COMPUTATIONAL COMPOSITES

UNDERSTANDING THE MATERIALITY OF COMPUTATIONAL TECHNOLOGY

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In memory of
Annette and Kamilla

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PART ONE: THE THESIS

Preface

> *I'm opposed to the idea that my work constitutes some contrived theory. I think it's better to use a substitute than a clear-cut theory. That's why my pieces are always fragmentary. Otherwise I could just as well have written a book where I could say: it's like this or like that. It takes longer this way but I end up achieving more. Unanswered questions are better than questions directly understood.*
>
> Joseph Beuys in conversation with Lieneke van Schaardenburg, 1968
> (Captured from the permanent Beuys exhibition at Hamburger Banhof, Berlin 2009)

The work presented in this dissertation would perhaps have been better approached with the ways of Joseph Beuys. Instead of writing out the questions and investigations, I should have continued to work with the materials and let that work express the material potential of computational technology. My academic background and the context of my work (including the limited time), however, claim a written account of my thoughts on the matter. The work is not finished—it cannot be. Incompleteness is a premise when doing research for design. The goal of this line of work is not to find *truth* but to open new spaces for design. It is to explore new opportunities with the materials at hand, to develop new potentials, and to build examples that populate the new design space. The dissertation is thus an account of work-in-progress.

The problematic addressed in the dissertation is generally shaped by a sensation that something is amiss within the area of Ubiquitous Computing. Ubiquitous Computing as a vision—as a program—sets out to challenge the idea of the computer as a desktop computer as means to explore the potential of the new microprocessors and network technologies. However, the understanding of the computer represented within this program poses a challenge for the intentions of the program. The computer is understood as a multitude of invisible intelligent information devices which confines the computer as a tool to solve well-defined problems within specified contexts—something that rarely exists in practice.

Nonetheless, the computer will continue to grow more ubiquitous as moore's law still apply and as its components become ever cheaper.

The question is how, and for what we will use it? How will it, for instance, be implemented in design, and architecture, and in what new directions we will take the technological developments? We need a new understanding of the computer to guide these developments as none of the previous apply to these new conditions and new oppertunities.

I propose that we begin to understand the computer as a material like any other material we would use for design, like wood, aluminum, or plastic. That as soon as the computer forms a composition with other materials it becomes just as approachable and inspiring as other smart materials.

I present a series of investigations of what this understanding could entail in terms of developing new expressional appearances of computational technology, new ways of working with it, and new technological possibilities. The investigations are carried out in relation to, or as part of three experiments with computers and materials, later referred to as PLANKS, Copper Computational Composite, and Telltale. Through the investigations, I show how the computer can be understood as a material and how it partakes in a new strand of materials whose expressions come to be in context. I uncover some of their essential material properties and potential expressions. I develop a way of working with them in a design process despite their complexity and non *a priori* existence, and finally I argue that these investigations form both valid and valuable research results within the context of design research.

The dissertation comprises an introduction over two chapters developing the argument for the investigations and describing the foundation they build upon, a third chapter summarizes the investigations, and the last part is a collection of five papers each more in depth dealing with the investigations. The first paper delineates the idea of the computer as a material for design, the subsequent three each explores different aspects of the aesthetic potential and how to work with the computer as a material, and the last paper accounts for the work's credibility in a context of design research. Three of the five papers are published, and two are in review. In three of the five papers have I been the primary if not the only author. However, the work on which the papers are based has all been done in collaboration with others.

By seeking to work together with a range of people whose backgrounds are in art, design, architecture, computer science, physics, and electronics I have tried to challenge and explore the material potential of computational technology from a wide set of perspectives. I have been the *primus motor* on the overall project and deliberately sought collaborations that would enable me to investigate the material understanding of computers from the perspectives, which I deemed interesting and necessary. Every collaboration has brought on new insights and new pressing questions and paths to explore and has as such been part of forming the overall project.

The idea of computational composites was conceived in discussions with Johan Redström who has a background in philosophy and interaction design. The PLANKS are conceived together with sculpture artist Henrik Menné and developed in collaboration with 1Scale1 and David Cuartielles who is part of the trio behind developing the Arduino board. Telltale and the notion of Becoming Materials was developed in relation to the Switch project at Interactive Institute in Stockholm, in which trained designers, architects, and computer scientists took part. The Computational Copper Composite and the conception of the material strategy are developed with Tomas Sokoler who has a background in computer science and physics. Finally, the argument that operationalizing materials can form the ground for a valid and valuable research contribution was developed with architect Cecilie Bedixen. My own background is in computer science from University of Copenhagen. I graduated from a program that included building a kernel, designing a network protocol, and implementing a simulation of a pipelined processor. In combination, these backgrounds form the main strains of inspirations throughout my work.

Understanding Computers

Every object made by man is the embodiment of what is
at once thinkable and possible

Ezio Manzini in "The Material of Invention" (1989, p. 17)

What is a computer? To this question there is no single answer. A computer is something or someone that computes, but beyond that it is impossible to provide a general definition. Still, however, the question is important because our understanding of what a computer is shapes our imagination of what we can do with it and what it can become as Ezio Manzini says. Indeed, if we wish to continually explore the potential of the computer we are forced to continually challenge our understanding of its power and its limitations—of its expressions and boundaries. Developing computers is thus not done independent of how we understand them just as our understanding of them is not developed independent of what they can do and how they appears to us. Indeed, if we take a look at the five most significant understandings of computers that have formed their development and *vice versa* we will see exactly how important it is.

THE COMPUTER AS A WORKFORCE

When the astronomical society took on the endeavor to predict the return of comets in late 1600 they had to figure out the comets' trajectory and realize how the planets' gravitational forces would affect them (cf., Grier, 2005). Once this was done in theory there lay before them a massive amount of computations in order for them to produce a date for the return of a comet. The first prediction was about Halley's comet. In the year 1757, it took two men and a woman (see Figure 1) every day from June until November to compute that date. They were sitting around a table in Palais Luxemburg presumably dressed in the formal court dress of the time including powdered wigs and writing with goose-quill pens on heavy linen paper. They had organized their work so that two of them would produce tables with an intermediate result, and the third would check the accuracy of the result as even tiny errors could amount to significant deviations in the final result. Their final prediction was that it would reach its perihelion between March 15th and May 15th in the year 1758, but the comet reached it on March 13th; thus, a couple of days outside the computed interval (cf., Ibid.).

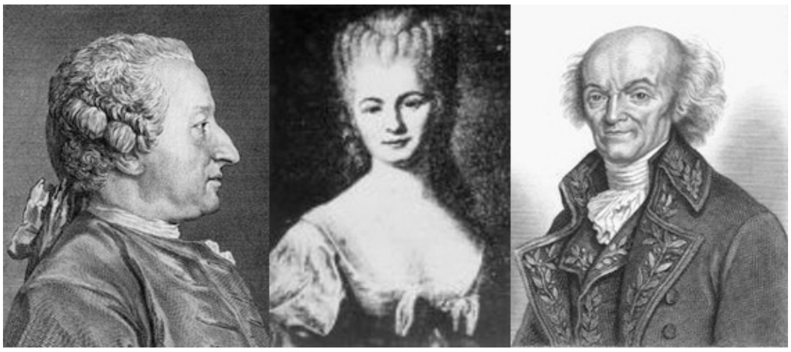

Figure 1 These are the expressional appearances of some of the first computers. Alexis-Claude Clairaut, Nicole-Reine Lepaute, and Josheph-Jérôme Lalande were the three human computers behind the first predictions of Halley's return in 1757.

The organization of work devised for the computations of Halley's comet's return marks one of the first examples of division of labor within scientific knowledge work. In 1765 this organization was institutionalized by the British Navy. They established a special department of human computers to produce the *Nautical Almanac* (a table with the stellar and lunar positions to assist navigation at sea) (cf., Ibid.). These computers were primarily mathematical scholars earning money for their studies and experience for their future mathematical careers.

With the French Revolution, and the fall of the wig wearing aristocracy Gaspard de Prony found new use for the former servants and wig dressers. He was appointed as leader of the Bureau du Cadastre commissioned to produce the trigonometric tables for the decimal grade system of angle measure (cf., Ibid.; Agar, 2001). de Prony lacked a sufficient number of mathematicians as they had been scattered all over the country by the revolutionaries and he was forced to find alternative methods. He realized that by breaking down the instructions to simple calculations even the uneducated women could compute the tables. This work, of course, had to be monitored by a fairly large staff of mathematical scholars who would instruct the computers and check for mistakes. Yet, they were able to produce tables at a much faster rate than ever seen before (cf., Agar, 2001; Grier, 2005).

In 1819 the two mathematicians, Charles Babbage and his friend John Herschel, traveled to Paris to visit de Prony. Especially Babbage was concerned with all the computed tables needed in the increasingly industrialized society and how the errors often found in the tables could have dire consequences (cf., Ibid.). The general trend in society was to devise machines for every possible task and as de Prony had shown that no particular skills were necessary if only the instructions were sufficiently simple Babbage decided to figure out how to design a steam engine that could produce computed tables without errors. His first proposal was for the Difference Engine, which seemed to work in theory and Babbage with help from engineers undertook the task of building it, but they ran into problems with achieving the sufficient precision using the rather coarse machinery (cf., Grier, 2005). Twelve years and £30,000 later the endeavor was finally abandoned[1] (cf., Agar, 2001). Instead, Babbage devised the layout of a new computational machine the Analytical Engine. This machine was inspired by the Jacquard Loom's cloth making machine, which would weave patterns according to a program read from a card with certain patterns of holes. Babbage's Analytical Engine would with one program become a Difference Engine but with other programs compute the various tables needed in society. This machine was, however, not built until four decades after Babbage had died in 1871. After the Analytical Engine there would pass yet another four decades with several machines of different designs and abilities and not until 1951 would the world see a machine architecture which resembles the computers in use today (cf., Ibid.).

Realizing that calculating the trajectory of a comet or the trigonometric tables for the decimal grade system of angle measures could be divided into an intellectual demanding task of devising the procedures or algorithms and a mechanical[2] task of executing the algorithms changed the organization of scientific work entirely. Automation was no longer secluded to manual labor and computers would gradually become a valuable tool in managing activities at, for instance, factories. Their operators would grow in number and change from being specialized engineers or mathematicians to clerks and secretaries. This change demanded more from the design of the machines both in terms of direct interaction with them but also in terms of what it meant to the organization of the workplace. So in a sense the understanding of computers as a workforce—human or not—is the foundation for research disciplines such as human computer interaction (HCI) and computer supported cooperative work (CSCW).

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[1] It has retrospectively been built for the London Science Museum and it is confirmed that it would have worked with the technology available at that time.

[2] "Mechanical" is here used in the general sense as an "unthinking process" and is not limited to the executions of a machine.

THE COMPUTER AS A MODEL FOR MATHEMATICAL LOGIC

From another corner of scientific development, albeit not entirely disconnected, David Hilbert articulates in the beginning of the 20th century a research program around the fundamental logic of mathematics (cf., Ibid.). One of the central questions in this program was whether, given a set of axioms, the derived systems of theorems could be proven complete, consistent, and decidable. A system is complete if a proof can be found if one exists, a system is consistent if a proof never exists for both P and not P, and a system is decidable if a method can be found to decide its completeness (the last is also known as the 'decision problem') (cf., Ibid.).

As a response to this question Kurt Gödel proved in 1931 that no system of axioms for arithmetic can be both consistent and complete and thereby that mathematics based on similar sets of axioms must also be either incomplete or inconsistent (cf., Hodges, 1988). Gödel used the mathematical subset of arithmetic, which enabled him to treat both axioms and theorems as natural numbers thus by ascribing a unique id to each derived statement he allowed statements to be self-referential (cf., Agar, 2001). He could then examine these self-referential statements and find that some of them were logically consistent but not decidable within that formal system (cf., Davis, 1988). The statements can be compared to the self-referential philosophical paradox: A Cretan says "All Cretans are liars" is he then telling the truth? It is a grammatically consistent statement, but we cannot decide whether it is true or false (cf., Agar, 2001).

What came out of this, relevant for the story of computers as a model for mathematical logic, were two things: Firstly, the idea of treating axioms and theorems alike and as numbers (also known as Gödel numbers) and thereby allow for self-referential statements. Secondly, a confirmation of the relevance of finding a procedure/ algorithm that on the basis of a description of a formal language and a mathematical statement in that language can decide whether the statement is true or false.

Using this line of thought combined with examining the limitations of purely mechanical operations Turing shows in 1936 that the 'decision problem' has no solution—meaning that no algorithm can be devised to determine any given system's completeness (Turing, 1936). He did that by devising a computing machine—today known as a Turing machine:

> We may compare a man in the process of computing a real number to a machine which is only capable of a finite number of conditions q_1, q_2, …, q_R which will be called "m-configurations". The machine is supplied with a "tape" (the analogue of paper) running through it, and divided into sections (called "squares") each capable of bearing a "symbol". At any moment there is just one square, say the *r*-th, bearing the symbol T(*r*) which is "in the machine". We may call this square the "scanned square". The symbol on the scanned square may be called the "scanned symbol". The "scanned symbol" is the only one of which the machine is, so to speak, "directly aware". However, by altering its *m*-configuration the machine can effectively remember some of the symbols which it has "seen" (scanned) previously. The possible behaviour of the machine at any moment is determined by the *m*-configuration q_n and the scanned symbol T(*r*). This pair q_n, T(*r*) will be called the "configuration": thus the configuration determines the possible behaviour of the machine. In some of the configurations in which the scanned square is blank (i.e. bears no symbol) the machine writes down a new symbol on the scanned square: in other configurations it erases the scanned symbol. The machine may also change the square which is being scanned, but only by shifting it one place to right or left. In addition to any of these operations the *m*-configuration may be changed. Some of the symbols written down will form the sequence of figures which is the decimal of the real number which is being computed. The others are just rough notes to "assist the memory". It will only be these rough notes which will be liable to erasure.
>
> It is my contention that these operations include all those which are used in the computation of a number.

(Ibid., pp., 231-232)

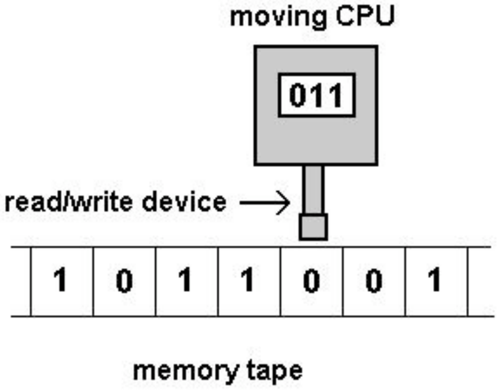


Figure 2 Schematic illustration of a Turing Machine

Research programs aimed at developing computational machines took on the idea of the universal machine proposed by Turing in his work of providing an answer to the 'decision problem'. Thus, the mental contraption conceived in an endeavor to prove the limits of mechanization as means to answer a mathematical problem turned out to hold valuable ideas for building electronic computers for a wide variety of purposes. Computers hereafter took the leap from being an advanced calculator to becoming multipurpose machines, which, as we shall see below, even led to other understandings of the computer.

The Turing Machine is still referred to as the ideal of computational technology, but it remains an abstraction, and hence it has no expressional appearance. Its aesthetics are purely an abstract (or mathematical) aesthetics.

THE COMPUTER AS AN INTELLIGENT BEING

When the digital electronic universal computer was finally built in Manchester in 1951 a new range of research programs were born. The computer was no longer just about calculating tables for society or astronomical trajectories, but it had become capable of generating poetry and playing tunes (cf., Agar, 2001). Turing, and others, had recently begun to explore the possibility of developing a computer capable of intelligent behavior in line with the activities of the human brain and Turing formulated a test (in 1950) through which the computer’s intelligence could be evaluated (Turing, 1950). It is known today as the Turing test.

Parallel advances in theories of neural networks and behavioral psychology, however, quickly found use of the new powerful computational machines and more systematic studies of both human intelligence and computational models of the same began (M., 2002). In 1955 and 1956 Alan Newell, Herbert Simon, and Cliff Shaw developed the first program designed to mimic the problem solving skills of a human being. It was called Logic Theorist and could prove 38 out of the first 52 theorems in Alfred North Whitehead and Bertrand Russell's Principia Mathematica (cf., Crevier, 1993). Later, Simon also contributed with empirical founded models of human problem solving and decision-making.

Artificial Intelligence (AI) was coined by John McCarthy and formulated as a research program at a famous conference at Dartmouth College in 1956 where, besides Simon and Newell, notabilities like Marvin Minsky, Claude Shannon, Nathaniel Rochester, and John McCarthy participated (Ibid.). The exact wording from the organizers of the conference was: “very aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it”(as quoted in Ibid., p. 48).

The field gradually spawned into diverse areas such as planning, leaning, language processing, motion, perception, social intelligence, and creativity always with a double-sided interest: one in studying humans and one in computational imitation—either following the same principles as humans or by using alternative methods (cf., Crevier, 1993; M., 2002).

Mechanical robots had flourished for centuries, but more often as entertainment devises (e.g., Jacques de Vaucanson’s digesting duck from 1739 or The Mechanical Trumpeter by Friedrich Kaufmann in 1810) or as flat out science fiction literature (e.g., in the authorship of Jules Verne and Isaac Asimov, and The Wonderful Wizard of Oz by L. Frank Baum published in 1900) than actual scientific attempts of designing an intelligent machine (cf., Buchanan, 2005). With the advances in computational technology robotics became a significant scientific research field, which in parallel to and in collaboration with AI would mimic the physical behavior of humans and animals (See Figure 4).

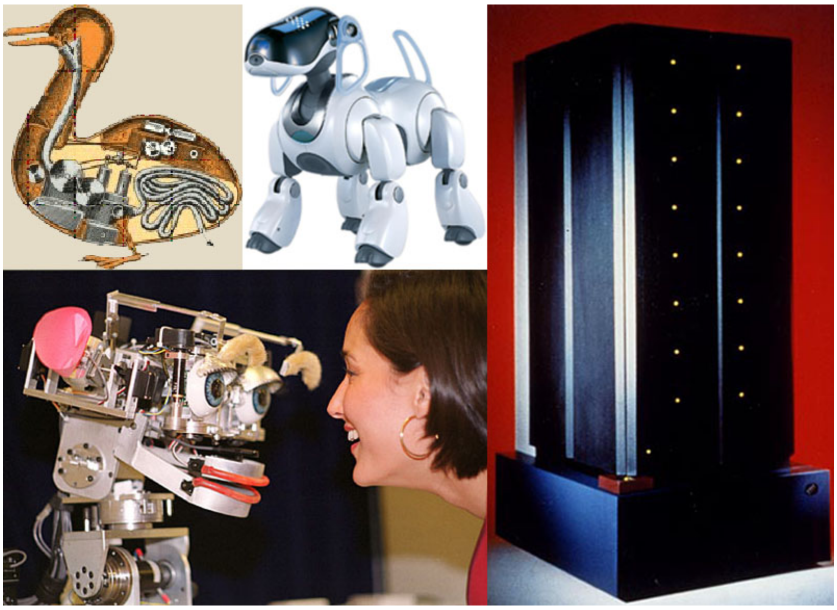


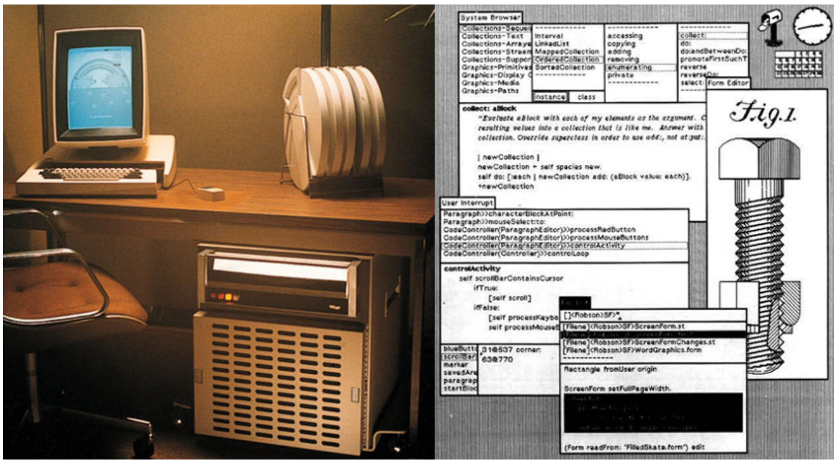
Figure 3 The top left corner shows a sketch of Vaucanson's digesting duck. Next is Sony's AIBO a robot pet dog from 1999 capable of learning some behavior. The right side shows the IBM RS/6000 SP2, which contained the Deep Blue chess program that in 1996 beat the chess champion Kaparov for the first time. Finally, the bottom left corner shows Kismet, which is capable of responding to and learning human emotions through facial expressions.

Today, the Artificial Intelligence program in the strong version, as described above, only has a few proponents left but the results produced in many of the derived research programs have had, and still have, significant impact both scientifically and on our society (e.g., the advances in algorithms or the use of robots to replace humans in dangerous work situations)

THE COMPUTER AS A MEDIUM FOR INFORMATION

In the fall of 1969 the first message was send between two computers one at UCLA and the other at Stanford University. The message was “o”nd was supposed to be “ogin” but the system crashed in one end before the rest of the word was transmitted (cf., Banks, 2008). The network was called ARPANET (Advanced Research Projects Agency Network) and was developed as a means for researchers around the world to share computer facilities, as they were still scarce. But, just as importantly to share information in order to advance research. The researchers used the net to send e-mails, access data, post messages on bulletin boards, and to play games (cf., Ibid.).

In 1970 the copier manufacturer Xerox decided to enter the computer market and formed the Palo Alto Research Center (PARC) (cf., Allan, 2001). They began developing "Alto" a computer based on visions of a portable notebook articulated by Alan Kay in his doctoral thesis from 1969. Ivan Sutherland and Douglas Engelbart also contributed with significant ideas of how the interface between the computer, and the human should be (e.g., the computer mouse). Their ideas were continuously developed as the work on Alto progressed, and by 1976 the first graphical environment with overlapping windows, pop-up menus, and icons was developed under the guiding metaphor "he Desktop" (cf., Ibid.).



```
collect: aBlock
    "Evaluate aBlock with each of my elements as the argument. C
    resulting values into a collection that is like me.  Answer with
    collection. Override superclass in order to use add:, not at:put:.

    | newCollection |
    newCollection ← self species new.
    self do: [:each | newCollection add: (aBlock value: each)].
    ↑newCollection
```

```
Paragraph>>characterBlockAtPoint:
Paragraph>>mouseSelect:to:
CodeController(ParagraphEditor)>>processRedButton
CodeController(ParagraphEditor)>>processMouseButtons
CodeController(ParagraphEditor)>>controlActivity
CodeController(Controller)>>controlLoop
```

```
controlActivity
    self scrollBarContainsCursor
        ifTrue:
            [self scroll]
        ifFalse:
            [self processKeybo
            self processMouse
```

```
31@537 corner:
63@770
```

```
[]<Robson>SF>*
[Filene]<Robson>SF>ScreenForm.st
[Filene]<Robson>SF>ScreenFormChanges.st
[Filene]<Robson>SF>WordGraphics.form
```

```
Rectangle fromUser origin

ScreenForm setFullPageWidth.

(Form readFrom: 'FilledSkate.form') edit
```

Figure 4 The picture on the left shows the Alto computer fully equipped with, cathode ray tube (CRT) monitor, keyboard, and mouse. The picture on the right shows the floating windows system with icons at the top right corner (Courtesy of Xerox PARC)

The proliferation of personal computers, however, did not take off until Apple II was launched in 1977 providing support for a color monitor and in 1979 the spreadsheet program VisiCalc was introduced by Personal Software Inc. only to run on Apple II, which increased sales even further (cf., Ibid.). And still it would take some years before computers were generally accessible and affordable.

Three other important events would also help form the coming of the Information Age. One was Intel's launch of the 4-bit 4004 microprocessor, followed by the 8-bit 8008 microprocessor one year later in 1972 (cf., Ibid.). The other was the software development providing word processing, desktop publishing, and advanced drawing programs giving professionals as well as laymen the opportunity to develop and deploy their creative skills at relatively small costs.

The third important event was Tim Berners-Lee's invention of the World Wide Web (WWW) in 1989 while employed at CERN (Berners-Lee, 1989). The WWW was, and is, a set of interlinked text documents, images, audio, video, and various web services. WWW makes use of the network originated from ARPANET but in a shape that has undergone some changes (e.g. in terms of the TCP/IP package protocol) and is today referred to as the Internet. The content of the WWW is located at servers around the world and the hyperlinks in shape of Uniform Resource Locator's (URL) enable access to information from any computer with access to the Internet by means of the Hypertext Transfer Protocol (HTTP) (cf., Banks, 2008; Schell, Bernadette H., 2007).

The role of the computer might still be a workforce used for research and at high-end industry, but the early use of the ARPANET showed how information storage and exchange gradually gained footing as the purpose of the computer. The personal computer was at first used for accounting and the spreadsheet and was a huge revolution in that respect, but gradually information applications such as of word processing, desktop publishing, drawing tools, music players and composers, video editors and viewers, etc. were incorporated. Today the computer is used and understood as a medium for information fostering improvements within that area, but also giving rise to research programs concerning the consequences of all the information production and sharing (e.g., new media studies, information psychology, and digital culture).

When presented with a desktop computer we immediately realize that it is about text and images. Indeed, it is difficult to imagine information technology looking much different exactly because the graphical display is such a strong platform to convey this kind of information. Hence, when computers are embedded in our kitchen appliances, the understanding of them as an information technology has also entailed a range of screens where levers and knobs used to be. Indeed, the strong focus on functionality within the Information Technology paradigm is probably due to the largely fixed form-language. The "display-keyboard" form sets confinements on the imagination of the computers' potential so much so that even the possibility of shaping the display layout has been reduced to a mere question of functionality (cf., Bertelsen & Pold, 2004; Udsen & Jørgensen, 2005).

THE COMPUTER AS A MULTITUDE OF INVISIBLE INTELLIGENT INFORMATION DEVICES

In the late 1980s Mark Weiser (1991) proposed to break with the confinements of the desktop-form language through implementing a multitude of different scales of computers throughout our environment. This latest[3] addition to our understandings of the computer was further developed as a research program at Xerox PARC throughout the first part of the 1990s.

Ubiquitous Computing was a vision of how our everyday lives would change with networked microprocessors embedded everywhere providing us access to any information anytime anywhere. The vision was that computers would aid our everyday activities by blending seamlessly into the fabric of our lives—that they would become as common and as unnoticed as electrical motors or paper. The vision is mainly captured in a scenario of a woman named Sal and her everyday morning activities at home, on her way to work, and at work.

> "Sal awakens; she smells coffee. A few minutes ago her alarm clock, alerted by her restless rolling before waking, had quietly asked, "Coffee?" and she had mumbled, "Yes." "Yes" and "no" are the only words it knows. [...]
>
> Glancing at the windows to her kids' rooms, she can see that they got up 15 and 20 minutes ago and are already in the kitchen. Noticing that she is up, they start making more noise. [...]
>
> On the way to work Sal glances in the foreview mirror to check the traffic. She spots a slowdown ahead and also notices on a side street the telltale green in the foreview of a food shop, and a new one at that. She decides to take the next exit and get a cup of coffee while avoiding the jam. [...]
>
> The telltale by the door that Sal programmed her first day on the job is blinking: fresh coffee. She heads for the coffee machine."

(Ibid., p. 102)

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[3] Since ubiquitous computing is the most recent understanding of computers it marks the offset for the work in this dissertation and will therefore be treated and critiqued more thoroughly than the others.

At Xerox PARC they developed three devises, all in the shape of rectangular touch screens mounted on top of the computers but at three different scales, the inch-scale (pads), the foot-scale (tabs), and the yard-scale (boards) (Ibid.; Want *et al.*, 1995). These devices would serve different functions through out the environment; for instance, the pads could function as ID-badges whereto doors in the building would respond by only open when the ID-badge granted access.

The vision has since been manifested in a series of projects where the computer becomes the perfect discrete personal butler who knows its master's every quirk and preference (cf., Gellersen *et al.*, 1999; Kidd *et al.*, 1999), or our physician telling us to workout more or remind us to take our pills (cf., Agarawala *et al.*, 2004; Consolvo *et al.*, 2006; Lo *et al.*, 2007), or our father teaching us how to cook (cf., Terrenghi *et al.*, 2006), or they relieve us from our bad conscience from not visiting our parents often enough by enabling us to monitor their mood, weight loss, medicine intake, if they have fallen, etc. (cf., Morris *et al.*, 2004; Mynatt & Rowan, 2000).

These projects all build upon and contribute to models of measurable events chosen to signify certain user actions or needs. The models, also called context-models, constitutes the intelligent dimension of Ubiquitous Computing and as research program it is referred to as context-aware computing (cf., Abowd *et al.*, 1997; Bauer *et al.*, 2001; Chalmers, 2004; Dey *et al.*, 2001; Dourish, 2004; Schmidt *et al.*, 1998).

In other words, the computer is now thought of as a multitude of invisible or seamless intelligent information devices designed to aid our actions—to help us lead a more worry-free and correct everyday life.

Aesthetics[4] in Ubiquitous Computing

While the initial program or vision contained little in terms of *how* to break with the form-language of the desktop computer and the pads, tabs, and boards arguably were not radical enough, Weiser and John Seely Brown later formulated the *Calm Technology*[5] program to

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[4] *Aesthetics* are throughout the first part of this dissertation used in the sense of the logic behind the expressional appearance of a design (see Hallnäs & Redström, 2006 for similar use). The concept is used less stringently through out the papers, but the intention is the same.

[5] Calm technology was part of a broader trend at the time where several programs had set out to explore the peripheral attention space or the use of *ambience* to convey information (cf., Buxton, 1995; Dourish & Bly, 1992; Ishii *et al.*, 1998; Pedersen &

specifically address this (Weiser & Brown, 1995; Weiser & Brown, 1996). They proposed to design the technology in ways that would encalm and inform. The idea was to let the technology perform in the periphery of the attention span and only demand the center of attention when something was amiss or when it was needed for something. While in the center of attention the user would be in control and able to manipulate the technology, but afterwards it would slide back to the periphery. The technology "must be attuned to but not attended to" (Weiser & Brown, 1995, p. 2). The program, however, remains rather vague in terms of describing *how* to achieve the calming and informing expressions. Only through The Dangling String by artist Natalie Jeremijenko do we get a sense of the potential expressional appearance of computational technology post desktop computers (see Figure 5).

Figure 5 The Dangling String by Natalie Jeremijenko. The two pictures show a quiet and a busy red string representing the activity on a local area network.

The Dangling String is an 8-foot plastic wire, which hangs from a small motor attached to the ceiling. The motor is connected to an Ethernet cable and with every bit of data passing through the cable the motor twitches a bit. A busy cable causes the wire to whirl where little or no network activity lets it hang quietly (Weiser & Brown, 1996). The peripheral way of providing information of network activity could easily replace the screen display of network traffic and only demand attention when the string, for instance, became uncharacteristically calm.

Sokoler, 1997; Wisneski *et al.*, 1998) however, I have chosen this version as it is a direct continuation of Weiser's own visions.

Tangible Bits is another program formulated by Hiroshi Ishii and Brygg Ullmer (1997) to address the expressional appearance of computational technology post desktop computing. Tangible Bits is about representing digital information with physical tangible forms. The program combines the gist of Calm Technology with the ideas behind graspable user interfaces (cf., Fitzmaurice & Buxton, 1997; Fitzmaurice *et al.*, 1995) and Durell Bishop's Marble Answering Machine (cf., Abrams, 2000). They propose three areas for developing the expressional appearance of computational technology: one is through creating interactive surfaces, another is the mapping of bits to graspable physical objects, and the third is ambient media for background awareness.

"To make computing truly ubiquitous and invisible, we seek to establish a new type of HCI that we call "Tangible user Interfaces" (TUIs). TUIs will augment the real physical world by coupling digital information to everyday physical objects and environments" (Ishii & Ullmer, 1997, p. 235). TUIs become the graspable equivalent to the prevailing Graphical User Interface (GUI). Where, for instance, an *icon* becomes a *phicon* with some significant shape, or that a graphical *handle* becomes a *phandle* in shape of a brick or a block on a surface, which would permit a three-dimensional manipulation. The program maintains a sharp distinction between bits and atoms—between the physical and the virtual. The virtual remains inside a computer of sorts but the interface is now a tangible *representation* of the virtual instead of being a graphical representation. For instance, the form of the bricks (Fitzmaurice *et al.*, 1995) or the musical bottles (Ishii, 2004) both represent a function that just as well could just as well have had a completely different expressional appearance. Oddly enough, however, they use the abacus as an example of a tangible interface even though its form *is* its function and not a representation thereof.

Critique of Ubiquitous Computing

Computers today are by and large ubiquitous (cf., Bell & Dourish, 2007; Greenfield, 2006). The pads, tabs, and boards are in some variation all around us in form of, mobile phones, smart phones, laptops, notebooks, advertising boards, virtual blackboards, etc. The way we use the computer, however, has remained fairly the same as the way we use a desktop computer—they are used as information technology conveying text, images, video, music etc.

Computers are not really embedded into our environment as envisioned in the Sal scenario and even though research projects have developed computers to reduce the frictions in our everyday lives they have not ventured into the broader market—perhaps because the premise was mistaken. The Sal scenario may in it self hold an idea of the good life that does not really coincide with reality in terms of desires (cf., Rogers, 2006).

Another reason may be that "we're just not very good at doing "smart"" (Greenfield, 2006, p. 3) in the way envisioned by Weiser—meaning that the computers' context sensitivity persistently deviates from the users own perception of their context (cf., Benford *et al.*, 2004). The task of modeling the measurable parameters so they would correspond to our perception of what is going on has, in many ways, turned out to be equal to modeling the human mind as attempted within AI (cf., Rogers, 2006).

The understanding of the computer that prevails within Ubiquitous Computing was by and large been inherited from the two preceding programs: Information Technology and Artificial Intelligence. Consequently, it becomes difficult to break out from the traditions within those understandings. They, and especially Information Technology, carry a function driven tradition where aesthetics, meant as the formal reasons behind it expressional appearance, play only a minor role (cf., Bertelsen & Pold, 2004; Udsen & Jørgensen, 2005). This causes problems for the aesthetic programs within Ubiquitous Computing (Calm Technology and Tangible Bits) whose primary goal was to develop a new form-language for computational technology. As long as it remains *Information Technology* the display-keyboard expression will prevail.

Furthermore, the Tangible Bits program runs into other problems when it proposes that we map bits on to atoms—or, let form follow function. The disproportions in complexity and scale between the computer and the physical matter that the human sensory apparatus can apprehend cannot easily be circumvented (cf., Djajadiningrat *et al.*, 2004; Redström, 2008), or as John Maeda argues (2000, p. 24):

> Prior to the development of modern technology, artifacts produced by humans obeyed an intuitive relationship between size and complexity. A small object corresponded to a simple function, whereas a larger object was associated with a proportionally more complex function. This simple relationship arouse from the macroscopic nature of technology at the time and is significant

> because it extended two sacred promises, one to the user and one to the industrial designer. The first is that the user would be able to construct a priori impressions of an object before actually using it, that is, literally *sizing up* the nature of the object at first glance. The second is that industrial designers would have a suitable amount of visual and tactile design space […] to express that functionality.

Neither of these promises withstands today—at least not for the same reasons. We have to discover or perhaps rather create new relations between form and function and, more importantly, we cannot expect computational things to be readily understood—they require interpretation. The problems that Ubiquitous Computing faces regarding the expressional appearances are by no means trivial or easily fixed, but the challenge must be met. We cannot continue to develop the technological potential if we keep pouring new wine on old bottles.

UNDERSTANDING AND IMAGINATION

As argued in the beginning of this chapter developing computers is done within the understanding of their purpose, what they can do, and how they appear to us, just as the understanding is formed by, albeit not limited to, those aspects.

The computer, in its basic principles, has stayed the same since the Turing Machine. It has remained a digital multipurpose computer. A situation which in itself has been called into question by the MIT professor Neil Gershenfeld who in a TED-talk claimed that "Ò*Computer Science* is one of the worst thing ever happened to either computers or to science because […] the canon of computer science prematurely froze the model of computation based on technology available in the 1950's and nature is a much more powerful computer than that" (Gershenfeld, 2006, my transcript). His point being that by maintaining the notion of *computer science* we have failed to question our understanding of what a computer is in terms of its constituents and design. Humans or Babbage's steam driven analytical engine might not be better in terms of correctness or scope of complexity, but their constitutions tied them to different contexts, particularly, different physical surroundings. In other words, if we put our minds to it we could probably develop other kinds of computers (e.g., analog computers) to better suit certain functions than digital computers do or apply them to entirely new contexts. In order not to throw everything up in the air at once I will continue, within this dissertation, to build upon the notion of the electrical digital computer and instead question everything else around them.

Even though we maintain the notion of the electrical digital computer there is still room for novelty since the understanding of computers have changed so dramatically. Artificial Intelligence, Information Technology, and Ubiquitous Computing have all contributed with significantly different applications and technological innovations albeit they have inspired and influenced each other too. The reason these multiple understandings of the same basic technology is possible is explained by Peter-Paul Verbeek and Petran Kockelkoren as the technology's lack of essence: " technological artifact doesn't have an 'essence,' no identity 'in itself.' It is, as Idhe calls it, 'multistable.' It depends on the context in which a technology finds itself, what that technology 'is.'"%Verbeek and Kockelkoren, 1998, #34707\, p. 36, see also\; Verbeek, 2001, #22971}.

With a multistable technology, with an obligation to seek new boundaries for what is *thinkable and possible*, and with a technology that continues to grow smaller and faster (cf., Larus, 2009; Moore, 1965) and continues to proliferate, the question remains, where do we go from here? What will we use the computer for in the future and in which directions will we take its development?

The problems that Ubiquitous Computing face, I argue, cannot be solved within the understanding of the computer as a multitude of invisible or seamless intelligent information devices. To truly break away from the desktop computer demands that we break with the computer as an information medium as those are inextricably linked. To escape from the misconception that the human intelligence can be revealed to a degree that enables us to put it on formulae we need to abandon the understanding of the computer as an intelligent being. And to find a way to bridge the discrepancy between the computational complexity in time and space with the human action space we need to develop a new aesthetics of computational technology.

In other words, we need a new understanding of the computer.

The Computer as a Material

Function resides in the expression of things

Leitmotif by Lars Hallnäs & Johan Redström (2002a, p. 107)

To develop a new understanding of the computer is in it self not done out of context—nor is it done from scratch. Every new understanding builds on tendencies, reaction against previous constrains, or the opening of new opportunities. For instance, the idea of a multitude of invisible information devises was largely formed on the basis of the new opportunities afforded by developments in microprocessors and network technologies as well as being a reaction against the constrains of the desktop computer.

Likewise, when the computer in both understanding and practice went beyond the desktop it also transcended the usual domain of computational technology (i.e., computer science) and into the realms design or architecture. Here new perceptions of the computational potential have emerged—new understandings of what the computer is and can be have taken form. Over the last decade design research has proved a particular valuable scene for seeking new ways of working with computational technology. Just as the development of cheap electronics has resulted in the fact that computational development is no longer confined to doings of experts. An obvious place to start would therefore be to look at what these non-technological scholars have created from the technological possibilities.

COMPUTATIONAL TECHNOLOGY WITHIN DESIGN RESEARCH

There have been a vast number of design programs and individual projects which have challenged our understanding of computers (cf., Berzowska & Coelho, 2005; Eyl & Green, 2004; Gaver & Dunne, 1999; Gaver & Martin, 2000; Gaver, 2002; Goulthorpe *et al.*, 1998; Kennedy, 2004; Mazé, 2007; Miranda & Runberger, 2006; Moloney, 2006; Oosterhuis *et al.*, 2003; Roosegaarde, 2007; Smets *et al.*, 1994; Sterk, 2003), however, three groups of design researches have devised especially strong programs[6] for developing new ways of using

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[6] *Program* is here used in accordance with the understanding presented by Hallnäs and Redström (2006) in which the program constitutes the general design intentions, the basic

computational technology. The first group is led by Anthony Dunne & Fiona Raby, and they work within their general program of Critical Design. The second is what appears to be a recurring collaboration between researchers at the Department of Industrial Design at Eindhoven University of Technology and the Mads Clausen Institute at University of Southern Denmark, who follows a general program[7] of what we could call *Aesthetics of Interaction*. And third, the collaborations of Hallnäs and Redström in collaboration with others, at Interactive Institute, Chalmers University of Technology, and Swedish School of Textiles; University College of Borås, their overall program could be referred to as *Computational Technology as a Material for Design*. The three programs overlap to some extent in methods and philosophy. They all adhere to the experimental traditions of design research—meaning they explore the potential of computational technology through building various stages of conceptual design. The physical outcomes of their programs could generally be described as *computational things*, which by Hallnäs and Redström's definition (Ibid.) refer to artifacts in which computations partake in creating the expressional appearance and function. Yet, each group introduces important aspects of the potential of computational technology.

Critical Design

Dunne and Raby from the Royal College of Art in London (RCA) have introduced the *Critical Design* program, which is about "raising awareness, exposing assumptions, provoking action, sparking debate, even entertaining in an intellectual sort of way, like literature or film" (Dunne & Raby, 2007a). In other words, they challenge cultural references as means of exploring new aesthetics—new ways of gestalting design. Computational technology is not a prerequisite in their design practice but used as a means to challenge the expressions and functionality of preexisting things and sometimes to be scrutinized itself in new constellations of computational things (cf., Dunne & Raby, 2001; Dunne, 2005).

In one of their latest projects, for example, they set out to challenge the *existing normal* (Dunne & Raby, 2007b). One of the designs is *The*

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approaches, and the ways of understanding the designed things. The program is the norm from which the designs are developed.

[7] This is my interpretation of their work, as they do not explicitly formulate programs themselves.

Statistical Clock which tells the number of fatalities reported on the BBC website by speaking the number aloud, one, two, three, etc. (See Figure 6). Here, not only has the information technology gained a new form, but also the information has been reshaped, reduced, and re-contextualized. In a similar vein is *The Risk Watch*, which reports on the stability of the country you are currently in through a calculated number. When you hold the watch to your ear, the rubber nipple deflects and lets you listen to the number (See Figure 6).

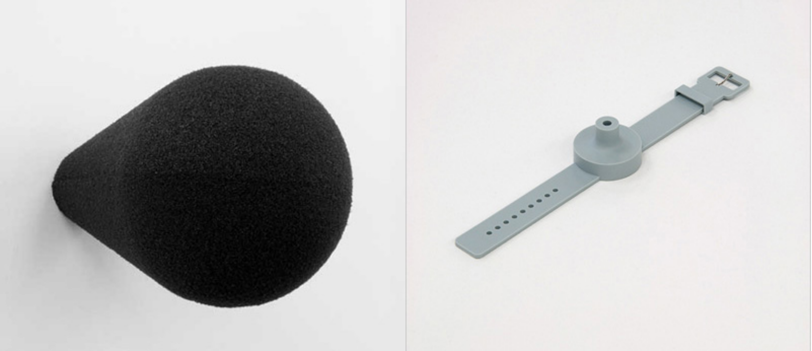

Figure 6 The picture on the left shows The Statistical Clock and the picture on the right shows The Risk Watch (With courtesy of Dunne & Raby).

The critical design program manages to question both functionality and expressional appearance of computational things. Dunne and Raby design to make us reflect upon the designs we encounter in our everyday lives and the cultural value they embed. The strangely familiar (see also Blauvelt, 2003) makes the need for interpretation explicit and breaks with the notion of immediate seamlessness of interaction with complex functionality.

Aesthetics of Interaction

Another interesting program, or series of programs, is carried out at the TU/Eindhoven and MCI Sønderborg. Generally, their strategy is to play with how humans behave in the world and let that form the aesthetics of interaction. An aesthetics—a logic behind the expressional appearances, which then becomes the first step in developing new forms and functions of the computational things (cf., Buur *et al.*, 2004; Djajadiningrat *et al.*, 2000; Djajadiningrat *et al.*, 2004; Djajadiningrat *et al.*, 2007; Frens *et al.*, 2003; Frens *et al.*, 2003; Jensen *et al.*, 2005; Overbeeke *et al.*, 2002).

The program is in opposition to the tendency of separating form and interaction as two distinct aspects of design where product design, for instance, primarily focuses on form, and computational design primarily focuses on interactions (cf., Ibid.; Djajadiningrat *et al.*, 2007).

They argue that since the human action space is more complex than is currently revealed in interaction with computational things there is room for improvement. Thus, through various techniques, such as acting out scenarios (e.g., hands only (Buur *et al.*, 2004)) or diving into historic ways of interacting with objects (e.g., machine cowboy (Djajadiningrat *et al.*, 2007)) they seek a sensibility towards the human action space which they then use to develop the *action-potentials* of computational things (Djajadiningrat *et al.*, 2004).

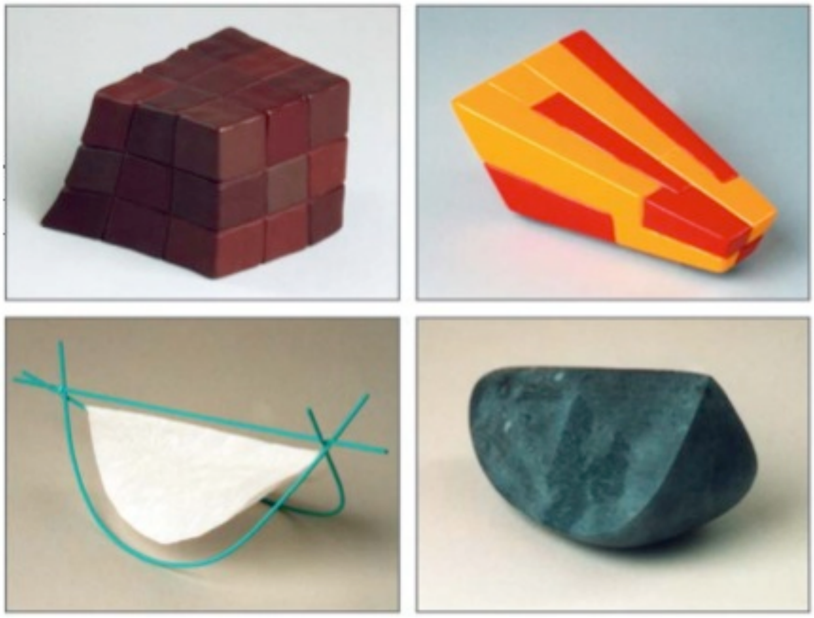

Figure 7 An example of a formgiving study from a class at Delft University 1995 where students had to create form that expressed each others opposite on one dimension while remaining the same on two others. Above they show many/inaccessible/slow-fast and below they show few/inaccessible/light-heavy (Ibid.). Even if these objects are not computational things they exemplify the importance of knowing the expressiveness of material form also when designing with computational technology.

Furthermore, they turn to material or *formgiving*[8] studies to explore the richness of the material world, which beyond visual appearance also has weight, texture, sound, and shapes to guide our actions (see Figure 7) (Ibid.). The point here is that to meet the complexity of the human action space the designs must surpass textual representations and enter the material realm. And for the designer to combine interaction and form both must be understood and acknowledged.

In summary, they aim at "redressing the balance between appearance and action" (Ibid., p. 294) to compensate for the narrow path computational things otherwise tend to follow.

Computational Technology as a Material for Design

The third, and maybe the most significant series of programs, for the work presented in this dissertation, is developed by Hallnäs and Redström with various colleagues (cf., Hallnäs & Redström, 2001; Hallnäs & Redström, 2002a; Hallnäs & Redström, 2002b; Hallnäs & Redström, 2006; Hallnäs *et al.*, 2002; Mazé & Redström, 2005; Redström *et al.*, 2005). Their overall strategy or ambition is to explore the aesthetics of computational things by seeking the boundaries of the design space laid out by each program. This is probably best described through a closer look at three of their programs: Slow technology, Abstract Information Appliances, and IT + Textile.

Slow Technology is formulated as a program to slow down the expressions of computations enough to let us experience them (cf., Hallnäs & Redström, 2001; Hallnäs & Redström, 2006). The purpose is to change the focus in use—to enable that the traditional "basic concern for efficiency in use turns into a basic concern for reflection in use" (Ibid., p. 154). The inspiration is taken from art, and the ambition is not to make tiresome and time-consuming artifacts but to use the technology to prolong a moment and slow things down. One example of a slow technology project is SoundMirror. SoundMirror record sound bites and play them back with delay. "The time series of fragments and delays have a certain structure that is possible to understand through careful reflection of what happens over a long period of time" (Hallnäs & Redström, 2001, p. 206). This program is probably the first to explicitly explore the temporal property of computational technology.

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[8] 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.

Abstract Information Appliances is a program about making the aesthetics explicit in designing computational things (cf., Hallnäs & Redström, 2002a; Hallnäs & Redström, 2006; Hallnäs *et al.*, 2001). The aesthetics are defined as "the formal reasons explaining and describing the appearance of given things" (Hallnäs & Redström, 2002a, p. 105). The program addresses the *function-expression-circle* in which "the expression of things in use seems to define functionality just as much as functionality seems to explain design expressions" (Ibid., p. 106). As a method to become aware of the aesthetic choices in the design process they articulate the leitmotif "function resides in the expression of things" (Ibid., p. 107) as an alternative to the prevailing principle of form-follows-function we, for instance, saw in Ubiquitous Computing.

Another central element in this program is to think of the computer as a design material. By doing this, the aesthetics of executing programs are revealed as temporal forms, and thus executing programs is no longer thought of as merely functional but the expression they entail become explicit.

The conceptual designs within this program either start as "discovering functionality in a given expression" (Ibid., p. 108) or as "discovering expressionals in appliances" (Ibid., p. 111). An example of the first is described as a 2m long tube open in both ends. It is to be held horizontally to balance the marble inside making sure it will not fall out. The exercise is then to imagine what it could be used for. They propose it to be a *waiting tube* where keeping the marble in constant motion, but without losing it, indicates that one is waiting for information. When the marble stops, either by perfect equilibrium or by falling out, the waiting stops. The sound of the marble in motion is picked up by small microphones and transmitted over a wireless network to indicate that one is in the mode of waiting for the desktop computer to provide information. This changes waiting from being a passive situation—an annoying void in the workflow—into a moment of high concentration.

Indeed, by thinking computational technology as a material for design they change it from being primarily functional to something that explicitly holds an aesthetic dimension.

The *IT + Textile* program is about exposing the "transformation everyday things undergo as we embed new information and computation technologies" (Hallnäs & Redström, 2006, p. 190, see also; Redström *et al.*, 2005). As opposed to using metaphors or familiar objects as conveyers of new computational functionality they here seek to develop a framework of understandings and methods to assist in explicitly challenging the expressions of the new computational things. They explore the expressions of textiles through weaving techniques and through embedding computational technology. Generally, they take the idea of the computer as a design material even further than in the previous program. Instead of merely seeing materiality as an abstract understanding of computational technology they make it concrete by both comparing and combining the computations with textiles.

The materiality, however, is only one dimension of the program. The other dimension is how these expressions are interpreted in a context of use and how they are "adopted, customized, adapted, hacked and reconfigured by a spectrum of users including individuals, families and communities in relation to intricate practices and evolving activities" (Ibid., p. 33).

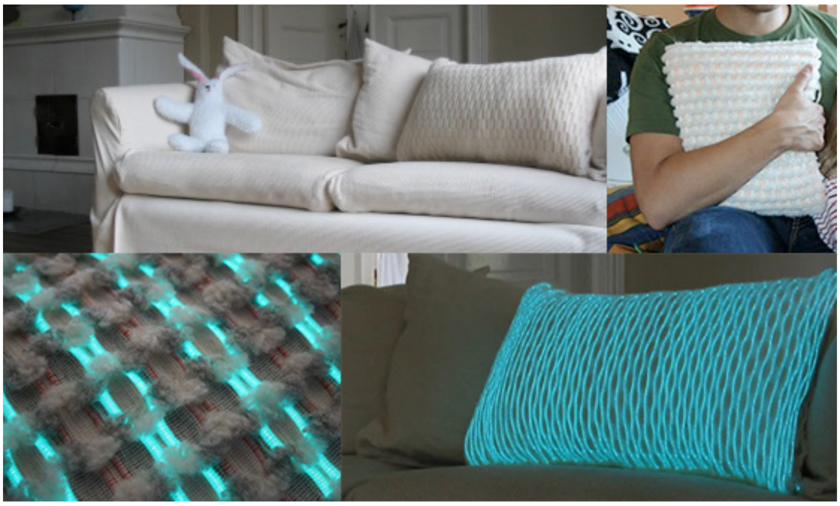

Figure 8 Interactive Pillows (Courtesy of Interactive Institute and Linda Worbin).

One example of an experiment within the program is *The Interactive Pillows*. This set of pillows is meant as a subtle way of communicating with your loved ones. When one pillow is hugged for a while, the other lights up in a gentle glow and turns warm and *vice versa*. The light may attract attention, and the warmth is used because it is generally associated with closeness. It is not an instant message rather it takes some time for the pillows to sense and react. The pillows are made from a textile woven with traditional as well as electroluminescent threads. While the computational technology here is embedded in a pillow, a widely familiar object, they are explicitly changing the expression of the object indeed; the expression is inextricably linked to the function, thus, the users are given some premises on which to interpret the new functionality.

Hallnäs & Redström's notion of the computer as a material for design introduces a new understanding computers. It is an understanding that has enabled them to focus on the temporal expressions of computational technology and to place aesthetic considerations at the center of their work. Their notion of material, however, largely remains metaphorical or rhetorical in the sense that they have not yet addressed *how* the technology is a material. Even when computers are embedded in the textile their presence is compared to that of a musical piece (cf., Ibid.; Redström, 2005). The temporal form, which computers enable, is taken as their prime, if not their only, expressional contribution to the overall appearance of computational things. Yet, the computer is physical through and through and the material understanding of computers may have more to offer than what is enabled by a mere metaphorical maneuver. A trend in this direction is called *physical computing*.

PHYSICAL COMPUTING

Physical computing is developed within the do-it-yourself (DIY) movement of microelectronics (cf., Haque & Somlai-Fischer, 2005; Igoe, 2007; MAKE,). The community is not unaffected by the thoughts of Ubiquitous Computing, but their primary motivator is the flooding of cheap microelectronics and the opportunity it offers to tinker to their hearts content. Computers have become tangible not through representational artifacts but through sensors, motors, and micro switches. Furthermore, corporate companies and groups within the DIY community have developed the accessibility of microcontrollers by placing them on circuit boards with a range of preconfigured digital and analog input and output just as communication with the microcontroller and the programming environments has become extremely easy to work with (cf., Arduino, 2005; BASIC-Stamp, 1992).

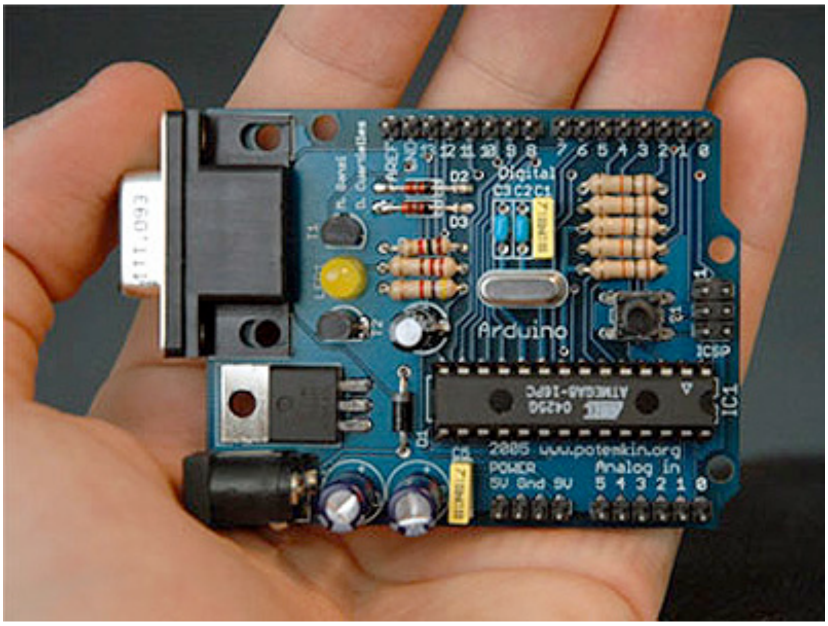

Figure 9 An Arduino board with an ATMEGA8 microcontroller, 14 digital and five analog input/ output options, and serial communication for uploading software (Photo with courtesy of Arduino).

According to Dan O'Sullivan and Tom Igoe, who both teach at the Interactive Telecommunications Program (ITP) at Tisch School of Arts at New York University, physical computing is about building *Intelligence Amplification* and empowering everyone to build their own tools by spreading knowledge on how the technology works (O'Sullivan & Igoe, 2004).

Physical computing is about using the relative limited computational power of the microcontroller to make connections between input and output of almost any material in all shapes and sizes. Thus, one of the key concepts is to understand the energy flow and the power of transduction. Microphones, motors, LEDs, etc., are all transducing one form of energy into another and thereby enabling a host of possible forms and colors controlled by the computations. And it is "best understood by doing it rather than talking about it" (Ibid., p. xxii).

Within physical computing the computer is in a sense reduced to a bridge between an input and an output. Doing that, however, emphasizes the rich potential of the expressional appearances it can generate—the function becomes the expression. The purpose of the computer is no longer just to convey information in traditional formats (e.g., text, images, and sound) but to affect the material world around us. Indeed, in what may seem like a paradox, the reduction of computational power and simplification of input and output apparently inspires a whole new world of expressional appearances and functions (cf., MAKE,).

COMPUTATIONAL COMPOSITES

By combining Hallnäs and Redström's notion of the computer as a design material with the hands-on practice of physical computing, we arrive at a fundamentally new understanding of computers. The computer understood as a material like any other material—as a physical substance that shows specific properties of its kind that can be proportioned in desired quantities, and that can be manipulated into a form. But, *how* precisely is the computer a material? What kind of material is it? How can we work with it as a material? What are its material properties? What does this understanding entail in terms of practice? How can we use it to develop new aesthetics of computational things? In this section I will present the first steps towards understanding the computer as a material, where next chapter is dedicated to specific investigation targeted at answering some of the questions.

Computational Composites

The electrical digital computer promises a world of computations, however, it is organized as inaccessible patterns of energy. It has no form, color, or texture perceivable to the human sensory apparatus. In and by itself it has no expression. Yet, our understanding of the computer and its purpose cannot be separated from the way it appears to us just as developing computational technology is inextricably linked to the expressional appearances it can assume.

To apprehend this apparent discrepancy between the formlessness and the necessity of form we need to realize that the computer in practice never appears by itself—at least not when it has research beyond the mathematicians sketchpad. It is always part of a composition with other constituents capable of providing form, color, and texture to the computations. Take, for instance, the current epitome of an information technology: the laptop computer. It has a shiny colorful display capable of rapidly displaying new images, a keyboard and a touchpad through which the computations can be manipulated, and all is encapsulated in a smooth aluminum case.

If we hereby have established that we cannot perceive a computer in and by itself, then computers cannot immediately be materials like wood or stone. Diving into the world of readily accepted materials, however, we find other examples of materials that need to undergo some kind of transformation before we can utilize their potential. In metallurgy, for instance, it is commonly known that most metals require purification and some even require the composition of an alloy for their properties to come to use. Take aluminum, for example[9], from its naturally occurring state as bauxite it can be refined to show properties such as corrosion resistance and lightweight, but it remains a weak and seemingly useless material (cf., Doordan, 1993). Only after blending it with other metals in an alloy does aluminum receive the strength and flexible form it is commonly known for (cf., Ibid.).

In that light computers can be seen as a potential material, as a material, which shows some desirable properties that we only have to refine and bring forward through combining it with other appropriate materials. Since the computer is no metal, those material combinations would be composites rather than alloys. Hence, the material form of a computer would be a *computational composite*.

Giving Form to Computational Composites

Understanding the computer as a material immediately places it in a context of a crafting or *formgiving* practice with an anchor in the rich sensory experiences that materials afford. Think, for instance, of a cabinetmaker's sensibility to the finesse of the wood before her, the hardness, the coarseness of the grain, the size and number of knots, the smell, the smoothness of the surface, and how it reacts when she planes, grinds, and saws. Her work demands training, and substantial knowledge of the type of wood she uses but when skillful she can gradually form a chair or a dresser through meticulous labor. Her work becomes a balanced negotiation between developing the form and the function—between aesthetics and utility.

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[9] This example recur in several of the papers and I realize this is somewhat annoying, however, the example was key in my realization of *how* the computer is a material and why this may be a fruitful understanding of them.

Indeed, the ability to balance form and function seems promising as a strategy to escape the functional supremacy present in the practice and understanding of Ubiquitous Computing. In both the chair and the abacus the function reside in the form—it cannot be made independent of it, just as the graphical display is the expressional appearance of the computer handling images. They have been developed together—the form and the function follow each other or as Hallnäs and Redström proposed, "function resides in the expression of things." This leitmotif invites us explicitly to play with the expression of things as a means to find new functions. Indeed, it almost suggests that something may reside in the expression that we have not yet discovered—not because it is hidden, but because we need to interpret the expression. As argued in the previous chapter, the complexity, and novelty of most computational things and the functions they fulfill imply that we cannot expect to immediately understand every new thing that we encounter. However, that is not unique to computational things. While the abacus may immediately afford that we move the wooden pearls back and forth on the strings, it surely requires interpretation to discover that the abacus can be used to assist calculations.

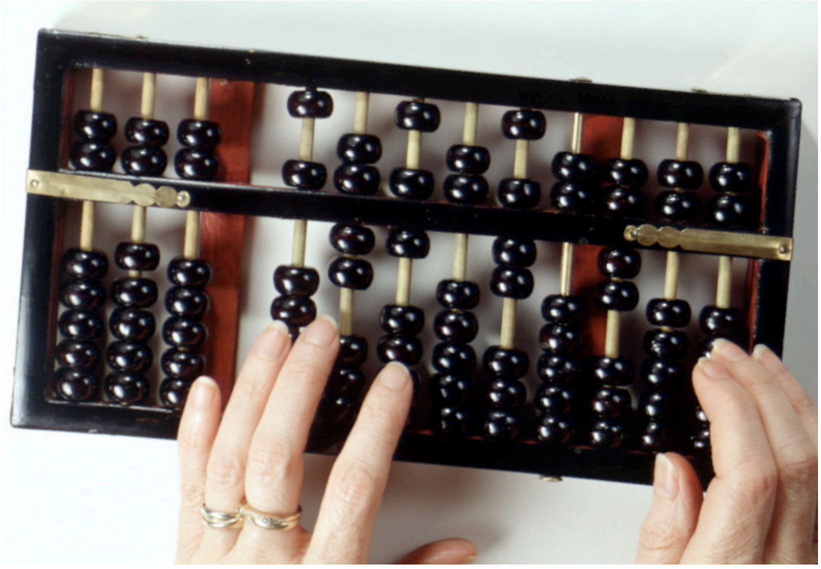

Figure 10 An abacus.

To be able to work with computational composites as did the cabinetmaker with wood would correspond beautifully with the emphasis on our rich sensory apparatus put forward by Tom Djajadiningrat *et al.* (2004) and also with the tinkering practices of physical computing as described above. Or as Redström express it "When working with a material, we find ourselves within a framework that does not necessarily depend on 'functions' in the rationalistic sense, but where questions of form, expressions and aesthetics provide a basis for exploring possibilities and characteristics of the materials at hand." (Redström, 2005, p. 37)

Before we can engage in a similar practice with computational composites, however, there are important aspects to be addressed; for instance, what kind of material is it? What are its properties, its potential, and limitations? How can we work with it? What new opportunities does it afford?

The Division of Labor and the Scales of Materials

When studying development and use of more traditional materials such as wood, steel, or aluminum it becomes clear that different types of access to a material are necessary because a chemist's approach to any given material is different from that of an architect. A difference caused by the need of minimizing the level of complexity. The matters focal to the chemist, such as the molecular structure and responsiveness with other chemicals, are circumferential to the architect, just as aesthetics and structural abilities are to the chemist. If they were both to know every matter concerning the material, they would probably become too entangled in technicalities on the wrong scale to achieve anything.

Hence, a material, while being the same physical entity, can be understood and treated different depending on the eye of the beholder. Computational composite can be seen as a new layer in-between the engineering/ programming and the design of the computational thing—a layer, which is largely about composing material properties that the designer can find inspiration in.

Examples of Computers used as Materials

The aesthetic disciplines of art, design, and architecture have for some time incorporated computers in their work. Not merely as a tool for drawing as in computer aided design (CAD), as climate and infrastructure regulators or stress monitors in architecture, or as support for the main function in ovens, vacuum cleaners, electrical toothbrushes, food processors etc., but as an essential element in creating new expressions.

For example, the responsive and interactive architecture assembled by Lucy Bullivant (cf., 2005; Bullivant, 2006), exemplified by the Tower of Winds by Toyo Ito (See Figure 11) or the digital and interactive art and design (cf., Freyer *et al.*, 2008; Lovejoy, 2004; Paul, 2003) exemplified by the Mirrors by Daniel Rozin (See Figure 12) all explore the potential aesthetics that computers can partake in generating.

Some have even developed material compositions that we in the current light could rename as computational composites. *Living Glass* (see Figure 13), for instance, which responds to human presence by opening thin splices in the glass letting through fresh air (Brownell, 2006), or *Super Cilia Skin* (see Figure 14 and Figure 15) which responds to touch and can sense and simulate movement such as wind flow of human touch (Brownell, 2008; Raffle *et al.*, 2003).

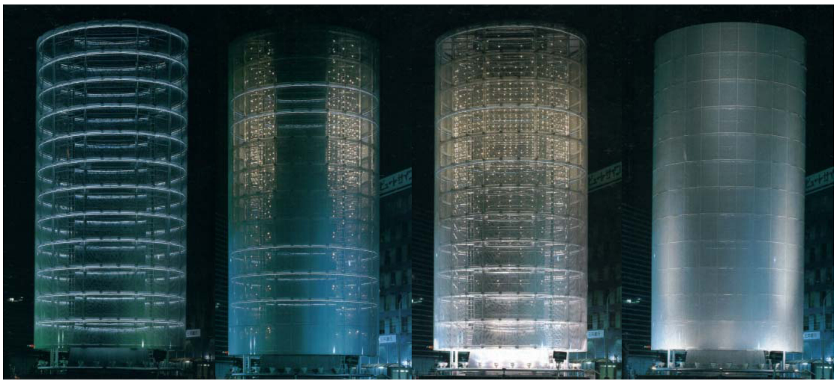

Figure 11 *The Tower of Wind* by Toyo Ito is a sculpture completed in Tokyo in 1986. The tower is a metaphorical representation of Tokyo with its ever-changing never-ceasing winds. The tower changes expression in response to winds' speed and directions (Photos with courtesy of Shinkenchiku-sha).

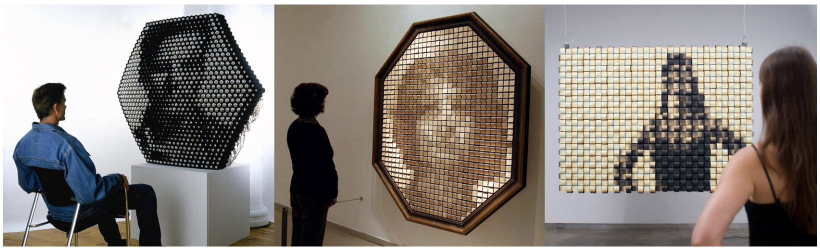

Figure 12 Three different mirrors by Daniel Rozin. This first is *The Shiny Ball Mirror*, the second is *The Wooden Mirror* and the third is *The Wave Mirror*. All build form different materials but with the same kind of technology and functionality (Photos with courtesy of Daniel Rozin).

Figure 13 *Living Glass* is a polymer glass substitute that opens and closes in response to human presence to control the air quality in the room. (Courtesy of The Living)

Figure 14 *Super Cilia Skin* is a touch sensitive surface made of orange felt and actuators (Courtesy of Mitchell Joachim).

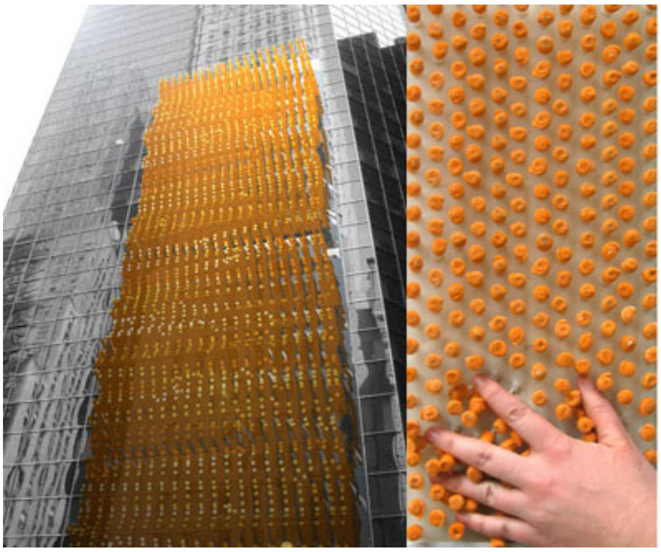

Figure 15 *Super Cilia Skin* pictured as a building façade and close-up (Courtesy of Mitchell Joachim).

Furthermore, there are other programs to highlighting the potential of combining computers and other materials. Marcelo Coelho *et al.* (2007; 2009) have, for instance, arranged two workshops on Transitive Materials in 2007 and 2009 as well as a special issue on Material Computing in the Journal for Personal Ubiquitous Computing to be published during 2009.

These projects may give us a hint about what can be done if we whole heartedly take on this understanding of computers but just as importantly if we manage to develop both the accessibility of technology as a material as well as provide methods to create prototypes and experiments with different expressions. Indeed, if this section forms the first steps towards understanding the computer as a material, if it constitutes the preliminary exercises to soften the ground, I will in the next chapter present a series of investigations which in different ways will shed light on its potential.

Investigating the Potential of Computational Composites

This island would generally be considered as very uninteresting; but to anyone accustomed only to an English landscape, the novel aspect of an utterly sterile land possesses a grandeur which more vegetation might spoil.

One of Darwin's first observations during his voyage on the Beagle
uttered upon anchoring at Porto Praya in St Jago (1997, p. 5-6)

As alluded to in the preface this voyage is barely begun. The understanding of the 'computer as a material' is investigated from several angles in order to develop our notion of what the material understanding entails and to explore its potential. My intention has been to take a small step in several directions rather than to go further in depth in one direction. This is done because proposing something as fundamental as a new understanding of the computer involves a range of concerns, such as: What kind of material is it? How do we work with it? What new sides of computations can it afford? And to learn whether it does help in expanding what is *thinkable and possible* we need to learn about all these aspects.

I have divided the investigations into four tracks: A theoretical, an aesthetic, a practical, and a methodological. The overall methodology has been to carry out design experiments in terms of developing physical prototypes as is common within design research (Binder & Redström, 2006; Brandt & Binder, 2007; Hallnäs & Redström, 2006; Koskinen *et al.*, 2008; Seago & Dunne, 1999). This basically means that the purpose of the experiments is to explore the space of possibilities unfolded out by the program. Where the program denotes the design intentions—the visions the questions, and the methods. The role of the experiments is to feed back to the program and thereby to help relating the program to the broader picture of design possibilities (i.e., did it bring anything new to the table?). Design research is not about a search for the truth but about a search for new possibilities. The four investigations can thus be seen as inquirers into different aspects of the experiments. The theoretical track is concerned with formulating and developing the program. The aesthetic track *is* the experiments and the outcome of them both physical and theoretical. The practical track is the contemplations of the techniques used for building the prototypes. Lastly, the methodological track is concerned with how the outcome of the experiments constitutes valid and valuable knowledge.

Through the investigations, I have shown how the computer can be understood as a material and how it partake in a new material strand of materials whose expressions come to be in context. I have developed material samples to form an experiential foundation of computational composites, and I have uncovered some of their essential material properties. I have developed a way of working with them in a design process despite their complexity and non a priori existence, and finally I have argued how these operationalizations of materials constitute both valid and valuable results within the context of design research.

The investigations have been carried out in collaborations with a range of others who have a background in art, design, architecture, electronics, and computer science in order to complement my own background in computer science. I have led the course of the overall project, and the collaborations have been deliberately sought as means to carry out the investigations I deemed interesting and necessary.

THE THEORETICAL INVESTIGATIONS

The theoretical investigations are divided into two. The first addresses the shift from a metaphorical understanding to a literal understanding by answering the question of how a computer is a material. This also constitutes the foundation on which all the subsequent investigations are formulated. The second theoretical investigation turns the question around and asks what kind of material the computer (or the computational composite) is in the broader spectrum of materials.

How is the Computer as Material?

As argued in the previous chapter the understanding of the computer as a material for design has an immediate appeal, as it will help placing aesthetic considerations at the center and to use that as a strategy to push computational innovation forward. Yet, there is a long way form a metaphorical exercise, to truly understanding the computer as a material

This investigation is crucial to understand *how* the computer, which we have gotten so used to understanding as information technology containing representations, can also be understood as a material. We need to know whether we can remain faithful to the general category of materials and to the digital computer at the same time. If corners have to be cut the understanding will remain metaphorical. The result of the investigation enables us to grasp the new understanding, at least in theory, and to begin to contemplate how we can work with the computational material—develop it, and design with it.

The investigation was carried out in collaboration with Johan Redström and Tomas Sokoler, and it is primarily described in the first paper (Vallgårda & Redström, 2007). Whereas the energy flow in computational composites through transducers is elaborated in the fourth paper (Vallgårda & Sokoler, 2009).

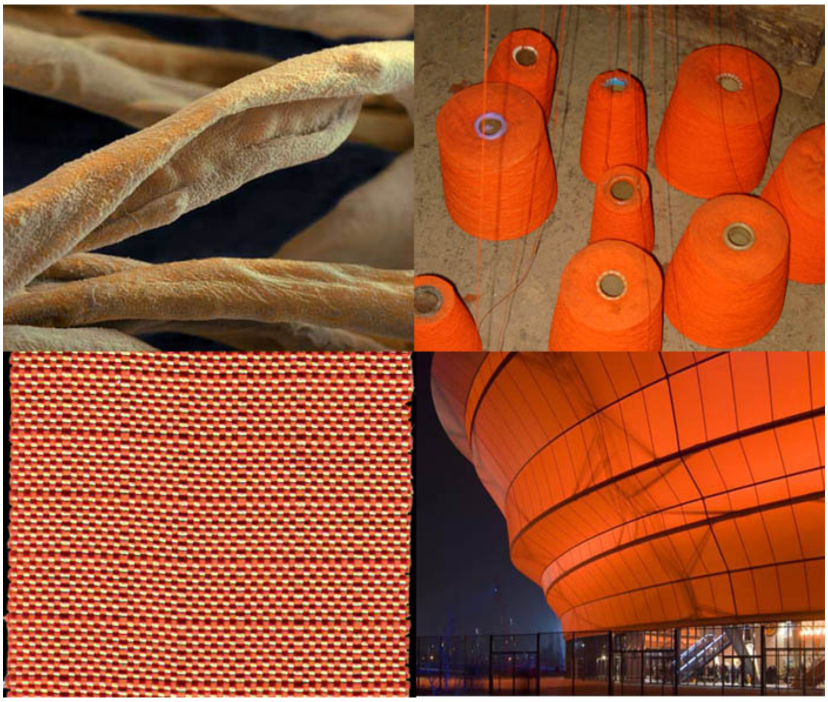

Figure 16 These are four examples of how the same material can be seen at different scales: the fibers, the threads, the fabric, or the as the surface of a building (here as the Zenith music hall in Strasbourg by Massimiliano and Doriana Fuksas)

We studied several accounts of both traditional and functional or “smart” materials and we did this from both a material science and a design point of view to get a sense of materials at both levels of abstraction (see Figure 16) (cf., Addington & Schodek, 2005; Beylerian & Dent, 2005; Braddock-Clarke & O'Mahony, 2006; Brownell, 2006; Brownell, 2008; de Ruiter *et al*., 2005; Doordan, 1993; Doordan, 2003; Everett, 1994; Gordon, 2006; Gregor, 1960; Hoadley, 2000; Hull & Clyne, 1996; Kennedy & Grunenberg, 2001; Lundsten, 1974; Manzini, 1989; Mori, 2002; Ritter, 2007; Smith, 1968). Materials are generally a somewhat elusive category when put under scrutiny. What seems to unite what we generally think of as material is that they are a physical substance, which shows specific properties for its kind, a substance that can be shaped according to skills and proportioned in volumes according to needs.

Materials are all structures at a molecular scale but even at larger scales it can be difficult to make clear distinctions between materials and structures (e.g., in textiles as shown in Figure 16) (cf., Gordon, 2006). This is crucial for understanding how the computational structure can be a material, here the computational structure refers both to the hardware and the program that in combination confines the flow of energy and thus constitutes the computations. The computational structure is like the cell structure in wood. The cell-structure is there, and it is certainly complex, but our interaction with wood concerns only the inner structure when we intent to study it or to improve some of its properties—either by direct manipulation (e.g., making it more flexible by punctuating the cells) or by combining it with other materials in a composite (e.g., plywood or MDF) (cf., Ibid.; Hoadley, 2000). Otherwise, we work with wood at a larger scale of abstraction—as when the cabinetmaker gives form to wood through planing, grinding, and sawing. The same goes for computers—the inner structure only concerns us when we wish to form the computations.

When zooming out on computers, however, they do not give us much in terms of expressional appearance. As argued in the previous chapter, a computer is never by itself it is always part of a composition with other materials—a computational composite.

In material science when composing material composites the exercise is to find combinations of properties that will compliment or enhance each other, but it is also about joining them together in ways that bring out the properties properly (e.g., to find an adhesive that is strong enough but does not deteriorate the material properties through chemical reactions). Composing a composite is about both physically and chemically balancing the energies that constitutes the material properties and holds the materials together (cf., Gordon, 2006; Hull & Clyne, 1996). In a computational composite the other materials must be capable of responding to the changes that are the computations (i.e., be able to change color, form, strength, degree of transparency etc.). For the other materials to respond to the electrical energy from the computer it must be transduced into other energy forms (e.g., thermal, kinetic, chemical). Sometimes this transductive property is immediately present in a material (e.g. shape memory alloys) but other times the transducer will be a separate element in the overall composition (e.g., heat emitting electrical wires, motors, Peltier elements).

A traditional struggle within material science has been to minimize the materials' interactions with the environmental conditions around it (e.g., to prevent it from deterioration, oxidation, or patination). This has changed with the invention of *smart materials*, which are explicitly fashioned to be capable of responding to their surroundings (e.g., the heat sensitive shape memory alloy or the thermo chromatic ink) (cf., Addington & Schodek, 2005; Ritter, 2007). Where the border—the surface—of the material is something we tend to experience as well-defined, it is in both traditional and smart materials something that could be considered an active zone of exchange of various kinds of energies (cf., Addington & Schodek, 2005). In computational composites, this contextual sensitivity can be made to play a central role and the flexibility of computations creates a substantial scope of possible interpretations of contextual factors. As long as transducers can be found to translate between the various kinds of energy the computational composites can be made sensitive to any event in its surroundings.

In other words, it is not wholly unreasonable to understand the computer as a material and to work with it in that way both as a material scientist and as a designer.

What Kind of Material is the Computational Composite?

The purpose of the second theoretical investigation was to see whether including computers in the general category of materials would demand changes to the category, which would indicate that computers could not really be included, or whether they with their properties and behavior, would resemble other already generally accepted materials. In case of the latter, the purpose was also to further examine what kind of material computational composites is. The investigation is most thoroughly described in the first part of the fourth paper: Becoming Materials: Material Forms and Forms of Practice (Bergström *et al.*, 2009).

The investigation was not carried out as a focused study; rather the question was present throughout all of the practical experiments. Large parts of the reflections, however, were carried out in conversation with textile designer Jenny Bergström, architect Ramia Mazé, and interaction designer Johan Redström. By experiencing the samples of computational composites, we had created we were able to comprehend some overall characteristics that we had not realized beforehand. To assist the investigation and the analysis of these characteristics we used a combination of recent accounts of smart materials (cf., Addington & Schodek, 2005; Brownell, 2006; Brownell, 2008; Ritter, 2007) and Manzini's (1989) analysis of the material marked in the late 1980's where he made a distinction between the traditional materials and functional materials.

Traditional materials are those we all have direct experience with, and which has been around, if not since the beginning of times, then at least for centuries (e.g., wood, clay, textile, metal). Functional materials, on the other hand, are the designed materials that flooded the marked after chemistry, physics, and engineering joined together in studying and improving materials (e.g., plastic, fiberglass, electroluminescent film) in what was to be called material science. The distinction became perceptible as the new materials generally were designed to be particularly good at something, and as they became too numerous for designers to be able to know them all by experience. Instead, designers had to discern one from another in terms of various accounts of their properties—what they could do. Manzini thus argued that the traditional materials are understood in terms of "what they are" where the functional materials are understood in terms of "what they do." Our argument is that more recent material developments have pushed the understanding of what materials are and how we handle them even further. The new smart or intelligent materials are by most accounts defined as materials that are capable of assuming two or more states with state changes triggered by specific environmental events and that these state changes are reversible (e.g., shape memory alloys or thermo chromatic ink) (cf., Addington & Schodek, 2005; Ritter, 2007). By this definition, it is not difficult to include computational composites based on our previous account of what they are and how they behave. Furthermore, by the distinction Manzini made, they would belong to the group of *doing* materials, however, even if we can describe their functionality (e.g., if the temperature raises above a certain threshold the shape will change) it is not the same kind of functionality we refer to when we, for instance, talk of fiberglass, and Living Glass (see Figure 13). The temporal behavior of state changes makes a significant difference when understanding these smart and computational materials. Thus, we propose an addition to Manzini's two groups of materials by adding a group where materials are understood in terms of "what they come to be." This understanding is what best captures the experience of the materials in their constant change according to environmental factors and use. Some of these materials may have a high degree of precision in achieving the same expression every time a condition is met, others may have a more complex relation between conditions and state changes, or the overall expression can become less distinct—less functional—and perhaps more poetic. Computational composites are materials that come to be—they are *becoming*.

THE AESTHETIC INVESTIGATIONS

The aesthetic investigations are carried out to see whether the material understanding of computers, and specifically the *computational composites* are indeed a viable foundation for creating new expressional appearances. Obviously, the aim is not to reach a "yes" or "no" conclusion rather it is to begin developing material samples that each explores different aspects of the design space that the material understanding delineates, and to analyze whether these samples bring new expressions to the table.

Two sets of experiments[10] are carried out. One, as the first deliberate attempt of putting the understanding into practice, and the second as a more specific study of the properties, or potential properties, of computational composites.

The First Computational Composite

The purpose of the first experiment was somewhat diffuse in terms of expected outcome except that it would provide a stepping-stone into the material realm—since materials cannot be understood through theory alone. While the examples in the previous section can be

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[10] *Experiments* in the sense used within design research and not within science, see the section "The investigation into research methodology" for further elaboration.

reinterpreted as computational composites this experiment was the first to deliberately design from the material understanding of computers.

The composite was conceived in collaboration with sculptural artist Henrik Menné who, through his own work, has explored the aesthetics of machines, materials, and automatized creation. See "The investigations into practice" below for elaborations on the development process and additional collaborators on the project. The experiment is most thoroughly described in the second paper (Vallgårda, 2008).

The design-brief or intentions behind the experiment took offset in the apparent discrepancy of suspending disbelief and creating disbelief. To convincingly introduce the computer as a material in a computational composite requires that we believe the result to be a material, but to demonstrate the potential for new expressions requires that the result is different from other materials as well as different from the computational expressions that we already know.

As a means to meet this challenge we made use of the concept of Para-functionality that Dunne (2005) introduced in early days of the Critical Design program. Para-functionality is a strategy to "design within the realms of utility but attempts to go beyond conventional definitions of functionalism to include the poetic" (Ibid., p. 43). In other words, we chose to use a traditional material as the other primary element of the composite to accommodate the suspense of disbelief. And as a strategy to demonstrate the larger potential we aimed for a poetic expression that played on other strings than the most common expressionals used with computational technology (i.e., beyond visual appearance).

The first computational composite became a wooden plank, or a series of them called PLANKS. Each PLANK is sensitive to sonic activity and responds to sounds of a certain volume by flexing outwards. The longer the sound continues the more the PLANKS flex, until they reach their maximum position. When you, for instance, talk to the PLANKS they respond by flexing towards you.

Each PLANK comprises an eight mm pine plank, an Arduino board with an ATmega168 microcontroller and a program to execute the events, a microphone to transduce the pressure from the sound wave into electrical energy, and a servomotor to transduce electrical energy into kinetic energy. All nine PLANKS can run on the same 5V power supply.

Figure 17 Nine PLANKS in action hanging on a steel stand.

Figure 18 The PLANKS in a silent and in a noisy environment—though not suficient to excite all the PLANKS. The microphones are directional and their sensitivity is individually adjustable making it possible to differentiate the expressional appearance in the apparently identical PLANKS.

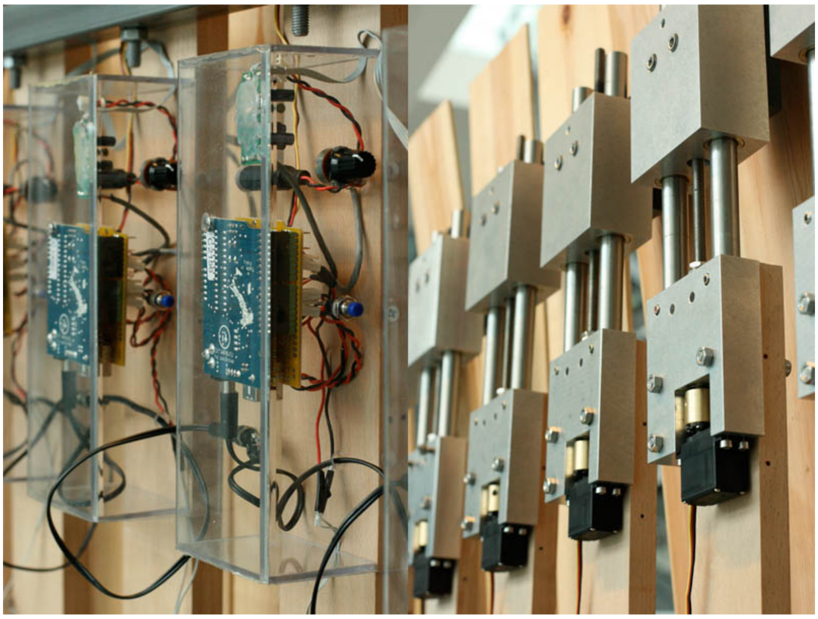

Figure 19 The picture on the left shows the computational layer with a reset button and a potentiometer to adjust the sensitivity. The picture on the right shows the servomotor turning the rod in the middle to contract the blocks and thereby flex the PLANKS.

Figure 20 The microphone embedded in the PLANK.

The PLANKS were the main outcome of this investigation. Their physical existence marks the transition from metaphor to material, and they form the first example of what can be done—they embody a spot in the design space formed by the material understanding of computers.

Furthermore, the PLANKS are not representations of anything—they are not displays of something either inside or outside. The PLANKS *are* their expressional appearance. They can be used as displays by a designer or an architect who, for example, could use one PLANK to display the level of noise in that area of a room (e.g., in a kindergarten) whereas using several PLANKS together creates an expressional appearance stronger than merely mediating information—it alters the space; it changes its volume. Hence, to use the PLANKS for a design is to make use of computational technology without being able to distinguish its function from its form. Thereby the PLANKS mark a first step towards a strategy that enables us to give form to computational technology and through that to develop new functionality.

Additionally, the process of designing the PLANKS made us realize the need for better understanding the computer's properties—to be able to articulate and discern the space of possibilities. What are the handles? What are the constraints? What are the strengths and what are the weaknesses of computational composites?

Exploring Potential Properties of Computational Composites

The second aesthetic investigation was thus designed to satisfy the need for a better understanding of the computer as a material. The purpose was to study the computer in a material context and to discern potential properties of computational composites. Since the only known material of the general category of computational composites is the computer they posses an open-endedness which only allow us to address their *potential* properties.

The work is carried out in collaboration with interaction designer Tomas Sokoler, who has a background in computer science and physics and who began working with Ubiquitous Computing and awareness in the mid 1990's (Sokoler, 2004). The work is presented in the third paper (Vallgårda & Sokoler, 2009).

Properties are the characteristics of materials that help us distinguish one from another. Properties are an important instrument in communicating between the layers of expertise when dealing with materials. The designer and the architect are primary concerned with the experience of the properties (e.g., how does the material feel and look and what can it withstand in terms of pressure and weather?) whereas the material scientist endeavor to understand and explain the properties and possibly develop new combinations. In this investigation we aim at describing the experience of some properties of computational composites as aid for future designers and architects, but to do that we need to take on the perspective of the material scientist and study the computer as a material. Yet, as computers are only available to us in composition with other materials the study will be a combination of theoretical contemplations of the computer's properties and a study of computational composites *par exemple*.

From Hallnäs and Redström we learned that the execution of programs means that computations are inherently temporal and thus, any computational composite exhibits *temporality* (i.e., they will happen over time). The temporal property means that computational composites, for instance, can happen slow or fast, with delays, in sync with something, or follow a rhythm. That something happens over time means that something changes. The computational changes must somehow be reflected in the composite material simply to be a computational composite. The change may not be in a one-to-one relation, meaning that not every computation may result in a change in the overall composite. Indeed, the relation between the computer and the other materials can be complex and in itself prone to changes. The *changes* in the composite can be experienced as *reversible*, or *accumulative*, if not completely *arbitrary*.

The program is the outline for the computations—the confinements on the energy flow—and consequently it is the structure controlling the changes in the overall composite. The program thereby defines the *causality* of the computational changes in the composite—it dictates the cause and effects of the changes. Furthermore, the program may take input during execution and thus update the basis for the computations. The computer can thus let the composite be responsive to change in the surroundings. The combination of input and *computed causality* means that the overall composite may exhibit almost any cause-and-effect relation (as long as transducers exist to transform the energies in both input and output). The computer can *moderate*, *exaggerate* or completely *transform* any causality we have grown accustomed to in our traditional material world.

Furthermore, the computational composite's sensitivity to its surroundings is not confined to its immediate vicinity. This, because the computer is capable of receiving and transmitting impulses over various types of radio or cabled networks. This *connectability* can also be used by the computational composite to share computations with other computational composites. This means, for instance, that two computational composites can behave as one even though they are physically separated.

We built two composite material samples that could be programmed to exhibit one of the properties more explicitly than the other. This was done as a method to subject each property to more direct scrutiny. The properties can, however never be completely singled out as the computer inevitably will exhibit several at the time. The two properties we chose to focus on in our first study were *computed causality* and *connectability*.

To maintain the ambition of demonstrating the new aesthetic potential while still keeping strong references to more traditional materials we chose, again, to use a traditional material as the other part of the composite, and to stay within traditional material behaviors while using the computations to dramatically change the expressions of those behaviors. We chose to play with heat and to do that in a copper computational composite. Copper is a metal with a high coefficient of heat transfer which makes it possible to generate relatively fast thermal effects and Peltier elements (as transducers) can easily heat up or cool down the copper (See Figure 21 and Figure 22).

Figure 21 The two Copper Computational Composites in the formation of tiles.

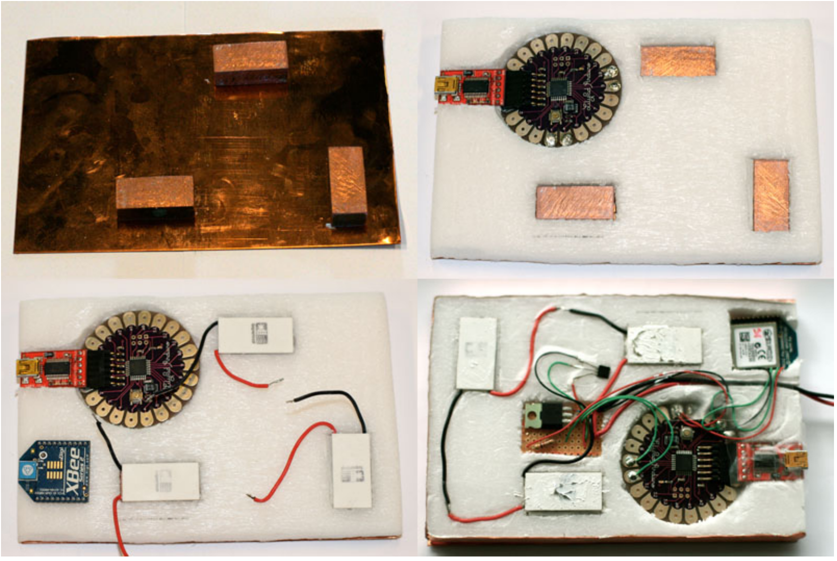

Figure 22 The composition of the Copper Computational Composite. The copper plate and blocks consume the excess heat form the white Peltier elements, the round LilyPad with the Atmeg168 microcontroller controls the events, the XBee module following the Zigbee radio standard enables radio communication, and a temperature sensor provides input to the computer.

Figure 23 The heat from a hand is enough to turn the composite cold within few seconds.

In the first version of the sample, we studied *computed causality*. What appears to be a normal copper tile is made to exhibit a reverse thermal effect, meaning that when it is heated up it turns cold. In the next iteration of this sample, it will also be able to turn warm when cooled down. This is possible since Peltier elements can reverse their effect. The experience of the reverse thermal effect is difficult to convey through text and images, but it is quite strong. The heat from a hand is enough to turn the tile cold within a few seconds (See Figure 23).

In the second version of the sample, what appears to be two separate copper tiles are, in fact, one—at least when it comes to thermal behavior. Ideally, when one of the tiles is cooled down, the other will drop to the same temperature and *vice versa* and they will thereby always maintain a thermodynamic equilibrium, as if they were one tile. In the current sample they maintain the reversed causality from the previous case, and when one is heated up both will cool down. Thus for the next iteration to achieve the ideal material sample we need to change a component for the Peltier element in order to be able to repeatedly reverse its effect as well as devise a program to administer the negotiation of temperatures.

The two versions of the samples had two purposes: One was as a tool for gaining insight into the relation between computers and the potential properties they offer computational composites. This, because direct experience is impossible and theorizing on how the computer's traits become properties in a computational composite is difficult without actually placing it in a material context. The samples played the role as a physical thinking tool in a similar way as models are used in, for instance, medicine, physics, chemistry, and architecture to understand a matter of high complexity or at a different scale (cf., de Chadarevian & Hopwood, 2004). Secondly, as the samples were not only models of what could be, but also real scale composites, they also served as a foundation for experiencing the effect of at least this interpretation of the properties. Working with *potential* properties is rather abstract for a future designer or architect and there is still only little upon which an experience can be built. Thus, the tiles (and the PLANKS) serve to inspire their imagination.

This investigation is far from finished. While *computed causality* and *connectability* has been the subject of this study, and we thereby implicitly have demonstrated *reversibility* and both immediate and remote *context sensibility* there are most likely to be several properties of the computer yet to be articulated and explored in a material context. This work constitutes the foundation that will, at some point, make it possible to practice *formgiving* in a way that will resemble the practice of the cabinetmaker.

THE INVESTIGATIONS INTO PRACTICE

The investigations into practice are concerned with how to give form to *becoming* materials and the oftentimes yet-to-be-designed computational composites and how the division of labor may play out in practice in terms of communicating between, for instance, the computer scientists, the material scientists, and the designers. The investigations took the form of conscious considerations of methods and strategies during both the design of the two material samples and during the design of Telltale—a piece of furniture responsive to the energy consumption in a household.

As it turns out, the same method that can assist explorations in the becoming expressional appearances also enables the division of labor in practice. The method can generally be described as developing of lo-fi, large-scale prototypes.

A Study of Designing with Becoming Materials

As part of a project on sustainability and raising awareness on energy consumption in urban neighborhoods carried out at Interactive Institute; Stockholm we conceptualized the Telltale. The Telltale is a transitional object in the sense that it continually transforms in accordance with the energy consumption in a household provoking the household members to consider their energy habits. It is a multipurpose furniture in the shape of a box. The rigidity of the box depends on the energy consumption, the lower the consumption the more rigid and *vice versa*. Moreover, the Telltale travels between households only to stay there about a month at the time and everywhere it goes it gathers permanent traces of how it has been treated.

The concept of the Telltale was developed in collaboration between a textile designer, an architect, an interaction designer, and myself. The studies leading up to the conceptualization involved an extensive study of materials with a transitional property meaning that they could assume two or more states depending on external factors or what we began to understand as *becoming materials*.

The outset of the study was an interest in the possibility of expressing energy consumption directly through changes in a material's expressional appearance. We collected a large catalogue with descriptions and pictures of becoming materials (see Figure 24). Upon returning to it, when developing the Telltale, we soon realized that in order to grasp the effect of changing expressions a more hands-on direct experience was needed. None of us were material scientists, and our interest in this phase was to develop the expressional appearance. Thus, with our knowledge from the pre-study of the vast potential that science (or at least computer science) would lend us in realizing almost any expression, we decided to explore the expressions through a series of lo-fi, large-scale prototypes.

Figure 24 Material pre-study: analyzing and cataloguing expressions of becoming materials based on pictures and descriptions.

As the Telltale was to be a sort of furniture we readily chose to limit our study to textiles or textile-like materials as means to accommodate the general materiality of living room furniture.

We were looking for an expression that would evolve in two tempi. One was the immediate response to a household's current consumption—an expression that by and large should to be reversible. The other was an accumulation of traces from the "misuse" of energy in all the households combined. In other words, we were looking for a reversible and an accumulative expression combined in one material. The flexibility of textiles soon gave us the idea of crumpling as the reversible expression, and the accumulative expression would then be created from the abrasions caused by the crumpling.

We collected a heap of different kinds of textiles and various sorts of rubber plates to form the basis of each samples. We then treated them with various qualities of paint, glue, soap, foil, etc. either to create a layer that would abrade and gradually reveal the layer below, or to give the textile stiffness that in itself would abrade. For example, did we treat a piece of canvas with whipped soap flakes to create the expression of fake-leather but with a much more sensitive surface. This method is often used for theater costumes and props (see Figure 26). Each sample was then exposed to various degrees of crumpling as a way to examine how it would change expression over time (see Figure 27, Figure 28, and Figure 29).

Figure 25 Textile samples in the making and textile samples drying.

Figure 26 Fake-leather in the making.

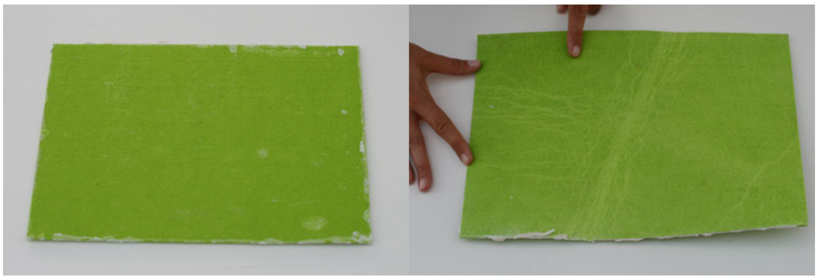

Figure 27 Green felt soaked in soap with almost invisible abrasions.

Figure 28 Black felt coated with three layers of gold paint with dramatic abrasions.

Figure 29 Black cloth coated with three layers of wood glue with well balanced abrasions.

Figure 30 The lo-fi full-scale Telltale mock-up on which we, for instance, were able to text the abrasions around the edges.

Based on a cloth sample soaked in wood glue which exhibited beautiful and sufficient abrasions (see Figure 29) we made a full-scale box to further test the expression (see Figure 30). From that we carried on building a construction, which inflates and deflates on demand. For further details see the fourth paper (Bergström *et al.*, 2009).

The point here is that when working with complex and technological compositions, it is easy to get entangled in time-consuming functional details and thereby loose touch with the overall expression. Through this fairly banal method, it is possible to explore different expressional appearances and to expose them to different situations to experiment with the expression over time. The explorations can then serve as a guide throughout the remaining development process.

A Study of the Division of Labor

The concept of the PLANKS was conceived with artist Henrik Menné. We began by building a lo-fi, large-scale prototype to gain a sense of the expression of moving planks (see Figure 31). The prototype was then used to communicate the ideas to David Cuartielles from 1Scale1 and Malmö School of Arts and Communication (K3) and a group of his students/ employees[11] commissioning them to develop the computational and electronic (transducers) part of the composite. Developing the computational side of the composite could not, however, be done independently of the planks and the overall structure. Thus, they also took on developing a full prototype as they had access to a wood workshop at K3. Several iterations and technical problems later, we saw the first working PLANK. With one working prototype we asked them to make ten, and they ordered special circuit boards designed to accommodate the needs in the PLANKS.

Upon delivery of the PLANKS, two problems arose. Firstly, the structure carrying the planks was not accurate enough to avoid friction causing the small servomotors to overheat, and we commissioned an engineer to redesign that part. Secondly, the PLANKS worked fine when connected to the laptop monitoring the microphone measurements, but when they were disconnected they failed. It turned out there was an error in the printing of the circuit boards, causing them to erase the boot loader upon disconnection, and we therefore switched back to regular Arduino boards. The invisible, yet physical, error at the boards took more than 40 man-hours to discover.

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[11] Marcus Eriksson, James Haliburton, Tony Olsson, Donghoo Kim, David Sjunnesson, Fernando Barrajon, Andreas Goransson, Mattias Nordberg, Keongook Seok

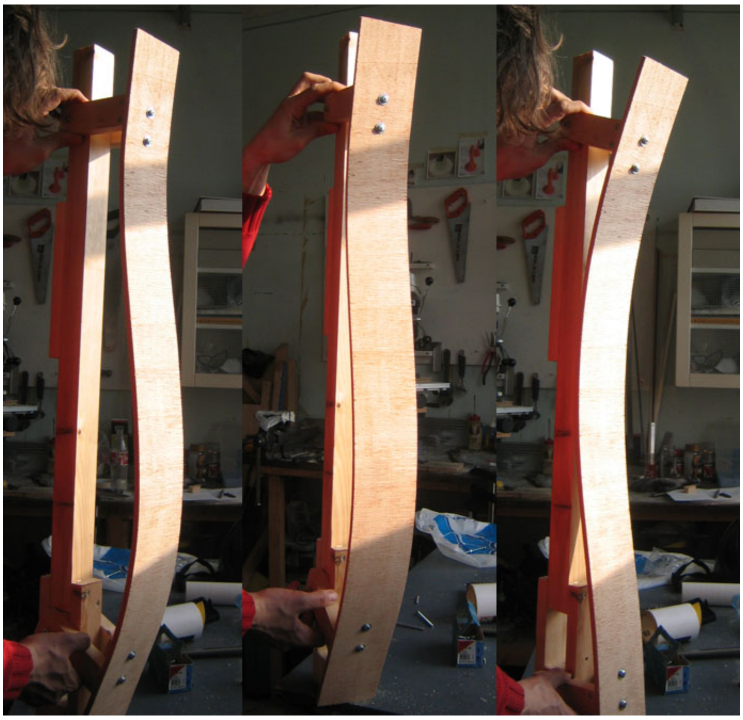

Figure 31 The first lo-fi large-scale prototype of PLANKS conceptualizing the idea.

The problems that arose during this project each exemplify the need for collaboration between people with several types of expertise. In order to develop computational composites, we need to cross current divides between art/design/architecture, computer science, microelectronics, material science, and engineering. On the other hand, the project proved that the various states of the PLANKS served as valid instruments of communicating the intentions between the various disciplines—none of the problems were caused by misunderstandings of the tasks to be carried out. Rather, the problems were caused by the lack of right expertise at the right places (and different views on deadlines). The PLANKS project took approximately a year and a half from start to finish.

Despite the hundreds of man-hours, and layers of expertise involved in the PLANKS they still only exhibit what could be called a rough prototype in terms of being planks to be used in an architectural context, for example.

These investigations into practice through practice show that *formgiving* with computational composites is a layered process both in the sense of expertise domains as well as technical developments. The lo-fi, large-scale prototypes proved helpful, both in creating a sense of the expressional appearances, as well as bridging the transitions between the layers.

THE INVESTIGATION INTO RESEARCH METHODOLOGY

The value of proposing a new understanding of computers as a means to developing new aesthetics for computational things is not something that is easily investigated within the confinements of a Ph.D. project. The real value can only really be determined in the long term and even then, it is influenced by a number of social and societal circumstances not related to the actual ideas. We could arrange workshop sessions with designers and architects to gain their reaction to the proposed understanding of computers as a design material and watch what they would make of it, but the result would hardly provide us with an insight beyond what these particular designers and architects made of the proposal. Furthermore, the variables that could influence the result (e.g., the way it is communicated, the practical setup for the session, the open-mindedness, and experience of the participants) are too numerable and too weighty to leave much certainty in the evaluation of the proposal. Hence, we cannot in practice determine the value of the proposal but only recommend it through delineating the perspectives it opens up for, and exemplify what it can entail. Or, to paraphrase the leitmotif, "the value resides in the expression of the materials."

The investigation into the research methodology has thus had the purpose of understanding how an open-ended proposal like this can be sustained by valid and valuable research. How come, developing these experimental material samples will be part of an academic research tradition?

This investigation was done in collaborations with architect Cecilie Bendixen from Danish School of Design. She studies how acoustic and aesthetic considerations can weigh equally when forming and situating textiles in an architectonic context. In other words, her research questions are parallel to the ones presented in this dissertation with respect to finding the appropriate research methodology. The investigation is presented in the last paper (Vallgårda & Bendixen, 2009).

Both of us had set out on our investigations following the traditions of experimental design research in which a program sets the principles for a design space, and the experiments serve to explore various facets and edges of the program (cf., Binder & Redström, 2006; Brandt & Binder, 2007; Hallnäs & Redström, 2006; Koskinen *et al.*, 2008; Rendell, 2000; Seago & Dunne, 1999). Traditionally these experiments engage the future context (i.e., the use situation) as a means to evaluate the outcome and on occasion assess the reaction of a gallery audience. However, we found those measures inadequate or inappropriate for the purpose of our experiments. Our projects aimed at developing new expressional appearances from known materials used in new contexts, and did not in that sense address any situation of use or any social or societal concerns. In our cases, we found that the value of the experiments was grounded in the material resistance and that the scientific validity was grounded in the way we approached the materials.

In neither case was the knowledge we sought readily available, meaning that we had to subject it to different kinds of testing to obtain it—an act, which we refer to as *operationalizing* the material. An example could be that to learn about the flexibility of a plastic composition we need to bend it until it breaks, and to learn what we can use it for we need to try an give different forms to it.

Another example is the Pratt chairs by Gaetano Pesce who is an Italian artists, architect, and industrial designer based in New York. He developed 1992 a series of nine chairs by injecting varying resolutions of polychrome urethane resin into molds (cf., Pesce, 2004). It is a study of both the material properties and aesthetic potential of urethane polymers as a material for design.

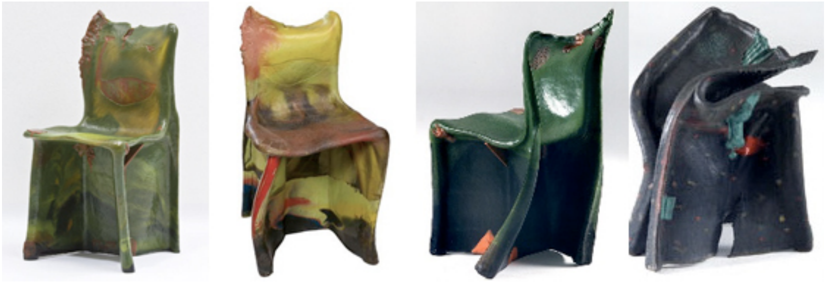

Figure 32 Four of the nine Pratt chairs that Gaetano Pesce made to explore the effect of different densities of urethane resin.

As said, design research is not about searching for truth it is about expanding the horizons for what is *thinkable and possible*, to form the basis for innovation. In other words, it is about rendering new spaces for design, about obtaining new knowledge of the materials with which we build, or to simply about developing new materials, forms and structures. It is an exploratory voyage into the yet unknown.

The key result of this investigation was that by operationalizing our respective materials (textiles and computers) as response to our research questions we were able to use the resistance from the materials as the ground on which we later could build our arguments. The validity of our research is found in the materials and their physical relations to the world around them.

REFLECTIONS

The material understanding of computers cast the computer in a new light. It accentuates its expressive potential and tones down the focus on functionality as well as on its technical complexity. It may even appear as if the full computational potential will not be exploited in computational composites. For instance, the computational power of the microcontrollers used in the PLANKS and the Copper Computational Composite is substantially limited in comparison with the processors found in information technology. On the other hand, the expressive diversity will probably become larger within the material understanding. Indeed, this understanding may implicate that the future innovations of computational technology do not lie in bigger-faster-more developments but in finding alternative use for the computational power we already posses.

The material understanding will not suit all contexts of computational design. Information Technology, for instance, will rightfully dominate the area where computers are used for semantic purposes. The investigations presented above indicate that it will be a suitable understanding when designing from an aesthetic point of view. Thus, it will possibly be an understanding that enables designers, artists, and architects to develop new computational things and to invigorate the expressional appearances of our environment.

The material understanding may not always be materialized in the form of independent computational composites, but instead be how we understand the relation between computers and other materials in our design tasks. The computational composites may form an experiential foundation, meaning that we may find inspirations in the expressions of the computational composites we encounter and use that to form the aesthetics of our designs as we did with the Telltale. The computational composites may also be a tool to push the engineering developments necessary for, for instance, the PLANKS or the Copper Computational Composite to become ready to use for other than demonstration purposes.

The material understanding may empower designers, artists, and architects to use computers in their design, but like any other new material it will take some practice before they become skillful enough to balance the aesthetics with the technical complexity. It may, for instance, take experiments like the ones Pesce did with the polychrome urethane.

Indeed, this understanding host a plethora of possibilities, some of which we cannot yet imagine, and they may unfold quite differently than proposed in this dissertation, but the idea did not come out of nowhere. The work within design research and especially within physical computing has already demonstrated a different take on computers that cannot be captured by either Ubiquitous Computing or Information Technology. *Computational composites*, and the material understanding, is a compilation of these trends but taken a step further by being demonstrated in both practice and theory as a coherent alternative to Information Technology and Ubiquitous Computing.

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PART TWO: THE PAPERS

Computational Composites

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ABSTRACT

Computational composite is introduced as a new type of composite material. Arguing that this is not just a metaphorical maneuver, we provide an analysis of computational technology as material in design, which shows how computers share important characteristics with other materials used in design and architecture. We argue that the notion of computational composites provides a precise understanding of the computer as material, and of how computations need to be combined with other materials to come to expression as material. Besides working as an analysis of computers from a designer's point of view, the notion of computational composites may also provide a link for computer science and human-computer interaction to an increasingly rapid development and use of new materials in design and architecture.

Keywords

Material, computational composites, interaction design, architecture, aesthetics.

INTRODUCTION

Throughout the last centuries, industrial design and architecture have been influenced, challenged and transformed by the development of new materials. The modernist design and architecture that came out of exploring new materials such as plywood, steel and reinforced concrete in the early 20th century is just one example. More recently, technological innovations such as smart materials and embedded computational resources have begun to influence design, in emerging areas such as smart textiles and interactive architecture.

Interestingly, also the context for human-computer interaction and interaction design is changing because of the availability of such new materials. Areas such as ubiquitous computing, augmented reality, and physical computing, have made it evident that the personal computer is just one out of many possible ways in which we can design how humans interact with computers. Another illustration of this development is the increasing integration of interaction design and more general product design, i.e., how designing the interaction with computers becomes part of what it means to design products in general, be it in the shape of digital cameras, mobile phones, or electronic toys.

Issues related to materials are quite central to design. To shape the expressions and functions of their designs, designers need to know about the materials at hand. Or as Ezio Manzini states in the first sentence of his book *The Material of Invention* (1989, p. 17): “Every object made by man is the embodiment of what is at once thinkable and possible.” Previously, what were 'thinkable and possible' were primarily linked to the direct experience with materials and manufacturing techniques; however, the contemporary invention of new materials and technologies make such an approach practically impossible (Ibid.). Language therefore becomes a crucial part of a design process as a way to understand material and technological possibilities. The language of materials developed within science and engineering, however, does not automatically transfer into the realm of design. It needs to be appropriated to a design context where issues of expressiveness, aesthetics, and product manufacturing are more important than the technical properties.

Given the observation that knowledge of materials is essential to design practice and its development over time, some intriguing questions surface: In what ways can we consider computational technology as material? To what extent would such an understanding be based on computer science, and to what extent would new perspectives on this technology have to be developed to address the perspectives and issues designers deal with? How can we understand, and work with, computational technology in relation to other materials?

In what follows, we present an analysis of computers as material in design. To illustrate that this is not just a matter of metaphors, we discuss some central characteristics of materials and show how they also apply to computational technology. Further, to address issues related to misconceptions about computations being almost 'immaterial' and thus not really a material we can work with, we introduce the notion of computational composites as a way of understanding how computation comes to expression through an integration with other materials.

BACKGROUND

As discussed by Grudin (1993) already some 20 years ago, the use of computers in general, and the notion of the human-computer interface in particular, is constantly evolving 'outwards'. Certainly, an example of such outward motion, the notion of Ubiquitous Computing now implies computers as part of, and embedded in, most kinds of everyday things and environments. The design of applications and interfaces has evolved towards a closer relation to other design areas also in terms of physical design. Approaches to interface design such as 'Tangible User Interfaces' can be said to point to an increasing interest in the combination of traditional design materials—and in physical objects as such—and computational technology. This stresses aspects such as the relation between information and its concrete presence to the user (cf., Wisneski *et al.*, 1998). The development towards a closer relation between interface design and industrial product design, is quite visible in this area, with the approach developed by Djajadiningrat *et. al* (2004) as one illustration.

Outside the realm of human-computer interaction and interaction design, related developments are taking place. The use of computers in design is expanding beyond the use of computer-based tools to support design work, to become part of the designed things themselves. Textile designers explore the use of dynamic patterns made possible through 'smart textiles' instead of the static ones that traditional printing techniques afford. Architects show an increasing interest in the interactive properties of new technologies, and perhaps especially in the possibilities to program dynamic structures—be it lighting, sound, climate control, or surface expressions. Or just consider how communication and graphics design merge with architecture through the use of wall-sized displays on urban buildings running commercials or dynamic billboard ads.

As interactive technologies find their way into new areas of use, new intersections between areas of expertise are being opened. Inspiring new forms of collaboration, such new intersections often challenge the traditions and methodological approaches for everyone involved. A task for the research community is therefore to develop theoretical and methodological frameworks that can function as common language and grounds. It is our hope that HCI/interaction design and computer science will take an active role in developing these new intersections, and that the notion of *computational composites* could be a contribution to establishing such a common ground.

Computers and Materials

In examples such as the ones above, the boundaries between what we could refer to as human-computer interaction and other areas of design dealing with interactive technologies and 'smart materials' to some extent begin to dissolve. Correspondingly, the notion of a computer—be it a ubiquitous one—is not very illuminating, and instead we begin to use notions such as *interactive products* (Preece *et al.*, 2002), *digital artifacts* (Löwgren & Stolterman, 2004), *computational things* (Hallnäs & Redström, 2006), etc.

We propose that, as computational technology is no longer just a tool, it could instead be seen as a material—a material much like any other material we use to design things. One of the first proponents of a similar perspective was Seymour Papert: "In this project, the students built devices for measuring time using any materials they wished. Some used string and a metal weight to make a pendulum, some used plastic containers to dribble sand—and some used computers. Our central focus is this use of the computer as just another type of material." (Papert, 1988, p. 1) "Just as pendulums, paints, clay, and so forth, can be "messed around with," so can computers. Many people associate computers with a rigid style of work, but this need not be the case." (Ibid., p. 2)

In another account of information technology as a material in interaction design, Löwgren and Stolterman (2004) suggest that it is a material without properties. As a material without properties hardly qualifies as a material, what they hint at is that information technology seems to exist in-between the material and the immaterial with properties so flexible it almost can take on any form we want. Such a perspective, however, makes it difficult to understand how this material relates to other materials we use in design, as it almost seems to exist in isolation on its own premises.

In the work of Hallnäs and Redström (2006), computational things are characterized by, on one hand, the temporal form that stems from computational processes and on the other hand the spatial form given to these processes by other materials with strong spatial form elements. A central example is the combination of computations and textiles, in which the dynamic properties of textiles are used to manifest temporal structures generated by computational processes (cf., Redström *et al.*, 2005). Here the computations come to expression through the textile and together they form a new type of material. One suggestion, then, is that while computational technology is material (as distinct from being immaterial), it cannot really exist on its own in free form. To resolve its seemingly strange existence in-between the material and the immaterial, and its dependence on other materials for its presence, we propose thinking of it as a type of composite: that computational technology is a material, which we have to combine with other materials in order for it to become a material we can use in design practice.

Before we go any further into what exactly a computational composite is, we examine what composites generally are made of—the materials.

WHAT IS A MATERIAL?

The general concept of *material* is an ill-defined one even within material science. Generally, we can consider a material as a physical substance that shows specific properties for its kind. It can be understood as a substance with no specific form, which can be shaped and proportioned in volumes according to needs. Materials can be divided into various kinds of groups, which exhibit similar reactions or properties. Examples of such groups are metallic and non-metallic, natural or artificial, brittle or ductile, translucent or opaque, and smart or ordinary. However, the meaningfulness of a grouping depends entirely on the point of view.

The Sliding Scale of Materials

There are a vast number of viewpoints from which one can contemplate materials and none of them is discrete. The scale of physical dimensions alone range from nanometers 10^{-9}m to kilometers, from molecules to steel wires (Gordon, 2006). Just as the state in which the material exists can vary from vapor to fluid to solid depending on the environment in which it is present.

Furthermore, the point of view changes with the purpose of engaging with the material, which often is correlated with the disciplinary background. Chemistry, physics, and engineering (even biology and geology in some cases) investigate and create materials *per se*, whereas for instance engineers, architects, industrial designers, and craftsmen of various kinds typically work with different applications of materials. However, the distinction between the disciplines is blurred and they often need to overlap for new materials to reach a market or for a market to demand new materials (Ibid.). Thus, working with materials is inherently an interdisciplinary affair. Designers need to have an understanding of a material to make use of it and material scientists need to manage several levels of abstraction to study material properties in depth and to develop new useful ones. The following description of *material* will therefore employ different perspectives from different disciplines at different entries on the physical scale, to address aspects relevant to an account of computational composites.

Structure and Material

There is no clear distinction between what we would consider a structure and what we would consider a material. To some extent, it is a matter of how the material is approached. At a molecular scale, every material is a structure as the molecules form different kinds of patterns, such as: grids, rings, and double helixes, structures that are held together by various forms of energy. These structures are significant for the properties the material exhibit. Thus, on one level of abstraction every material can be seen as a structure.

Even at other levels of granularity can we find structural behavior in what we normally would be reluctant to call a material. Wood, for example, comprises a complex cellular structure, which resembles a collection of tiny drinking straws held together by chemical bonds. Wood grows by applying a new layer of 'drinking straws' right under the bark every year as long as it is growing (Ibid.). Another example is a pile of brick which is clearly a structure, but cement, masonry and cast iron are considered materials even if they also are stronger in compression than they are in tension for the same reason: they are all full of cracks (Ibid.). Thus, whether something is a material or a structure largely depends on the eye of the beholder.

Material Surface

Every material has a surface: an interface to the surroundings. It is typically the surface we encounter when we experience a material—its texture and color. The surface, however, can also play a significant role regarding the strength of material. Glass, for instance, is a material that in theory ought to be much stronger because of the strength of its chemical bonds, but our everyday experience shows a different result (Ibid.). This is because of an inherent tendency in glass to cause tiny cracks in the surface. Cracks, which in turn causes a redistribution of tension resulting in a more fragile material than can be determined from the strength of its chemical bonds. Fiberglass, on the hand, can be made tremendously strong because it is easier to keep their surface smooth (Ibid.).

A surface of a material is largely dependent on the state it is in, whether a liquid or a solid substance. However, a surface is rarely in a completely stable state. Environmental conditions such as water, air, and sunlight, can cause oxidation leading to corrosion in metals or dissolution leading to corrosion of ceramics. Chemical reactions can cause the materials to change their properties, for instance their mechanical strength, their color, or their texture. Sometime this change is desired for aesthetic value, or even because the chemical reactions function as glue between two materials, but more often the surface needs to be treated to prevent alterations and thereby enable predictability.

Material Properties

As stated in the beginning of the section, we can generally view a material as a physical substance, which shows specific properties for its kind and which can be manipulated into something specific. A key word here is *property*. Besides availability and expense, properties are what make us choose one material over another.

Every material has a set of properties, which again varies based on the point of view. For a chemist, these are normally defined at a molecular level as to reflect potential chemical reactions. For an architect, on the other hand, such properties could include strength, optical properties, electrical properties, thermal properties and insulation, acoustic properties, deformations, deterioration, and appearance (Everett, 1994). Thus, defining the properties of a given material is not just a matter of properly describing the given material, but about doing so with respect to a certain interest or perspective.

This relation between perspective and material properties is one reason why descriptions and frameworks developed in, say computing science, does not automatically transfer into interaction design, or from engineering into architecture. Even if such frameworks are closely related and to some extent overlap, they still need to take offset in their focal point of interests to reflect the concerns at hand.

Composite Materials

Combining two or more materials in composites is a way either to enhance a specific property or to introduce new combinations of properties in a material. This is often done with respect to strength, stiffness or toughness, but can also be done with respect to appearance, optical properties etc. (Brownell, 2006). A composite designed to improve material strength is usually made from a matrix and a fiber, where the three most common matrix types are polymer, metal and ceramic and fibers are usually made from ceramic such as glass or carbon, but can also be others kinds (Hull & Clyne, 1996).

The properties of the individual constituents can give a clue about the properties of the composite. It is, however, complicated to predict the actual properties of a composite, as its structure, e.g., the direction and shape of the fibers, and the interface between the constituents, will affect the result (Ibid.). For instance, is anisotropy common for composite materials, meaning that they show differences in strength when measured in different directions—like an egg. As for the interface between the constituents, various chemical reactions can happen, which may affect the general properties. The exact constituents, the structure and the fabrication process to create a composite material are therefore often chosen with a specific application in mind (Ibid.).

One example of a composite material—or more correctly an alloy—is aluminum. Aluminum is refined from the naturally occurring bauxite to a state called pig-aluminum (Doordan, 1993). Although aluminum at this state has properties such as corrosion resistance and its lightweight, it is a weak and seemingly useless material. Only through alloys with other metals does it receive the strength and flexible form it is commonly known for (Ibid.).

Material and Product

The distinction between a product and a material is also blurred: what can be a product to the material engineer might be a material to the designer. This is especially true when it comes to the highly engineered composite materials that enter today's market, such as glazing with integral sun control louvers or self-cleaning clay tiles (Brownell, 2006). Generally, however, for something to be considered a material, at some state at least, it must make sense to talk about shaping a chosen volume of it into something new—to create a new intent with it. To make a roof with the self-cleaning tile or to create a glass facade with the special glazing that allow for a seamless light control system. Therefore, even if the distinction between products and materials also is a question of viewpoint, not all products are materials.

This short introduction serves as the background on which we now wish to introduce the idea of computers as material in design.

COMPUTERS AS MATERIAL

Perceiving computers as a material is, as we said, more than a metaphorical maneuver. It is a question of accepting their similar characteristics as significant enough to hereafter work with the computer in the same manner we work with materials like aluminum or glass. This section will point to parallels between computers and other materials regarding their substance, their structure, their surface, and their complex states of being.

The Substance of Computers

The common reference to computational technology as 'information' technology holds connotations of it being something that deals with representations, signs, and meanings. This understanding has led to the perception that computers are more than electrified machines. On the level of abstraction on which we wish to encounter the computer, it does not deal with representations. Computational technology at this granularity handles only voltage according to stored sequences of (practically) discrete voltage levels and maybe input streams likewise of (practically) discrete voltage levels. They are, however, often called algorithms and data respectively. Every program has a physical manifestation when it enters the computer, even if the input device has representational keys that the programmer push to enter the program into the computer, a translation of the push of each key into voltage happens before it enters the computer.

Other labels commonly used when talking about computational technology are *software* and *hardware*, where software refers to programs that the computer executes, and hardware refers to the computer *per se*. This distinction tends to cause some confusion as software holds the meaning of both the abstract representation of a program, whether in binaries or in a higher level programming language, and the program in its physical manifestation, whether stored or in execution. The point of this is that both software and hardware are physical and can be manipulated as such, and that computers therefore can be seen as a substance albeit a rather complex one.

Furthermore, when working with substances it is meaningful to talk about dimensions; to have more of a computer means to have more processing power. That it is capable of treating more instructions per clock cycle than a less capable computer. A computer, however, is a device in the sense that it cannot physically be cut in half and still exist as a computer. Thus, where a traditional material's threshold for being diminished lies at the point where the molecular structure would no longer exist as a structure or where the fibers (e.g. in wood and textile) are no longer fibers, the threshold for the computer is where its structure needs to be intact. The computer's threshold, therefore, lies at a much higher point on the physical scale.

The Structure of Computers

Underneath the view of a computer as a substance, we find, as was the case with other materials, a complicated structure containing several different elements all, which plays a significant role in the computational process. At one level of the physical scale these can be listed as a central processing unit (CPU), memory, buses and input and output devices (I/O devices). At a lower level, we would include the arithmetic logic unit (ALU), the registers, the central circuit, the clock etc. and at even finer granularity, the individual digital circuits would be revealed. As with other materials the structure of the components is important for the overall properties of the computer. Another resemblance here is the role of energy in the structure. The state of computers can be found by examining the levels of voltage in the circuits and in a sense computers would not be computers if it were not for the voltage to constitute the processes. This is analogous to how energy in other materials holds the molecules together as a structure and thereby constitutes them as materials. With this comparison, we leave the structural view of the computer and instead we focus on the computer as a material.

The Surface of Computers

A computer's surface is the interface to the streams of discrete voltage levels, which exist within the input and output devices. The input device allows an exterior to provide new sequences of voltage levels, which can take the form of either data or algorithms, just as an output device delivers sequences of discrete voltage levels that can be interpreted as the result of computations. However, as the surface lies within the devices and not on either side we need to examine the devices more carefully.

Let us take the keyboard as a common example of an input device. The interface to the computer lies not in the keys *per se*, but in the discrete voltage levels resulting from an interpretation of the push of a specific key. Often, a keyboard is designed to enable a variety of different languages by enabling different encodings of every key. This is done within the computer, and the change is usually not visible on the keyboard itself. The interpretation of a key does not change, however, if the key changes color, form, or texture. Thus, we can find the surface of the computer exactly where we start to deal with discrete voltage levels. The same is true for the output device. Therefore, it becomes apparent that the surface of the computer needs to be coupled with other materials for us to better control what will happen with the computations. To directly insert meaningful sequences of discrete voltage levels is practically impossible for humans to accomplish.

If the input and output streams constitute the surface of the material then the input stream can be seen as the rear side and the output as the front. Even if they seem equal, they serve completely different purposes; where the output stream is the expressive side of the material, the input stream is the possibility of moderating the expression. An alternative would be to understand the computer as a self-contained system without an input or output as known from theory of computable functions of the original Turing machine (Milner, 1993; Goldin *et al.*, 2004). However, such view leaves out the possibility of interaction and thus the ability to change the result of ongoing computational processes. In other words, this would make it less relevant as a material for design and thus for this endeavor.

The Properties of Computers

At one level of abstraction, the property of a computer can be seen as the computations (at a lower level it is a matter of strict causal processes treating sequences of discrete voltage levels which then can be interpreted as computations). A property that is completely different from that of other materials, but a property no less. The computations allow for conditioned changes of whatever the output devices are combined with—pixels on a screen, shape of a wall, or patterns on a floor. However, in its raw form it holds only this abstract ability to compute, there are no mechanical properties of strength or stiffness to back it up, nor any acoustic, aesthetic, or optical properties to speak of.

The strict causal process which constitutes the computations happens in a circuit board; however small and however shaped. The properties of a computer can therefore be compared with those of aluminum in its raw form, both holds potential for interesting and useful properties and both needs to undergo a treatment for the potential to be fulfilled. The computer needs to be combined to other materials for the computations to have an impact; thus we arrive at the notion of *computational composites*.

COMPUTATIONAL COMPOSITES

In the last section, we argued that a computer is a material, but also that its computational property, in its raw form, is difficult (if not impossible) to exploit. The conclusion was that the computer needed to be part of a composite with other materials to become useful in design. In this section, we will explore how the computations can come to use through different types of composites.

Composites are made to enhance specific properties or to introduce new properties by combining certain materials in certain ways. With computational composites, it is primarily a question of introducing new combinations of properties; namely, to introduce the ability of digital computations together with tensile properties, optical properties, electrical properties, thermal properties and insulation, acoustic properties, deformations, deterioration, appearance and so forth.

The Property of Computational Composites

Computations in this situation mean that events can happen conditioned by a set of data and an algorithm. Thus, it enables the other parts of the composite to behave beyond their otherwise normal behavior. Expressed more precisely, a computational composite can exist in a number of *states* (e.g. colors, shapes, or positions). Whenever a set of conditions is met, a *transition* towards a new state is begun. The conditions and their fulfillment are *controlled* or *computed* in one of three ways:

1. With both algorithm(s) and data set predetermined.
2. With only the algorithm(s) predetermined, and the data set collected dynamically.
3. With a predetermined offset of conditions that changes dynamically, for instance based on a dynamically collected set of data.

An algorithm or a data set can also express approximated randomness and thus create a seemingly chaotic behavior in the composite when that is desired.

The computations enable not just flexibility and change in the material expression, but they enable controlled transitions between states in the composite material. The *control*, the *transitions* and the *states* are the key aspects to take into considerations when composing a computational composite. The type of design choices to be made on all three accounts entails that it often will be necessary to compose computational composites with a specific purpose in mind, just as is true for other material composites. The control itself, for instance, must be a meticulously designed as a series of controlled transitions between states inside the computer of which only few become output and thus result in transitions between states in the composite material.

The Structure of Computational Composites

To honor the possibilities of computations, the composite need to be able to make the transitions as well as to stay in the chosen states. Thus, not only must the controls be carefully designed, but the rest of the composite must also match the controls. To assist the analysis of the structure of computational composites we now introduce two metaphors for the surface of the material: the *front* and the *rear*.

The *front* of the computational composite needs to be designed such that a computed result (the output) translates to a transition towards a new state in the composite. In dual or multiple state materials, such as shape memory alloys, nickel chromium wires, or liquid crystal displays, this can be done simply by letting the computations control the flow of electrical current, i.e. making electrical current function as 'glue' between the elements. Materials with only one state of being, such as steel or concrete, need more than electrical current to honor the possibilities of the computations. Single state materials can exploit the computations only by being in a structure with an additional actuator (e.g. a motor, or heat sensitive color) that can utilize the electrical current. All these translations combined can be seen as the 'glue' between the different materials in the composite.

The *rear* side of the composite is the access to the input stream as described above. The input stream consists of what we refer to as algorithms and data and constitutes the control of the composite. As such, it plays a central role in the composite material and the possible product to be made of it. The rear side can be designed such that it is constantly accessible throughout the life of the material (or product), or the algorithms can either be formed or frozen during the design of the material or during the design of the product. The same holds for the data set.

Dynamic input can happen through sensors or through connections with other computers. A sensor usually detects input by measuring: change of light, change of scenery, change of temperature, or change of pressure. The measurements then need to be translated into discrete voltage levels to enter the computer. This translation can happen in various ways: if it is a matter of a two state input, the translation is straightforward; otherwise, methods, such as a register over sequences of discrete voltage levels with the direct input from the sensor as a key to look it up, can be utilized. Generally, as computers can be integrated in networks so can computational composites and thereby form large structures of the same material.

This leads to another aspect of the composite composition, as the computer, including the input and output streams, can exist in the composite in various degrees of *integration*. The degree of integration depends largely on the purpose of the composite; if the complication of computations entails a computer of a certain size, seamless integration can be impossible; or if dynamic input is needed, the input stream could require a device that resembled a tool more than a rear side of a material. More explicitly, the degree of integration depends on: the type of input needed, the size of the computer, the access to power supply or battery lifetime, whether it is a standalone computer or it is in a network, either in a server/client architecture or a distributed one; but it also depends on the other type of materials used, and the states which they need to assume. However, as long as the computations are utilized to control transitions between states in the composite material, it is a computational composite.

EXAMPLES OF COMPUTATIONAL COMPOSITES

In this section, we will explore examples of computational composites to render the concept more tangible. The first examples are different types of displays. Together they hint at the vast potential of embedding computations for both practical and aesthetic purposes. The last examples introduce flexible form as another mode of computational expression. Flexible form can for instance be used to alter the size of a given space by adjusting to specific purposes within that space.

Besides being examples of new kinds of materials, they are also illustrations of successful interdisciplinary collaboration between research, design, craft, and art. As such, they illustrate what working with computational composites might be like also in terms of the interdisciplinary approach needed to develop them.

Computational Textiles

The e-broidery project (Post *et al.*, 2000) propose several examples of computational textiles in which they use materials for the computer's electrical circuits that correspond to the flexibility, durability, washability, and conformity of textiles. Thus, the computer is literally woven into the fabric. Metallic silk organza, for instance, can be used to create a conductive layer in which each thread can function as an individual ribbon cable because of the woven structure of the fabric (Ibid.). The organza, working as a conductive layer, can be attached to other fabrics to insulate it from the surroundings and from folding. Another example of such a material is the conductive yarns made of stainless steel, which can replace any traditional wiring to and from the microprocessor (Ibid.).

In a later and more developed design called the Electronic Plaid™ made by International Fashion Machines (see Figure 33), a computational textile enables controlled change of color using the same principal of woven electronic circuits combined with color change inks and drive electronics (Orth, 2002). Presumably, a computer controls the electrical current in the circuits, which in turn initiate a color change (state change) under the right conditions. Thus, the electrical current is the 'glue' of the composite and the color changing ink is the actuator. The plaids are programmed in modules of eight pixels made of four to eight different electronic yarns that create the pattern (Ibid.).

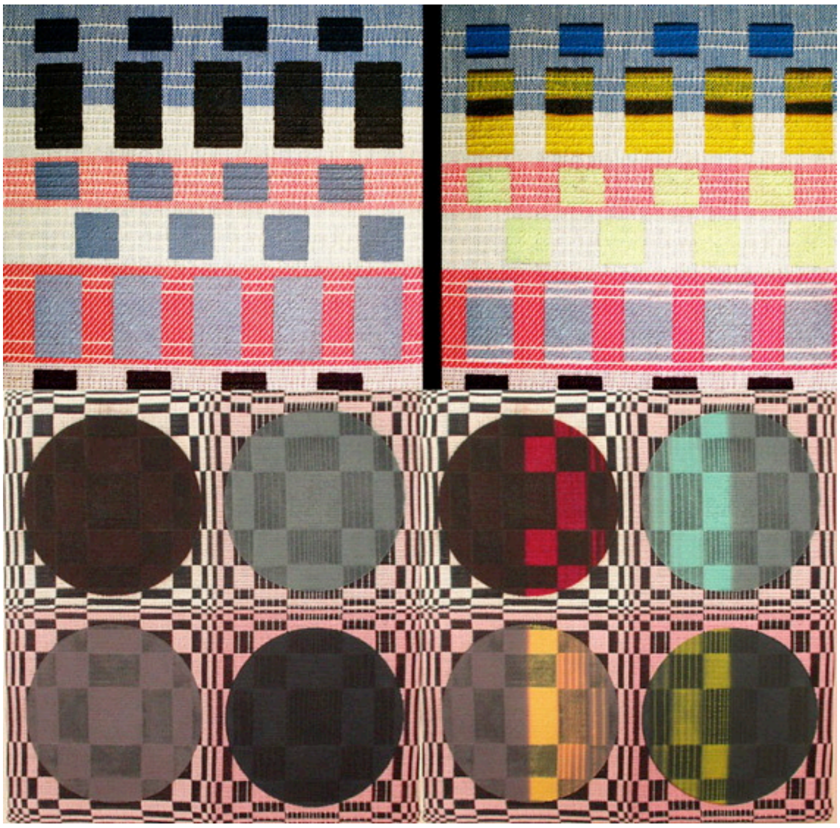

Figure 33 Two examples of computational textile, courtesy of IFM

This material is plastic, flexible, soft, and decorative, but it is sensitive to environmental conditions such as sunlight and water, and shows little mechanical strength. Thus, it is primarily suited for indoor wall displays or decorations and maybe even furniture (Ibid.). The variety of dynamic expressions the material can display is limited to the four to eight different yarns per pixel, which can change between just a few colors. The material as available from International Fashion Machine is pre-programmed meaning that both algorithm and data input are determined before use. However, the design of the interaction with the textile needed not be determined beforehand it seems feasible to integrate automatic dynamic data collection for example various types of environmental sensors. This open-ended approach leaves for instance room for an interaction designer to decide how the textile is to be used.

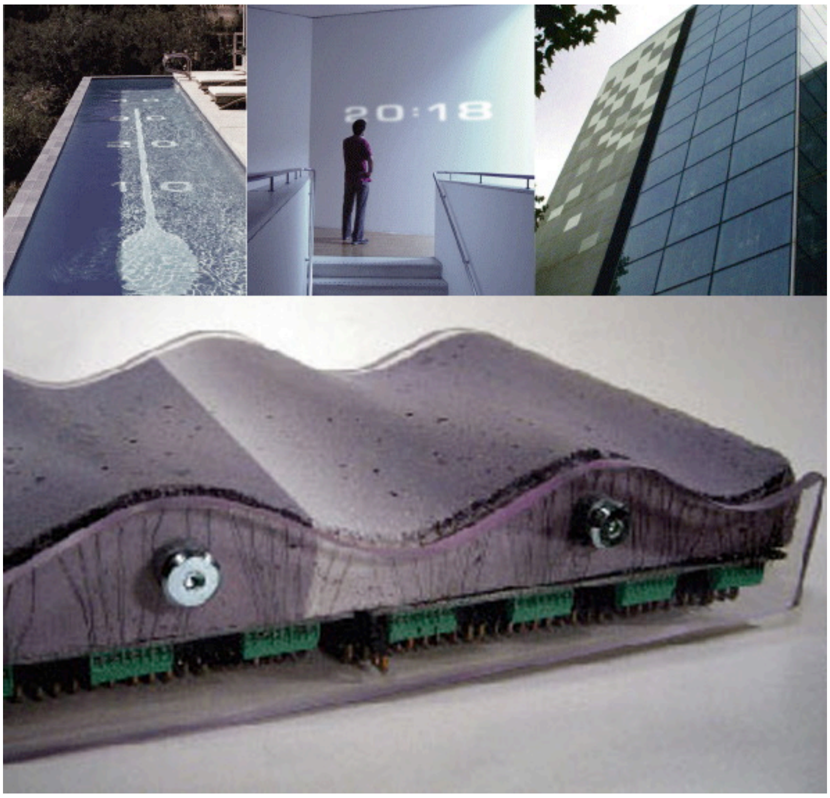

Figure 34 Example of computational concrete, courtesy of Glaister, Mehin, and Rosen

Computational Concrete

Another example that relies on a similar type of composite structure is the Chronos Chromos Concrete (see Figure 34). This computational concrete is a composite material that holds the properties of ordinary concrete and still is able to dynamically display text or other patterns through color change (Glaister *et al.*, 2004). The material behind the color change is thermodynamic ink, which is blended into the concrete. Beneath the concrete surface are mounted nickel chromium wires that heat up when electric current is passed through them. Then, when a certain temperature is reached in the concrete, it causes its color to change (state change); a process that takes at the minimum of five seconds (Glynn, 2006). As was the case with computational textile, the electrical current plays the role of 'glue.' The material is mechanically robust and thus suited for large-scale architectural installations. Its display dynamics is, however, restricted within the five seconds, and the patterns seem to lack sharpness up close. Even so, the developing potential seems extraordinary and the prototypes to date developed show concrete examples of a computational composite.

Computational Tensegrity

There are several projects where the walls or the whole building structure can move or change shape and thus either expand or diminish spaces on either side. Such ideas existed even before the digital computer was invented. Cedric Price's vision of the Fun Palace or Rogers and Piano's plans for the Centre Pompidou all build on ways of utilizing machines to create dynamic spaces. In less spectacular projects, but not less novel, several experimental architects today explore the possibilities in computations to enable dynamic spaces. Here, we take a closer look at two examples of how this can be achieved.

oframBFRA (The Office For Robotic Architectural Media and The Bureau For Responsive Architecture) has created a full-scale prototype of a tensegrity structure, which can be used as a responsive wall (see Figure 35) (Sterk, 2003). A tensegrity is a skeleton structure that consists of members in continuous tension and members in discontinuous compression. They are interconnected in a way that allows each member to contribute to a self-stressing structure. In the oframBFRA variation the tensegrity is a repeated module that consists of three compression members that meet in a tripod formation that is held together by tension cables (Ibid.). This forms a structure that can be subjected to alteration in tensions within each module causing the local rigidity to change and thus induce the entire structure to change shape (Ibid.). Thus, by introducing an actuator controlled by computations on the apex of each module the tensegrity can perform controlled transformations between a wide number of states (Ibid.). This is an example of a composite material where the complexity of the structure within the material resembles that of wood, but as it is presented by oframBFRA, to a much larger physical scale. The tensegrity can be covered by membranes, which enables it to form shelter and separate spaces. The dimension and control of the tensegrity are not a given; it can be scaled to suit different needs, and the controls can equally be designed for those purposes. oframBFRA suggests that the controls should rely on predetermined algorithms and let the data for the algorithms be dynamically collected through sensors that detect changes in the immediate environment.

Figure 35 A prototype of an actuated tensegrity structure, courtesy of oframBFRA

Moving Structure

In Moving Structure (Hladík, 2006), the architect Pavel Hladík exploits combinations of Teflon foils and the two states available in shape memory alloys (SMA) NiTiCu (See Figure 36). A SMA change shape according to temperature with a straight shape in its cold form to a bended shape (up to 5 %) when it is heated. The shape for the hot state is created during construction and remembered when the SMA is later reheated. The SMA's transition state lies at around 30°C but can be protected from the environment through a heat protection layer and thus become more controllable (Ibid.). In Moving Structure, Hladík forms structures of spiral formed SMAs, Teflon foil, and lightweight heat emitting conductive fibers that coupled to a computer become a computational composite. The Moving Structure forms a material suitable for walls in many different situations (Ibid.). As with the tensegrity structure, the algorithms and data sets are not necessarily predetermined and can therefore be designed to the chosen purpose of the material.

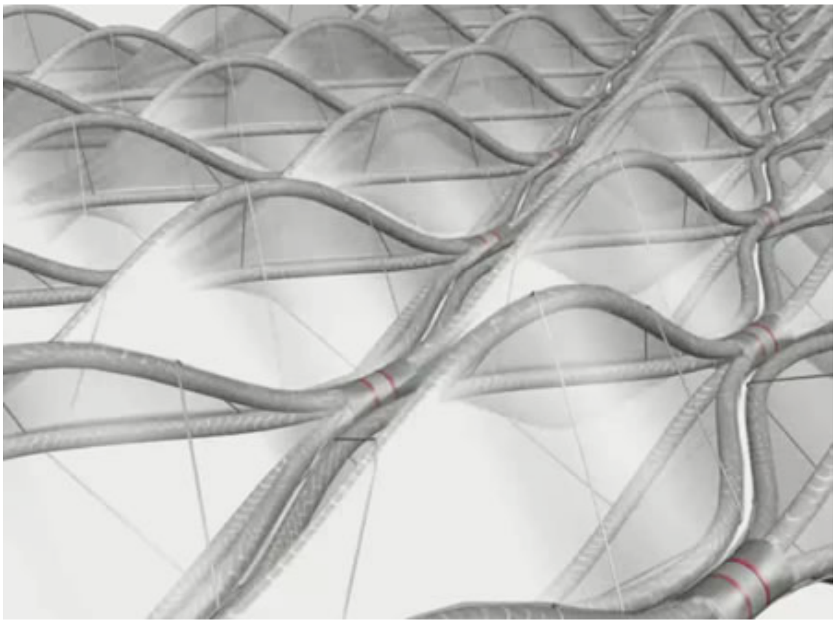

Figure 36 The SMA work as an actuator changing the shape of the entire material, courtesy of Pavel Hladik.

Further Examples

These were just a few illustrations of what computational composites might be like, and many more are available. The area of computationally enhanced textiles is, for instance, rapidly growing (cf. (Redström *et al.*, 2005; Braddock-Clarke & O'Mahony, 2006) just as there are a wide variety of displays which utilize different materials to express the result of computations. One such example is the Pixel Skin 02, designed by Orangevoid, which also utilizes the two-state material SMA to achieve changes in a surface (Anshuman, 2006). Another example is the Wooden Mirror by Daniel Rozin. It utilizes wood, which does not have an inherent actuator to ensure transitions between states, but by cutting it into pieces and appending a motor as actuator he achieves a similar effect as the Pixel Skin 02 (Rozin, 1999). The HypoSurface (Goulthorpe *et al.*, 1998) integrates the display with a shape changing surface and in that endeavor rely on an even more complicated set of actuators which push it towards the boundary of being a material, however, it still poses material like properties. Lucy Bullivant's "Responsive Environments" (2006) holds examples of even more moving, interacting and responsive materials and products.

The list seems endless, but most of these examples are still at a stage of research and need more refinement to become robust and reliable materials. Many of them have been designed as one-off installations or art pieces and not really as material to be produced in larger quantities. There exists, however, a few deployed examples such as the Diaphragm of L'Institut du Monde Arabe in Paris by Jean Nouvel, where he use irises to let different amounts of light through the windows based on light-sensor input.

DISCUSSION

Based on the observation that knowledge of materials is essential for design practice we raised a series of questions in the introduction: In what ways can we consider computational technology as material? To what extent would such an understanding be based on computer science, and to what extent would new perspectives on this technology have to be developed to address the perspectives and issues designers deal with? How can we understand, and work with, computational technology in relation to other materials? Based on the analysis presented, we now conclude the paper with a discussion of these questions. We will also relate them to existing design practices and technological research traditions, to point to future work in this interdisciplinary field.

The analysis of computational composites as presented in sections 'Computers as Material' and 'Computational Composites' provides our suggestions as to how computers can be considered a material: that computers can be understood as materials in the traditional sense and that computer's properties only become available when existing in a composite with at least one other material. We also argued, that in order for design practice to come to grips with computational technology, we need to develop our frameworks beyond the one we now find in computer science, as it is necessary to deploy a new perspective on the technology. Given the development processes toward using other materials in design, the need for such reappropriation is not unexpected—in fact, it is what happens most of the time in the interdisciplinary context of material development.

Language and Framework

When studying development and use of more traditional materials such as wood, steel, or aluminum it becomes clear that different types of access to a material are necessary because a chemist's approach to any given material is different than that of an architect. A difference caused by the need of minimizing the level of complexity. The matters focal to the chemist, such as the molecular structure and responsiveness with other chemicals, are circumferential to the architect, just as aesthetics and maintenance are to the chemist. If they were both to focus on every matter concerning the material, it would be hard to talk of a focus. The consequence of this is that every level of interest concerning the material needs to have a framework of concepts at their disposal. These frameworks need not be discrete and isolated from one another, but they must contain concepts that support the different perspectives. We find the same division of perspectives necessary for computer technology to propagate beyond computer science and into design or architecture. Therefore, it is necessary to try to conceptualize different perspectives of computational technology and thus complement existing computer science frameworks. HCI and interaction design have the potential to play an important role in this development.

Design of Materials

Our notion of computational composites is a framework that could allow for design practices in industrial design and architecture to work with the material on a different level of abstraction; an abstraction that we believe still accommodates the complexity needed for designers to propose feasible designs containing computer technology. The abstraction does not, however, remove all complexity of the material and the question remains: How can a designer use a material that is so complex it needs to be designed first? As the examples of computational composites illustrate, there seems to be a continuum of development and use ranging from the design of a new 'raw' composite material to be used in ways yet to be determined, to the development of a certain application, product, or environment. Again, this situation is not unlike what we find in other areas of design. Textiles may serve as an example. At one end of the scale, textile engineers research and develop fibers, materials and production techniques. Based on this, textile designers create textiles for designers to utilize for clothes, furniture, or art. The development of textile artifacts happens in layers that, though certainly intimately connected, do deal with different sets of issues. Even within design and development of traditional computers we find a division of labor and interests. In the case of computational composites, however, the matter to be designed and developed is different from a traditional computer; it demands more of a material science perspective on the result than a traditional computer science perspective. Furthermore, interaction designers, architects and artists are bound to play a much larger role developing the material on its way to become a product.

Developing computational composites is not a matter of simple distinctions between technology and its application it is about rather intricate and highly developed layers in-between. With respect to interaction design, this opens some interesting perspectives. For instance, there could be a choice between working with the development of new materials (as in how the textile designer creates new fabrics we all can buy and make new curtains from), and working with finalized products based on such materials (as in how the fashion designer makes garments we wear). We might even say that traces of such layers exist in previous developments of human-computer interaction, with the notion of end-user programming, or in the interest in DIY kits for ubiquitous computing applications. We even find traces of similar layers in more ordinary computer use. Users of desktop computers differ significantly when it comes to how 'deep' their customizations of the machine is: from just filling it with personal content such as documents and images, to extensive personal modifications of both software and hardware.

A Non-Functionality Perspective

Working with computational materials in the ways discussed in this paper, could also be a complement to existing approaches to interaction design. It does not depend on specific notions of functionality in the same ways as the development of 'applications' does (Redström, 2005). Instead, it centers on notions such as material properties, which represent a rather different starting point for explorations of new possibilities—especially so when it comes to the increasing collaboration between designers of different domains on how computing can be utilized.

Thus, with the notion of computational composites we are not only seeking to provide a material view on computation that various designers could benefit from—we also propose a material science perspective on computer science that could open up for new forms of collaboration between computer science and architecture, human-computer interaction and design.

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PLANKS: A Computational Composite

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ABSTRACT

What is a computer in interactive architecture and smart materials? How can we articulate the computer in order to be in sync with the design space it populates in these contexts? The design experiment presented here entails creating a physical manifestation of a computational composite—a concept used to articulate the computer as a material for design. The experiment is meant to explore part of the expressional landscape available through this material composite perspective. In the experiment, it is especially the computers ability to redefine established cause-and-effects between materials and their environments just as it is the computers ability to create a discrete dependence on contextual factors installing an explicit element of temporal form, which are explored.

Keywords

Computational Composites, Design, Experiment, Expressions, Materials, Wood

PROBLEM STATEMENT

"Technical knowledge and language are the well from which design and invention draw stimuli for planning. And they are also the basis of the organization of means that constitute the practice of design" as Manzini write in his Material of Invention (Manzini, 1989, p. 47). While technical knowledge and language of the computer are necessary to be able to incorporate computers in any design practice, the computer can be articulated in many ways and it can even be many things all dependent on the point of view.

Computers in a design context are often portrayed as *elusive* and *abstract* elements, which also can provide a multitude of functionality (cf., Weiser, 1991; Löwgren & Stolterman, 2004; Norman, 1999; Streitz

& Nixon, 2005). However, this dissociation of the computer as an always and ever *physical* element, which builds on a simple set of principles that are just multiplied into complexity, is problematic and unnecessary. It is problematic because it creates a promise of accessibility to symbolic logic without constraints as well as an unrestrained form-language neither of which exists. It is unnecessary because it is possible to develop a set of concepts to describe and explain the basic properties of the computer as a material for design and through that address new expressions of computational technology. For a successful design practice with computers the discrepancy between *what is* and *what we say is* cannot become too wide. The articulated design space must somehow be coherent with the actual one.

Articulating and understanding a technology in different ways is about emphasizing and playing down different aspects of what it is. It is necessary not to get lost in technical specification when they are not immediately relevant, and not to be tangled into an application domain when developing technical details. There is a division of labor and consequential a division of language and knowledge within every genre of technology. Take textiles: specialized engineers research and develop fibers, materials, and production techniques, which textile designers utilize in their work designing new textiles. Fashion or industrial designers in turn use these textiles to create clothes, furniture, or art. Through this process of textile design and use the goals and methods are not the same, and therefore the knowledge and the language are not the same either. The textile engineer works on a highly theoretical basis, yet she never escapes the physical and tangible aspects of her work field. The clothes designer primarily works with the sensory experience of the fabric and needs to know little about the material fibers and production, however, she cannot be completely ignorant if what she makes should last or be practical. Furthermore, the articulation of a textile is never just a technical specification; it is always accompanied by either the textile itself or by an experience with similar textiles. Therefore, knowledge and language of textiles or any other design material cannot be expressed through words alone. Doing that risk causing misunderstandings or even worse, lead to an abstract rendering whereto no one can relate. Articulating the computer as a material for design is not done by developing a conceptual framework—we need *physical samples*.

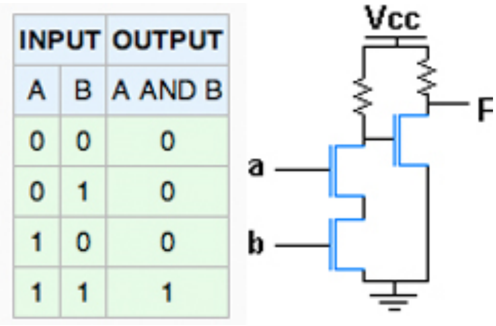
This paper explains the concept of computational composites—a concept articulating the computer as a material for design. Following this is an outline of an experiment in which we build a physical manifestation of a computational composite that explores new expressions of computational technology. Summing up is an analysis of what the experiment could lend us particularly in relation to a design practice involving computers in architecture and design.

ARTICULATING COMPUTERS

Articulating the computer as a material for design is about describing it through the characteristics of other design materials not as a metaphorical exercise, but as a perspective to help guiding what needs to be emphasized and what is less important. The computer in this context is not a machine for symbolic logic nor is it information technology ready to use—it is somewhere in-between and yet far of. It is the computer's physical being, which constitutes the foundation for understanding the computer as a material for design.

While the computer is physical through and through it is not enough to see it as a substance to understand its potential; thus, some basic theoretical knowledge about its structure is needed to be able to utilize it for design.

A computer's main substance is electricity. It is made useful through managing two extremes of electrical potential measured between two points of a circuit, one as close to zero as possible and one above a certain threshold. A build-in clock controls the timing of each measurement. The computer can operate with sequences of high and low voltage through the use of registers. The structure of the circuits enables basic logic operations such as AND, OR, NAND, NOR (Figure 37). Combining these operations and the storage capabilities allow highly complex computations. Therefore, the computer can perform complex conditioned actions based on fairly simple principles.



INPUT		OUTPUT
A	B	A AND B
0	0	0
0	1	0
1	0	0
1	1	1

Figure 37 Example of a circuit structuring the logic AND operation--only if both a and b are high (represented by 1) will the circuit measure a high voltage level (courtesy of Wikipedia)

This structure results in a surface of the computer, which consists of an acceptance, and a transmittance of these high and low voltage measures. Traditionally, materials are perceived to have a clear and recognizable surface. However, the border between the material and the environment is in fact less demarcated (Addington & Schodek, 2005). The exchange of chemical components (e.g., oxygen causing corrosion) or the change of conditions in the immediate environment (e.g., a rising temperature causing change of color) exemplifies that the surface is better thought of as active zones or as actions (Ibid.). This perspective corresponds with the surface of the computer in which the exchange of different levels of voltage constitutes its “active zone.”

Yet, the surface of a computer is barely physical and unquestionably hard for any person to interact with directly. And while the computer in theory can do all the complex computations, we would find it difficult to relate to them as a material for design. However, except for the Turing machine, we hardly ever hear of a computer in and by it self and this is the key to approaching it as a material for design. In a previous paper (Vallgårda & Redström, 2007) Redström and I found that composites—in which several materials are combined in one new material to provide a new combination of properties (cf., Hull & Clyne, 1996)—can be how the computer becomes a material for design. Accordingly, the concept of *computational composites* refers to an assemblage of materials in which one is a computer. Also, the assemblage must be combined in a way that utilizes the computations in the composite's expressions. Yet, as a computational composite the computer becomes a kind of the so-called smart materials.

To design a composite material is generally about choosing a set of materials with properties, which would compliment each other and through structural and/or chemical conjunction form a new material (Ibid.). The tradition of composite materials design allows the use of production methods, glue, as well as structural remedies to combine the material components. In the project reported here, we are interested in exploring the primary property of computers—their ability to compute—and what that means in a material context. This consequently becomes their ability to control transitions between states in something else and let that be dependent on events outside the computer. And this perspective is important to keep in mind when designing with computational technology. For the computations to come to expression, however, the other components of the composite must be resilient to oscillation between states and possibly sensitive to changes in the environment either near or distant.

The resulting properties of a computational composite are—as with any other composite material—inextricably related to the properties of its components. A computational composite, however, is always able to be in one of two or more states and to change between the states based on a set of designed conditions. These conditions can either be designed with a closed data set, or they can take in measurements of an environment. Furthermore, where most traditional materials change expressions over time—often referred to as patina—computational composites changes between states as a controlled reaction to the conditions.

A computational composite will always contain some transformation of energy, and at some point the energy will have an electrical form. Most often computational composites need an external power source, but sometimes it can be built into the material composition (e.g., through solar energy panels or windmills). The energy transformation can happen within smart materials (e.g., shape memory alloys or nickel chromium wires) or through special actuators (e.g., motors or solenoids). The changes in the environment also need to be measured and transformed into a form, which the computer accepts. This can be done with various buttons or through complex sensor technologies designed to deliver input to a computer (e.g., measuring proximity or humidity). The transducers needed to transform the energy through out the material may not make a computational composites seem like a material, and perhaps we would even have a tendency to name them machines, however, we claim that it is partly a matter of scale and partly a matter of technological development. There are several smart materials on the market with a machine like behavior only this behavior happens at a molecular level and therefore not accessible to laymen including most designers (e.g., self-cleaning clay tiles or glazing with integral sun control louvers (Brownell, 2006).

Computers are used as a material for design whenever they are used in products and environments. Even if they are not thought of in that way computers are used to make other material elements behave in a certain manner. The concept of *computational composites* provides a way to understand the mechanisms of the computer, its properties, and especially its relation to other materials. *Computational composite* offers a perspective that addresses the computer and its properties for design and depicts its uselessness as an independent element. Even if the computer in a context of an object or thing may not take on the form of a computational composite because all the elements in the product are interwoven and talking about composites consequently would be meaningless the concept still allows us to understand the relations between computers and other materials. Just as importantly, the concept inspires to design a new middle layer of computational materials for others to use in their designs—parallel to how textiles are used.

EXPRESSING COMPUTATIONAL COMPOSITES

Thinking of the computer as a material allows a new range of potential expressions. A material's potential expressions rely partly on its inherent properties and partly on the environmental conditions (including the social context). Most of the properties of computational composites, as a general class of material, can be delineated based on the theoretical articulation, but some needs to be learned through creation, experimentation, and physical manifestations just as any comprehensive communication of a new material must rely on more than the written word.

Creating a physical manifestation of the concept of computational composites could take on many directions. Thus, to pursue a path, which will enable us to learn more about the potential expressions of computational composites, we have formulated a design brief setting up some boundaries and goals for this specific experimentation.

1. The project should work with expression before function, building on a concept and a leitmotif proposed by Dunne and Hallnäs &

Redström respectively. Dunne's (2005) concept of Parafunctionality is an approach that enables the design of something seemingly familiar but with an angle that allows provocation, surprise, or dysfunction, which removes the focus from the efficiency of the design towards its aesthetic expressions. Hallnäs & Redström (2006) operates with the leitmotif "functionality resides in the expression of things," (p. 166) which encourages the designer to take the expression seriously and even work with expressions first and through that invite experimentation around new functionalities.

2. The expressions explored in the project should go beyond those visually perceived. The emancipation of the computer from the constraints of information technology also includes a demonstration of how the computer can integrate material expressions that rely on a more complex sensory experience. The richness of expressions expands dramatically when taste, listening, smell, touch, and the body's sense of space become part of the vocabulary for computational design (Pallasmaa, 2005).

3. The explored expressions should also explicitly reflect the computational composites strongest property: a controlled oscillation between two or more states.

4. Finally, the result of the project should be recognized as a computational composite. Meaning that it should hold strong references to acknowledged materials and it should in theory, if not in praxis, could be mass-produced and used by others to design something from. If this point fails, the attempt of a physical manifestation articulating the computer in a new way has been unsuccessful.

There are several ways into this project, and almost every choice has been made and refined in a dependence on other choices. The following description, therefore, takes an offset in the strongest denominator for the result—the choice of material, which constitutes the other main part of the composite material. For this we choose wood.

Figure 38 A Grete Jalk Chair from 1963 made from two pieces of plywood bend into shape.

Wood is strong compared to its weight, it is flexible yet hard; it is durable and sustainable (Gordon, 2006). Wood changes in appearance and strength over time usually resulting from environmental conditions. Wood is a natural material and is often used sliced as timber or carved into form. Wood, however, is also common as engineered material where wooden strands, particles, fibers, or veneers are bound with various adhesives known as plywood, Masonite, or MDF (Medium-Density Fiberboard) (Hoadley, 2000). Engineered wood is popular in architecture and design due to their strength, their plasticity, and their low cost.

The inspiration for this project comes more specifically from plywood. Plywood was developed to give new dynamics to wood (see Figure 38). Plywood comprises an uneven number of layers of veneer (typically five) glued together cross grain. The grain in the surface has the same direction, which allows a high flexibility in shaping the wood into bend forms because the other layers ensure the strength (Ibid.). Others have done projects inspired by or directly using plywood, take EL Plywood (Kennedy, 2004); for example, in which the Kennedy and Violich studio utilize the layers in plywood by embedding flexible circuits between the sheets of wood giving them the possibility of dynamic illumination directly at the surface of the material.

In this experiment, we want to provide wood with another type of dynamics—that of temporal form (Others have explored the temporal form as an inherent effect of computations (cf., Hallnäs & Redström, 2001; Mazé, 2007) a dynamics in which the wood can oscillate between two or more states. Yet, we want to explore expressions that are more than just visual effects. We seek expressions that will be "measured equally by the eye, ear, nose, skin, tongue, skeleton, and muscle" (Pallasmaa, 2005, p. 41) as Pallasmaa describes the experience of qualities of space, matters, and scale in architecture. Such expressions will partly rely on the memory of previous experiences with similar materials (e.g., the taste of a material is an experience primarily acquired during childhood (cf., Rasmussen, 1966)) but primarily, of course, on the current design. This makes us work with expressions dependent on changes of shape and size, of texture, or even of presence, and to include the whole body in the experience. Furthermore, such changes of shape, size, etc., needs to be of a significant volume to have an impact.

The flexibility and durability of wood inspire us to let thin planks of wood continuously move between a bent and a straight shape. We borrow from the layering of plywood to articulate the layers of this composition where one layer is the computer, another is the "adhesive" in form of a motor, which transforms the computations into movements in the planks, and the final layer will be the plank itself. This expression will emphasize the physicality of computers and take the dynamics of plywood a step further. However, we have not yet established the design of the computations or the environmental conditions, which it might depend upon.

Computations can be used to emphasize, transform, delay, and otherwise manipulate any natural or established cause-and-effect. So while the expression of any material is dependent on its inherent properties and the environment, the design of a computational composite provides an opportunity to more explicitly design how the material should react to the environment and, for instance, bring in a more poetic dimension to the expression. Traditionally wood is affected by humidity, temperature, light, and to some extend wind, which can make it shrink and expand; grow week or rot; bend or break, as well as change color. However, the elusive flow of sound waves is known only to cause small vibrations in wood, i.e., in a wooden guitar. This expression, we will emphasize playing on a synesthetic effect were sound waves are no longer amplified; instead, the oscillation becomes perceivable to the body through larger scale vibrations or waves in the planks. The planks become hypersensitive to sound.

The sound sensitive waving planks are deliberately different, yet we name them PLANKS to emphasize their relation to the established assortment of wooden materials (see Figure 39).

Figure 39 A close-up of the PLANKS each bending outward when touched by sound and straightening when in silence.

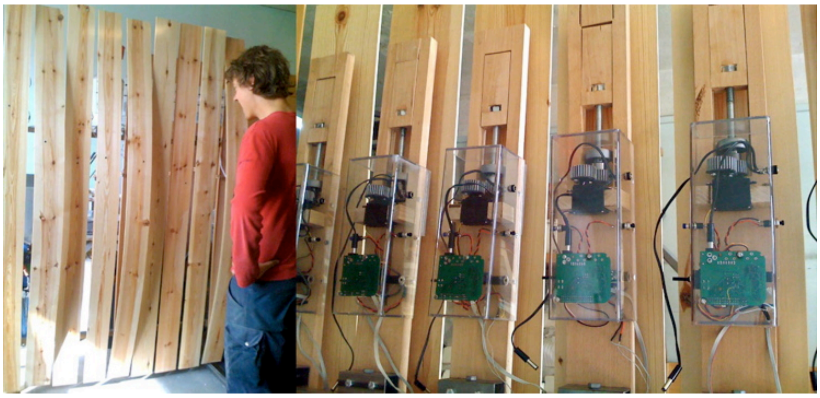


Figure 40 The first picture show the PLANKS in action. Second picture shows a close up of the computational layer and the ''adhesive layer'' including the motor (Unfortunately, the prototype illustrated here turned out to have a construction error and it only worked for a short while. New ones are being built.)

PLANKS: TECHNICAL SPECIFICATIONS

The composite is made in the shape of two-meter long planks. The components of the PLANKS are organized in three layers. The surface layer is responsible for the outward expression and comprises a 8mm thin untreated plank of pine and an electrets microphone (see Figure 40). The "adhesive" layer transforms the impulses from the computer into the surface layer. The "adhesive" layer comprises: a structure to carry the construction, a servomotor, a switch, metal gearing, wiring, a threaded rod, and bolts. The third layer is the computational layer and comprises a small computer equipped with a simple algorithm, a microphone amplifier, a potentiometer, and wiring (see Figure 40).

Each PLANK functions individually. The computations are designed so they activate the servomotor when the microphone (through an amplifier) generates a change in voltage that is above a certain threshold. The threshold is adjusted through a potentiometer to fit the actual context (thus, the context sensibility is tuned through an input to the computer which basically is an adjustable resistance). The computer will allow the servo motor to run for a couple of seconds equivalent to pushing out the surface plank a couple of centimeters. As soon as the motor stops the computer will again react on voltage measures from the microphone. When, however, there have been a silent for 10 sec the motor is triggered to rewind—again for a couple of seconds. If the measurements continuously are above the threshold, the surface plank will continue outwards until it reaches its maximum at approximately 25 cm from the straight position (a measure tested during construction and defined within the computer individually for each PLANK due to small construction and material discrepancies) the motor will not be activated even if there are sounds above the threshold instead it will wait a couple of seconds before "listening" again. A PLANK reaches a minimum when it is straightened sufficiently to turn off the switch mounted at the construction layer. At the minimum position it will start listening again. The PLANKS are dependent on external power supply; however, up to ten PLANKS can be supported by the same 12V power supply.

The PLANKS composite comprises a negotiation between each element (or material) and it is this negotiation, which makes up the properties of the composite. Properties which are different from the sum of the properties of the parts—some are restrained (the computer) and others are challenged (the pine planks). Furthermore, several PLANKS together will not react in unison because of the small differences in the materials and construction adjustments as well as the individual placement of the directional microphones. Several PLANKS together will, however, react on their neighbors—more specifically on the sounds made by the others' motors—resulting in a dynamics apparently unpredictable and autonomous.

The PLANKS are not in production. While this would take quite some sophistication of their structural design, it would more importantly be beside the point. The PLANKS are meant as a material for reflecting upon design with computations and the possibilities they present.

DESIGNING WITH COMPUTERS

Designing with computers requires an understanding of what they are made of, what they can do, and especially how they connect to their surroundings. Computations are indeed invisible to the eye and even the rest of our sensory system. Nevertheless, they do have a physical existence. Hence, if we want to use them for design we need to know their results relates to other materials. To give form to computational things or objects is then perhaps not a matter of packaging (cf., Dunne, 2005; Mazé, 2007), but a matter of forming the computations in combination with other materials. Materials that are capable of receiving the desired input and expressing the results of the computations in a suitable set of states.

In architecture, materials are used to make space and define volumes. Computational composites are through their explicitly active surfaces capable of changing volumes and blur space. The PLANKS used as a high panel in a room would, for instance, create a space of changing volume. As the volume of sound increase in the room the volume of space would decrease. Or a door made of PLANKS could provide cracks for visitors to peep through if they said “sesame.” The suggested “uses” of the PLANKS may seem a bit off, but that is exactly the point. The PLANKS are designed to lend insights into computational composites and through that the potential of computers as material in design.

The PLANKS are physical manifestations of the concept of computational composite with an emphasis on the expression and a negligence of any practical use. The PLANKS represent a combination of properties from wood and computations resulting in an untraditional expression of both. The layering of the material enables a focus on the individual components and how they are combined while the surface still allows an experience of the aesthetics of the expression. The layering is also meant to emphasize the possibility of replacing one layer with another and thus achieve in a new composite with a new expression.

The PLANKS represent a material where the computer is used to redefine a cause-and-effect known from nature. The computer interprets the sound waves transformed through the microphone and uses them as triggers causing a state change in form of a reshaping of the PLANK. Furthermore, the computer is used to establish an explicit temporal form. The expression of a PLANK is discretely linked to the context, and thus the expression changes over time as the context changes. The temporal dimension makes computational composites a type of material with a strong characteristic of becoming—it comes into being in context.

The PLANKS are an attempt to articulate the computer--to show that computers exist as a material for design and that this entails an understanding of the computer as a physical element. That all computing is “physical computing” even if our most common interaction with computers appears symbolic. Additionally, the PLANKS are an attempt to explain the relation between computations and how they connect to other materials as well as it is an exploration into the potential expressions of computational composites as a material for design. Lastly, the PLANKS should help delineate a space of computational design, which is more coherent with the actual potential than any story of immateriality and virtuality.

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A Material Strategy: Exploring Potential Properties of Computational Composites

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ABSTRACT

If function resides in the expression of things we are obliged to develop the space of possible expressions for computers if we aim at developing new functionality. In this paper we propose a material strategy to emphasize the aesthetic potential of computers. We argue how computers in material compositions can be part of a *formgiving*[12] practice. Through a theoretical study and through physical explorations of the potential properties of computational composites we form an understanding of the material and outline the foundation for a formgiving practice. Primarily, we focus on *computed causality*, which is the computer's ability to exaggerate, moderate, or completely transform the cause-and-effect of a material reaction, and *connectability*, which is the computer's ability to act as a unity when being physically separated. We explore an instance of these potential properties through two samples of a computational copper composite in which the computer controls the thermodynamic behavior.

Keywords

Computational Composites, Connectability, Computed Causality, Copper, Expressions, Formgiving, Materials.

INTRODUCTION

How do we design with computers? How do we bring computability into deign and architecture beyond its use in design tools? Computers' unfathomable potential promises a world of possibilities, but isolated, their form is in all practicality invisible and our interaction with them

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[12] The concept exists in the Scandinavian languages as *formgivning*, in Dutch as *vormgeving*, and in German as *Gestaltung*.

has therefore puzzled researchers and practitioners since the invention of the 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 variety of forms to bridge the gap between the human action space and the apparently formless computer have been developed. The graphical display and the alphanumeric keyboard, for instance, serve as a generic form for most computer systems. In these the system is expressed through the layout of the display. Others find the graphical display too limited or rigid to express the system and have invented other forms, which challenge a larger part of the human sensory apparatus (cf., Holmquist *et al.*, 2004; Ishii & Ullmer, 1997; Fitzmaurice *et al.*, 1995). Common for all is the ambition to pilot the user's interactions with the computational technology. We exercise our understanding of affordances (Gibson, 1979); skills, rules, and knowledge (Rasmussen, 1987) and we realize that there are more to appealing interfaces than efficiency and effectiveness (Norman, 2004). Still we struggle to make meaningful, interesting, inviting, coherent, and comprehensible results of the form and its function (cf., Overbeeke *et al.*, 2002; Dunne, 2005; Hallnäs & Redström, 2006; Gaver *et al.*, 2009).

As design problems are inherently indeterminate or *wicked*, meaning that they incorporate a future of interpretations and use, they play out with no true boundaries or constrains on the subject matter, and they have no guidance from a fixed relation between form and function as their relation is a constant negotiation. We are therefore obliged to rely on various strategies of partial understandings to shape our work (cf., 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 *et al.* (2004) describe two strategies: the first as a communication strategy where the purpose of the design task is to communicate the functionality of an artifact by depending on the users' knowledge and experience—the designer needs to find a form that communicates the pre-existing function. This strategy makes use of various perception studies to generate and shape the designs (cf., Rasmussen, 1987; Eysenck & Keane, 2000) and the results generally rely on metaphors, iconography, and representations. The second strategy they describe as an interaction strategy in that the functionality only arises through the users' interaction with the artifact. This strategy seeks to bring into play the whole of the users' sensory apparatus, thus it relies on studies of the users' behavior and action space which also leads to a sensitivity towards the richness of the material world (cf., Djajadiningrat *et al.*, 2000; Overbeeke *et al.*, 2002; Buur *et al.*, 2004). Both are used with apparent success within the limits of dealing with *wicked design problems* and 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 would point out a third—a material strategy. A strategy that we believe will suit the inclusion of computations in design and architecture as well as generally heighten the aesthetic qualities of computational design. It takes offset in the expressive qualities of the technology and its materiality. Here the "function resides in the expression of things" as Hallnäs and Redström articulates it (2006, p. 166). This strategy is about developing the aesthetic potential of computations and in that find a value beyond beauty—to develop new forms and expressions by utilizing the material potential of technology and through that form new functionality (cf., Vallgårda, 2008; Hallnäs *et al.*, 2002; Hallnäs & Redström, 2001; Redström *et al.*, 2005). The material strategy is closely linked to the craft related notion of *formgiving*, which Smets *et al.* (1994) has introduced to the practice of computational design. *Formgiving* is the act of deliberately manipulating a material into a form. It is, for instance, what is done when molten glass is carefully blown into a vase—a formgiving practice that takes years of training as the mastering of the tools is crucial for a successful result. The negotiation between the molten glass, the blowpipe with the punty, and the glassblower demands timing, precision, and sensibility.

To follow the material strategy requires an understanding of and experience with the computer as a material just as it requires mastering of techniques needed to manipulate the material. In this paper we aim at deepen our material understanding of computers. We build on the notion of computational composites as laid out by (Vallgårda & Redström, 2007). A computational composite is a material composition in which the computer is one constituent. The composite formation is necessary as the computer in and by it self is inaccessible for the human sensory apparatus, yet the computer is physical and in that hold an ability to affect other materials. With the work presented here we aim to become more familiar with the computer from this point of view—to learn about its properties and what we in practice can do with them. We propose a range of potential properties of computational composites: *temporality and change*, *accumulation and reversibility*, *computed causality*, and *connectability*. However, we only explicitly explore the two latter through material samples. Computed causality is the potential property of a computational composite to exhibit any desired cause-and-effect where connectability holds the potential for physically disjoint material pieces to act as still physically joint in the same material mass. Before we reach the introduction of the potential properties in the second part of the paper we address the material understanding of computers more thoroughly as well as attempt to get a grip on *formgiving* and what it would demand of our familiarity with the computer as material to truly enter into a formgiving practice.

THE MATERIAL UNDERSTANDING OF COMPUTERS

The material understanding is a way to acknowledge the physicality of the computer and the fact that it can be manipulated into innumerable forms, however, only ever expressed through other materials. 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 continuous physical phenomena—most common of which is electrical energy handled in a binary digital set up. 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.

Computational Composites

As mentioned above the material way of understanding the computer also points out its lack of expressiveness and human perceivable form. We cannot sense when the low voltage current turns on or off in the output flow nor can we directly influence the binary pattern of electrical current going into in the computer. At first this may appear as an obstacle to a material understanding, however, several materials exist that lack significant qualities before they become useable. Take aluminum for example. In its natural occurrence, as Bauxite, it is so weak that even if it is remarkable light and flexible it is practically unusable (Doordan, 1993). In the right alloy, however, it gains the strength to match its lightweight and flexibility and in that form it is one of the most widespread metals we have (ibid.). This is similar to when the emergence of material science fostered a spectacular contribution of composite materials where even such a brittle material 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.

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 hence 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 where the other material constituents in a computational composite in most cases reside in domains of energy different from the electrical such as for example the 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 domain of electrical and other domains of energy. This flow of energy across domains is defined as a process of 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 enabling transduction. Such transducers could be light-emitting diodes (LED), motors, shape memory alloys, nickel chromium wire, Peltier elements, as we shall see later, or a range of other mechanisms. We could say that the transducers are the adhesive element in this type of composite materials. For further details on the thoughts behind computational composites, see (Vallgårda & Redström, 2007).

In practice, the current state of computational composites tend to be more in the shape of art pieces or one-off prototypes than fully developed materials ready for designers to use, however, the ideas invested in these examples are crucial for the ability to technologically mature of this new material branch. One of the more mature material compositions seems to be computational textiles (cf., Post *et al.*, 2000; Redström *et al.*, 2005), which to some extend has reached a state of production, for instance, in terms of Leah Buechley's sewable electronics (Buechley & Eisenberg, 2009; Buechley, 2009) or the products from International Fashion Machines (Orth, 2209). But even compositions with glass exist (cf., Benjamin & Yang, 2006; Dalsgaard &

Halskov, 2009)), with metal (Brownell, 2008, p. 53 & 56), with concrete, or with wood as the two examples below will demonstrate.

Chronos Chromos Concrete

Chronos Chromos Concrete (Ritter, 2007) is a design project developed at the Royal College of Art in London in 2006. The project is about making concrete less stubborn and more adaptable. 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. It is not given by this material composition how the computer should behave if it should be sensitive to elements in the surroundings. In a sense this material resembles a traditional computer display, however, the form-language possible with concrete is significantly different and consequently the possible expressions and applications will differ.

Figure 41 Chronos Chromos Concrete: the 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 (Ibid.).

PLANKS

PLANKS (Vallgårda, 2008) is a combination of an art and research 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 consists of a pine plank, a servomotor, an Arduino board with an Atmega168 processor programmed with a simple algorithm, and a microphone and each PLANK works independently of the others. Whenever the microphone picks up a sound the computer check to see if it is above a certain threshold and in case it is it commands the servomotors to flex the plank a bit. If the sound continues to be of a certain volume the PLANK will continue to bend outwards until it has reach a maximum and only when there has been silent for a while will the PLANK gradually return to a straight position. In other words, the microphone transduces the sound wave into an electrical input for the computer, and the servomotor transduces an electrical energy to a kinetic energy hence the PLANK moves. In a sense the composite as a whole can be seen as a material that transduces sound into movement.

Figure 42 PLANKS: planks of pinewood flex as a reaction to sonic activity in their vicinity. Each plank work individually and can thus 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 (Ibid.).

Division of Labor

One of the significant advantages with a material understanding of computers is that it invites a layering of knowledge and distribution of responsibilities. Different areas of expertise address a material at different granularities; hence, they understand and can work with different aspects of the material. For example, the fiber engineer, the textile designer, and the fashion designer all play their specialized role in the design process from thread to garment.

If the engineer and the computer scientist take care of developing the technology from a smaller-faster-more philosophy, and designers create the usable and desirable computational products then in-between is room for a material layer in which the computer becomes part of a composite material ready for the designer to use. The material designer knows the properties and potential of computers and materials and is able to create compositions, which challenge and utilize both—or this is the vision. The division of labor as described here is somewhat simplified, in practice it would be more intertwined and complicated, but it gives a picture of the idea and can serve as a basis for the following argument.

Complexity and Granularity

The complexity, speed, and size of computers has lead some (cf., 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 and the interaction was not a separate concern but intrinsically linked to the artifacts' form and function (cf., Manzini, 1992; Djajadiningrat *et al.*, 2007). When the products instead became purely electrical driven the relation between form and function were weakened and the struggle of the interface began (cf., 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 (cf., Manzini, 1992; Ibid.). Also, the input, output, and the functional core were perceived as separate entities.

With a background in the division of labor, instead of seeing the complexity, speed, and size as hindrances for coupling of form and function we can say that it is a question of granularity in perception—the level at which we understand the computer. We can find an analogy in wood. As wood is a natural occurring material we have always approached it as a material first and only later begun 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 swell in one direction and shrinks in another under moist conditions and we know that when wood gets wet it looses some of its strength and stiffness. But most of us do not know why. We are not as 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. That small cracks causes 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.

This analogy leads us to believe that if we likewise become able to experience the computer's behavior under various conditions we would be capable of abstracting from the specificities and complexities of its inner workings and instead work with it primarily based on this experiential knowledge. That we, by addressing the computer at a different scale, can develop the material understanding that is crucial to a formgiving practice. As argued earlier, however, the computer can only be experienced through a composition with other materials and never directly and therefore it is probably impossible to gain the same kind of material familiarity as we have with the behavior of wood. Further, the material composition around the computer will influence the computer's behavioral range thus it makes little sense in practice to talk about the computer's properties—it will always be properties of the computational composite. Before we proceed with the study of potential properties of computational composites, however, we will address the practice of formgiving that we make the basis of our research approach and the material strategy.

FORMGIVING

Formgiving is traditionally linked to the practice of craft[13] 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. 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 form-giving to focus a study of the relation between how visual forms convey information—how "the visible form of an artifact […] suggest its non-visible attributes" (Ibid., p. 80). Blauvel *et al*. (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. That by creating computationally enhanced building blocks it is possible to utilize computations without getting too entangled in the technological details.

In another direction Malcolm McCullough (1996) and Andrew Richardson (2005) both propose to understand the skilled practice of programming computers as a sort of abstract craft. As we will return to in the following section, however, the apparently abstract task of programming cannot be distinguished from the materials it is to control—meaning the entity must be formed in unison.

Djajadiningrat *et al*. (2004) use *formgiving* to argue for a more rich interaction space, which takes more of the human sensory apparatus into account. Djajadiningrat *et al*. (Ibid.) give their students a task to create two forms which on two dimensions are the same (e.g., it is old and light) but on a third are each others opposite (e.g., one is fast the other is slow). The purpose was to study the power of forms. This approach bears relations to the Basic Course that Johannes Itten held at Bauhaus from 1919-1922 (Itten, 1975). In this course Itten taught the students about 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 thus he was not directly concerned with functionality but more with the effect of expressions. His argument for the basic course was that before the students could be truly creative—regardless of their preferred medium

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

or aspirations—they must master some basic knowledge of forms, colors, textures etc. (Ibid.).

With a material understanding of computers formgiving seems to offer a way of working and thinking that also coincides with the notion of "function resides in the expression of things." That we through hands-on material manipulation of computational composites can learn to give them form and create objects and spaces with new expressions and in that with new functionality. The current state of computational composites as primarily one-off prototypes and art pieces combined with the material's strong embedded expressions, however, probably entail a more complex relation between the designer and the material than we, for instance, see between the carpenter and wood. The open-endedness of computational composites will probably mean that any formgiving practice evolving around them also includes considerations of the design of the material. To form something from the Chronos Chromos Concrete, for instance, also means forming the color changes. Whereas giving form to the PLANKS provides less space for altering the material expressions. The division of labor between the material development and the forming of products will thus in practice probably be more intertwined and responsibilities will overlap. In a parallel project we have studied the value of using large-scale lo-fi prototypes to assist the design of both material expressions and object forms in an intertwined process (Bergström *et al.*, 2009).

By definition a thorough knowledge of the materials at hand belongs to the practice of formgiving—a knowledge, which does not confine to theoretical contemplations but must be experienced. As already argued, computational composites are unlikely to ever become available in the same sense as the classical materials such as wood, clay, metal, or textile. Instead the material experience most often will be founded in references to similar composites and behaviors. This referenced or substituted experience, however, also entails that the theoretical understanding of the computational composites must be more elaborate and that the language to express it likewise. The remaining of this paper is thus dedicated to develop our understanding of computational composites through both theoretical investigations and physical explorations in shape of material samples. The samples serve both as our aid in learning about and describing the potential properties of computational composites, but they also contribute to the ever expanding repertoire of referential prototypes that gradually will become the experiential foundation for computational composites and thus in combination with the theoretical understanding form the foundation for a new practice of formgiving.

POTENTIAL PROPERTIES OF COMPUTATIONAL COMPOSITES

Material properties are the experienced characteristics of a material that enables 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. We can see the properties as the language we use to articulate our understanding of a material. Over the last 50 years extensive material developments have generally excluded designers from knowing all available materials first hand. They can know some and use those as references to get a sense of any new material description they encounter (cf., Manzini, 1989). Learning about a new material, thus, rely partly on direct experiences and partly on descriptions.

Material properties are often specified under conditions such as room temperature and normal humidity and described in two dimensions. Velvet is smooth, soft, stretchy, and it shimmers in the light, where stainless steel is smooth, hard, shiny, smells like metal, and does not oxidize in contact with water, for example. A still picture, however, is even less suitable to capture the properties of computational composites due to their changeability and behavior over time in space. Moreover, discriminating the properties of computational composites is not an immediately feasible task for several reasons. Computational composites are an open material category and we therefore can only talk of *potential* properties when we address the general category of computational composites. One reason for the openness is that only the computations are specified in the general category and though they form the reason for introducing this material category a composite is never just the sum of its parts. The components will, in their mutual connections, restrict each other's scope of actions but the unison will possible bring entirely new expressions and potential applications. Another reason is that computers are inherently flexible in the sense that they by them selves can be made to behave in almost any way. Indeed, Löwgren and Stolterman (2004) argued that the computer is a material without properties for these reasons. Thus, it is primarily the other components of the composite that will set the boundaries of the possible behaviors, as they also will give body to the computational expressions.

Nevertheless, as computational composites are unlikely to be mass-produced in any (specific) composition (as most new composite materials are) and thus become common enough to be a well-known point of reference it is necessary to address this rather broad concept as a whole in order to grasp the potential of what can be done with it. Still, it contradicts the ambition of creating an experiential foundation to assist a formgiving practice.

To handle the span between the openness of the material category and the specificities of a computational composite sample we therefore need to balance between the general and the specific—between the theoretical and the physical. We have developed a material sample of a computational composite but we have done so to specifically study some of the computational abilities that we thought would be of interest in a material context. We have operationalized the material constituents in combining them in the material composite and through that sought to give body to our ideas of interesting properties (cf., Vallgårda & Bendixen, 2009). Our approach is thus a constant interplay between our ideas of what can be done and the resistance we meet from developing the material composition—an interplay, which gradually deepens our understanding of the material potential and constrains.

FOUR POTENTIAL PROPERTIES

What we present here as potential properties of the general category of computational composites is thus the result of the interplay between our theoretical contemplations and the composites we made. In the subsequent section we will present the specific material sample and how the properties played out.

Temporality and Change

Hallnäs et al. (2002) was probably the first to articulate a material property of computers. Since computers execute programs (compute) and that inevitably is a temporal process, they argue that temporality would be an inherent property of computational technology. Further, “This makes *temporal gestalt* the central form element of this material: as we execute programs, temporal structures are created.” (Ibid., 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. Every material changes over time but in this case the change come 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.

This property of temporality expressed through change is not exactly potential since it is inevitable in any computational composite; however, it 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 the movements in the PLANKS or the change of color in the concrete.

Reversibility or Accumulation

Closely linked to the ability to change is the ability to store both energy patterns and discrete levels of energy. The memory in a computer is what enables it to remember and recall a previous state. The memory is used as assistance during a program execution. In a computational composites it can be used directly to create an accumulative expression where the effect of a cause (e.g., an environmental change) is added to the overall expression as a kind of patination, alternatively it can also be used to re-establish a previous state of expression—an ability only seen in a few other materials (e.g., shape memory alloys or thermo chromatic ink). In case of the PLANKS the ability of moving back and forth exhibits the property of reversibility whereas the Chronos Chromos Concrete could be made to gradually change color as an effect of, for instance, the amount of pollution in the air (as a concrete computational version of "This is the air we breathe" Bergström, 2008)

Computed Causality

The computer's ability—based on an input and an algorithm—to compute an output means that it can establish any desired cause-and-effect or merely exaggerate, or moderate existing causalities. Further, the computations in a digital computer also offer an extensive room for interpretation and re-interpretations as it consist of a system of binary events. Every input and every output must confine to the same binary format and in this transformation something may be lost but the standardization itself offers a possibility to subsequently transform the result into any chosen format. A sensor input from a microphone, for instance, may become the movements of a piece of wood through transformation to a binary format, through computational manipulations, and through energy transductions (motor) as happened in the PLANKS. The combination of computed control and the freedom of transformation allow a large degree (only limited by the existence of a suitable transducer) of control over the causalities of the computational composites—an ability that we could call *computed causality*.

Connectability

Connectability is the computer's ability to connect and communicate with other computers. This property is founded in computers' ability of handling protocols and thus through attached radio devices 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, namely the radio or an equivalent technology, but the combination of the two is so common 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 were it physically conjoined. This obviously holds a wide variety of expressions owing the specifics to the other materials of the composite, but basically the computational composite is a distributed material.

It is probably important to emphasize that this is not in any way a finished list, in fact, we tend to believe that the list is impossible to finish—partly due to the openness of the material and partly due to the constant technological development. Instead we see these properties as points in the space of potential—as starting points for developing an understanding of the material. To experience what they could entail in practice we have built a composite specifically to explore *computed causality* and *connectability*. We have built one composite that, by altering the computational layout, is capable of exhibiting one property more explicitly than the other.

THE COMPUTATIONAL COPPER COMPOSITES

The copper composites appear as two copper tiles but with somewhat different thermodynamic behavior than other copper tiles. We have chosen to play with the transportation of thermal energy (heat) and the effect of temperature differences within the material as well as the effect of temperature changes in the environment. We are looking to bring aspects of the material world into play that we only rarely see used in combination with computers—and *vice versa*. The search for radical or untraditional expressions and behaviors is done partly to demonstrate how thinking this way about computers and materials can lead to paths of design, and partly as a communication strategy as unexpected behavior will demand more of those experiencing it in terms of contemplating what is happening—that unexpected behaviors will inspire them to start thinking about what else can be done (parallel to the concept of Parafunctionality, Dunne, 2005).

The copper composites are built as two identical material samples that we, through altering the computational settings (version one and two), can transform to exhibit each of two outlined properties: *computed causality* and *connectability*. The composites will inexplicitly also exhibit *temporality and change* as well as aspects of *reversibility and accumulation*; however, we have left it for future work to study those more explicitly. Generally, a material cannot be made to exhibit only one property and the potential properties outlined above are only rarely separable from each other. What we have done, therefore, is to make one at the time more explicit in the overall expression in order to better explore them.

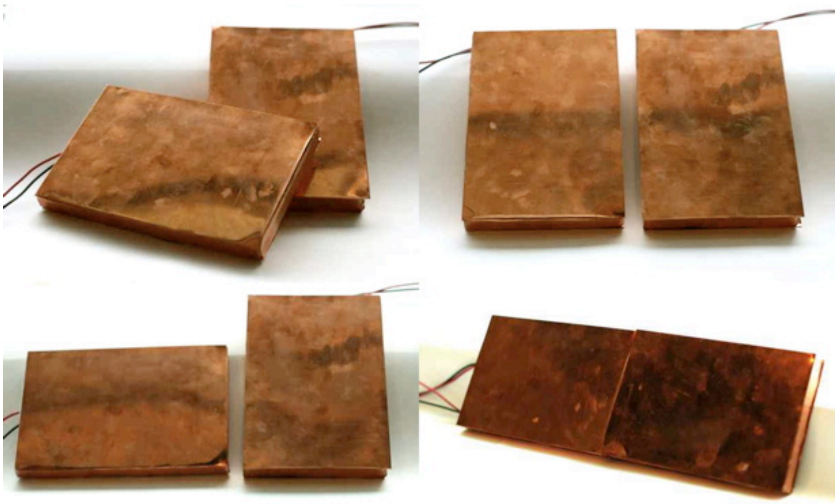

Figure 43 Four pictures of the two copper tiles.

The copper composites are tiles made up of four major constituents albeit the fourth constituent is only used in the second version. First, of course, we have the standard copper material with its thermal properties and in particular its high coefficient of heat transfer making it possible for us to generate relatively fast thermal effects (See the top left of Figure 44).

Second, we have the transducers. For the transduction between electrical and thermal energy we have used Peltier elements (See the bottom left of Figure 44). Peltier elements are in effect heat-pumps capable of transporting thermal energy (heat) from the cool side to the hot side of the elements under the influence of an applied electrical field (cf., Melcor, 2009). Where ordinary heat-pumps, as found in a fridge, works by having a liquid (cooling fluid) go through a series of phase transitions controlled by the compression and expansion of the liquid Peltier elements utilize the change of energy states as the electrons move across the element and in effect transports energy. Furthermore, by simply reversing the direction of the applied electrical field across the Peltier element the direction of the thermal flow is reversed meaning that we could start heating what was the cool side. We have for now only implemented the one-way transport of thermal energy from cold to hot. However, a relatively simple modification (in next iteration) would allow for a bidirectional control of the flow of thermal energy (heat). Finally, staying true to the role of a transducer, the Peltier elements are bidirectional elements capable of turning thermal energy into electrical energy. Inputting thermal energy (heat) by applying a temperature difference as opposed to a voltage difference across the element electrical energy is generated. This capability of the Peltier elements to act as generators of electrical energy or temperature sensors is as yet an unexplored property of our copper composite. Instead we use a separate temperature sensor. The Peltier elements required energy field is delivered by an external power supply under the gated control of the computer part of the computational composite.

Third, we have the LilyPad single board computer (See the top right of Figure 44). The LilyPad is built around the Atmeg168 microcontroller and has numerous analog as well as digital I/O capabilities on the board. LilyPad is part of the Arduino family tying in with an ever-growing open source community sharing software as well as blueprints for hardware online. Fourth, we have an Xbee (series 1) radio module following the ZigBee standard and thus capable of forming ad-hoc peer-to-peer networks over reasonable distances (between 30-90m depending on the environmental conditions).

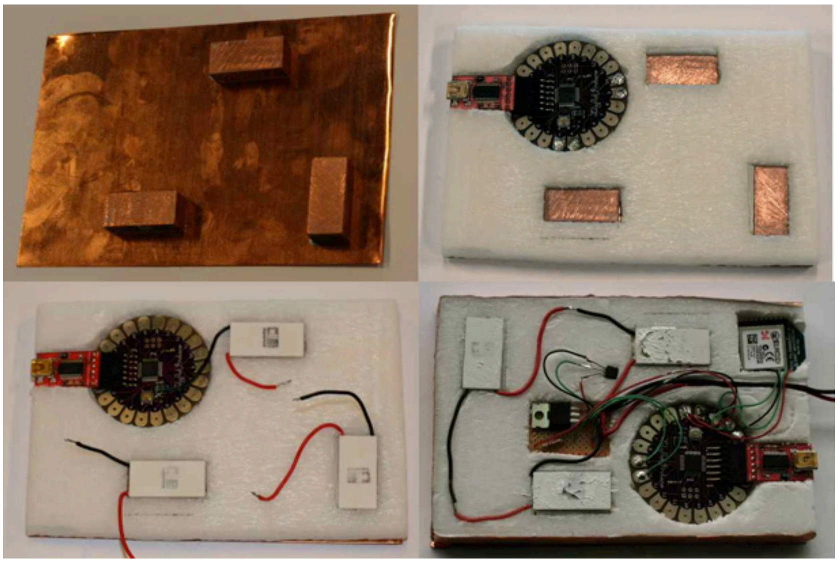

Figure 44 In the top left picture we see the copper formation inside of the tile. In the top right picture there has been added a layer of insulation and the LilyPad. The bottom left picture shows the addition of three Peltier elements and the last picture show the wiring of all components, including the Xbee module in the top right corner of the tile.

Computed Causality

Computed causality is the rather unique ability for a computational composite to exhibit (almost) any desired cause-and-effect. To play with thermodynamics is to play with one of the more fundamental aspects of our material world and to turn the experience of thermal behavior upside down must thus qualify as a radical case of computed causality. Notably, it is only the *experienced effect* of thermal behavior that is altered. We do not claim the computer actually capable of turning the laws of thermodynamics around. However, these exercises are all about creating new expressions and new experiences.

The premise of the composite is that in general we expect a piece of metal to stay warm for a period of time if it is exposed to heat. Obviously metals differ with respect to their specific heat capacity and coefficient of heat transfer, however, our general experience with heat is that it stays for a while in the bodies exposed to it. Hence, we have chosen that when the copper composite (version one) is exposed to heat it will turn cold. Ideally—or in the next iteration—the composite will equally turn warm when exposed to coldness.

Figure 45 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.

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 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.

The experience of this inverted thermal causality 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.

Connectability

Imagine that you cut a material in two and move the two parts away from each other. Now imagine, that the two parts exhibit synchronized behavior as if they still were one despite the fact that they now are separated by physical distance.

In the second version, to enable an immediate experience of the property of connectedness we made the two copper tiles follow each other meaning that if one starts to cool the other immediately follows thereby giving the impression of twins in sync over distance. The process of cooling is still triggered by exposure to heat as we explored in version one. Now, however, the temperature is also exchanged between the two parts of the composite material over a peer-to-peer network and the first to reach the critical temperature triggers both to be cooled down.

The experience of this version is less strong possibly due to the rather abstract behavior and less direct relation to traditional material behavior. Ideally—or in the next iteration—the two tiles will always seek a thermal equilibrium in both directions. Hence, if one is heated the other will turn equally warm 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 thus physically separated.

FORMGIVING COMPUTATIONAL COMPOSITES

By addressing the technology at a level of granularity where some of the possibilities in terms of both form and function have been constrained, we oddly enough believe to empower the designer. Even designers with highly developed technical skills can be entangled in the technological specificities and thus loose sight of the overall expression and purpose. Formgiving computational composites will in practice often concern two stages of the otherwise possible division of labor because the materials are unlikely to be completely off-the-shelf accessible. Thus giving form to a computational composite will often also entail composing the constituents of the composite. As such, the potential properties become the language to bridge the two stages—what enables working with an idea of a material expression when conceptualizing a form. However, the language does not substitute hands-on experience—it only supplement. To experience some of the possible expressions and learn how to utilize them will be as important to a designer of computational artifacts as learning how to administer the molted glass and blowing tube as a glassblower.

To follow the leitmotif of "function resides in the expression of things" it is necessary to practically develop the new expressions—to build a landscape in which we can experience new functions and new potentials.

FUTURE WORK

Besides the immediate next iteration of the copper composite tiles with the Peltier transduction in full function and a study of *reversibility and accumulation* there are an almost infinite number of projects to dive into. The material strategy is about a way of understanding design of computational objects, as process of giving form to materials, and that one of these materials may be a computer. It is about developing new forms of practices around manipulating and developing computational composites and in that find a path to new expressions and new functions. The material strategy is about finding a value in aesthetics beyond that of beauty and through material developments and explorations contribute with new designs and new uses of the technology. Indeed, continuing to explore potential properties of computational composites, developing computational composites with new compositions of materials, transducers, and computations, and developing techniques and methodologies to form a practice around the material strategy are the three primary objects for future work within this program.

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Becoming Materials: Material Forms and Forms of Practice

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ABSTRACT

Developments in material science and computational technology afford new material possibilities. The new materials are capable of explicit changes between states in response to their surroundings. They hold an aesthetic potential that can neither be understood in terms of static properties nor in terms of functionality. Their expressions come to be in context and over time—they are *becoming*. These materials constitute a challenge in relation to how they are used in design practices but also in relation to how they are research and developed. In this paper we propose a framework to understand the potential of these becoming materials and through our own practical experience we propose a practice, which encompasses both the material development and the material application.

Keywords: Smart materials, computational composites, becoming, material practice, prototyping, design.

INTRODUCTION

About half a century ago, when material science became a discipline, the material development expanded far beyond traditional materials such as wood, glass, or metal. Combining elements from chemistry, physics, and engineering, materials science was able to study the material as a whole, and to develop knowledge about why materials behave the way they do (Gordon, 2006). This knowledge then became one of the driving forces in the development of materials, such as polyvinyl chloride PVC and fiber optics, and new material compositions such as fiberglass and plywood (Ibid.). Many of these materials were and still are invented for specific purposes, and with such advanced properties that they sometimes replace functions previously fulfilled by entire products.

In his seminal analysis (Manzini, 1989) of this material development Manzini addresses how it not only has opened new possibilities for design but also how the new functional materials have imposed an important change in how we understand and can work with materials. He argues that historically,

> *once a material was considered to be "known", references to that material became a handy abbreviation for the set of relations between the conditions of use and the performances that typified that material. The value of this synthetic form of expression – that is it's socially accepted and unmistakable meaning, was based on two conditions:*
>
> - *there were few materials and they were quite distinct one from another, so that each corresponded to a well defined field of relations;*
> - *materials remained constant over time in terms of qualities and properties, and their variations (or the introduction of new materials) were slow enough to allow the adaptations.*

(Ibid., p. 32)

With the technological progress of material science, however, the materials available to design changed from having well-known properties and expressions to become their functionality with abstract sets of properties. In light of the prevailing linguistic turn at the time Manzini argued for the need to develop a language to support or substitute the direct material experience. That designers no longer could expect to become craftsmen specialized in giving form to specific materials, but they were obliged to find new ways to navigate the available possibilities (Ibid.). The new materials were characterized by their functionality more than their *existence*, and thus designers had to ask "what does it do?" rather than "what is it?" (Ibid., p. 34) in order to understand a material's potential applications and performances. Manzini referred to this as a change from working with materials that merely are to working with materials that do—where the function is its prime denominator.

In practice, however, traditional materials still play a central role, not the least as reference points for expressiveness and experiential qualities (cf., Beylerian & Dent, 2005; de Ruiter *et al.*, 2005; Ritter, 2007). Still, a sense of materiality—a sense of texture, strength, and appearance—can only be conveyed through such descriptions if they also hold reference to experienced materials. Thus, the practice that evolved around the then new functional or technical materials turned out to be a combination of functional descriptions and experiential references to the core selection of materials of which some are the traditional ones.

The material development has since taken yet another turn as the new kind of materials' unique attribute is their ability to change continuously in relation to both external factors and internal programs. These materials are often referred to as smart or computational. The new materials make use of technological innovations from areas such as nanotechnology, computer science, electronics, and traditional material science, to allow designers to literally design and program material behavior over time, including mechanisms for real-time responses to environmental factors. This realm of complex contextual dependent behavior and expressions means that descriptions will not suffice and that experiential references hardly exist. Indeed, these materials are only rarely being mass-produced and exist therefore, more as a promise of potential than physical samples. We therefore see a need to get a handle on this new material potential in terms of both understanding and practice. And like Manzini argued two decades ago, we now argue that these new smart and computational materials require us to develop new concepts to support design thinking and practice. Unlike Manzini, however, we do *not* think that this implies an even further shift to language as the primary mode of communicating these possibilities. Nor do we believe that a sole experiential foundation will enable designers to comprehend and make use of the potential, which these materials provide. Rather, we find it necessary to meet the technical and aesthetic complexities of these materials with a combination of language (including programming languages) and material experience. For this, we need to develop concepts to capture the potential and complexity as well as ways of working with the aesthetics and experience of these new materials—a new material practice.

In what follows, we will take a look at the new material turn and propose that we understand these materials in terms of *becoming*—as we through this notion will be able to capture the new complexity in temporality and contextual dependence. The notion of *becoming* also lends references to perspectives and practices from the higher order challenges dealt with within contemporary design and architecture. Practices that we let inspire our proposal for how to incorporate these increasingly complex materials in an ordinary design practice. Throughout we will illustrate the theoretical contemplations with examples from our own experimental work with materials where the last example, through which we experiment with how to approach these materials in a design practice, will play a more significant role.

BACKGROUND

The new material turn is based in the development of 'smart' and computational materials. Where *smart materials* refer to the development of new composite materials with advanced functionality capable of sensing their surroundings and change accordingly. NASA defines smart materials as "materials that 'remember' configurations and can conform to them when given a specific stimulus" (as quoted in Addington & Schodek, 2005, p. 8) Axel Ritter (2007) operates with a broader definition and describes smart materials as the "term for materials and products that have changeable properties and are able to reversibly change their shape or colour in response to physical and/or chemical influences, e.g. light, temperature or the application of an electrical field" (Ibid., p. 8). Common to the definitions though, seems to be a functionality that enables materials to progress and reverse through multiple discrete states and (in some cases) to change states in response to external and contextual factors. An archetypical example of a smart material is shape memory alloys. These alloys, often made of a nickel chromium composition, are capable of 'learning' a form induced when exposed to heat. When the temperature thereafter rises above a certain threshold, the alloy will 'remember' its hot shape and when it drops below that threshold it will change back to its cold shape.

A specific strain of smart materials includes computation (cf., Vallgårda & Redström, 2007). They are material composites in which computations are employed as the factor to process contextual input and upon that control the expression or formation of the material composite. Integrating computation into material composites enables extensive and direct control over the materials context-dependent behavior. While, physical and chemical connections entail certain cause-and-effects relative to the material's environment—every material, given time, will reflect the context it has been part of through expressions such as deformation, patina and disintegration, computational materials allow another and expanded range of cause-and-effects. With computations materials can be made to exaggerate, transform, delay, or create completely new reactions to contextual situations in terms of changing expression or functionality. The ability to allow this behavior lies in the abstraction of the sensed context into binary sequences of electricity flow. This binary abstraction enables the contextual situation to be combined and processed in a wide variety of ways within the computer's logical circuits and consequently be passed on through a transducer as commands to change the expression or function of the overall material.

The central most novel aspect of these smart and computational materials is their ability to continuously change depending on context, which goes well beyond deformation due to normal physical or chemical disintegration or ordinary wear-and-tear. These changes are not accumulative, like patina, but discrete, reversible, and can be made independent of history. No material is context-independent, but these new materials are able to relate to context in ways not previously possible—indeed, their expression can be directly and immediately linked to specific events occurring outside of the material. The new materials are able to continuously transform in response to chosen events; thus, where *being* and *doing* can capture some of these behaviors they do not capture the consequences which suggest that we once again needs to shift how we think about materials.

When Manzini addressed the materials' presence and behavior in terms of *being* and *doing* it were an attempt to capture the practical and cultural understanding of the materials' merits, and the terms thereby reached beyond a mere statement of technological possibilities. Likewise, we seek a description that surpasses the technological terms of 'smart' and 'computational' and captures the merit of these materials in a practical and cultural context. From a similar line of thought two almost identical descriptions have been proposed used about these kinds of materials. One is *transmaterial,* which refers to the transformational qualities of these materials and used as a title of a catalogue series of such materials (Brownell, 2006; Brownell, 2008). The other—*transitive materials*—has been the name of a couple of workshops dealing with these kinds of materials and it refers to the "bridge between computational devices, and the physical structures" (Coelho *et al.*, 2007, p. 1) made possible with these materials. However, while they capture the transformational (and transitional) potential of these materials they do not capture the explicit contextual dependence upon which the transformations take place—an aspect of these materials, which is highly relevant for designers to understand in order to incorporate them into a design practice. Instead, we suggest thinking of these materials as in a constant state of *becoming*. Their transformations of expressions are continuous negotiations with their environments.

PLANKS Example

There have been made numerous and diverse examples of materials which would fit the description of *becoming*, for example, compositions with textile (cf. Post *et al.*, 2000; Redström *et al.*, 2005), with concrete (cf. Ritter, 2007, p. 88), or with glass (cf. Benjamin & Yang, 2006; Dalsgaard & Halskov, 2009), but to illustrate more fully the properties and possibilities with these materials we will elaborate on one of our own designs of computational wood.

PLANKS (Vallgårda, 2008) are computational extensions of plywood in which one layer of ply is exchanged with a computational layer and where the adhesive layer between is replaced by a transducer, which translates the computations into the wood—here in shape of a motor. In response to sound above a certain volume, the PLANKS gradually bend outward and, as long as the sound continues, they either keep bending or stay in their maximum bent state. When there is less sonic activity in the local environment, they gradually return to their original, straight position. If, for instance, the PLANKS were to cover the walls of a room, the room itself would literally become smaller as the activities happening within produce a lot of noise. In contrast, if you are suddenly left alone in the room, the PLANKS could amplify this sensation through expanding the space. Material performance can have a direct effect upon the spatial perception and embodied experience of users within the environment and, thus, might also have a reciprocal effect upon the behaviors of users and the activities that might take place.

Figure 46 Two large pictures show nine PLANKS in action. The three small show the electronics, the mechanics and the microphone respectively.

The PLANKS are not intended for production but were made to experiment with the aesthetics of computational composites. The choices of cause-and-effect reactions are not found in a natural vocabulary of material properties they rather play on synesthetic effects where sounds are transformed into the decrease of space, or the sound waves are emphasized into visible and bodily perceivable waves in the wood.

BECOMING MATERIALS

The concept of *becoming* in a philosophical sense incorporates aspects of open-ended evolution and emergence as well as an inevitable indeterminacy over future eventualities. In this general sense the term refers to processes of change and transformation that characterizes everything from basic matter and energy to living organisms and cultures. In Deleuze's critique (1994) of the static and timeless picture of reality described in classical physics, and the rigid determinism implied, he introduces the term to describe the open-ended becoming of the world (se also Deleuze & Guattari, 1988; DeLanda, 1999). Unlike theories of essentialism, in which matter is viewed as an inert receptacle for forms that come from the outside (transcendental essences), matter in neo-realist/materialist theories is seen as possessing immanent resources for the generation of form from within. Matter becomes an active material agent, one that does not need form to come from the outside and impose itself on a static conception of *what is*' (or, in the terms of this paper, *being* materials).

While this understanding of the becoming of the world as constantly shaped through material negotiations is important for understanding the broader aspects of our material existence what we aim at with the notion of *becoming materials* is in fact a bit more commonsensical. We wish to address the uniqueness of these new materials, which cannot be done without addressing their immanent potentials of context dependent change, yet we remain sensitive to the dynamics offered in terms of direct or indirect negotiations between the materials and their surroundings. The *becoming* in *becoming materials* thus hold reference both to a practical attribution of changeability and to an aesthetic potential of a continuous negotiation of expressions in which the materials come to be.

Even in a commonsensical sense, however, all materials can be said to hold an aspect of becoming. Wood, for instance, swells and shrinks as a consequence of the level of humidity in its surroundings and steel reflects light differently depending on intensity and angle of the light. Indeed, any material can be described in terms of being, doing, and becoming. Some materials, however, possess properties and behaviors that are best—or perhaps uniquely—characterized by one of these aspects. And here we argue that smart and computational materials can only really be described in terms of the complex interactions that cannot be reduced only to terms of being and doing. They but must be understood as always in movement, changing and evolving interdependent upon and intertwined with multiple factors—both factors internal and external to the material including factors programmed in advance and those controlled and altered long after in contexts of use. Expressed in another way, the potential properties of these materials simply cannot be captured by or reduced to the terms of conventions found in materials catalogs and handbooks (cf. Beylerian & Dent, 2005; de Ruiter *et al.*, 2005), as they describe context only in terms of a generic, static, and limited, range of factors. Becoming materials can only be understood and described in terms of how they change expression, in context, over time.

The context in which these becoming materials take part and are sensitive towards may include climatic factors such as temperature and humidity, environmental factors such as sound and lighting level, and human factors such as direct input by users or indirect effects of user modulation of climatic and environmental factors. Also, with use of network technologies, context is not even determined by spatial or temporal constraints, since influential factors may originate in any place or in another point in time and yet still impact upon the here and now. As such, environmental factors have a much wider and more diverse range of effects on becoming materials than traditional patina, human factors can affect more than ordinary wear-and-tear. As people engage directly, or indirectly, in activities that affect the environmental parameters to which the material is sensitive, they take part in the dynamics of the material becoming. This indicates an overlap between the concerns of material development and those of design—an overlap, which will be the theme throughout the rest of this paper.

Becoming in architecture and design

The notion of becoming materials as we propose also relates to developments within design discourse and practice. While modernist art and architecture tended to reify the notion of an essential, ideal, or archetypical material expression, the avant-garde experiments with relativity and vitalism, and the postmodern cybernetics with metabolics and parametrics, have developed approaches to material, technical and social complexity (Kwinter, 2001). In line with such developments our notion concerns technical and aesthetic aspects, natural and human factors, and the complexity of interactions happening between and evolving over time.

Many contemporary theories of design emphasize dynamic, emergent, and performative aspects. Neither form nor material is conceived as static, or even as stable, and fixed—design might also include “objects that—rather than being solidly located in space—tend to flow through time”, as Manzini argues (Manzini, 1989, p. 26). Instead of a “building as a fixed entity or a given stable object (which is the standard notion of building today),”Grosz (Grosz, 2001) argues for an architectural theory that recognizes that “a building is made up of other spaces within it that move and change." In such terms, material forms are conceived in continuous formation, as design programs and practices of use interact at different spatial and temporal scales. Further, noting that "after it is built, structure is still not a fixed entity. It moves and changes, depending on how it is used," Grosz (Ibid., p. 7), which poses a new set of questions: "What sorts of metamorphoses does structure undergo when it's already there? What sorts of becomings can it engender?"

Designing and becoming

The aesthetic potential of becoming materials poses a challenge in a design situation. The performances and expressions of becoming materials depend upon the environment and users—and, in parallel, users vary their performances in reaction to the qualities and dynamics of material expressions. This give-and-take of cause-and-effect unfolds as a complex interplay among material, environmental, and human factors. The dynamic is explicitly temporal; it is a constant negotiation with daily and seasonal cycles, climate conditions, and human behavior. A negotiation also implies that the material hold a position. That the material's contextual dependence is determined, at least to some extent, in advance of future contexts, since the material design involves an intentional selection and combination of material parameters and the program of any computation integrated within a composite. As a consequence, we might consider the composition and performance of becoming materials, decided and designed in advance, are a sort of 'script' that inevitably prescribes some possibilities for future use (cf. Akrich, 1992; Redström, 2006; Verbeek & Slob, 2006; Mazé, 2007). This script range the possible expressions that might arise as the material comes to be in future use—which, in turn, prescribes certain perceptions, reactions and activities in use. Yet, on the same merit, the designer of the material will not have direct control over how the expressions play out—there is an inevitable asymmetry between design intent and actual use, between "absent makers" and "occasional users" (Latour, 1999, p. 189). Material expressions are left, quite explicitly, up to uses in contexts that are still unknown and often unpredictable within materials development and design.

Nonetheless, despite this asymmetry, there is an increasing overlap between the design of materials and the design of applications for such materials, just as there is an increasing overlap between the functionality of materials and that of products. To the extent that applications are designed to anticipate use and users, there is an overlap between the concerns of material science, computing science, design disciplines, and social sciences. Becoming materials require consideration of factors well outside their basic internal composition, since they produce a range of effects at the scale of the wider built environment and social activity.

Energy Curtain Example

To illustrate how material becoming hinges upon interaction within the context of use, we might consider another example. The Energy Curtain (Backlund *et al.*, 2006) was sparked by an investigation into how smart textiles and ubiquitous computing artifacts might power and recharge themselves. The curtain is made of a fabric woven with fiber optic threads and with solar cells covering the back. The solar cells are connected to a battery that, when charged, provides energy to a row of LEDs attached to the fiber optic threads. It functions as any ordinary curtain, but also has the supplemental function as a light source at night. The curtain has been designed to depend explicitly upon context and use—the curtain must be drawn shut during the day to be able to collect sunlight and there must be sufficient sunlight for the batteries to be charged. The supplemental function depends on active and ongoing use—it prescribes a certain physical gesture and habitual activity in order to effect an aesthetic and functional transformation of the context. The function programmed in the material literally requires a reciprocal program of use.

Studies of Energy Curtain within different households in Finland as the winter turned to spring, for instance, exposed how the curtain's direct expression of (lack of) sunlight altered people's perceptions and actions, increasing sensitivity to the seasons and prompting certain experiments to cheat nature (Routarinne & Redström, 2007). Further, this interplay involves other artifacts and activities that take place or change over time within a context. For example, the curtain's functionality made some households to rethink natural and artificial light sources, prompting rearrangement of furniture, altering the function of a room, and encouraging new routines around using lights. An example of the effect that the designed scripts of becoming materials can have upon use, this illustrates the increasing overlap between the concerns of materials development, interaction design, even user behavior and sustainable design.

Figure 47 Energy Curtain. Above, collecting energy during the day and then returning it at night. Below, in use in a household and shown in an alternative use situation.

NEW MATERIAL PRACTICES

The technical and theoretical developments relevant to the notion of becoming materials have important implications for the aesthetic possibilities and hence for the material practice. The anticipation of use and context and the design of cause-and-effects constitute an increased overlap between the materials and their applications.

Where Manzini (1989) argued for a shift towards a linguistic approach to design as the material possibilities exploded with the development of functional or *doing* materials we propose a combination of linguistic descriptions and experimentation with physical samples to handle the complexity of smart and computational materials. Instead of the modernist tenet ‘truth to materials’, in which an ideal expression of concrete or plywood might be achieved, we will follow the trend of contemporary design practitioners who are developing new working methods and techniques for investigating emergent and unexpected aesthetic and functional effects. Or expressed by Mori: “As new materials are invented and technological advances made, architectural practice has moved from working within the limits of static materials to transforming them into dynamic elements by combining, laminating, casting, and weaving” (Mori, 2002, p. xiv).

Indeed, this means developing new methods for experimenting with the materials in sites central to established forms of material practice, including design studios and workshops. Sites, which at the same time are undergoing a revaluation—as a model for a particular type of knowledge production and as a unique contribution of design to practices of inquiry in a range of other domains and disciplines (Salama & Wilkinson, 2007). Further, we must also consider aspects of becoming ‘in the field’—in locations and situations in which aspects of becoming emerge in use and are sustained by users.

It can be difficult to experiment with the performances particular to becoming materials, since these can occur at microscopic scales and processing speeds far beyond the threshold of ordinary human perception. In order to engage in the development of becoming materials, we need to develop experimental methods for exploring possible aesthetic and functional expressions and effects in real-time and full-scale. Within conventional design and development processes, conceptualization typically happens in advance of and over a longer period of time than is the case with material development. Indeed, making is often handed off to specialists or manufacturers—thus rendering material practice subordinate to a set of functional or other requirements. However, given the increasingly designed nature of new materials, we must develop new forms of material practice grounded in our sensory, practical, and cultural experience (Allen, 1999).

In order to incorporate aspects of use into the development process, we might try to incorporate methods and techniques that have been developed within design for exploring what use might be like and for staging discussions with potential users while the development process is still in a stage when it can benefit from such influence. Our response to these issues—technical as well as aesthetic, contextual, and temporal—has been to develop prototyping practices based on real-scale but lo-fi and low-tech materials samples. Through a series of practice-led design research programs, as exemplified by the PLANKS and the Energy Curtain presented above, we have developed ways of experimenting with certain material expressions over time, as a basis for experiencing and building a common understanding of the possibilities for contextual dependent temporal form (cf., Redström *et al.*, 2005).

The material samples that we develop and work with are meant to express and explore aspects of what the eventual expressiveness of the material might be like in order to probe its consequences for design and for use. The samples themselves might be further developed or applied, but more importantly they exist as means for communicating ideas and experiences as well as technological possibilities between designers, engineers, potential users etc. They can capture aspects of the material practice, which is difficult or impossible to communicate through language alone.

To be able to create such real-scale samples, however, we sacrifice technical precision to a certain extent. In developing computational composites, for instance, we might compromise the detailed technical crafting of mechanical or electronic components so that we can be able to more rapidly prototype and thus explore how the whole might be experienced at the scale of human perception. Of course, some of this lo-fi characteristics of the material samples also translates into how we experience the material—it may not quite live up to what we would expect of the final design—but such material samples nevertheless provide a valuable basis for design experimentation and for communication with other designers, engineers, and users. It is also important to keep in mind that this approach is not intended as an alternative to or replacement for more traditional models of materials and technology development. Instead, we see this as complementary, a process that shifts the focus from the technical components to a more aesthetic and holistic perspective on material presence from the start. Below, we describe one such experiment in more detail.

Telltale Example

Telltale is a piece of furniture that collects traces of energy habits. Connected remotely to a household's electricity meter, the object responds to increases or decreases in energy consumption. Increases cause the object to become less robust and *vice versa*—as the object is used in more weakened states, the surface becomes more prone to fading, flaking, crackling, or wrinkling, such that repeated energy (mis)use leave traces on its surface.

Telltale is a transitional object rather than a privately owned consumer product. Traveling from household to household and staying for some time in each, it communicates locally, to its immediate users, but also carries traces of those that came before, introducing an awareness of others' energy transitions and an experience of the cumulative effect of local actions. The unique aesthetic of Telltale is a joint product of energy consumption and daily use; the length of its lifespan is dependent upon personal histories and collective effort. Inspired by some current approaches to treating dependence on energy in terms of addiction, the Telltale concept relates to the psychological theory of 'transitional objects' that accompany people from one stage in life to another (Attfield, 2000).

The expression of Telltale should therefore reflect the character of a transitional object, including an overall expression of transformation, aging, and ephemerality during a more long-term trajectory family life and material culture across multiple homes. In addition, it must also express more immediate and short-term patterns of energy consumption within a particular household. Thus, the materials in Telltale have two contextual dependent temporal forms. The first is deliberately slow, intended to build up as a visual pattern of a strangely familiar material through ordinary wear-and-tear—over time, this pattern grows in a way that is slightly organic or even geographic in appearance, in a second color revealed within the material that gives the object an overall appearance less of disintegration than of transformation. The second is a more immediate response to daily energy use. It is expressed as a change in the mechanical properties that give Telltale its more (or less) stable structure as a piece of furniture and thereby its functionality for everyday activities such as sitting.

To understand and design with the material expression of these two temporal forms, we made a range of material samples that were capable of changing back and forth between one shape and another, as well as degrading in certain ways as an effect of use over time. The final design might be based on new materials—for example, bi-component fibers combining durable and disintegrating components in a composite with dynamic and programmable structural components so that the shape might be controlled in detail. However, before we could make essential design decisions, we needed to begin experimenting with what such a material might be like over time, in multiple contexts, and in different situations of use. Here, a real-scale and lo-fi prototype using relatively simple techniques such as layered materials, various surface treatments, and underlying structural elements have been important in facilitating design experimentation from the start.

Figure 48 Experiments with material expressions for Telltale. By applying a fragile layer within the composite or an added surface treatment, we were able to explore the range of materials expressions at different points in a process of wear and tear

The initial materials samples made for Telltale allowed us to experiment with various changes of expressions, some of which would be able to change back to an original state, or switch between different states, while others would be aggregate, permanent, and irreversible. More than twenty samples were created, each of approximately the same size, but with very different materials and surface treatments, as well as different times and durations in which the treatments were applied, which had an effect on how brittle, durable, and bonded the composite would become after setting and drying. Exposing the samples to various abrasions, we were able to anticipate the physical impacts and processes that the material might undergo in future contexts. From the results of this experimentation, the team was able to collectively make assessments and initial selections in relation to the desired visual and textual expressions.

We also realized that the material expression would be dependant upon the construction and orientation of the furniture object—for example, aspects of wear-and-tear would appear different where the object had been sat upon and where three material surfaces were joined at each of the four corners. In order to explore these variables, we constructed a full-scale three-dimensional sheath out of one of the more promising techniques from the materials samples. Although the sheath did not have a mechanical structure able to support body weight, we were still able to simulate the effects of abrasions on the object made in relation to the size, gestures and orientation of the human body. On the basis of these two experiments, we gained as sense of the expressional scope and were able adjust the material composition and performance criteria, as well as considering variables of scale in use and the speed of material deformation on different parts of the object.

Figure 49 Experimenting with the effects and abrasions of the Telltale in a full-scale prototype made of cotton and wood glue.

We recognized, however, that such variables were also depending on context and use. We decided to build a more robust and usable full-scale prototype that could be deployed into one or more households for short periods of time. This prototype would help us to gain a better understanding not only of the patterns and structure of possible material expressions of Telltale but of the effects on use and users. Studying the prototype in context might also provide valuable indications of how individuals and families might perceive and interpret the material expressions, how they might react and adjust their use of the object or their energy consumption in response, and how becoming materials might change the conversations and interactions among family members around the object.

To prepare for this study, and based on the two initial experiments, we began investigating different structural possibilities. It was not possible to work with the final technology at this stage—indeed; we are still in the process of discovering which mechanical and structural performances might be appropriate. However, on the basis of our knowledge of some performative potential with new materials, we sketched out different versions of an internal structure that might simulate the mechanical and computational performances of possible material composites. For example, one projection was based on a material that would rise and fall in discrete, geometric sections and another was based on a more continuous and fluid inflation and collapse. Rough prototypes were made in three dimensions at a small and then a full scale, borrowing on Buckminster Fuller's principle of 'tensegrity' (Motro, 2006).

Figure 50 Above: the Telltale tensigrety construction with an exercise ball in the middle. Below: the Telltale in use.

A prototype to be deployed into the household study has now been constructed. The change in shape is a result of simple inflation and deflation of the airtight material construction, which is accomplished by a customized motorized pump that also measures air pressure in relation to measurements collected on a daily basis from the household energy meter. For purposes of rapid prototyping, the core of the construction is a large rubber exercise ball that has been integrated into a cube made from rubber with reinforced seams and corners that fits into the textile sheath. A new sheath has been constructed and treated so as to disintegrate at a faster rate in order to collect perceptions within the limited time constraints of the study.

The Telltale prototype is a composite—while the materials are not intended to be the final technical or material solution, the layered construction does represent certain properties that will continue to be essential to future versions, including visual pattern (two and three dimensions of the sheath), geometry of the shape (currently accomplished through reinforced seams and edges) and in/destability of form (currently accomplished through a combination of airtight materials and mechanism for in/deflation). Potentially, a single composite material or a more integrated construction of composites might accomplish this. Furthermore, the Telltale would also contain the capacity for remote sensing, processing, and time-based actuation of data from the electricity meter.

Even though this is not intended as a final solution in any respect, we have nonetheless given careful consideration to methods for prototyping different aspects in ways that might provide important feedback to incorporate in future versions. While some aspects have been prototyped to test the look, touch and feel of Telltale, others are experiments with principles of the material, mechanical and structural performance over time. While it will be robust enough to sit on and use during the study, functional aspects with respect to the speed of in/deflation will only be periodic (and not immediate) and the wireless reading and processing of data from the electricity meter will be accomplished through an analog Wizard-of-Oz technique. Choices about which and how to treat different aspects of the prototype to elicit feedback for further design development have been based on a tradition of prototyping techniques within experience prototyping and interaction design (cf. Houde & Hill, 1997; Buchenau & Suri, 2000; Ashby & Johnson, 2002).

DISCUSSION

The becoming-ness of the new materials opens new possibilities for design in terms of creating responsive and adjustable environments but as argued throughout the paper it also poses some significant challenges. They are not simply discovered (by science) but applied (by designers)—and they are not only shaped by, but also shape, use and users. This means that designers need to know the technical possibilities in order to build an understanding of the materials and their potential applications, as well as the potential experiences and behaviors effected by the materials in future use. Becoming materials' technical complexity necessitates involvement from several disciplines (i.e., materials science, computer science, electronics, and various branches of design) for new materials to be developed and for developed ones to be used according with their potential. The technical side, however, is complemented by equally complex aesthetics, which entail a heightened sensitivity towards the context and use over time compared to both functional and traditional materials.

While a process oriented towards technical perfection moves forward by means of improving the properties of a material, a process oriented around aesthetics needs to explore potential expressions at the level of human perception and experience from the start. In practice, this often entails a huge gap between the technical development process that, in the case of many new materials operates at microscopic or even nano scales far below the threshold of human perception, and the design process concerned with high-level issues such as use, experience, and aesthetics. This creates a paradox for design—although we may want and need to work with the aesthetics of materials from the start of the development process, it is often not possible to work directly with the actual materials until the very end.

Because of these difficulties it might be argued that design should wait until the actual technology is fully developed and available in order to avoid misconceptions that might arise from discrepancies between the prototyping techniques and the final technology. However, one consequence of such an argument would be that design would only ever be placed ‘downstream’ of science and technology, reacting to rather than participating in and contributing to materials development.

This paradox for design with respect to new and becoming materials is in many ways quite similar to problems in other areas of design that are close to technology development, such as interaction design. In fact, interaction designers have been active in transforming practice in order to deal with the need for interdisciplinary collaborative work as well as experimental prototyping processes. A repertoire of techniques has been developed in order to explore material expressions and use experiences long before the final technology is implemented or even decided. For example, paper-based and Wizard-of-Oz prototypes that suggest how an interface might behave or be used within various contexts (cf. Ehn & Kyng, 1991; Buchenau & Suri, 2000; Mazé & Bueno, 2002; Dunne, 2005). These can range from low- to high-tech, from low-fidelity mock-ups to highly-resolution models, from unique one-offs to limited production runs. In addition to the expanding range of techniques in interaction design, we can also identify related materials practices—for example, as architecture operates at the intersection of craft techniques and new technologies (Mori, 2002; Runberger, 2008).

While, typically, arguments emphasizing material practices over language-based approaches to (artistic and design) research are attempts to articulate the experiential knowledge of the (often crafts) practitioner, our argument departs in some respects. Even as we see the benefits and necessity of building on established and existing materials traditions and techniques, we also argue for recognizing and making explicit emerging approaches to material practice today. Such approaches are a response to the particular challenges (as discussed, involving both technological and interdisciplinary aspects) of contemporary research and design development in the field. Indeed, the expanding range of concepts and methods within material practices is also a proactive engagement with a new scope of aesthetic expressions in art and design. Further developing a conceptual language as well as new forms of material practice can provide a basis for knowledge transfer and collaborative work between disciplines.

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Developing Knowledge for Design by Operationalizing Materials

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ABSTRACT

There is a material side of design that we cannot address through the studies of use and social practice—the properties and potentials of materials, forms, and structures must be explored through another kind of studies. Based on two cases of experimental design research we analyze of what such studies could consist—how we can operationalize material objects by engaging them in situations that give us access to their properties and enable us to explore their potential.

INTRODUCTION

In experimental design research (cf., Binder & Redström, 2006, Brandt & Binder, 2007, Hallnäs & Redström, 2006, Koskinen *et al.*, 2008, Rendell, 2000, and Seago & Dunne, 1999) we see a myriad of different experimental setups. Generally, however, the experiments comprise three elements: a question, an operationalization of the subject matter, and an evaluation of the result. The question can be more or less explicitly formulated. It can be anything from a distinctive hypothesis to a vague conception. Nonetheless, it sets the scene for the subsequent actions. The operationalization is the kernel of the experiment. It is the action in which the answer is sought. It is the action that engages the subject matter in an eligible manner and through the subject matters' resistance gives us access to knowledge about it. For example, when measuring the length of a table with a ruler does the ends of the table provide the resistance that gives us access to its length, or when inviting people to use an artifact their interaction with the artifact will provide the resistance that gives us insight to its usability. Thus the operationalization is formed by the question, but it is also formed by the subject matter. Lastly, the evaluation is a correlation of the question and the result of the operationalization. The result of the operationalization may invite us to reconsider the question and may even constitute an answer. Hence, the type of evaluation depends on both the question and the operationalization, and can be anything from statistical analysis to aesthetic estimations.

In design research it is common to encounter *use* as the operationalization of artifacts (cf., Brandt & Binder, 2007, and Koskinen *et al.*, 2008). For example, when we design an artifact we are inclined to determine its value through exposing it to a situation of use (cf., Routarinne, 2007 or Wensveen, 2002). Such exposures enable us to study how people interact with it, if they use it as intended, or if they perhaps reinterpret the intentions. Another example is when artifacts are employed in situations of use, not to learn about the artifact themselves, but to learn about forms of interaction and the contexts of use (cf., Brandt, or Gaver *et al.*, 1999). In all these types of experiments *users* are employed as the reality whose actions, in the situation of use, constitute the resistance that we measure the artifact against, or the resistance that provides the premises for future designs. Since design always contains an aspect of use these operationalizations are significant in developing knowledge for design. Design, however, is more than use and forms of interactions. Design is also materials, forms, structures, expressions, production techniques etc. Yet, what do operationalizations look like when focus is on these other aspects of design, when materials or forms are the subject matter?

Ezio Manzini argued, “every object made by man is the embodiment of what is at once thinkable and possible” (1989, p. 17). We can push the borders for what is thinkable by making new connections and push the boarders for what is possible by improving our knowledge of the subject matter, and developing new possibilities. All of which, will constitute valid and valuable contributions in a discipline of design research. Indeed, rendering a new area of imaginable possibilities is what is also referred to as rendering a new *design space*. The question remains, however, how do we do that in a material context? What does it take to make probable that the new material connections lead somewhere? How can we obtain knowledge of the materials that are not immediately accessible to us? What does it take to produce the new material possibilities? It seems that conducting experiments is an inevitable strategy to honor these endeavors, and in that light the questions can be narrowed down to: What constitute acceptable operationalizations? When can we say to produce a sufficient and suitable resistance as the basis for developing knowledge?

Through two cases of experimental design research we analyze some examples of operationalizations and discuss how they enable valid and valuable research contributions. First, however, we elaborate what we comprehend by valid and valuable research contributions. Second we present the two cases. The first case is an exploration of textile formations based on acoustic qualities in an architectonic context. The second case proposes a new understanding of the computer as a material for design. Both refrain from any user evaluations, but they do rely on general notions of human perception and sensorial presence in the world.

VALID AND VALUABLE KNOWLEDGE

When conducting design experiments as a research strategy we need to be sure that what we take from these experiments are in fact, valid and valuable knowledge. Experiments in design research do not always hold the same stringency as experiments are expected to hold in science, which is probably resulting from differences in the general research purpose. Where science, roughly speaking, is engaged in revealing the truth about their subject matters design research is engaged in developing ways to make new and better designs. Thus experiments in design research require another way of judging their validity and their value.

Michael Biggs (2006) argues that work is judged as design research based on three necessary and sufficient conditions: its originality, its contextual grounding, and its dissemination to peers. Based on this we could say that a work is a *valid* research contribution if it through dissemination contributes original knowledge on a subject matter. Explicit contextualizing and meticulous studies enable us to determine the originality of a research contribution, but to enhance the chances of originality in the process we are obliged to seek new approaches—to make new connections. Whether the contribution does indeed constitute knowledge is, however, a somewhat trickier question. To ensure this, both in prospect and in retrospect, the premises that the knowledge is founded on must be accessible to us—they must be articulated and substantiated. If they are not immediately accessible, they must be made it through various ways of operationalizing the subject matter as, for instance, through the experiments described above. Furthermore, the *value* of a research contribution can be described as its relevance to the context intended—that it improves the general knowledge of the subject matter. The relevancy is determined by relating the new knowledge to its expressed context either through previous written accounts (i.e., previous research contributions) or through operationalizing the context. The value of a research contribution is, however, not necessarily the same as its applicability in praxis. These are the understandings on which we will judge the work in the following two cases.

CASE ONE: THE TEXTILE FROM OF SOUND

The Textile Form of Sound is a project investigating the relation between sound, textile, and form. The purpose is to study how acoustic and aesthetic desires can be equally obtained through forming and situating textiles in various ways in an architectonic context.

How spatial forms can regulate sound and through that create strong aesthetic qualities has been widely studied within architecture both in theory and in practice (cf., Long, 2006, Rasmussen, 1957, Blesser & Salter, 2007). These studies, however, primarily deal with spatial forms derived from conventional building materials such as stone, glass, and wood, with little or no mention of textiles.

Figure 51 Bagsværd Church, designed by Jørn Utzon is an example of how the regulation of sound have influenced the form of the room especially the ceiling. Photo by: Søren Kuhn

Furthermore, research in acoustic regulation with textiles, has primarily been focused on textiles' inherent acoustic properties meaning the properties procured by virtue of the fibers, their density and weight, and the way they are joined together (cf., Tooming, 2007, Rindel, 1982, Persson & Svensson, 2004). Whereas research, on acoustic properties obtained through forming and situating the textile, has been scarce. Sound, however, is a physical phenomenon dispersed through space, the physical formations of the space are likely to influence it. This makes probable that three-dimensional forms of textiles, and their situations will have an equal influence on the acoustics of the space. Also, when introducing form and situation into textile sound regulation it opens a new realm of aesthetic expressions ready to be explored.

Based on three different experiments this project sets out to study various aspects of the relations between textile, form, and sound. The first experiment investigates techniques to create textile architectonic forms. The second experiment measures the acoustic properties of various textile forms and situations. And the third experiment (still ongoing) combines the results from the others and investigates how textiles techniques can create forms to regulate acoustics and still perform aesthetically in an architectonic context.

Experiment One

In the first series of experiments, we employed different textile techniques to create functional forms yielding to an aesthetic ambition of expressing a spatial sensation. The purpose of these experiments in the overall project was to develop an understanding of textile forms as architectural elements.

Textiles generally consist of fibers woven into each other in a way that forms a plane. The plane appears continuous as a material capable of dividing space, but it is merely an accumulation of small spaces enclosed by material. Inspired by this duality we experimented with different scales and weaving techniques to, on one side, emphasize the perforated structure, and on the other side keep the continuous plane capable of dividing space. Furthermore, a woven textile consists of layers. By separating them and introducing a depth in the plane the textile will literally gain two sides each expressing their aspect of the duality. In a woven structure, however, the threads intertwine in a way that makes them curve. These curves hold together the structure as a plane but counteract the intention of separating the layers to enhance the spatial airy expression. So we developed a special weaving technique, which avoids curving the threads and still created the closed plane. The figure below is a demonstration of the technique used on ten cm wide textile bands as threads.

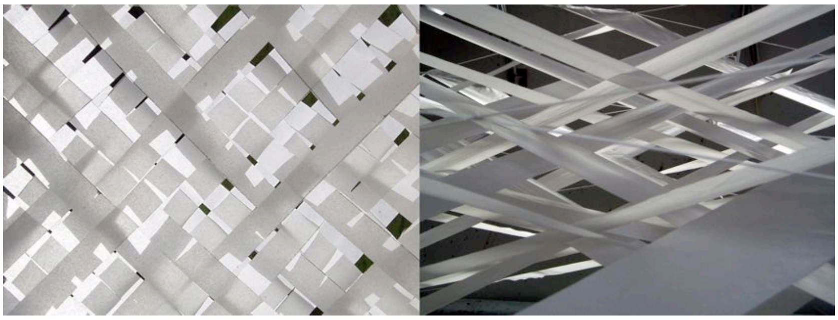

Figure 52 Left: the textile structure is seen from the front. Here it forms an almost closed plane. Right: the textile structure is seen from the side. Here it forms an open matrix of crossing bands.

This weaving technique let us create a textile form in which the space extends into the plane and dissolute it as a continuous element. This textile form blurs the boundary between the spaces on each side, but still it maintains a visual screen between the two. It will let the wind flow through while the sunbeams are withheld.

Experiment Two

The second series of experiments was an investigation of the acoustic importance of textile form and location in an indoor space. The aim was to form a general understanding of the correlations between acoustic qualities of a space and the textile's forms and locations in that space. We conducted altogether 100 experiments.

In one of them, we investigated the acoustic absorption potential in relation to the distance between the textile and the wall. Sound consists of waves, and its frequency determines the wavelengths. The experiment was conducted in a laboratory using a frequency analyzer to measure the reverberation time, meaning the persistence of sound in the room after the original sound was made. When sound waves are absorbed in the textile, the reverberation time goes down. We started by analyzing the most simple textile form—the straight plane, in order to focus on the relations between the situation of the textile and the reverberation time. The textile was a canvas of woven cotton (325 g/m^2) mounted on wooden frames in pieces of five m^2. In the laboratory we placed the mounted canvas in distances of 2, 50, 100, 150, or 200 cm from the wall. The test sound was made blowing paper bags, which created a sound containing the whole spectrum of frequencies.

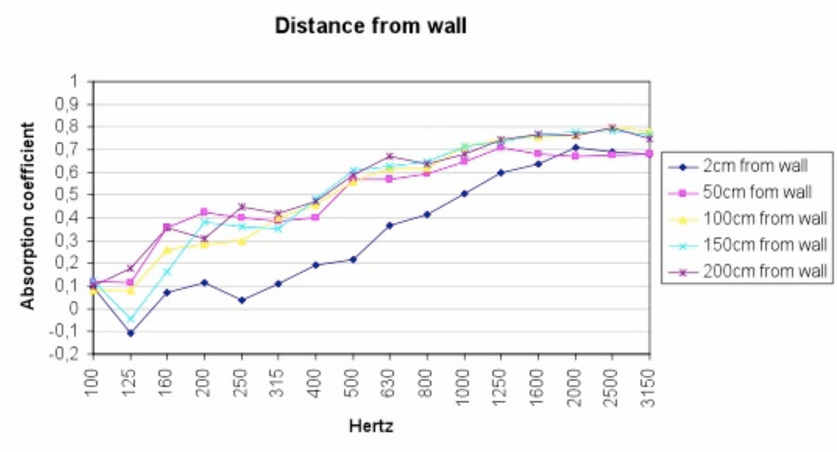

Figure 53 A diagram showing the reverberation results of five different canvas locations.

Analyzing the test results it became apparent that the distance between the canvas, and the wall played an important role. The diagram (in Figure 53) shows that the reverberation time is approximately the same when the canvas is placed 50, 100, 150, or 200 cm from the wall. In these locations the canvas turned out to exhibit only little absorption of the low frequencies, more in the middle range while it proved most efficient with respect to the high frequencies. Where the canvas placed two cm from the wall generally exhibited lower absorption abilities—especially regarding the low and middle range frequencies. Thus, the textile plane should be placed above two cm from the wall to exhibit its full potential of frequency absorption. Fifty centimeter, however, is a sufficient distance just as any distance between 50 and 200 cm is equally efficient.

Experiment Three

In the third experiment we combine the knowledge from the two preceding experiments to investigate how to develop textile forms with acoustic regulation abilities suitable for architectonic contexts. This experiment is barely begun.

The architectonic context is narrowed down to three acoustic interesting spaces: multiple divided spaces (e.g., office cubicles), spaces for performance (e.g., auditoriums), and passages (e.g., hallways). The general approach is inspired by Utzon’s church (See Figure 51) in the sense that the acoustic effects will lay the ground for the textile's forms and locations within the three types of spaces. The process will be a negotiation between acoustic measures and aesthetic qualities to gradually create textile forms suitable for the chosen spaces. The aim is to explore the textile shape of sound in an architectonic context and thus develop knowledge of how textile forms can enter architecture as more than subsequent acoustic patches.

CASE TWO: COMPUTATIONAL COMPOSITES

Computational Composites is a project about understanding computers in a design context. There are several notions of the computer; for example, as a logic machine, as an instrument to manage complex models and procedures, as a media device, as an information, or communication technology, or as a tool for word-processing, accounting, or drawing. When it comes to understand its role in design, however, there seems to have been more attempts of concealment (e.g., the invisible computer (Norman, 1999), the unremarkable computing (Tolmie, 2002), or the seamless and ubiquitous computer (Weiser, 1991)) than of articulating its inner workings and its properties relevant when utilizing it in designs. With this project we thus, sat out to investigate and articulate the computer in a material and practical context of design.

Computational Composites

The first part of the project was a theoretical comparison of the computer and traditional materials as used for design. The purpose was to see whether a material view of the computer would afford an understanding and enable an articulation suitable for developing new expressions of computational artifacts.

For example, we realized (Vallgårda & Redström, 2007) that a computer in and by itself is worthless and that it always must be in composition with other materials for the computations to come to expression. We derived at this notion from the fact that computations consist of energy manipulated in a delicate system of capacitors and connections and that the binary construct is a matter of whether energy is flowing or not. Though humans possess a sensitive sensory system, we cannot immediately detect whether the energy flows or not—at least not at this level of voltage. From a material point of view this means, that a computer needs to be part of larger material composition to come to expression. Hence, we arrived at the concept of *computational* *composites*, which is the material form that a computer must always find itself in when it is an element for design. A composite, composed of a computer, and one, or more materials capable of responding to the energy output of the computer and reflect the binary changes accordingly.

Experiment One

The first experiment (Vallgårda, 2008) was designed to ascertain whether the material understanding of the computer appeared advantageous in producing new expressions. The task was to create a computational composite and to do it so it had no immediate or useful functionality but a potential to spark the imagination of other computational composites. To escape the traditional expressions of computations—including the various tangible displays—we chose to take an offset in the other parts of what was to be the composite. The idea was to change the expression of an already familiar and traditional material through the computer's ability to conditionally control changes between two or more states. Also, the expression we sought was to be strangely familiar as an attempt to make the parts and the whole stand out at the same time giving the observers some handles to rearrange the material components in their imagination (cf., Blauvelt's strangely familiar (2003), or Dunne's parafunctionality (2005)).

We chose wood for its tradition, its flexibility, its strength, its natural occurrence, and its general disassociation with computers. As expressive modes we chose a combination of sound and movement creating an almost humanoid cause-and-effect (*if* sound *then* movement). The resulting material (called PLANKS) is a plank of pine gradually bending towards the observer when the sound rises above a certain threshold (adjustable to the context) and gradually rising to a straight position with declining sonic activity.

Figure 54 Nine PLANKS placed on a stand shown from the front and the back with the visible computational layer.

The PLANKS are not displays of computations rather the computations are a way to achieve an expression of the material, in this case, through translating sound into movement in the wood. The PLANKS, however, can be used to build displays, for instance, of the noise in the room, but they can just as well be used to add a non-practical aesthetic expression to the walls of a room. The PLANKS exemplify a computational composite but more than that they hold an expression new to both wood and computers. They exemplify how we can combine different material components in new ways, how we can make ordinary materials behave differently by adding computations to their composition.

Experiment Two

If the first experiment established some ground for the potential of working with the computer as a material it did not give much insight into the computer's material properties. Material properties can be seen as the characteristics of the material that tells us how it will behave and appear in certain situations. Knowledge that is valuable when discriminating one material over another in a design situation.

Hallnäs and Redström (2006) already identified temporality as a significant property of computations. They argue that as computations are sequences of events in time, any meaningful incorporation of computational technology must adapt a temporal form. More can be said, however, about the potential of the computations in a material context. Through studying the principles of the computer, we can easily determine some properties and infer whether they may play a role in a material context. To be able to understand how they will come to expression as material properties, however, we need to explore them in praxis. With this series of experiments we will study: the ability to control events outside the computer and the ability to form networks with other computers.

Control is about causality. Through more or less sophisticated algorithms (confinements on the energy flow) the computer can exhibit practically any desired cause-and-effect (if X then Y). In a material context this means, for instance, that any normal behavior in a material can be exaggerated, moderated, reversed, or in other ways modified. The only restrain is that there exist elements (transducers) outside the computer capable of sensing the causes and execute the effects on the computers command.

Figure 55 Illustration of a computational composite that turns colder the more you attempt to heat it up.

To experience this property we are in the midst of making a computational composite with the ability to turn cold when warmed up and warm when cooled down. Through using copper, Peltier elements (elements for heating or cooling depending on the direction of the current), temperature sensors, a power source, and a small computer we create a composite material with a behavior contradicting any previous experience with copper and similar metals. The copper still behaves as it always does when exposed to shifting temperatures, but the computer inverts the general behavior through exercising a control over the Peltier elements and thus producing a counter effect.

Connectedness in a material context is traditionally about apparent physical coherence. Introducing the computer's ability to form wireless connections of computations produces an opportunity to form composite materials that are physically divided yet behaves, as were they physically coherent. This could for example be a physically disjoint material behaving thermodynamically as if it were one entity, which would mean that if one part of the material were cooled down all the parts would respond through adjusting to a new equilibrium.

The experiment is designed to explore the experience of the connectedness in a disjoint material. With the same ingredients, as used above, we build a material sample allowing us to explore the relations between the computations and the material.

Figure 56 An example application of a material, which is physically dispersed but thermodynamically coherent. For instance, the warmer the cop is the warmer the back of the seat and the area of the table gets and *vice versa*.

The Becoming in Materials

If these experiments in their ways establish the ground for making the connection between computers and materials, it leaves us obliged to ask what type of material the computational composites are. What have we done to our understanding of materials by including computers?

According to Manzini (1989) we seem to operate with two views of materials: their *being* and their *doing*. The first view especially addresses the generic materials we have known and worked with through generations (e.g., stone, wood, textile, clay). Materials, which can serve many purposes and which properties we know through direct experience. The other view especially addresses the materials developed with designated purposes, materials that are characterized by their functionality (e.g., plastic, electroluminescent film, or self-cleaning clay tiles).

Through experiencing computational composites both the ones made in the experiments, and those done by others (cf., Chronos Chromos Concrete (Ritter, 2007) or smart textiles (Post *et al.*, 2000)), and through contemplating what type of material a computational composite is it becomes apparent that a significant trait in these composite materials is their ability to change expression between two or more states and to do so repeatedly—sometimes in accordance with changes in the environment. We know other materials to patinate, degenerate, and decompose thus; gradual change is not new to materials. We also know materials to repeatedly change expression according to contextual conditions—the most apparent being light, which can change the expression of a surface; for instance, when the sunbeams move over a façade during the cause of the day they change its color drastically. Computational composites, however, invites us to see this behavior in time as more significant as these materials explicitly holds the ability to constantly assume other states (expressions) under certain conditions makes them constantly *come to be* in interaction with their environment. To comprehend these materials' potential we thus need to apply a third to Manzini's two views namely that of *becoming*. Thus the computational composites along with other new smart materials (e.g., shape memory alloys or thermoplastics) emphasize a new aspect of the material world.

OPERATIONALIZATION

These two cases represent a series of different approaches to developing new knowledge for design. Both, however, rely on operationalizations of materials to form the ground for their reasoning. We will in the following sections use the cases to develop an understanding of these operationalizations. How they are designed to ensure suitable and sufficient resistance.

First, however, let us recapitulate what we mean by operationalization. Operationalization is the act of exposing a subject matter to a situation in order to gain access to knowledge about it—its properties and potential. We need various ways of operationalizing the world around us to engage with the parts that are not immediately present or knowable to us. For example, we can immediately see that the leaf on a tree is green, but we need to expose it to various chemicals and study it in microscopes to know why. Operationalization is thus, the act that enables us to present the subject matter as distinctive premises, which then can form the foundation for reasoning. The premises are not independent of the type of operationalization but partly defined by it; for instance, the table length is given in centimeters if the ruler is divided in centimeters. Furthermore, the operationalizations also provide the resistance to shape or reshape our ideas. They can inspire new connections and contribute to developing new possibilities.

There are two main influences on the operational design in a material experiment. The first is the purpose of the operationalization—what type of knowledge is it that we are seeking? The second is the material conditions, what type of material or form are we are dealing with—how approachable is it?

THE OPERATIONAL PURPOSE

In the two cases presented above we see two different purposes for the material operationalizations. One is to explore an idea, either an articulated theory or merely an urge. The operationalization will in this case be a manipulation of materials as a means to form a resistance to the idea, for example, to explore how the idea can be materialized, or merely to exemplify its value through embodiment. This type of operationalization is about forming and exploring a new design space. The second type is formed by a desire to gain a better understanding of the material or form at hand. This type plays a more indirect part of rendering new design spaces, as its purpose is to allude to the spectrum of possibilities through knowledge of what lay before us.

Rendering New Design Spaces

In the first series of experiments in the first case various techniques are applied to textiles in order to create forms that satisfy a rather vague set of aesthetic and functional intentions. Manipulating the textile into a form is the act of operationalizing the material—we engage with the material resistance. In this particular case, it brings forward an architectural form, which explicates a relation between space and material also found in woven textiles. First, magnifying the threads into ten cm wide bands accentuates the spatial relations within textiles and makes them available for direct experience. This magnification also provides the premise on which we can reason textiles' applicability as a spatial element on an architectural scale. Second, developing the new weaving technique, which avoids curving the bands, enables us to create a form that has both depth and width, and which exhibit the almost paradoxical aesthetics of being airy and permeable yet a continuous plane. This textile form suggests a relation between space, material, and scale, which satisfy the intentions of the textile architectural elements. This form, however, is only one in a series of forms that together constitute a more elaborate satisfaction. They claim novelty in their forms and techniques, but they do not claim to be exhaustive representations of the all-possible forms. By embodying some significant aspects of the relation between textiles and architecture, however, they render a new design space—they expand the border of what is *thinkable and possible*.

In the first case's third series of experiments, the operationalization will be to develop textile forms with specific acoustic qualities and to install them in chosen architectural contexts. The operationalization will be to shape and reshape the textile using all the knowledge obtained in the previous experiments and to estimate how the textile forms can find a functional and aesthetic place within the architectural contexts. The purpose of these experiments is thus, also to render a new design space for architectural acoustic textile forms.

In the second case, the experiments are weighted slightly different. First, developing the concept of *computational composites* can in itself be framed as an experiment where the notion of materials is used to explain the computer. This experiment is not a negotiation with materials, but a negotiation between conceptions. We operationalize the notion of computers by exposing it to the notion of materials. Through meticulously explaining every aspect of the computer in terms of material traits the premises for understanding the computer as a material for design are laid out. But, whether this concept hold any value is difficult to judge from theoretical endeavors alone. It is a new way of thinking, and it is possible in theory.

The first material experiment is therefore arranged to evaluate whether the material approach is feasible in practice and whether the concepts can inspire new expressions of computers in a material settings. It is an operationalization, which is to embody the suggested new design space of computational composites. It is a materialization of a computational composite seeking the resistance from the actual construction and from the possibilities rendered by the new concept. The choices of materials and expressive effects are made from the need to achieve a new expression of a material for design. The strategy was therefore; first, to focus on the expression and let the function be secondary, second to aim for something strangely familiar, and third to build a prototype of a material sample that in theory can be utilized in design of something. The resulting composite material is the outcome of a negotiation between the concept of computational composites, the elements of the strategy, and the materials. For example, as a possible offset for the composite we examined wood since it is a material not traditionally associated with technology. We identified some expressions in wood made possible only through a composition with a computer-controlled force. We found that a thin plank of pine had the strength and flexibility that would allow us to continuously flex it to an interesting degree. We estimated that such behavior could create a strangely familiar expression since bended planks represented a common expression, but moving planks did not. The sonic sensitive bending planks embody only few aspects of the new possibilities claimed by the concept of computational composites, but it is sufficient to establish some value of the concept. It is able to link the theoretical articulation of computers as a design material to a practice of design.

Gaining New Knowledge of Materials

In the first case's second series of experiments, the textile forms are tested for their acoustic qualities. The operationalizations constitute placing the textile forms in the room and expose them to the sound of an exploding paperback, and a specialized instrument catches the outcome of the operationalizations (the reverberation time). Together with acoustic theory this instrument provide an alternative to rely directly on human perception. It enables us to perform the experiment with simpler operationalizations than if we were to rely directly on user experience. The layout of such a study would, most likely, require an experience report from a significant number of users. Instead, we rely on an instrumentalization of the user experience. In this experiment, the measurements serve as the premise on which we can reason about the tested textile forms' ability to absorb the range of frequencies and the significance of their situation in the room. This type of operationalization enables development of new knowledge of the materials and forms, knowledge which is valuable to render what is possible.

The second case's other experiments are grounded in the material science tradition of studying the properties of materials—properties being the characteristics that enable us discriminate one material from another. The computer, however, cannot be studied in and by itself due to its lack of humanly perceivable expressions. We are therefore obliged to divide the study of its material properties into a theoretical inquiry of computers to identify possible material properties and a development of material samples especially attuned to express those properties. The two materializations embody only a small sample of what can be done to gain a better understanding of the computer as a material for design, but equivalent experiments will gradually materialize the computational composites as a new material for design. These material samples constitute the operationalization that enables us to discern what is possible with computers in a material context.

The last element of the second case is not an actual experiment, but a reflection on the premises revealed by the computational composites and put in a context of Manzini's notion of material views. The outcome serves as an additional focus on materiality and captures aspects of materials that always existed, but has not been significant to design before the introduction of smart materials and computational composites. Also, placing the new computational composites in relation to other materials contributes to a better understanding of them as materials.

MATERIAL ACCESSIBILITY

Textile is a material directly accessible to us, we can weave, cut, shape, sew etc. and thereby get an immediate tactile experience that helps us form an understanding of the materials potential. Computers, on the other hand, are only accessible to us by proxy and thus, to gain an understanding of its potential we strongly depends on a theoretical superstructure. The two materials thus can be seen to represent each end of a spectrum in terms of accessibility. The two cases also differ in their experimental setups. In the first case the textile allows for an immediacy of testing an idea, just as the ideas seems formulated in more direct negotiation with material manipulations. In the second case the layers between the computer and the researchers affect the ways with which ideas can be formulated and tested. The immediacy is to some extend substituted with theoretical contemplations; thus, the role of the material resistance in developing knowledge of the computational material for design is toned down in comparison, however, still necessary to ensure the validity of the theoretical contemplations and also at times to inspire new ideas.

Another dimension of material accessibility, one less expressed in the two cases, is the matter of skill needed to operationalize them. While weaving and sewing requires some skill it is not hard to master, and merely bending and cutting textile requires no particular skills; thus, operationalizing textile is also in that respect very accessible. In comparison, blowing hot glass into an object requires plenty of training so even if glass is tangible (and breakable) in its cold state it is not accessible to us in terms of operationalizations with same immediacy as textile. Further, the computer's energy flow is generally formed through arranging representations in form of a program, an act which also has undergone some theoretical abstractions to bridge the gap between humans and the inaccessible energy flow. The skill of programming is, because of the abstractions, another reason for the slighter immediacy and more weight on the theoretical superstructure needed to operationalize the computer to gain knowledge about it.

CONCLUSION

In this paper, we have shed some light on what operationalizations in material experiments can look like and how they can produce valid and valuable knowledge. We have, for instance, argued that manipulating textiles into architectural forms constitutes a valid premise for developing knowledge for design _exactly because the material is engaged as a resistance to the ideas. On the same account, we have argued that computational composites constitute a valuable perspective on computers in respect to forming new expressions. We have also argued that the accessibility of the materials influences the means with which we can operationalize them—the less accessible the more weight needs to be given to the theoretical superstructure. The other significant influence on the operational design is the reason to carry out the experiment whether it is a quest for deeper understanding of a subject matter or whether it is a quest for new frontiers.

One point of focusing on the operational part of experiments is the opportunity to show why the material resistance constitutes a valid and valuable foundation for developing knowledge for design in line with, for instance, user studies. Another point is that it enables us to become better attired in subsequent experiments to determine which type of operationalizations will suit the purpose better.

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Abstract

The problematic addressed in the dissertation is generally shaped by a sensation that something is amiss within the area of Ubiquitous Computing. Ubiquitous Computing as a vision—as a program—sets out to challenge the idea of the computer as a desktop computer and to explore the potential of the new microprocessors and network technologies. However, the understanding of the computer represented within this program poses a challenge for the intentions of the program. The computer is understood as a multitude of invisible intelligent information devices which confines the computer as a tool to solve well-defined problems within specified contexts—something that rarely exists in practice. Nonetheless, the computer will continue to grow more ubiquitous as moore's law still apply and as its components become ever cheaper. The question is how, and for what we will use it? How will it, for instance, be implemented in design and architecture, and in what new directions we will take the technological developments? We need a new understanding of the computer to guide these developments as none of the previous apply to these new conditions and new oppertunities.

I propose that we begin to understand the computer as a material like any other material we would use for design, like wood, aluminum, or plastic. That as soon as the computer forms a composition with other materials it becomes just as approachable and inspiring as other smart materials.

I present a series of investigations of what this understanding could entail in terms of developing new expressional appearances of computational technology, new ways of working with it, and new technological possibilities. The investigations are carried out in relation to, or as part of three experiments with computers and materials (PLANKS, Copper Computational Composite, and Telltale). Through the investigations, I show how the computer can be understood as a material and how it partakes in a new strand of materials whose expressions come to be in context. I uncover some of their essential material properties and potential expressions. I develop a way of working with them in a design process despite their complexity and non *a priori* existence, and finally I argue that these investigations form both valid and valuable research results within the context of design research.

Co-author Statements