A Material Strategy:
Exploring Material Properties of Computers

Anna Vallgårda [1&2,*] and Tomas Sokoler [2]

[1] *Swedish School of Textiles, University of Borås, Borås, Sweden*
[2] *IT University of Copenhagen, Copenhagen, Denmark*

As design problems are inherently indeterminate or wicked, we have to rely on various strategies when practicing design. In this paper, we propose a material strategy that emphasizes the expressional potential of computers. We argue how computers, in principle, can be understood as a material for design and how they can be part of a *formgiving* practice. We embark on the beginning of establishing a practical understanding of the computer as a material by articulating a number of material properties of computers. Two of these properties, *computed causality* and *connectability*, are given shape through material samples of a computational composite. The composite is in the form of a copper tile of which the computer controls the thermodynamic behavior. The material strategy proposed here which produced dramatic results is still in its infancy, but by adopting a material understanding of computers and beginning to embody the space of opportunities it unfolds, we take the first steps towards a new way of designing computational objects and architectures.

Keywords – Computational Composites, Connectability, Computed Causality, Design Strategy, Formgiving, Material Properties.

Relevance to Design Practice – This paper presents a way of incorporating computational technology in other material design traditions such as industrial design, art, and architecture.

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Introduction

What if designing computational objects was about *formgiving*[1] ? What if we, with the right mindset and suitable experiences with computers, would be able to design computational objects and architectures as balanced negotiations between form and function similar to how a carpenter gives form to wood or a fashion designer creates new garments? Computers' unfathomable potential promises a world of possibilities. In isolation, however, their form is in all practicality invisible. Including them in a formgiving practice requires a way of addressing this formlessness.

Since the invention of the computer, researchers and practitioners have pondered how to bridge the gap between the human action space and the apparently formless computer. Under names such as ergonomic design, human-computer-interaction, interaction design, and experience design we have set out to form and express systems and objects that in different ways harness the computer's potential. A certain form-language has been developed in terms of the graphical display and the alphanumeric keyboard which allow the functions to be expressed through the layout of the display and interacted with through the pressure on the keys. Some, however, have found the graphical display too limited or rigid to express the desired functions and have invented other forms which involve a larger part of the human sensory apparatus (Fitzmaurice, Ishii, & Buxton, , 1995; Ishii & Ullmer, 1997; Holmquist, Schmidt, & Ullmer, 2004). Common for all these endeavors is the ambition to pilot the user's interactions with the computational technology. Researchers exercise their understanding of affordances (Gibson, 1979), skills, rules, and knowledge (Rasmussen, 1987), and realize that there is more to appealing interfaces than just efficiency and effectiveness (Norman, 2004). Still, researchers struggle to make meaningful, interesting, inviting, coherent, and comprehensible results of the form and its function (Overbeeke Djajadiningrat, Hummels, & Wensveen, 2002; Dunne, 2005; Hallnäs & Redström, 2006; Gaver, Bowers, Kerridge, Boucher, & Jarvis, 2009).

Design problems are inherently indeterminate or wicked in that they incorporate a future of interpretations and use, they play out with no true boundaries or constraints on the subject matter, and in that they have no guidance from a fixed relation between form and function being that their relation is a constant negotiation. We are therefore obliged to rely on various strategies of partial understandings to shape our work (Buchanan, 1992). The view on the subject matter, the partial understandings brought into the work, and the role of form and function vary with each strategy. Djajadiningrat, Wensveen, Frens, and Overbeeke (2004) describe two such strategies. The first is a communication strategy where the purpose of the design task is to communicate the functionality of an artifact depending on the users' knowledge and experience. Here, the designer needs to find a form that communicates the preexisting function. This strategy makes use

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Corresponding Author: anna.vallgarda@hb.se

of various perception studies to generate and shape the designs (Rasmussen, 1987; Eysenck & Keane, 2000) and the results generally rely on metaphors, iconography, and representations. The second strategy is described by the researchers as an interaction strategy where the functionality arises only through the users' interaction with the artifact. This strategy seeks to bring into play the entirety of the user's sensory apparatus. As such, it relies on studies of the user's behavior and action space which also leads to sensitivity towards the richness of the material world (Djajadiningrat et al., 2000; Overbeeke et al., 2002; Buur, Jensen, & Djajadiningrat, 2004). Both strategies are used with apparent success under the constraints of dealing with wicked design problems. Though they demonstrate two significantly different views on the subject matter, there are situations where each finds a convincing application. In addition to these, we point out a third — a material strategy.

Material Strategy

A material strategy, we believe, will heighten the expressive qualities of computational objects and architectures because it takes its departure in the expressive qualities and materiality of the technology. The leitmotif for the strategy is "function resides in the expression of things," articulated by Hallnäs and Redström (2006, p. 166). This means that the expression or the form is pivotal to the functionality and that one cannot be designed independently of the other. Thus, the material strategy leaves both form and function in a state of ongoing negotiation throughout the design process. The strategy is thereby closely linked to the craft-related notion of *formgiving*, which Smets, Overbeeke, and Gaver (1994) introduced to the practice of computational design. Formgiving is the act of deliberately manipulating a material into a form in which functions resides.

One example of a well established formgiving practice is glassblowing. When molten glass is carefully blown into a vase, for instance, the formgiver possesses an understanding of the silica mixtures, their properties, and behaviors in relation to temperatures. She also masters the blowpipe, the tongs, and the oven, which enables her to skillfully negotiate the form and the function of the resulting design. Practicing formgiving with computers could be possible if we understood the computer as a material, and if we understood its material properties and learnt how we could utilize and work with it as such.

Figure 1. Picture of glass being shaped by a skilled glass blower (with courtesy of Glasriket).

To accomplish this, to learn about the computer's materiality, we must study it. We must explore its properties and its behaviors. However, even if the inner workings of a computer are physical and have the ability to affect other materials, they are not perceivable through the human sensory apparatus and can therefore only be studied and used for design in composition with other materials. We therefore build on the notion of computational composites as laid out by Vallgårda and Redström (2007). A computational composite is a material composition of which the computer is one constituent. Composite materials always represent an enhancement of some properties of its constituents and a suppression of others; therefore, studying the computer's properties and behaviors will always be indirect. We look at computational composites as revealing a space of opportunities confined only by the physical limitations of the actual constituents of the composites. To learn about the computer's materiality, we must explore this space by embodying it with material samples. We must seek its boundaries as a means to grasp its range. Although new inventions are likely to continue its expansion, we believe it is possible to gradually attain a familiarity with these composite materials that will be elaborate enough for designers to develop a practice around giving them form. Developing this knowledge of computers' materiality is, therefore, a constant negotiation between ideas formed by experience, the development of new material samples, and theoretical analysis. Taken together, they will enable us to identify and articulate aspects that will help us navigate the space revealed by computational composites.

Indeed, we believe that over time the material strategy will be viable in an endeavor to develop significantly new aesthetics[2] of computations. Further, we believe that it will support the development of new forms and expressions by utilizing the materiality of computers, and through that create new functionality (Redström, Redström, & Mazé, 2005; Hallnäs & Redström 2001; Hallnäs, Melin, & Redström, 2002; Vallgårda & Redström, 2007). Others have proposed to break from the prevailing form-language

Anna Vallgårda, PhD, is a Post Doctoral fellow at the Swedish School of Textiles, University of Borås. She did her PhD at The IT University of Copenhagen where the majority of the research in this paper was conducted. Her research revolves around exploring the computer as a design material. Through a series of experiments, she has developed theories and methods of how to work with and understand the computer as a material for design. The purpose is to expand the repertoire of expressions used for computational artifacts and environments as means to create new experiences and functions. Currently, she is investigating possible structures of knitted textiles to become part dynamic reversible and irreversible expressions controlled by computers.

Tomas Sokoler, PhD, is an associate professor with the Innovative Communication group at the IT University of Copenhagen. His research takes place at the intersection between Pervasive Computing and Interaction Design. As such, his research in general aims to both define and explore the landscape of possibilities for humans to interact with digital technology as we continue to move beyond the known patterns of interaction from the traditional desktop computer. Sokoler takes a design oriented and explorative approach to his research incorporating the actual construction of working prototypes/sketches. For the last couple of years his research has been directed towards the design of digital technology for senior citizens. In particular, he has been exploring how the integration of digital technology with mundane activities can help bring forward openings for social interaction within groups of people aged 55 and above.

(Fitzmaurice et al., 1995; Ishii & Ullmer, 1997; Holmquist et al., 2004) and the material strategy has certainly been inspired by their way of thinking. However, we believe that the material strategy will be capable of taking a step further for two reasons. First, the material strategy abandons the understanding of the computer as confined to being an information technology. Second, albeit related to the former, the material strategy approaches the design task as a whole with the development of form inextricably linked to the development of function, rather than relying on a "form following function" leitmotif as is most common within tangible computing (Vallgårda, 2009).

The next section outlines a material understanding of computers, describes computational composites, and provides examples to help get a grasp of the space of opportunities they reveal. The following section develops the notion of formgiving and relates it to computers. Finally, we propose using material properties as handles to navigate the space of computational composites. We identify and conceptualize a range of properties and begin to explore a few of them in terms of what expressions they can entail. Overall, the explorations are done as interplay between developing material samples and theoretical contemplations. The result is a first step towards achieving the necessary familiarity with the material. The samples provide an opportunity of physically experiencing the effect of the properties, and the conceptualizations enable us to think about them and take them into account in a design process.

Understanding the Computer as a Material

In this section we address how to understand the computer as a material by providing an idea of what a material is and how the computer as an apparently formless and often abstractly rendered invention can be considered a member of such a physical category.

What is a Material?

With the development of new functional materials that has taken place since the 1950s, our perception of materials has changed. Traditional materials like wood, clay, textiles, stone and metals are still widely used today but they now have competition from a vast amount of designed materials and material composites. This has had two important consequences for how we understand and work with materials. First, with the vast number of materials and the pace with which new ones reach the market, it is no longer possible for designers to become familiar with the materials and their properties first hand (Addington & Schodek, 2005; Beylerian & Dent, 2005; Brownell, 2006, 2008; Gordon, 2006; Ritter, 2007). Instead, designers rely on descriptions, general classes of materials, and references to experiences with traditional materials (Manzini, 1989). Furthermore, the materials are seldom mass-produced and exist only in prototypes until they are demanded for a purpose (Addington & Schodek, 2005; Gordon, 2006). As a second consequence, the distinction between materials and products has been blurred. Functions that previously took entirely separate products to perform are now often possible to do with the material alone, like glazing with integral sun control louvers or self-cleaning clay tiles (Brownell, 2006).

Clearly, the material scene that we argue computers to be a part of is already highly diverse. That does not mean, however, that everything is a material. A general definition of a material, then, could be understood as a physical substance that shows specific properties of its kind which can be proportioned in desired quantities and manipulated into a form.

The Computer as a Material

To understand the computer as a material, first and foremost we need to acknowledge the physicality of the computer. Despite our comparatively long tradition of talking about virtual or information technology and about the computer as manipulating binary numbers, every computer that surpasses the mathematician's sketchpad is a physical structure that manipulates physical entities. The most common example of this is the continual process of distributing and redistributing electrical charge that takes place as storage operations and computations are performed. The computer is physical and not virtual, and that is the primary premise we must accept to understand how we can relate to it and work with it.

Additionally, the computer can be manipulated into innumerable forms. In and by themselves, however, they lack expressiveness and human perceivable form. It is beyond human perception to sense, in any direct way, the placements and displacements of electrical charges and the exchange of energy that takes place as imperceptible electrical currents flow to and from the computer. At first, this may appear to be an obstacle to a material understanding; however, several materials exist that lack significant qualities before they become usable. Aluminum, for example, in its natural occurrence in Bauxite is so weak that even if it is remarkably light and flexible it is practically unusable (Doordan, 1993). In the right alloy, however, it gains the strength to match its light weight and flexibility, and in that form it is one of the most widespread metals we have (Doordan, 1993). This is similar to when the emergence of material science fostered a spectacular contribution of composite materials where even a material as brittle as glass proved useful in one of the toughest lightweight materials – fiberglass (Gordon, 2006). In that light, it becomes appropriate to understand the computer as a material — a material which needs to be part of a composite with other materials in order to come to expression on a human scale.

Computational Composites

It holds for any composition of materials, whether it involves a computational constituent or not, that it is through the exchange of energy that one constituent of the material affects the other constituents and the properties of the composite as a whole (Hull & Clyne, 1996). As such, energy works as the common currency that cuts across constituents. Computers most commonly, disregarding the small dissipation of energy through heat, reside in the domain of electrical energy, while in most cases the other material constituents in a computational composite reside in domains of thermal, mechanical, or chemical energy. Thus, in order for the computer in a computational composite to affect the other material constituents and vice versa, there needs to be a way for energy to flow back and forth between the electrical domain and the other domains of energy. This flow of energy across domains is defined as transduction and is what defines the role of a transducer. In other words, for a computer to become an effective constituent of a composite material, the composite must include a transducer. Examples of transducers include light-emitting diodes (LED) turning electrical energy into light; DC motors turning electrical energy into mechanical movement; shape memory alloys turning electrical energy into mechanical movement and deformation; and Peltier elements, as shown here later, turning electrical energy into thermal energy. We could say that the transducers are the adhesive element in this type of composite material. For further details on the notion of computational composites, see (Vallgårda & Redström , 2007).

The computational composite can thus be seen as one strand of the more general category of smart materials (Addington & Schodek, 2005; Gordon, 2006). To get a sense of what a computational composite entails in practice, let us examine some samples.

Embodying Computational Composites

The concept of computational composites opens up a space of opportunities that, with material samples, will gradually gain shape as well as expand even further. One example is Chronos Chromos Concrete (Ritter, 2007) which was created at the Royal College of Art in London in 2006. Chronos Chromos Concrete is designed to make concrete less stubborn and more adaptable by enabling it to change color on demand. A concrete block is embedded with a heat element (nickel chromium wire) and the surface is treated with heat sensitive ink (thermo chromatic ink). Together they function as two layers of transducers. The computer plays the role of the controlling constituent in charge of the energy flow through the nickel chromium wires. To form something from the Chronos Chromos Concrete means to give the concrete a physical form, but it also means forming the color changes by way of developing the program for the computer's control as well as the paths of the heat emitting wire. As seen in Figure 2, this material can be used for a wide range of purposes.

Another example is PLANKS (Vallgårda, 2008), a project developed at the IT University of Copenhagen in 2009. The purpose of the project is to explore how materials that are not traditionally associated with computational technology can help to form new expressions of computations. Each PLANK (Figure 3) consists of a pine plank, a servomotor, an Arduino board with an Atmega168 processor programmed with a simple algorithm, and a microphone. Each PLANK works independently of the others. The microphone transduces the sound waves into electrical input for the computer, which in turn triggers the servomotor to transduce electrical energy into kinetic energy and ultimately bend the PLANK. If the sound continues to be of a certain volume, the PLANK will continue to bend outwards until it has reached a maximum. Only when there has been silence for a while will the PLANK gradually return to a straight position. To form something from the PLANKS means to use them more or less as they are, which is a surface material rather than a structural element. Their

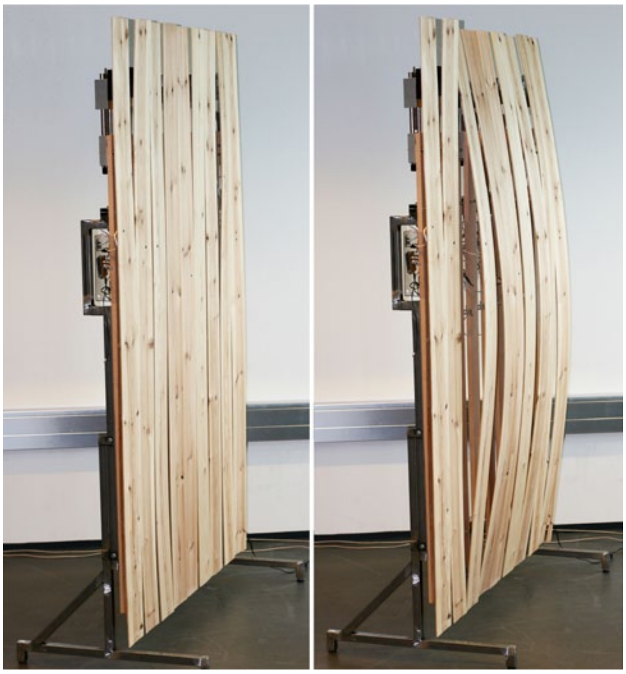

Figure 3. PLANKS: planks of pinewood flex as a reaction to sonic activity in their vicinity. Each plank works individually and can be used for a variety of different purposes such as wall panels or doors. The composite is made from pine planks, motors, microphones, and an Arduino computer (Vallgårda, 2008).

Figure 2. Chronos Chromos Concrete can change color in response to a computer's output.
The composite is made from thermo chromatic ink, nickel chromium wire, computers, and concrete (Ritter, 2007).

dynamic forms demand a sense of how the expressions will play out in context over time. The PLANKS could, for instance, be used as wall paneling decreasing the size of the room as the noise level increases, or even as a wall that cracks open when approached with an "open sesame."

Like these two samples, most computational composites tend to be art pieces or one-off prototypes rather than fully developed materials ready for designers to use. However, this is not significantly different from other genres of material developments (Beylerian & Dent, 2005; Brownell, 2006, 2008; Ritter, 2007). Also, the ideas invested in these samples are crucial for the ability to technologically and imaginably mature this new material branch. One of the more mature material compositions is computational textiles (Redström et al., 2005; Post, Orth, Russo, & Gershenfeld, 2000), which to some extent has reached a state of production, as seen with Buechley's sewable electronics (Buechley, 2009; Buechley & Eisenberg, 2009) or the products from International Fashion Machines (Orth, 2009). However, even the less technically developed examples with glass (Benjamin & Yang, 2006; Dalsgaard & Halskov, 2009), metal (Brownell, 2008, p. 53, 56), or concrete and wood, as we saw above, embody a potential for the computer as a material.

As a means to get a sense of the space of opportunities, we have chosen to depict (Figure 4) some exemplary samples that in various ways embody computational composites along two dimensions: material vs. product/building, and the degree of open-endedness of the material properties. There are other dimensions, like the degree of technical maturity, whether it is suited for surface or construction, or the degree of energy consumption. The two we have chosen, however, better reflect the topic of this paper. With this sense of computational composites and how they can be embodied established, how they can be combined with the concept of formgiving needs to be discussed.

Formgiving

Formgiving is traditionally linked to the practice of craft[3] in the sense that craft is the skillful act of giving form to a material. It incorporates the material knowledge and the practical skills associated with that particular material. Formgiving and design are not the same in that formgiving is often linked to one primary material, like glass in the previous glass blower example. The knowledge and experience within the formgiving practice based on the traditional materials have, however, influenced how we design. The Danish design boom in the 1960s (with Wegner, Jacobsen, Mogensen, etc.) was, for instance, an example of a cabinetmaking/architecture tradition successfully integrated with mass production. While designers and architects around the world had taken up materials like plastic and steel and had started to design on the premises of industrialization, the Danish architects lagged behind in that development resulting in a more gradual integration of the traditional formgiving and industrial design.

Wanting to integrate the inherently unfinished computational material with the "outdated" design practice of formgiving may seem odd in that it treats computers like a traditional material (granted with a notable theoretical superstructure). Developing hands-on practices exploring their potential, however, could bring some new expressions and new areas of use into an otherwise almost fully industrialized design tradition. One could say that we argue to take a step backwards in order to enable steps in new directions.

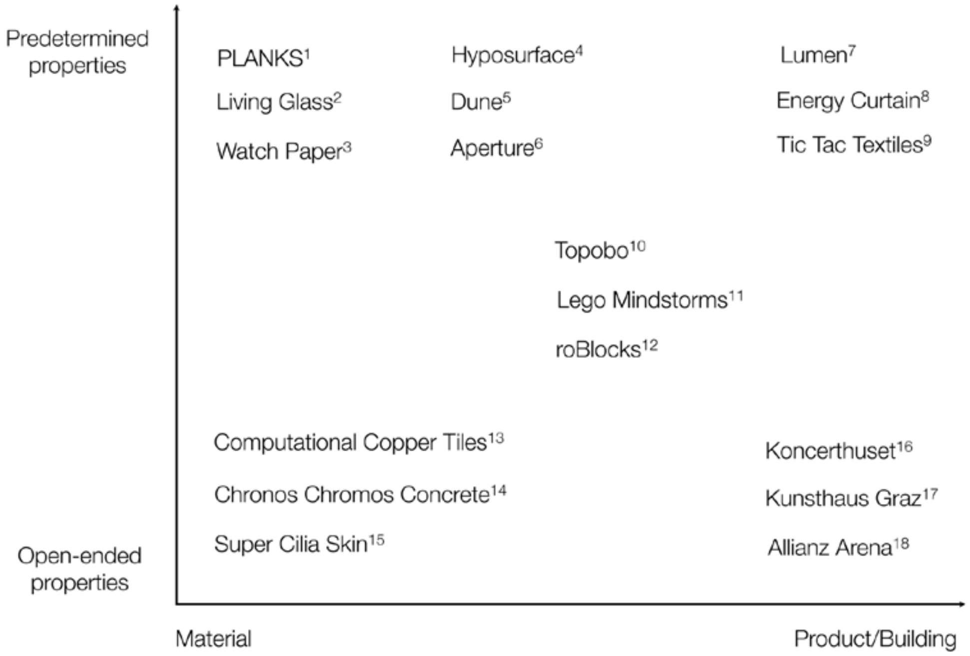

Figure 4. This diagram shows samples that in different ways embody the idea of computational composites. The samples are distributed along two axes: Materials vs. Product/Buildings and the open-endedness of the material properties. 1 (Vallgårda, 2008), 2 (Benjamin & Yang, 2006), 3 (rAndom International, 2004), 4 (Hyposurface, n.d.), 5 (Roosegaarde, 2006), 6 (Eyl & Green, 2004), 7 (Poupyrev, Nashida, Maruyama, Rekimoto, & Yasufumi, 2004), 8 (Ernevi et al., 2005b), 9 (Ernevi et al., 2005a), 10 (Raffle, Parkes, & Ishii, 2004), 11 (Lego, 1998), 12 (Schweikardt & Gross, 2006), 13 (see the following sections), 14 (Glynn, 2006), 15 (Raffle, Joachim, & Tichenor, 2003), 16 (Nouvel, 2009), 17 (Cook & Fournier, 2003), 18 (Herzog & Meuron, 2005).

Giving Form to Computers

The notions of craft and formgiving have been used in relation with computational technology on several occasions. Smets et al. (1994) use the notion of formgiving in a study of the relation between how visual forms convey information, or how "the visible form of an artifact […] suggest its non-visible attributes" (Smets et al., 1994, p. 80). Blauvelt, Wrensch, and Eisenberg (1999) contemplate various ways of introducing computing to the practice of craft. They examine, for instance, how a hinge, a thumbtack, and a ceramic tile can express new functionality through computations and how these items then can be used to create more advanced artifacts. They argue that by creating computationally enhanced building blocks it is possible to utilize computations without getting too entangled in the technological details.

In another direction, McCullough (1996) and Richardson (2005) both proposed to understand the skilled practice of programming computers as a sort of abstract craft. In this context, however, with an understanding of the computer as a material, we would argue that the apparent abstract task of programming cannot be distinguished from the materials it is to control – meaning the entity must be formed in mutual dependence.

Djajadiningrat et al. (2004) use formgiving to argue for a more rich interaction space which takes more of the human sensory apparatus into account. In their research, they gave their students a task to create two forms which on two dimensions were the same (e.g., old and light) but on a third were each other's opposite (e.g., one is fast and the other is slow). Similar student programs have also been carried out at Carnegie Mellon (Baskinger & Gross, 2010). The purpose in both cases was to study the power of forms — an approach that bears relations to the Basic Course taught by Itten at Bauhaus from 1919-1922 (Itten, 1975). In this course, Itten introduced the students to all kinds of textures, forms, and colors in a series of hands-on exercises. Although Bauhaus is more famous for the "form follows function" dictum, Itten came out of an art tradition and, as such, was more concerned with with the effect of expressions rather than functionality. His argument for the Basic Course was that before the students could be truly creative — regardless of their preferred medium or aspirations — they must master some basic knowledge of forms, colors, textures etc. (Itten, 1975).

Nevertheless, the computer's complexity, speed, and size have led some (Manzini, 1992; Hallnäs & Redström, 2006; Redström, 2008) to argue that we will have difficulties bridging form and function in computational objects. Their argument builds on the historic development of technology and interaction. When products were mechanical or electro-mechanical, the form was largely given by the function. The interaction was not a separate concern but intrinsically linked to the artifacts' form and function (Manzini, 1992; Djajadiningrat et al., 2007). When the products instead became purely electrically driven, the relation between form and function were weakened and the struggle of the interface began (Djajadiningrat et al., 2007). The interactions took place through standardized switches or sliders controlling a wide variety of different functions, though still in a one-to-one relationship. Then, when the computers entered the scene, the interrelations between form and function grew even wider. Each switch became the control of several different functions at the same time, thus demanding a separate display to convey the functional mode (Manzini, 1992; Djajadiningrat et al., 2007). Also, the input, output, and the functional core were perceived as separate entities.

Instead of seeing the complexity, speed, and size as hindrances for coupling of form and function, we argue that it is a question of perspective and granularity – the level at which we understand the computer. Understanding the computer as a material may offer a solution. We can find an analogy in wood. Wood is a natural occurring material we have always approached first as a material, only later beginning to study the chemical and physical foundation for its behavior. We have learnt by experience what various sorts and sizes of timber can endure in terms of weight and pressure. We also know that we can saw and nail wood and we have learnt how to do it without splitting it. We know wood swells in one direction and shrinks in another under moist conditions, and we know that when wood gets wet it loses some of its strength and stiffness. But, most of us do not know why. We are not familiar with the underlying cellular structures that are the core of this behavior. We are not in general knowledgeable of how the cells behave when we apply pressure at the end of piece of timber. We are unaware that small cracks cause the straw-like cells to separate which enables them to buckle and stretch according to their helical constitution – a flexibility which prevents the timber from breaking (Gordon, 2006). And we are not knowledgeable of the even lower level details of the six layers that constitute the cells, nor do we know about the chemical diversities between different sorts of wood. We have not in general bothered to learn these things about wood because it is not necessary in order to use it for design.

Indeed, we find that a material understanding of computers and a familiarity with their expressional scope in Itten's sense would enable a formgiving practice. Formgiving seems to offer a way of working and thinking that also coincides with the notion of "function resides in the expression of things" (Hallnäs & Redström, 2006, p. 166). Through some sort of hands-on material manipulation of computational composites, we can learn to give them form and create objects and spaces with new expressions and with new functionality. Challenges remain however, as the current embodiments of computational composites are primarily one-off prototypes and art pieces the direct hands-on experience of which can be difficult to accomplish. Also, the complex expressions possible with computational composites will probably entail a more complex relation between the designer and the material than we see, for example, between the carpenter and wood. Further, the open-endedness of most computational composites will mean that giving form to these materials includes considerations of the design of the material itself.

In order to develop a formgiving practice with computational composites, it is therefore necessary to combine a theoretical superstructure with a certain degree of material experience to form a frame of reference. In essence, this is not different from other formgiving practices but the weight given to the two aspects may be skewed towards a theoretical understanding due to the somewhat intangible materiality of the computer. Also, the frame of material reference in the beginning may be composed by experiences with more traditional materials as well as experiences with computations from an information technology realm. Thus, it is necessary to begin to articulate the theoretical superstructure in a context of materiality as well as to develop computational composites that in time can constitute a more appropriate frame of reference. Accordingly, we have begun to articulate and explore some of the material properties of computers and in turn the potential material properties of computational composites.

Material Properties of Computational Composites

As pointed out above, computational composites reveal a vast and diverse space of opportunities. In order to develop a formgiving practice around that, we need some handles to navigate it and to understand what is being done. “Every object made by man is the embodiment of what is at once thinkable and possible” (Manzini, 1989, p. 17). By articulating the material properties, we could obtain one such handle that would make them *thinkable*.

Material properties are the experienced characteristics of a material that enable us to discriminate one material from another, and they are signifiers for what we can do with the material. We may explain material properties through science, but we describe them based on experience. Material properties are therefore generally specified by the conditions they are experienced under (i.e., temperature, humidity, and light). Take window glass, for instance. At room temperature we experience it as hard but brittle, as transparent, and with a smooth surface. Science, though, will tell us it is in a liquid form (a so called glass-state), only at room temperature it floats so slowly that we cannot perceive it. Material properties can be seen as the language we use to articulate our understanding of a material in practice.

Articulating material properties of computers will inevitably be based on indirect experiences through some form of computational composite since the expressions of computers in and by themselves are beyond direct human perception. Indeed, this lack of direct perception has lead Löwgren and Stolterman (2004) to argue that the computer is a material without properties. We argue, however, that the computer’s specific ability to physically affect other materials is what makes it possible to treat it is a material with material properties.

Nevertheless, identifying material properties of the under-researched category of computational composites poses some challenges. First, the signifier for the category (the computer) is only one component, while the others in the composite are unknown at this point of generalization. Second, no material composite is just the sum of its parts (Hull & Clyne, 1996). The constituents’ individual properties will influence each other and will restrict each other’s scope of actions, but in unison they can also exhibit entirely new properties. Third, ongoing technological developments constantly change and expand the space of opportunities created by the computational composites, thereby changing existing properties and enabling new ones. Thus, any identified material property of computers will only be potential to a computational composite. In a sense, this makes the task of identifying and articulating material properties of computational composites an intrinsically wicked problem. As such, we have to rely on a strategy consisting of interplay between specific material samples and general theoretical contemplations, which through future iterations will provide us with a reasonable idea of the material properties of computational composites (Vallgårda & Bendixen, 2009).

Because computational composites are not abundant and because they are the result of design decisions, we cannot rely solely on studies of existing samples as a means to articulate their potential properties. Instead, we combine our imagination grounded in experiences with computers, materials, and theoretical knowledge of computers, physics, chemistry etc., with the understanding we gain from developing the physical samples of computational composites (Vallgårda & Bendixen, 2009).

What we present here is an articulation of the possible material properties as we see them within the space of computational composites as it unfolds now. Material properties help us understand what is possible with computational materials and thus important handles in developing and executing the material design strategy. In time we may propose others, just as we may change their descriptions, but this is a beginning.

Temporality

Hallnäs et al. (2002) were probably the first to articulate a material property of computers. Since computers execute programs (compute) and since that inevitably is a temporal process, they argue that temporality would be an inherent property of computational technology. They explain that “this makes *temporal gestalt* the central form element of this material: as we execute programs, temporal structures are created” (Hallnäs et al., 2002, p. 158, original emphasis). Basically, this means that whenever a computer is in play the expression will be something that happens over time; it will change. We could say that the physical expression of the computer’s temporality is change. Every material changes over time, but in this case the change comes from within and is not necessarily a consequence of the surrounding environment, just as the change may be reversible. It is not decay; it is active behavior. The property of temporality expressed through change can be more or less explicitly exploited. For instance, the changes can be gradual at a slow pace and thus camouflaged to the naked eye, or they can be an explicit part of the expression as in the change of color in the Chronos Chromos Concrete (see Figure 2) and in the E-plaid (see Figure 5), or simply the movements in the PLANKS (see Figure 3).

Temporality is therefore an essential property to consider both when designing the computational composite and designing with the computational composite. No object or architecture exists which embodies computational composites that is not able to exhibit change.

Reversibility and Accumulation

Closely linked to the ability to change is the ability to change in distinct formations. Changes can be reversible or accumulative, or

Figure 5. This is two examples of E-plaid by International Fashion Machine, which gradually changes color and thus significantly changes expression (Seymore, 2008).

Figure 6. The Telltale is a piece of furniture that exhibits both reversibility and accumulation through its composition of materials and computations in use over time (Bergström et al., 2010).

any combination thereof. In computational composites there are two sources of memory: one is the computer and the other is in the material components. The other materials' memories are primarily dependent on their chemical and physical constitution and will for the most part only be able to accumulate (e.g., as patina or decay). Only in the rare cases can we see a case of reversibility within the other material (e.g., shape memory alloys). The computer's memory, on the other hand, is more flexible. It is used to store patterns of electrical charge distributions during the execution of a program and is what enables the computer to store and recall a previous state. Due to this design, it can both be in a state of accumulation and reverse from one state to a previous, as long as appropriate transducers exist to sense and execute.

The experience of these potential properties can be quite diverse. Accumulation in a computational composite can be used to create a kind of patination, where one or more factors (internal or external) gradually leave their marks and create changing expression. Chronos Chromos Concrete could, for instance, be made to gradually change color as an effect of the amount of pollution in the air (a concrete computational version of "This is the air we breathe" Bergström, 2008). Alternatively, the accumulative ability could be used to establish a threshold in the computer for the repetition of a factor, and when that threshold is met the composite material could change its overall expression. In this case the expression of the accumulation is less immediate. For example, if the PLANKS kept bending outwards instead of resetting when silent, or the permanent change of expression seen in the Burn-out Tablecloth below in Figure 7.

Reversibility, on the other hand, can be used to reestablish a previous state of expression. For example, if a certain factor has caused the composite to change expression, then the absence of that factor could also cause the composite to return to its previous expression. The PLANKS, for instance, has the ability to change between a straight and bent state depending on the sonic activity. One example that exhibits both accumulation and reversibility is the Telltale (Figure 6). The Telltale is a piece of furniture whose robustness depends on the energy consumption in the household it belongs to. The Telltale deflates and inflates according to the fluctuations in the consumption and, as such, exhibits reversibility. Any use in the deflated state causes permanent accumulating scars due to its lack of rigidity in that state, and over time it will exhibit the long-term energy consumption of the household.

Computed Causality

The computer's ability to compute based on an input and to make the result available through an output means that in principle it can establish any desired cause-and-effect. The computer can thereby be a powerful tool in playing with our experience of the laws of nature. Also, the computation in a digital computer offers extensive room for interpretation and reinterpretations as it consists of a system of binary events. Indeed, every input and output will adhere to the same formations of electrical charges inside the computer. Therefore, only the availability of appropriate transducers determines what is interpreted and how it is expressed. For example, a sensor input from a microphone may become the movement of a piece of wood through transformation to a binary format, through computational manipulations, and through energy transductions (motor), like that seen in the PLANKS. This ability can be used to exaggerate or otherwise moderate existing causalities, or it can be used to establish entirely new connections between causes and effects. A computed causality can be apparent or concealed, it can be strong or subtle, and it can even undergo changes. The material composites that exhibit this property will be responsive materials that in various ways are able to respond to the environments they enter in.

Figure 7. Left: Burn-out table cloth where mobile phone activity around a dining table is reflected in a burned pattern (Landin, Persson, & Worbin, 2008). Middle: Detectair, a jacket that detects pollution and lights up (Mateyko & Troyer, 2010). Right: Dune reactions based on a complex set of newly established causalities managed by the computer (Roosegaarde, 2006).

Figure 8. Top row: Telemurral; a distorted video link between two dormitory hallways (Karahalios & Donath, 2004). Bottom row: Interactive Pillows, when one is hugged its counterpart lights up (Redström et al., 2005).

It is comparatively common to see material samples, designs, and architectures in which computers are used to establish entirely new relations between otherwise discrete events. For example, the Burn-out Tablecloth in which the threads gradually burn depending on the degree of mobile phone communication in the vicinity (Figure 7, left), or Detectair, a jacket that senses environmental toxins in the atmosphere and alerts and protects its wearer (Figure 7, middle). Another example is Dune, which exhibits a complex relation between human motion and noise and the behavior of the fibers (Figure 7, right). It is less common, however, to see the computed causality used to meddle with existing and familiar causalities. By understanding the computer as a material, it immediately becomes interesting to investigate how it can meddle with our notion of material behavior formed by our substantial experience with traditional materials. This aspect of computed causality is the object of a material investigation described in the next section.

Connectability

Connectability is the computer's ability to connect and communicate with other computers. This property is founded in computers' ability of handling protocols through attached radio devices to produce connections with other computers. It is arguable a second-degree property in the sense that it requires an additional device beyond the core computer, for instance a radio or an equivalent technology. The combination of the two is so common, however, that in any practical sense it can be seen as a property of computers. The expression of the property is that of connectedness – that something physically separated is capable of behaving as if it were physically conjoined. This obviously allows for a wide variety of expressions owing the specifics to the other constituents of the composite. We experience connectability in the myriad of designs and architectures where computers bring events into play that happens elsewhere. This property is especially used in ambient displays that seek to establish an ambient link of communication between physically distant social situations. An example of this is Gaver's seminal Feather, Scent, and Shakers that in discrete ways lets the users know that their loved ones are thinking of them (Gaver, 2002). Other examples include the Telemurrals that through a distorted and merged video transmission socially connect two dormitory hallways (Figure 8, top row); and the Interactive Pillows that light up when their counterparts are hugged (Figure 8, bottom row). However, placed in a material context, as opposed to a communication context, we immediately come to think of what it would mean to have a distributed material — a material physically separated but behaving as if it were physically conjoined. Thus, we have made that one of the foci of a material investigation described in the next section.

Temporality, reversibility, accumulation, computed causality, and connectability are the five material properties we have identified so far, yet we still need to become more familiar with what they entail in practice. As every one of these properties can result in a host of different material expressions depending on the composition of materials, as well as how they are combined, it is principally impossible to explore them in their entirety. Nonetheless, that should not stop us, only we have to rely on a strategy where we move between general theoretical contemplations and specific material samples, and accept the incompleteness of the outcome. We begin our explorations with the two properties that seemed to open the most new spaces by being articulated in a material context: computed causality and connectability. As material properties never appear isolated, several will inevitably be present at once. We do, however, focus the computational composite as much as possible around one property at the time by developing expressions that explicitly utilize that property.

Computational Copper Composites

The material for the study will be a computational copper composite. The copper composites appear, at first, as two ordinary copper tiles, but they exhibit a somewhat different thermodynamic behavior (Figure 9). We have chosen to play with the transportation of thermal energy (heat) and the effect of temperature differences within the material, as well as with the effect of temperature changes in the environment. A context dependent thermal behavior is not an expression commonly associated with computers, but it is a central aspect of almost any other material. To develop a computational composite that explicitly integrates this traditional material aspect as its main changeable expression lends us a platform to explore the computer's material properties within the traditional material realm. Indeed, by treading this unfamiliar territory when it comes to computational expressions, but remaining within a traditional material realm, we will be able to demonstrate the design potential — the potential for developing new aesthetics, new forms and functions (parallel to the strategies of the Strangely Familiar (Blauvelt, 2003) or Parafunctionality (Dunne, 2005).

Through two versions of these two identical computational copper composites, we explore new expressions of computed causality and connectability. The composites will indirectly also exhibit temporality as well as aspects of reversibility and accumulation; however, we have left it for future work to study those more explicitly. As argued, a material cannot be made to exhibit only one property, and the properties outlined above are only rarely separable from each other. What we have done, then, is to make them more explicit one at a time in the overall expression in order to better explore them.

The Material Composition

The copper composites are tiles made up of four major constituents, albeit the fourth constituent is only used for the exploration of connectability. First, of course, we have the standard copper material with its desired thermal properties and, in particular, its high coefficient of heat transfer making it possible for us to generate relatively fast thermal effects (top left of Figure 10). Second, we have the transducers. For the transduction between electrical and thermal energy, we have used Peltier elements (bottom left of Figure 10). Peltier elements are in effect heat-pumps capable of transporting thermal energy (heat) from the cool side to the hot side of the material under the influence of an applied electrical field. The Peltier elements are bidirectional in the sense that they can switch the direction of the thermal energy flow simply by reversing the direction of the applied electrical field. We have for now only implemented the one-way transport of thermal energy. However, a relatively simple modification (in next iteration) would allow for the bidirectional flow. The Peltier elements' required energy field is delivered by an external power supply under the gated control of the computer component in the composite. Additionally, the composite contains a temperature sensor. Third, we have the LilyPad single board computer (top right of Figure 10). The LilyPad is built around the Atmeg168 microcontroller. The LilyPad enables us to alter the program to create different sets of computations in the tiles. Fourth, we have an Xbee (series 1) radio module (bottom right of Figure 10) following the ZigBee standard capable of forming ad-hoc peer-to-peer networks over reasonable distances (30-90m depending on the environmental conditions).

Figure 9. Pictures of the two copper tiles.

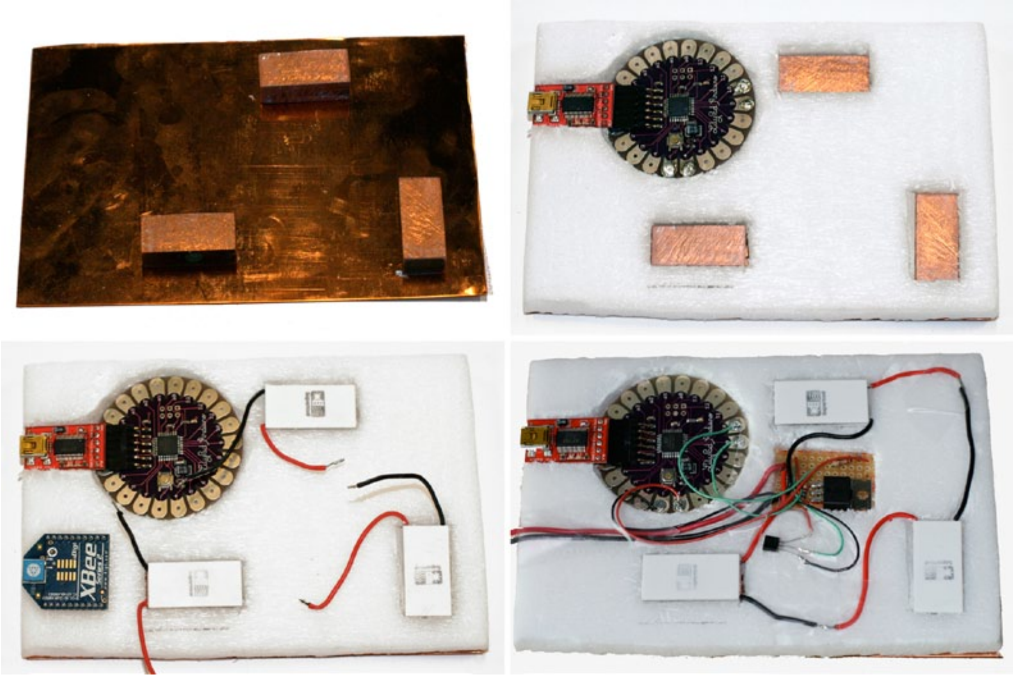

Figure 10. In the top left picture we see the copper formation inside of the tile. In the top right picture, a layer of insulation and the LilyPad has been added. The bottom left picture shows the addition of three Peltier elements, and the last picture show the wiring of all components, including the Xbee module in the top right corner of the tile.

Exploring Computed Causality

Computed causality is, as described above, the rather unique ability for a computational composite to exhibit almost any desired cause-and-effect. It can be used to moderate, exaggerate, or to make entirely new causalities. With this exploration we will study one of the less common uses of this property, namely to alter existing material causalities. We will make the copper composite exhibit inverse thermodynamic behavior.

Thermodynamics is one of the more fundamental aspects of our material world, and to turn the experience of thermal behavior upside-down provides an opportunity to explore what such unexpected expression entails. Notably, it is only the experienced effect of thermal behavior that is altered. Obviously, we do not claim the computer is actually capable of turning the laws of thermodynamics around; in fact, we need to add energy to make it happen. However, these exercises are about exploring the experiences of the new material properties.

In general, we expect a piece of metal to stay warm for a period of time if it is exposed to heat. Although metals differ with respect to their specific heat capacity and coefficient of heat transfer, our general experience with heat is that it remains for a while in the bodies exposed to it. Here, when this copper composite is exposed to heat, it will turn cold. Likewise, and in the next iteration, the composite could turn warm when exposed to coldness.

The temperature sensor placed just below the surface reports the temperature to the computer, and when it rises to a certain degree the computer will turn on the Peltier elements. The Peltier elements will gradually (within approximately 10 seconds) cool down the surface of the tile and the excess heat created on the other side of the Peltier elements is accumulated in the copper inside and on the back of the tile. By remaining within the realm of traditional material behavior, albeit turning it upside-down, we directly articulate a potential of redesigning our material environment. Instead of letting the computer reign as an abstract machine capable of more or less arbitrary causalities, we identify a role for it in the material world we are familiar with. The experience of this inverted thermal causality (Figure 11) is difficult to capture in writing and in pictures, but the sensation is strong. The manipulative power of altering nature's (or other established) cause-and-effects is an intriguing design parameter when scouting for new expressions and new functions.

Figure 11. By placing a hand on top of the tile one senses the tiles reaction to the heat form the hand as it after a short period turns cold.

Exploring Connectability

In the next set-up, we study the property of connectability in a computational composite. As argued above, the connectability in a material context enables us to think of a distributed material behaving as if it were continuous where every part of the material would change color, texture, or, in this case, temperature whenever one part changes.

Here, the copper tiles have maintained the expression of thermal cause-and-effect from the previous exploration, but now both tiles are in play. The temperature is exchanged between the two parts of the composite material over a peer-to-peer network through the Xbee module. The first to reach the critical temperature triggers both to be cooled down. In other words, the two tiles follow each other's behavior so when one starts to cool (as a result of being heated) the other immediately follows. They give an impression of a continuous material although they are two discrete entThe experience of this version is less intense, possibly due to the rather abstract behavior and less direct relation to traditional material behavior. Possibly in the next iteration, the two tiles could always seek a thermal equilibrium in both directions. As such, if one is heated the other will turn equally hot and vice versa. That will require a greater amount of communication and negotiation, but it will probably provide a stronger experience of actually being one material although physically separated. In general, however, by articulating this computational property in a material context, it becomes possible to see how it can be utilized for creating connected yet dispersed aesthetics and/or functions regardless of any social communicative needs.

With these material properties, especially computed causality and connectability, we have identified some handles to help us further explore the space of opportunities afforded by the computational composites. Exploring the computer's properties in a material context gives us a better sense of what we can do with this complex material. What we have done is to follow an exploratory approach executed as interplay between the general and the specific — between theoretical conceptualizations and material manifestations. Furthermore, we have developed some detailed examples of how the computer can become part of a material composition, and how we can alter the expression of the overall composite by changing the series of computations (programs), and thereby give it new expressions and functions.

The Material Strategy

As an alternative to the communication strategy and the interaction strategy described by Djajadiningrat et al.(2004), we have proposed a material strategy for design. The material strategy includes a material understanding of the computer and a formgiving practice. As of now, however, it more or less remains a vision thereof. With the explanation of the computer as a material, we have outlined a space of opportunities that this strategy promotes. With the descriptions of some of the material properties, we take a step towards a comprehensive understanding of the computer as a material. With the copper computational composite, we have embodied two possible expressions of computed causality and connectability, which also demonstrate how this view on computers inspires new expressions founded in materiality rather than information or communication. Further studies and especially more samples are needed to embody the space of opportunities to provide a landscape in which we can form an experience with these complex materials. Until then, the vision of a formgiving practice remains a description in this paper. In other work, we have begun to develop this practice (Bergström et al., 2010), yet here also more work is needed to generate appropriate methods and techniques. Most likely, a formgiving practice will also develop as we become more familiar with the computer as a material for design. To recapitulate, the essence of the strategy is to design computational objects through ongoing negotiations between form and function through direct manipulation of computational composites.

Figure 12. Illustration of how a distributed material could be used, exemplified here with a material that responds to the temperature of its distributed parts. When the cup holds hot tea, the table and back of the seat will warm up too.

Endnotes

[1] *Formgiving* exists in the Scandinavian languages as *formgivning*, in Dutch as *vormgeving*, and in German as *Gestaltung* and is traditionally used to denote the specific practice of giving form to materials as done in, for instance, the practice of craft.

[2] *Aesthetics* is here used in the sense of developing new logics behind the expressional appearance of a design [see Hallnäs and Redström (2006) for similar use].

[3] Or the work of hands as it is called in the Scandinavian languages (håndværk, hantverk, håndverk) and in Dutch and German (Handwerk).

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