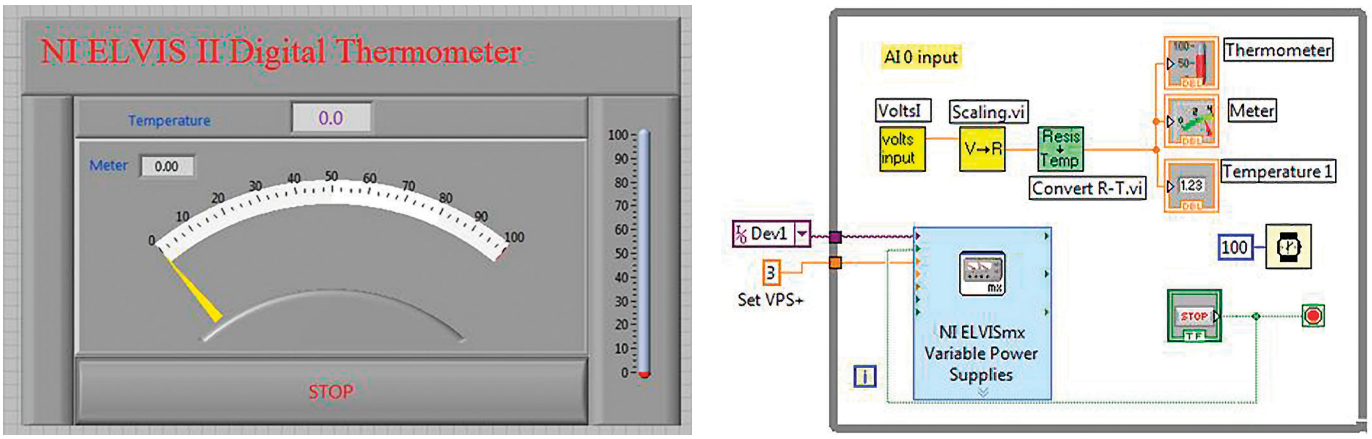


Figure 5. Screenshots of LabView illustrating data-flow diagrams.

of these programming practices and material programming.

Visual programming. Visual programming works by replacing textual code with visual notations (i.e., 2D representations) and tools as means to construct software (Figure 5) [4]. Thus, visual programming utilizes people's ability to easily recognize and work with visual patterns, thereby minimizing the need for learning. Visual programming is good in aiding rapid development, particularly in the early stages of design. This is partly due to the low threshold for changing the logical structure of a program,

Figure 6. Tangible programming: Strawbies [5].

Figure 7. Programming by example: Topobo [6].

which makes it easy to experience multiple design alternatives in an explorative manner.

Material programming would also utilize this latter quality, since programming and execution happen in the same material realm. A textual or graphical overview of the data structure and algorithms would, however, not be an integrated part of the practice, although it could be made available elsewhere.

Tangible programming. Tangible programming environments use physical objects to represent various programming elements, commands, and flow-control structures (Figure 6) [5]. Here, the manipulation and arrangement in space of these objects are used to construct an algorithm. Similar to visual programming, tangible programming enables a visible and tangible organization of a program that eliminates levels of abstraction. Yet, by relying on physical manipulation, tangible programming is even less abstract than visual programming, which means it is even less capable of supporting the development of complex algorithms. However, the important advantage is that it references some of our experiences in the physical world.

Both tangible and material programming thus operate in the physical world. However, while the tangibility in tangible programming typically remains a rather cognitive activity, removing the designer from the material at hand, material programming would be an embodied activity tightly coupled to the material's expressive potential.

Programming by example. Programming by example is a practice in which the programmer demonstrates an algorithm to a system by recording a set of actions through an artifact/interface, which can then be played back in that artifact/interface (Figure 7)[6]. Programming by example is typically applied in situations where the artifact is a one-off and is accessible and tangible, such as in the design of shape-changing interfaces and robots. Like visual and tangible programming, programming by example has a low entry threshold for beginners and those from non-technical disciplines. Further, its complete lack of abstractions makes composing the behavior immediate. The allure of programming by example in a design context is that it allows designers to use their tacit/bodily knowledge in a manner similar to how non-computational products are designed, however constrained by what the materials, actuators, and sensors in the artifact allow.

In programming by example, we recognize material programming's quality of working almost directly with the design material to be programmed. However, programming by example often results in a limited, artifact-specific design space. Instead, the tools used in material programming allow the designer at least one layer of abstraction, enabling a larger action space and thus potentially more sophisticated designs. Also, the envisioned tools would allow a wider array of applications that exclusively utilize a computational composite's properties, due to their specific connections to the materials.

WHY A MATERIAL PROGRAMMING PRACTICE?

In this article we presented the notion of material programming as a future practice for designing computational composites [1]. Such a practice would

FIGURE 5 IMAGE BY N. I. (HTTP://WWW.NI.COM). FIGURE 6 IMAGE BY FELIX HU

be a way for designers to explore and experience the dynamics of the computational materials with which they are working. This will in turn support the designers' kinesthetic creative practice. We believe they will then become capable of composing more sophisticated and complex temporal forms in their designs. We propose this practice knowing that the current technology and materials are not entirely ready to support it, but we are convinced that they could be in a not-too-distant future. The future material programming practice will not look like the one proposed above, so the contribution here is therefore in arguing for the qualities such a practice would embody, which are fourfold:

First, a material programming practice would not rely on any direct representation of the programming actions performed on the material, beyond the material itself. A material programming practice thus unites the programming and running modes, while avoiding unnecessary abstractions that could shift attention from the material. The argument here is, that the better the interaction designer knows the material at hand, the more sophisticated and finished the designs will be. Instead of shaping these temporal dimensions through detached means (e.g., by writing code on a detached computer only), the actual interactive behavior of the material is explored and programmed on the material, in real time and in-situ.

Second, we see how the tools bring us closer to an actual form-giving practice in interaction design. Through this practice, the unique interactive and physical properties of the particular materials easily play a key role in both concept development and actual creation. In a way, material programming could be more in line with traditional crafting practices, where several dedicated tools are used for crafting a material and can be mastered through practice and skill gained over time. This is not unlike a silversmith's work. The Force tool, for example, provides the possibility of exploring different rhythms and directions of movement in a shape-changing computational composite, supporting an understanding of the properties of the computational composite at hand.

Third, since the physical interaction with the material is central to this programming practice, the designer can slowly develop tacit bodily skills and knowledge of how to use the expressive properties of both tools and materials. The tools allow the interaction designer to use her body in ways similar to that of crafting non-computational materials, enabling and utilizing the designer's expressive potential. This could, for example, be reflected in the smooth and refined actions of sliding the thumbs on the Force tool's sliding areas to explore the speed and acceleration of a material's shape change.

Fourth, the tools allow for at least one level of abstraction, which enables the designer to utilize the ability of programmed cause and effect in the computational composites. In other words, the input/output ratio does not have to be one to one but rather can assume other temporal forms and dependencies in between. Further, we also see a good possibility for these materials to be coupled with more advanced computational power, once embedded in designs. Thus, we imagine the programming of the material coupled with more advanced algorithms and databases in a back-end design, which would probably rely on traditional textual programming. In that sense, computational composites and material programming can be seen as the front-end of a cloud-based Internet of Things, from a programming perspective.

Finally, an important bonus is that a material programming practice would likely appeal to a wider array of design and craft practitioners. As such, the design of our future artifacts and environments would not rely only on designers brought up in technological educations and practices. We envision that this wider array of participants would probably lead to a more varied range of material expressions.

As proposals of new ideas and research programs go, a full realization of a material programming practice would not happen tomorrow. Working toward it would require collaborations from material science, computer science, and interaction- and industrial design. In the end, it will look quite different from the sketched tools proposed here. With this work, however, we intend to start giving form to the new possibilities we have before us.

Endnotes

1. Vallgårda, A., Boer, L., Tsaknaki, V., and Svanaes, D. Material programming: A design practice for computational composites. *Proc. of the Nordic Conference on Human-Computer Interaction*. 2016, article no. 46.
2. Vallgårda, A. and Redström, J. Computational composites. *Proc. of the Conference on Human Factors in Computing Systems*. 2007, 513–522.
3. Svanæs, D. Kinaesthetic thinking: The tacit dimension of interaction design. *Computers in Human Behavior 13*, 4 (1997), 443–463.
4. Myers, B.A. Visual programming, programming by example, and program visualization: A taxonomy. *Proc. of the Conference on Human Factors in Computing Systems*. 1986, 59–66. DOI: 10.1145/22627.22349
5. Hu, F., Zekelman, A., Horn, M., and Judd, F. Strawbies: Explorations in tangible programming. *Proc. of the 4th International Conference on Interaction Design and Children*. 2015, 410–413.
6. Raffle, H.S., Parkes, A.J., and Ishii, H. Topobo: A constructive assembly system with kinetic memory. *Proc. of the Conference on Human Factors in Computing Systems*. 2004, 647–654.

Anna Vallgårda is an associate professor and head of the IxD lab at the IT University of Copenhagen. Her research is focused on the practices of interaction design as well as on developing new material expressions for interactive artifacts.
→ akav@itu.dk

Laurens Boer is an assistant professor in interaction design in the IxD lab at the IT University of Copenhagen. He conducts constructive design research to investigate and speculate about new forms and applications for computational materials.
→ laub@itu.dk

Vasiliki Tsaknaki is a Ph.D. student at KTH Royal Institute of Technology and Mobile Life Research Centre in Stockholm. Her research is on the intersection of interaction design, material experiences, and crafts—including hybrid crafts. She also works with critical views on the making of interactive artifacts.
→ tsaknaki@kth.se

Dag Svanæs is a professor at NTNU in Trondheim, Norway, and an adjunct professor at ITU in Copenhagen, Denmark. His research interests include design tools, tangible interaction, participatory design, usability methods, medical informatics, and the philosophical foundations of interaction. His current research focuses on the role of the body in design.
→ dags@idi.ntnu.no

DOI: 10.1145/3057277