Eight Challenges of Future Electronics Toolkits

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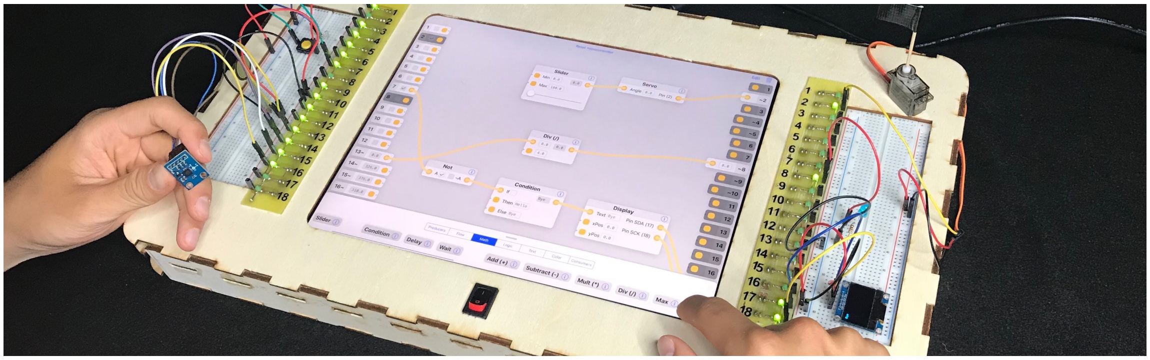

Fig. 1. Flowboard [8] is a system we designed to learn embedded coding using flow-based programming. It addresses some of the Eight Challenges, such as C1 (Materiality), C3 (Learning vs. Prototyping), and C7 (Process Integration).

We present eight challenges that electronics prototyping toolkits are facing, and that HCI research can help to address. These observations are based on our own and related work. We close with a short sample vision of future electronics prototyping.

CCS Concepts: • **Human-centered computing** → **Interaction techniques**; *HCI design and evaluation methods*; **User interface toolkits**.

Additional Key Words and Phrases: Physical Prototyping; Embedded Environments; Electronics Toolkits, Challenges

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INTRODUCTION

HCI research has a long history of developing electronics prototyping toolkits [21]. They focus on, e.g., designing [20] and debugging [4, 32] circuits, bridging the gap between coding and electronics in embedded development [8], home appliances [5], wearables [12], robotics [9, 19] and physical circuit building [6]. However, they are facing several challenges. Some are long-standing issues that have a better chance of getting resolved now thanks to recent developments in electronics and computing. Others are new challenges introduced as the next levels of abstraction, complexity, and innovation make their way from R&D into requirements for prototyping toolkits. We propose eight such challenges that deserve further attention from our community. Note that we are focusing on traditional early, "one-off" prototyping. *Isotyping* [15] multiple copies and moving towards production poses additional challenges.

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CHALLENGE 1: MATTER MATTERS

Ever since simulation became practical, a fundamental conflict has plagued electronics toolkits: *What is the value of physical vs. virtual prototyping?* What are the benefits of building a prototype from real parts, rather than simulating it?

The *disadvantages* of "going physical" are straightforward, especially from a background in computing and technical HCI: A circuit simulation is quicker to change than a physical prototype, it can provide better insights into a circuit (putting a virtual scope on a trace is free), its components don't break, and it does not require specialized hardware.

The *advantages* of physical prototyping, other than limited simulation fidelity, are less obvious to the technical mind. But in psychology and didactics, the advantages of physically handling something to solve a problem or learn about a phenomenon are well known: Embodied Cognition [31], Distributed Cognition [17], and Tangibles research [10] have documented that physically handling objects is key to determining what users take away from an interaction.

Leading current platforms like Arduino, micro:bit, and Raspberry Pi emphasize physical prototyping of the hardware aspects of a project. But circuit simulation is a popular feature of related IDEs: TAC [2] supports flow-based programming and previewing the required circuit before building it. Fritzing [20] recently added maker-friendly circuit simulation [11]. Bifröst and Wifröst [24, 25] integrate previews of hardware and software behavior, and our own FlowBoard [8] (Fig. 1) lets users create real circuits while seamlessly bridging the gap to the associated code.

Overall, physical construction should remain part of the prototyping experience, even as complexity and abstraction levels continue to rise. We thus need to understand what level of physical prototyping is most beneficial for which use case. Visually impaired users, for example, benefit particularly from physical over virtual prototyping [16].

CHALLENGE 2: ADAPTIVE COMPLEXITY

As Gordon Bell put it, "the cheapest, fastest and most reliable components of a computer system are those that aren't there" [7]. Similarly, each electronics toolkit is ideal for a particular range of complexity, offering great support without needlessly complicated system layers: According to a seminal tools paper [27], every toolkit has a learning *threshold* to start using it, and a *ceiling* of how complex projects using it can become. This leads to problems: Beginners are baffled if their first project requires them to wrap their heads around a complex toolkit; but if toolkits black-box and simplify elements of electronics prototyping, it also limits their flexibility and utility beyond a certain complexity [8, 21].

Recent hardware and software developments suggest we can do better: If the project is simple, the toolkit should be configurable—or indeed configure itself—to simplify its own complexity to match: An FPGA gets re-flashed to represent a few simple logic gates instead of a complex MCU if that is all a project needs. The more complex the task, the more complexity the toolkit includes and reveals. This also helps with Challenge 4 (Responsiveness), but it should also take the user's knowledge level into account, and it must not de-skill users by changing the toolkit unpredictably. What mechanisms (see Challenge 5, Embracing AI) can electronics toolkits implement to become so adaptable or adaptive? Which elements must stay static? Answering these questions may lead to a new type of electronics toolkits.

CHALLENGE 3: PROTOTYPING OR LEARNING?

This is another long-standing, unresolved challenge. A professional prototyping with an electronics toolkit also learns about it, but her primary goal is creating the prototype, not learning. According to Piaget [**?**], a student learning about microcontrollers will benefit from working on a project [**?**], but his primary goal is learning. Existing toolkits, however, are often applied indiscriminately to both scenarios, which muddles the design goals for a toolkit. A clear prioritization here provides focus. E.g., our *Flowboard* aims at children discovering embedded coding in informal learning scenarios.

Thus, we can accept that it does not support creating very complex prototypes and has a low performance ceiling. However, when designing toolkits, whether for learning or prototyping, it remains crucial to make learning *how to use the toolkit itself* as effortless as possible. This helps reduce its "extraneous cognitive load", the "unnecessary" part of learning that does not contribute to the actual learning of the content of interest (the "intrinsic cognitive load") [29].

CHALLENGE 4: RESPONSIVENESS

As toolkits offer more powerful abstractions, the performance of simple operations often suffers. Arduino's digitalWrite() is safer and more convenient, but over ten times slower than controlling pins directly (roboticsbackend.com/arduino-fast-digitalwrite/). Our FlowBoard lets learners write Arduino routines with flow-based programming, but the serial Firmata protocol it uses to control the Arduino makes it even slower than digitalWrite() [8].

The human deadlines for acceptable system responsiveness, such as 100 ms for reacting to discrete input events, and as little as 1 ms for, e.g., tracking continuous touch gestures [18], are well known, but often violated through toolkit abstraction layers. Future toolkits need to provide ways to (a) verify end-to-end latency, and (b) support minimizing it by "cutting through" layers of abstraction where needed, or by using new technologies. FPGAs, for example, allow circuit simulation without the inherent delays of microcontrollers executing code.

CHALLENGE 5: EMBRACING AI

We already mentioned employing modern AI to adapt to user knowledge and project requirements, circuit design tools are adding semantic auto-complete functionality [23], and advanced intelligent tutor systems for electronics exist [26].

Beyond this, however, lies the fundamental question of how we should be interacting with a toolkit: in the traditional tool metaphor, in which we initiate actions and the toolkit carries them out, or in the "otherware" metaphor [14], a conversational collaboration with a (non-human) partner? The latter is a clear trend in professional design tools, in which AI generates designs in a design space that the designer then selects from, iteratively triggering further exploration by the tool, and co-creativity in AI-infused design tools is an emerging topic in HCI [30].

CHALLENGE 6: MATERIALS

When discussing electronics toolkits, many people may have standard electronic components and PCBs in mind. However, as electronics continue to permeate our everyday lives, we need to support working with new design materials [28], from smart fabrics that sense interaction through integrated circuitry, to shape-changing soft robotic actuators [9], to biodegradable and edible circuits. This may put a renewed emphasis on physical prototyping instead of simulation (Challenge 1), since the haptic experience is a key aspect of these new materials: What should future toolkits simulate virtually, and what needs to be physical?

CHALLENGE 7: INTEGRATING PROCESSES

Most research has looked at supporting electronic design in isolation. Similarly, other fabrication research has produced numerous tools, but they also usually focus on a single aspect of prototyping, such as 3D printing or laser cutting. But while prototypes increasingly require a co-design of form and function, prototyping toolkits that help integrate all multiple, or even all aspects of design and fabrication, from electronics to mechanics and code, remain scarce. This remains a key challenge, although commercial production-level design tools such as Autodesk's Fusion360 are making great advances in this direction, and recent research in electronics prototyping is also beginning to focus on these challenges, e.g., how to prototype electronics for uneven surfaces [33].

CHALLENGE 8: SUSTAINABILITY

While Challenge 1 pushes for more physicality in prototyping, fabricating one throw-away prototype after another just to correct minor mistakes can generate unacceptable amounts of e-waste. Sustainable prototyping has become a topic in HCI fabrication research [22], but electronics have received only occasional attention (e.g., in [13]). Can future electronics toolkits prioritize the use of sustainable materials where possible, both for their own physical components and for the prototypes their software tools help to create, as in [3]? This, of course, links back to Challenge 6 (Materials). And when should toolkits fall back to simulation to conserve physical resources [1]?

A VISION: E+

As a thought experiment, we conclude with an (admittedly blurry) vision of how "E+", a hypothetical future electronics toolkit, might support prototyping, and point out how it addresses each of our challenges, C1–C8:

Susan is an engineer prototyping a small, "Tribble"-like care robot that should serve as a companion for elderly patients. She enters a first textual query, and her AI-powered design tool "E+" proposes some initial physical shapes (C5 AI). After a few rounds of selections and drilling down into that design space, E+ prints a first non-functional prototype, made from fully recyclable materials (C8 Sustainability). Susan fine-tunes this shape physically with her hands; the prototype adjusts through shape change, and applies a local dimple pattern she creates to the entire object automatically (C1 Matter). Using voice and gestures, Susan specifies the surface to be furry in most places; a matching cover for the prototype is 3D-designed and fabricated automatically (C6 Materials, C7 Processes).

Susan now moves to the embedded electronics. She decides that, for acceptance reasons, the bot is not supposed to be online. E+ responds by loading a simpler, non-networked system architecture into the prototype's FPGA core (C2 Complexity). She attaches a physical speech module to the prototype, and E+ teaches her how to configure and program the module for her specific use case, with E+ automatically applying relevant design guidelines (C3 Learning). Next, Susan tells E+ that the bot should also react to being picked up and touched. E+ shows Susan where to connect the analog touch circuitry, places touch-sensitive areas using a human hand model, 3D prints a new shell with touch-enabled regions (C7 Processes), and ensures lag-free response to touch interactions by expanding the FPGA core with capacitive touch logic (C2 Complexity, C4 Responsiveness).

ABOUT THE AUTHORS

Jan Borchers is a full professor of computer science and head of the Media Computing Group, which he founded at RWTH Aachen University in 2003, after faculty appointments at Stanford and ETH Zurich. His current interests lie in new user interfaces for software development, soft robotics, 3D printing, and personal fabrication, tangible, textile, and shape-changing UIs, and augmented reality. His lab is among Germany's most successful groups at ACM CHI, and he established Germany's first Fab Lab in 2009. His book *Arduino in a Nutshell* has been downloaded over 200,000 times. He can be found at https://hci.rwth-aachen.de/borchers.

Anke Brocker is a researcher and PhD candidate in Jan's group. Her research focuses on tools and processes that help users create prototypes and understand fabrication processes. Her interest in toolkits ranges from electronics to soft robotics and haptics, and she is an active Fab Lab user and educator. She can be found at https://hci.rwth-aachen.de/brocker.

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