Rematerialization of the virtual and its challenges for design and technology education

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In addition to the virtualization of material and social processes, the 21st century is also characterized by rematerialization of the virtual—using augmented, embedded, and ubiquitous technologies to augment all kinds of material objects with virtual dimensions. Embedded technologies are in a never-ending loop of creating unforeseen exchanges between people, tools and artefacts and constantly co-modifying the environments of action. They can create extrasensory information layers on our perception, and they learn and accommodate to actions of people and other sensing items, who react and change their behaviours accordingly. While the rematerialization of the virtual creates new opportunities for learning from and with the tools and artefacts that augment human actions, it also challenges many existing practices of craft education. To this end, we introduce the reader to key technological trajectories that drive a need for teaching cross-boundary design competences that combine computational thinking with understanding of the social and material nature of human activity. We present an overview of a sociocultural approach for framing adaptive ecosystems that supports the evolving process of learning and making. We give examples of embedded technologies to illustrate the rematerialization of the virtual and suggest a pedagogical framework that bridges craft education and computing education for the development of the skills and mindsets needed for making the futures of digital society.

Keywords: computational thinking, maker pedagogy, learning by design, design & technology education

Introduction

While the driving force of computing in the early age of automation was *dematerialization*—shifting organizational, industrial, and societal processes from the material world to computational processes in the virtual world (Castells, 2000)—there has been a growing parallel process of *rematerialization* of the virtual—using augmented, embedded, ubiquitous technologies to cause the virtual to amplify the material (Schwab, 2016). Unlike more traditional tools or everyday artefacts, smart items are unceasingly sensing, communicating, and interacting with each other and with their environment, and they can create additional layers on top of our sensory systems. This has had several consequences for people's perceptions of the relationship between technology, self, and society (Brynjolfsson & McAfee, 2014). Examples are numerous. Augmented reality glasses project virtual elements on top of your field of vision. Virtual guides give tours of cities, museums and exhibitions. 3D printing makes material objects from virtual blueprints, creating more understandable interfaces between the virtual and material world.

Furthermore, the growth of the Internet of Things advances the embedding of sensors, actuators, computing, and communication to objects of all kinds (e.g. Eagle & Greene, 2014). The ability of household items to communicate with each other opens the door for endless combinations of smart actions: washing machines that refuse to wash clothes together that need different washing programmes, medicine jars that warn their owners if their cold chain has been broken, and ovens that know the exact temperature that the food inside them should be cooked at and when it is ready. As the technology for all these already exists, and as the size and price of embedded technology are being driven down, there is little doubt about the future of embedded, intercommunicating technology (Kellmereit & Obodovski, 2013).

These technologies characterize the 21st century both positively and negatively. People never need to get lost driving, can instantly translate between dozens of world languages, stream video and music, and get eerily accurate recommendations for pieces of art that they would enjoy, and carry the world's information in their pockets (Tedre & Denning, 2019). But people also fear growing income inequality, total surveillance and massive tracking, polarization of political views, and behaviour-altering social media (Kelly, 2016). Handicraft skills have been extended by automation, CNC, laser, and robotic technologies. Moreover, the ongoing march of automation is rapidly penetrating knowledge work sectors, which for long were believed to be relatively safe from automation (Greenbaum, 1979). Similarly, coding, once touted as a central 21st century skill, is being rapidly automated through advanced class libraries and software development kits, high-level languages and tools, and new engines and environments. Advanced machine learning techniques are no longer the domain of doctoral research in computing, but have become drag-and-drop exercises in cloud services, such as AWS, Azure, and Google Cloud. Design itself is being automated by fully automatic generative design software and genetic algorithms. Accordingly, many skills that were hoped to help land people jobs in the digital era are obsoleting due to the automation of those very jobs (Brynjolfsson & McAfee, 2014).

In response to global challenges compounded by the pace of automation, many companies and public sector organizations have begun to create strategies that pursue new products, interfaces, processes, environments, skills and user experiences through collaborative design. Collaborative design, which leverages the iterative design process, typically extends the boundaries of individual organizations by involving diverse stakeholders in design and development projects (Björgvinsson, Ehn, & Hillgren, 2012). Nelson and Stolterman (2012) argue that design and design thinking are now needed, applied, and understood more deeply outside of the normative confines of the professional fields that create our material culture, such as design, craft and art. While design has important traditions in many fields such as architectural design, industrial design, educational design, information systems design, and software design, the era of rematerialization challenges workers in those fields to cross disciplinary boundaries.

If the future of work and living is based on cross-boundary designs, and intelligence is distributed across combinations of people, smart artefacts, and cloud services, rematerialization of the virtual also challenges many of the existing practices of design education. For a long time, in the wake of the rapid virtualization of society's processes, design education efforts focused on understanding new kinds of digital, virtual design (Janlert & Stolterman, 2017). But the rematerialization of the virtual and ubiquitous embedding of digital technology have fundamentally changed design, irrevocably intertwining the design of the virtual with the design of the material. However, due to the lack of skills and models for seamlessly integrating computational thinking and material making in education, implementation at the school level is often reduced to disconnected learning, with the use of hand tools taught in crafts lessons and mechanical programming skills taught as a separate project or school subject.

This article aims to provide theoretical and pedagogical insights for connecting computational/material thinking and making in education. First, this article introduces a number of key technological trajectories and embedded technologies that drive a need for cross-boundary design competences. Secondly, it presents an overview of a sociocultural approach for framing adaptive ecosystems and proposes a pedagogical foundation of learning by design that combines computational thinking with the social and material nature of human activity. Thirdly, the article aims to sketch the deepening process of learning and design, particularly with regard to the ways that making with embedded technologies may be incorporated into schools and other educational settings. To conclude, the article proposes a pedagogical framework for cross-boundary design process that connects computing education and craft education, and considers directions for future research.

Rematerialization of the virtual

When actions, processes and phenomena in the material world are modelled, represented, processed and run or simulated on computers, they become virtual. All information processing systems also interface with the material world through, for instance, sensors that read data from the world, screens and lights that relay information to users, and actuators that make things move by spinning, pushing, and pulling. In addition to this, they also interface with the social world through, for instance, adapting to users and social contexts, doing tasks autonomously, exhibiting certain ‘smart’ behaviours, and producing, consuming, and conveying information. Whereas virtualization of processes was a keyword of the Information Age, miniaturization of information processing and communication technology enabled the embedding of virtual elements into a rapidly increasing number of material items (Castells, 2000; Schwab, 2016). This move towards what is often called ‘ubiquitous computing’ or ‘pervasive computing’ started at the turn of the 1990s as a gradual shift from personal computers to the computerization of everyday items (Weiser, Gold & Brown, 1999). This shift signified a change in the role of information technology towards augmenting material and social worlds with virtual extensions—a change that inextricably weaved together the older notions of ‘socio-technical systems’ and ‘cyber-physical systems’. Most recently, amplified by machine learning, the fusion of virtual and material is challenging old conceptions of sociotechnical systems. In the late 2010s design, the virtual, the social, and the material are becoming irrevocably intertwined (Schwab, 2016; Janlert & Stolterman, 2017).

Ubiquity, interconnectivity, cloud computing and machine learning are complicating the old material/virtual dimensions of design and creating altogether new design dimensions. For example, smart items force designers to extend their thinking from plain material and the technical constituents of items such as shape, texture, colour, and manufacturing techniques, to the interactions of those items with the users and the physical world, to their communication with other smart items, to their behaviour, and how they adapt to changes in their environments of use. Smart items require rethinking the relationships between the virtual, the material, and the social. For example, items can be aware of their place and their surroundings, they can react to changes in their state and context of use, they can self-optimize their operation, and they can communicate to other items or to the cloud when and where they are in use, who is using them and for what, whether or when they will need maintenance (Kellmereit & Obodovski, 2013; Eagle & Greene, 2014).

When the virtual, the material, and the social are combined in the everyday systems people use, the ability to work with them becomes an important asset for work and everyday life (Brynjolfsson & McAfee, 2014). For example, smart items are the building blocks of home automation, where all energy-based elements of a house are equipped with sensor, control, and communication technology to create interconnected, occupancy-aware embedded systems. Understanding smart items and home automation, as well as modern access control, biometric security, and fault prediction, is important not only to designers, but to every citizen, as are the principles of how smart household appliances weave into these networks of technologies. The more powerful the technology, the more important it is to improve education to make them not appear as magic, but as human-designed tools whose apparent intelligence arises from their smart designs and programming.

In addition, the competences and knowledge needed for navigating the rapidly changing technological landscape requires understanding how the virtual meets the social and the material. For instance, experiments have shown the feasibility of using smart clothing to create additional senses that people become intuitively aware of. After a few weeks of wearing a belt that faintly vibrates towards the magnetic north, people gained an intuitive sense of where the north is without having to consciously think about it (Nagel et al., 2005). Similar technologies can be applied to create an endless range of ‘sixth senses:’ take, for instance, subconscious sense of air quality, traffic jams, and nearby accidents.

However, before readily adopting smart technologies, such as the smart clothing mentioned above, people need to understand what makes those technologies smart—such as biometric sensing, location awareness, and distributed computing technology—so that they are able to assess the risks that those products entail, including leaking personal biometric and location data to third parties. At a more general level, understanding the social, material, and virtual elements of geotracking is quickly becoming an important public awareness issue. While geotracking is required for extremely popular location-aware apps and solutions, it carries numerous threats to privacy, cybercasing, and malicious use (Friedland & Sommer, 2010).

Another example of blurring the boundaries between the material and the virtual comes from augmented reality, which adds extra layers of reality on top of the material world. These extra layers might, for instance, provide additional sensory information, such as bring the invisible or inaudible within human experience, amplify or suppress certain sensory information, impose media content on the material environment, or create reminders, instructions, warnings, and notifications (Shull & Damian, 2015). Augmented reality can be used as a platform for services that add a layer on top of the user's field of view, providing, for example, real-time translation of everything the user sees, real-time recognition of threats, identification of people, or x-ray vision. Haptic feedback has been used to give people a 'sixth sense' of phenomena around them, such as the presence of other users of the same technology (Shull & Damian, 2015). The hardware doing the processing is, similar to many other ubiquitous technologies, typically not in the portable device, but data are sent and processed in the cloud, where massive server farms receive the data, do the requisite computing usually using machine learning algorithms, and send back the data for the device to act accordingly.

Table 1. Example technologies fusing the material, social, and virtual worlds

Embedded technologies	**Examples of sociotechnical phenomena**
Smart items	Items that know where they are, containers that know what they hold, objects that can measure anything about their external environment, and rental items that know their location, renter, price per hour, usage patterns, and other relevant data.
Home automation	Automated and interconnected ambience controls such as curtains, lighting, soundscape, occupancy-awareness, temperature, security, and access control, as well as context-aware home appliances, such as fridges that know their consumables and their expiry dates, in one interconnected system.
Smart clothing	Clothes that, e.g., monitor the wearer's biometrics (heart rate, temperature, sweating, etc.), that warn the wearer about air pollution, create extra senses about the environment, or refuse to be washed using a wrong washing programme.
Geotracking	Tracking locations of objects and people through, e.g., embedded GPS, mobile positioning, or face recognition from CCTV, as well as through people's mobile apps, location metadata in posts and pictures, machine recognizable monuments, or other virtual traces they leave about their physical location.
Augmented reality	Projecting virtual elements on people's sensory fields, such as automatic translation of signs, recognizing flowers that people see, playing games with virtual characters, or creating additional 'senses' through sensory augmentation.

The technologies in Table 1 have created new possibilities for human action, but common to them is that they all merge the material, virtual, and social worlds to different degrees. Although much of early computing education has focused on understanding computing as purely a virtual phenomenon, material realizations of computational systems have frequently been introduced (Kafai, Fields & Searle, 2014). However, as material/virtual development is changing, so are the skills necessary for mastering that technology. Most of all, the technologies in Table 1 require us to rethink our views on learning and mediated action, as discussed in the following section.

Rethinking learning and action in the rematerialized world

As technology has become a part of our everyday environments there has been growing interest in understanding human-technology interaction, often informed by sociocultural or cultural-historical activity theories (Kaptelinin & Nardi, 2012). Instead of maintaining the myth that innovative design happens solely in the head of an individual designer, the sociocultural perspective recognizes design, and more generally human activity, as systemic processes that connect subjects (the actor or actors participating in the activity), the object of their activity, and tools and resources as mediational means for acting on the object (Vygotsky, 1978; Cole & Engeström, 1993). Accordingly, every design situation is a complex and unique mixture of objects, subjects, and a materially mediated array of tools and artefacts that shape human interactions and the actions bearing them (Huizing & Cavanagh, 2011). Moreover, this theoretical standpoint generally views that human activities are always bound to the context in which they take place (Sfard, 1998). Figure 1 represents Vygotsky’s basic mediated-action triangle (adopted from Cole & Engeström, 1993).

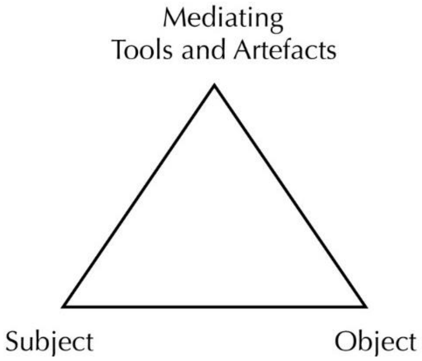

Figure 1. Mediated action (Cole & Engeström, 1993)

Moreover, mediated action through artifacts is one of the founding premises of sociocultural and cultural-historical theories (Cole & Engeström, 2007; Jarvis & Pell, 2005). Cole (1996) argues that artifacts are simultaneously ideal (conceptual) and material when they are embedded in the process of goal directed human actions. Artifacts and tools both shape the possibilities for thought and action, and, in turn, are shaped by the subject who uses them (Vygotsky, 1978; Schoultz, Säljö & Wyndhamn, 2001; Daniels, Cole, & Wertsch, 2007). Rather than looking for human competences solely in our minds or bodies, sociocultural studies of mind posits that our knowledge is expressed in our abilities to use these external artefacts and tools, and to integrate them into the flow of our doings, whether these are intellectual, physical, or mixed (Säljö, 2010).

However, the growth of the Internet of Things, embedded computing, low-cost sensors and actuators, and ubiquitous communication are dramatically changing the interrelation between the basic elements of mediated action. We now see the emergence of smart, networked artefacts and tools that create unique, personalized experiences for the subjects who interact with these affordances. Unlike more traditional material tools and everyday artefacts, such as hammers or chairs, smart items are unceasingly sensing, communicating, and interacting with each other and with their environment. From a sociocultural perspective, embedded technologies are in a never-ending loop of creating unforeseen exchanges between people, tools, and artefacts, and they are constantly co-modifying the environments of action. They learn and accommodate to the actions of people and other sensing items, who react and change their behaviours accordingly. Correspondingly, most ground-breaking designs are able to read and analyse the basic elements of mediated actions and are then able to use that information to create added value and smart actions in that particular context. This highlights the need to design material artefacts with embedded intelligence that co-learn and work well with people.

In addition, learning in the rematerialized world highlights the tacit dimension of knowing (Polanyi, 1966) interwoven in action. The more that technology becomes an integral part of our material and physical environment, and the more it interfaces with the human body, the more subjects participating in activities will learn through bodily experiences with the technology. In this context, the ability to effectively carry out an activity resides not only in one's ability to use tools and artefacts at hand; it also increasingly depends on one's ability to acknowledge the flows of information behind the material surfaces as well as one's ability to understand the ways in which technology can and cannot augment human knowing, making, and communication.

Pendleton-Jullian and Seely-Brown (2018) argued that having agency in such a constantly changing activity system also challenges the existing models of design learning. While the ability to frame a context in a new way has always been the core of design thinking (Paton & Dorst, 2011), the same technological advances that are radically changing our interaction with the world have created unparalleled opportunities and needs for catalysing learning systems that emerge from the dynamic exchanges and choices made within the system (Pendleton-Jullian & Brown, 2018). This challenges previously disconnected domains and traditions of design and calls for cross-boundary competences for harnessing computational thinking and making as vehicles of learning and creating action in the world. Accordingly, the rematerialization of the virtual has important implications for educating future designers and makers who can co-design material artefacts that are made intelligent through computation.

Pedagogical frameworks for computational thinking in design education

Interweaving computing technology into essentially all aspects of daily living sets new kinds of demands on educational system reforms. Computational thinking (CT) has become a popular notion for a broad variety of educational efforts to integrate computing skills and knowledge into school curricula and subjects (Tedre & Denning, 2016). However, educators are confused by the multiple definitions of computational thinking, and they struggle with the lack of pedagogical models for connecting computational thinking in and across different subjects and their related disciplinary practices (Denning, 2017). Accordingly, there is an ever-increasing need for pedagogical models that support the growth of CT in a manner that is deeply grounded in understandings of skill development and learning (Guzdial, 2015; Grover & Pea, 2018). A number of initiatives have started to emphasize the material and design aspects of CT, from computational participation (Kafai & Pebbler, 2011) to computational making (Tenenberg, 2018), and computational design (Denning, 2017b). Culturally sensitive computational design is one of the sought-after traits of developers, and computational thinking has shifted towards the ability to sense and feel the dynamics and communication patterns of groups, organizations, and societies, and towards designing computational artefacts that resonate with the identities, cultures, and fashion statements users project (Denning & Tedre, 2019).

In exploring the ways to connect computational thinking with material making in education, this article draws on the following definition of CT:

> the mental skills and practices for designing computations that get computers to do jobs for us, and for explaining and interpreting the world as a complex of information processes (Denning & Tedre, 2019).

This view that bridges CT and design as a way to explain and understand the world has implications for how these skills and mindsets can be learned and harnessed in educational efforts. One way to do this is to return to the pioneering ideas of Seymour Papert, who envisioned a world in which children design, create, and program artefacts and by doing so learn important skills of computational thinking, making, and action in the world (Resnick, 2017; Guzdial, 2015; Grover & Pea, 2018).

Papert's constructionism emphasized that children are likely to create new ideas when engaged in designing and building material artefacts that can be reflected upon and shared with others (Papert, & Harel, 1991). To Papert, projecting out—or externalizing—our inner thoughts, feelings and ideas to others was as important as internalization of our actions (Ackermann, 2004). Papert (1987) argued that computers should be seen as material, alongside a variety of other materials (such as art and craft supplies) that are used to explore, externalize, and develop ideas. He presented an iterative process of self-directed and design-oriented learning in which children invent for themselves the very tools and mediations that best support the exploration of ideas (Ackermann, 2004). Rather than a collection of fully-prescribed, build-a-thing tasks, these projects engaged learners in a sustained process of inquiry and intellectual play with powerful tools, including computers (Papert & Harel, 1999). Ackermann (2004) pointed out that Papert's arguments about mediated action resonate with sociocultural theories of learning originating in the work of Lev Vygotsky (1978).

While empirical studies suggest that learning by designing can be applied in many different educational contexts (e.g. Enkenberg, 1993; Hennessy & Murphy, 1999; Kolodner et al., 2003; Seitamaa-Hakkarainen, Viilo, & Hakkarainen, 2010; Kafai & Burke 2014; Blikstein & Worsley, 2016; Vartiainen, 2014; Vartiainen et al., 2018), that pedagogical approach is somewhat out of favour in many education systems today (Resnick & Rosenbaum, 2013). Many current models of instruction consist of rigorous, disciplined, and scripted tasks and instructions from a teacher who guides the learners to re-discovery of some unifying principle (Blikstein & Worsley, 2016). In such models of instruction, the content of teaching is sequenced into part-tasks and steps to follow, and learners' success is largely assessed in terms of their ability to reproduce what they have been taught (Wells, 2008). Schmidt, Resnick, and Ito (2016) lament that too many schools train their learners to do the types of tasks and work that are being automated by computers and robots.

Contrary to the 2010s hype about bringing computational thinking into education (Guzdial, 2015), many educational researchers have also warned that little is gained without understanding the pedagogical foundations of computing education. For example, Idit Harel, who worked closely with Papert, criticized schools for preferring 'pop computing'—one hour of drag-and-drop entertainment with code—which is far from the deep understanding of concepts and mastery of practices that characterize the computing communities (Harel, 2016). Denning and Tedre (2019) presented a long continuum from basic CT for beginners to advanced CT for professionals, and suggested that the two are worlds apart. In a similar vein, digital design and fabrication with modern manufacturing technologies, such as 3D modelling and printing or laser cutting, face the risk of the 'keychain phenomenon'—mass-producing artefacts with little or no effort either at creating one's own designs or learning of the computational principles involved (Blikstein & Worsley, 2016). There is a worry that the current CT education fails its expectations on two counts: It might not prepare learners for the future of work and research, and it might not help learners to understand and prepare for the mechanisms of the world they inhabit (Denning & Tedre, 2019). To avoid these pitfalls, there is a dire need for pedagogical models that support learners to grow as confident and competent computational designers and thinkers who understand the complexity and ubiquity of information processes that they encounter in their daily actions and interactions with the material world.

Learning computational thinking through materially embodied design

Just as virtualization of material processes gave rise to educational movements and educational research horizons of the virtual kind, rematerialization of the virtual is spawning educational initiatives of its own kind. For example, Resnick's Lifelong Kindergarten lab has extended Papert´s visions by combining two different types of making: making LEGO models and Logo programs, which were further developed as Mindstorm kits and the Scratch programming language (Resnick, 2017). Scholars like Martinez (2013) and Blikstein (2016) emphasize the importance of maker projects in which the learners use high- and low-tech tools—from arts and crafts supplies to laser cutters, 3D printers, or microprocessors—to design and produce material artefacts. The growing body of research also documents the ways in which making with sensors and wearable technology is introduced in education. In the pioneering work of Kafai and her colleagues, learners used high- and low-tech materials to design clothing, accessories, or home furnishings with embedded electronic and computational elements such as programmable Arduino-based microcontrollers with sensors (for light and sound, among others) and actuators (such as LEDs and speakers) (Kafai, Fields, & Searle, 2014; Fields, Shaw, & Kafai, 2018).

The initiatives above (Martinez 2013; Blikstein, 2016; Kafai, Fields, & Searle, 2014; Resnick, 2017; Fields, Shaw, & Kafai, 2018) illustrated the importance of engaging learners in creation in two distinct modalities—virtual and material—by connecting seemingly abstract computing and concrete, hands-on, do-it-yourself craft. They showed that through robust pedagogical design it is possible to engage learners in increasingly complex uses of technology in which the learners themselves design and construct technology. Learners gain an identity of technological mastery and feeling of ownership rather than just one of consumers of off-the-shelf products. Those initiatives also revealed how the ideas and intellectual curiosity of learners can be a powerful and generative fairway for exploring key concepts in computer science in a highly meaningful, engaging, and contextualized fashion. Those studies are also examples of a wave that is shifting the focus in education from traditional conceptions and stereotypes of gendered crafting, technology, and computer science towards development of cross-boundary design projects and artefacts in gender-neutral and inclusive education.

Based on the theoretical, pedagogical, and practical insights presented above, this article aims to further a vision of the educational opportunities of rematerialization in order to strengthen the still limited line of research on how to support the development of computational thinking through materially embodied design. Rather than describing how computational thinking and design should be taught, the following section presents a process that comprises an increasingly complex set of activities of what learners can *do* to engage in similar kinds of practices and ways of thinking that professional designers develop though their work. Accordingly, the first step involves observations of interactions between embedded technologies and humans, and the highest level involves sophisticated coding and co-design for transforming the ways in which technology-charged artefacts and humans work with each other during specific, context-bound activities.

A process of making and thinking through computing

1. Exploration of existing artefacts and actions through data.

In our cross-boundary process description of computational thinking and making, the first step is concerned with raising learners' awareness of ubiquitous computing technology and the ways in which it affects human behaviour in everyday situations. This can be done, for example, by observing the interactions of people and the ambient technology they encounter daily at their homes, offices, schools, cars, and so on. This includes extending the awareness that computers need not be visible (pervasive or ubiquitous computing), that 'using' does not require an intention to use, and that human action is mediated by various kinds of material and physical artefacts in which the technologies are increasingly enmeshed. Systematic observations of how computing is hidden in the architectural environment (e.g., walls, doors, piping), in furniture (e.g., tables, chairs, carpets), or in everyday objects (e.g., household appliances, clothes, tools) (Streitz et al., 2007) can also trigger and contextualize learners' own design ideas and reveal questions that would otherwise go unasked.

Design is also a process of making something for and with others, and thus, it requires the ability to recognize the perspectives of diverse users, producers, experts, and others involved (Nelson & Stolterman, 2012; Kafai, 2016). It also requires the ability to recognize the moods and realities of others and to innovate designs that resonate with those moods and realities. One way to approach this is to challenge learners to imagine themselves in someone else's shoes or in a new community, for example, by exploring data from communication history, activity history, and tracking locations of items and persons. The learners can be asked to identify patterns of action and study how people interact with their environment and under what conditions. They can be challenged to question the existing practices of people and communities and move beyond what people say they do—that is, focus on the underlying needs, desires, and mediational means affecting human activity and experience.

By studying and profiling human behaviour though real-life data, the learners can also recognize how collecting and processing personal information is a core function of smart artefacts and environments (Streitz et al., 2007). As argued by Valtonen, Tedre, Mäkitalo and Vartiainen (2019), understanding interconnectivity and the ways in which various data streams generated by users are combined and used for a multitude of design intentions is an important part of computational thinking. Instead of remaining consumers of technology at the mercy of designers and developers of artefacts, interfaces, and systems that affect human behaviour, learners need to understand that data collected through them is more intimate than ever before: not only what we do, where we do it, and when we do it, but also what we will do next, and how we will feel while doing so (cf. Streitz et al., 2007). Increased understanding of ubiquitous information flows and always-plugged-in lifestyle can also be harnessed as a basis for pondering the design ethics and deep dilemmas of computational thinking—such as questions about privacy, security and automated surveillance (Denning & Tedre, 2019).

2. Framing and modelling design context.

There is a degree of consensus that modelling real-world phenomena is an essential crosscutting practice of CT, design, and science. As a design strategy, modelling existing artefacts and situated action can lead to a deeper understanding of the state of the design context in question (Enkenberg, 1993). Here, the learners can be guided to analyse and break existing artefacts, interfaces, or systems down to their constituent parts ('current situation'), and then re-design these interactions to model the structure of the desired situation, e.g. in the form of a graph or procedural representation (Enkenberg, 1993). In this way, the learners can explore and imagine what would happen if a certain element in the current situation is changed and, at the same time, further clarify a design problem that can be addressed through such intentional intervention. Situation graphs are also an important tool for communicating mental models to others (Papert & Harel, 1991). This cyclic process of framing the design context and problem, and modelling possible solutions can be repeated as many times as necessary until a mature image of a desired outcome has been reached.

3. Making conceptual, functional and visual models.

In order to develop computational *practices* related to CT, the learners also need to harness their observations and models about the world to design their own smart artefacts. This can be done, for example, through exploration and construction using sensor technologies that detect the environment (e.g. location, light, moisture, sound, temperature) and/or user biometrics (e.g. heart rate, temperature, sweating) (Kafai, Fields, & Searle, 2014). Modern machine learning education environments offer easy access to showcase to learners how machine learning works without the need to program them (Druga, Vu, Likhith, & Qiu, 2019). For model-building, students need to design a conceptual model as well as develop a functional model (Enkenberg, 1993) that defines what job an artefact does for its users, why, where, when, and how. They need to describe the incoming and outgoing data flows, data interactions and processing, and the instrumentation needed. For this purpose, easy-entry learning tools are key. After that, learners can code and customize their sensors with the support of re-usable code blocks and libraries. That way, the learners do not necessarily need to rebuild everything from scratch, as they can build on the work of others in pursuit of personalization or improvement. Students can be led to think at different levels of automation from the mechanization of simple manual jobs, to robotization of multi-task jobs, automation of complex jobs by shifting the control over to computers, and automation of knowledge work.

When creating material artefacts with embedded computing, learners also need to sketch and design the physical and material form, shape, and structure of the artefact in question (Kangas, Seitamaa-Hakkarainen, & Hakkarainen, 2013). Design of the visual and physical appearance can be done, for example, with the support of material exploration as well as with computer-aided design (CAD) applications. New applications are easy to use and offer a wealth of design resources, building blocks, code snippets, and instructions for making and customizing one’s own ideas, models, and artefacts. Through virtual reality (VR) and augmented reality (AR), learners can also model their 3D design ideas in physical locations (Chandrasekera, 2014). Likewise, they can use AR to embed additional information, visualize information flows, or guide the users of their artefacts (e.g., knowledge of materials used). Importantly, in a multimodal process of design, the learners not only engage in making aesthetic, material, or technical choices within a single modality, but also learn about interrelations within and across multiple sign systems (Kafai & Peppler, 2011). At the same time, they will begin to understand how computational design has become deeply intertwined with aesthetic experiences and emotionally appealing qualities of the design.

4. Making material prototypes.

Seitamaa-Hakkarainen et al. (2010) argue that designing of material artefacts cannot be reduced to a mere play on ideas; in order to understand and improve the ideas they embody, they have to be given a physical form by means of making, prototyping, and manufacturing. This shift from digital to material form typically requires learners to reconsider some earlier design decisions, as they are faced with various kinds of design constraints in practice, such as time, tools, material resources, and required technical skills or expertise. Prototyping ideas and manufacturing them in material form can be enhanced by digital fabrication and computer-aided manufacturing technologies such as 3D printers, laser cutters, or CNC routers (Blikstein & Worsley, 2016). This approach involves engagement in multimodal and parallel processes of conceptual reflection and material experimentation, in which prototyping possible solutions can occur many times over until a desired outcome has been reached (Kangas, Seitamaa-Hakkarainen, & Hakkarainen, 2013).

5. Testing, evaluating and developing smart artefacts and actions.

Nowadays, many design projects use rapid iteration and agile methods by testing low fidelity prototypes rather than designing an entire product, and discover only at the end that it does not work (Easterday, Lewis, & Gerber, 2018). As a design and learning strategy, carrying out investigations and systematic data collection (e.g. observations, interviews, usability testing) for the evaluation and further development of prototypes serve as basis for making informed design decisions and development work. The learners can explore, for example, how their own designs are adopted and involved in social practices, how they modify existing practices, and how their adoption changes their meanings or imposes new requirements for them. Systematic evaluation of the merits and limitations of prototypes leads to not only better outcomes but also supports learners to understand how reflection on advances and learning from failures is an important part of iterative product development.

Liljeström, Enkenberg, & Pöllänen (2014) note that in the emergent process of design, the student should also make visible their own process of learning, for instance, in the form of process portfolios. Portfolios, including self-generated data (such as photos, video clips, and sketches) also provide an important mirror for metacognitive thinking and feedforward discussions for the students themselves (self and peer assessment) as well as for the teachers. According to Fields, Shaw, & Kafai (2018), design portfolios can be seen as meta-artefacts, or 'objects-to-think-with', in which students can express what, why, and how they have made a computational artefact and thus begin to reflect and narrate, in their own personalized ways, their own learning process and identities as computational designers.

6. Co-creation of networked artefacts and actions.

Embedded technologies also offer new opportunities for community-based interventions in which the learners deliberately create new social practices (Tissenbaum, Sheldon, & Abelson, 2019). For example, Easterday, Gerber, & Lewis (2018) created a large network hub that connected multiple people, tools and resources to confront complex social design challenges. In the context of school education, such community-based interventions can be implemented, for example, by co-constructing sensors that collect real-time measurement data about certain wicked problems, such as air quality or noise pollution. This enables the learners to make meaningful statements about local conditions and orchestrate collective actions that leverage the benefits of distributed data collection and expertise. When sharing the design problems and process with a larger connected community of learners, teachers, and external experts, the students can also learn how to confront wicked problems at greater scale and complexity than any given learner might be able to handle alone (Easterday, Gerber, & Lewis, 2018). Active contribution in such joint design efforts can also increase an individual and collective sense of responsibility to participate in the world and, in so doing, influence people, events and circumstances for the better (see OECD, 2018).

To sum up, we draw on previously presented technological trajectories of rematerialization and theoretical insights and propose a process of learning that connects computing with material making in education (Figure 2).

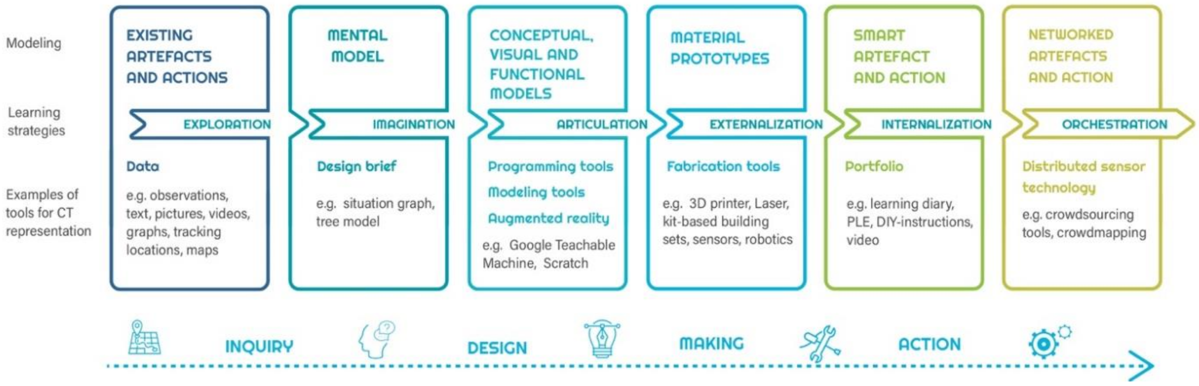

Figure 2. Design-oriented learning process for computational/material thinking and making.

While the model presented above emphasizes students own ideas and active agency, teachers have a critical role in orchestrating co-design and invention efforts (Viilo, Seitamaa-Hakkarainen, & Hakkarainen, 2011). Similar to sociocultural studies of mind, this model does not posit standard developmental capacities on certain ages of students (Schoultz, Säljö & Wyndhamn, 2001), but highlights teachers' own contextual creativity when building diverse physical, social, and material scaffolds tailored to each class's unique aims and project at hand. However, deep understanding of concepts and mastery of practices takes time to develop and thus, requires engagement in sustained and long-standing pursuit of developing artefacts and related knowledge practices (Hakkarainen & Paavola, 2009). From this perspective, the general goal of instruction involves encouragement, means, social settings and metacognitive support adjusted to student's evolving interest and skills, within their dynamic zone of proximal development (c.f. Vygotsky, 1978; Rogoff, Mistry, Göncü & Mosier, 1993).

Moreover, design-oriented learning projects often extend boundaries of school subjects and therefore, they provide novel opportunities for teacher collaboration as well as for connecting with external experts (Kangas, Seitamaa-Hakkarainen, & Hakkarainen, 2011; Vartiainen et al., 2018). External expert may provide on demand support, but importantly, mediate their tacit knowledge, epistemic practices as well as values when solving emergent problems (Seitamaa-Hakkarainen et al., 2012). By offering the students the chance to collaborate with their peers, to take part in face-to-face interactions with domain experts, and to be involved in networked actions with a more dispersed population, the students are also offered different forms of participation (Jenkins et al., 2008).

According to Zhang, Hong, Scardamalia, Teo, and Morley (2011), creative teaching can be best supported through a principle-based approach, which defines core pedagogical values and insights, but encourages and facilitates teachers' reflective interpretation, collaboration and contextual design. To support these educational initiatives on computational-material making and design, we further summarize a set of design principles that organizes the interaction between the subjects, objects, and tools in the emergent process of learning and computational design (Papert, 1987; Enkenberg, 1993; Seitamaa-Hakkarainen et al., 2010; Kafai & Burke, 2014; Tedre & Denning, 2016; Tenenberg, 2018; Vartiainen et al., 2018; Tissenbaum, Sheldon, & Abelson, 2019):

- Learners pursue meaningful projects and open-ended design problems that arise from exploration of real-world phenomena, are ethically sound, and feel personally interesting
- Design-oriented learning process of computational/material thinking and making is aimed at modelling the practices and habits of mind that expert communities develop through their work on designing computing-charged artefacts, social practices, and apps
- Learners are provided with multiple modes, materials, and tools to externalize and develop their computational thinking with the support of peers, teachers, and communities
- Through the processes of co-design and co-development learners can participate and contribute in collective efforts and actions
- The context and process of learning and action constantly evolve through design and computation in the world

Concluding remarks

The technological trajectories described in the previous section highlight the emergence of an era that fuses the material, social, and virtual, and is driven by big data, massive computing, tracking, automation, and a new kind of machine learning embedded in everyday environments and artefacts. As such, many tasks and skills are already being automated, including many of those that were hoped to create jobs in the digital society. At the same time, those forces that are radically changing the labour market are providing myriad new opportunities for augmenting human activity and learning through rematerialization of the virtual. While embedded technologies are creating new solutions that can enrich our lives, they are also creating unparalleled needs for developing cross-boundary design competences that combine computational thinking with understanding of the social and material nature of human activity. These design skills and technological benefits have an unfortunate downside, too: without forward-looking educational policy and action, they will foster a new digital divide in which jobs and wealth will be the privilege of those with the competences to participate in the creation of increasingly intertwined virtual, societal, and material worlds. Those gaps manifest themselves in socio-economic indicators such as employment, economic inclusion, and gendered participation (Brynjolfsson &

McAfee, 2014), but also in debates about learning and participation in a technology-driven society (Jenkins et al., 2008). Behind these concerns are two different social and technological trajectories: on the one hand, the growing uncertainty of employment in all occupations, and on the other hand, flourishing new forms of work that bring together computing, arts, crafts, and humanities with design thinking and collective creativity (Brynjolfsson & McAfee, 2014).

While design skills are often presented as a positive driver of innovation, entrepreneurship, and future societal activities, the new divide between the haves and have-nots engenders serious questions for education. Jenkins et al. (2008) note that education should no longer merely focus on questions pertaining to digital media access (digital divide), but increasingly on inequalities in skills of participation (participation gap). These concerns require educators to ensure that every young person has access to the skills needed for full participation in the digital culture (Jenkins et al., 2008) and is able to grow as a responsible designer and maker of the future of technology-driven society (Kafai & Peppler, 2011). As such, makerspaces and communities, inside and outside a school, have an essential role to play in creating a more equitable opportunities for making, learning, exploring and sharing mediated by various kinds of high tech to no tech tools.

While rematerialization of the virtual challenges many of the existing practices of education, it also opens new opportunities for design-oriented learning that bridges together computational thinking, making, and collective creativity. Vossoughi and Bevan (2014) argue that in many ways making and thinking with technology mirrors, or at least echoes, traditional forms of scientific and artistic investigation in which artefacts and devices are built, tested, and used for purposeful activities. Engagement in the process of computational thinking and making also helps to understand how design ideas develop through systematic exploration, explanation, and interpretation of the world. Personal fabrication and "grassroot innovation" may also become an alternative to mass consumption as more people gain access and skills to harness digital design, fabrication and computing opportunities (Kohtala, 2017). On the other hand, some researchers criticize the environmental dimension of digital fabrication and making, as they may lead to perception and production of easily replaceable and disposable artefacts (e.g. Mota, 2011; Maldini, 2016).

Researchers have also called a deeper understanding of the risks of the rematerialization. While these novel connections between virtual and material have aroused great enthusiasm, there is an evident need for understanding how pervasive sensing in our homes, workplaces and leisure activities provides unforseen data about our physical activities and other physiological, cognitive, and biochemical parameters related to our everyday actions and interactions (McGrath & Scanaill, 2013). On the other hand, when the learners themselves design and program smart artefacts, they not only create program code or texts, but they also engage in many of the same critical, creative, and ethical considerations that researchers consider relevant practices for 21st century learning (Kafai & Peppler, 2011). This includes the critical understanding of the rematerialization of virtual and how it is rapidly changing the foundations, structure, and dynamics of our thinking, behaviour and misbehaviour, and even our values.

While programming requires domain-specific skills and understanding, many of the core design and CT practices are key skills for the twenty-first-century learner (Grover & Pea, 2018)—take, for example, the skills of communicating and collaborating to solve complex problems, the ability to adapt and innovate in response to new demands and changing circumstances, and the skills of using technology to create new knowledge and expand human capacity and productivity (see Binkley et al., 2011). Kafai and Burke (2014) promote computational participation, which they define as the ability to solve meaningful problems together with others, the ability to design systems for and with others, and the ability to draw on practices, concepts, and perspectives of computer science to understand the cultural and social nature of human behaviour. Co-designing, making, and programming in networked communities can also be seen as ways of interacting within a larger socio-technological system for generating and deploying information and pooling knowledge within collective intelligence (Jenkins et al., 2008). What is more, the ability to work with hybrid technology supports the broader goal of banishing magic from the technologically rich world: by understanding how everyday ubiquitous technology works, it no longer looks like magic but like something one can control, design, and create. It also helps students recognize that collaborative design and computing play a key role in meeting many of the wicked problems of technology-driven society.

Future directions

This article has described the emergence of embedded technologies and some theoretical underpinnings of learning and mediated action in the interface between the physical and digital domains. The article suggests a number of ways of harnessing these unforeseen opportunities in education; however, these descriptions are by no means meant to be final, but rather intended to lay out some directions for further theoretical and empirical work. These theoretical views can be explored and developed through sustained design experiments on what kinds of design and learning processes emerge in small- and large-scale projects that connect computational thinking, making, and action in the school context. This includes the intention of creating classroom-based projects with small-group activities, enhanced by socio-technical tools that promote the improvement of ideas and collaboration within and outside the community of education and institutions. We suspect that the Finnish education system creates an interesting research context for studying and developing these pedagogical insights, as it provides teachers a great amount of autonomy to construct their teaching practices (Niemi, Toom, Kallioniemi & Lavonen, 2018) as well as emphasises cross-curricular themes, the development of transversal (generic) competences, as well as project-based studies situated in diverse learning environments (Finnish National Core Curriculum [FiNCC], 2016). Other design experiments could also study international collaboration and explore the process of design and computation when tackling wicked problems with an extended network of learners, teachers, researchers, experts, and interested others.

Cross-boundary design also creates an ever-increasing need for methods for tracking emergent learning activities and interactions. While the current research literature takes a largely qualitative (ethnographic, case study, interview, descriptive) approach to studying design and making in education (Vossoughi & Bevan, 2014), some newer studies incorporate automated data collection and analysis for capturing the open-ended design processes (Blikstein et al., 2014). In terms of studying and developing cross-boundary skills, there is a rising interest in mixed-method approaches that combine participation data (user-generated content such as DIY-videos and instructions, and portfolios) with social network analytics of social interactions and networked activities. Such data can be used for predictive and explanatory purposes, as well as for reflection, formative assessment, and on-demand scaffolding.

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