A Maker's Mechanological Paradigm

Seeing Experiential Media Systems as Structurally Determined

by

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ABSTRACT

Wittgenstein's claim: anytime something is seen, it is necessarily seen as something, forms the philosophical foundation of this research. I synthesize theories and philosophies from Simondon, Maturana, Varela, Wittgenstein, Pye, Sennett, and Reddy in a research process I identify as a paradigm construction project. My personal studio practice of inventing experiential media systems is a key part of this research and illustrates, with practical examples, my philosophical arguments from a range of points of observation. I see media systems as technical objects, and see technical objects as structurally determined systems, in which the structure of the system determines its organization. I identify making, the process of determining structure, as a form of structural coupling and see structural coupling as a means of knowing material. I introduce my theory of conceptual plurifunctionality as an extension to Simondon's theory. Aspects of materiality are presented as a means of seeing material and immaterial systems, including cultural systems. I seek to answer the questions: How is structure seen as determining the organization of systems, and making seen as a process in which the resulting structures of technical objects and the maker are co-determined? How might an understanding of structure and organization be applied to the invention of contemporary experiential media systems?

DEDICATION

For my loving wife, Diana, who always believed in me, even through all the times I couldn’t tell her what my dissertation was about, because I didn’t yet know myself.

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PREFACE

In some sense, the subject of study in this dissertation is myself. Or perhaps a better way of framing my meaning is to say that my topic of research was highly motivated by my own observable patterns of thinking, making, researching and writing. This work, and my methodology may be considered, at least in part, to be autoethnographical (Knowles & Cole, 2008). In the process of evolving my research, defining this research in the form of a dissertation proposal, and ultimately translating this, with significantly more transformations, into a dissertation, I wrote folders full of outlines, concept maps, literature reviews, partial chapters, introductions and conclusions. All of them, excepting a final few, felt like false starts. The trails of ideas either terminated prematurely in a tangle of brambles, or much more frequently, bifurcated and trifurcated into an exponentially expansive network of paths, leaving me just as lost as I was in the brambles. In the months, then years, of this process playing out, I kept returning to the form of thinking that brought me to this PhD program in the first place: thinking through making. I found continual comfort, focus and mental stimulation while in the flow of conceiving, designing, building and programming new systems. In this tangible work I found a solidity of function, a unity, an "internal resonance" (Simondon, 1958, p. 13) that was hidden to me in my writing efforts. I began to look at the process of making, and ultimately the nature of human-made objects as the subject matter for my research. I discovered, with helpful guidance from my committee, theories of enaction and embodiment, philosophies of craftsmanship--and, importantly, the field of mechanology. From these foundations, I was able to stop looking for what research to do and write about, and finally recognize that I had been conducting a form of research all along. Henk Borgdorff (2006) describes how such a practice may be seen as research,

> Art practice qualifies as research if its purpose is to expand our knowledge and understanding by conducting an original investigation in and through art objects and creative processes. Art research begins by addressing questions that are pertinent in the research context and in the art world. Researchers employ experimental and hermeneutic methods that reveal and articulate the tacit knowledge that is situated and embodied in specific artworks and artistic processes. Research processes and outcomes are documented and disseminated in an appropriate manner to the research community and the wider public. (Borgdorff, 2006, p. 23)

This document presents a synthesis of, and extension to theories on the nature of human-made objects and the process of making them. I present this research with a focus on the materiality of my contemporary media practice. As this dissertation evolved I recognized that it, like my other studio products, was a system that I was building and that all my prior research, making and writing was an essential part of this ‘paradigm construction project’.

CHAPTER 1

INTRODUCTION

In this dissertation I seek to answer these research questions:

How is structure seen as determining the organization of systems, and making seen as a process in which the resulting structures of technical objects and the maker are co-determined? How might an understanding of structure and organization be applied to the invention of contemporary experiential media systems?

I contextualize the generation of these questions within this introduction, starting with these observations on the process of making, from my point of observation as a maker and as an observer of other makers. Media artists often start with a desired interaction, behavior, or other dynamic functionality in mind. They go about programming, wiring, constructing and networking their system with functionality as their guiding vision. Other media artists start with specific materials, which might include code, electronics, language and other intangible materials, and work to define the forms and relationships between these materials. Either path may lead to a system that satisfies the primary end goals of the creators, but both approaches may have significant compromises. A strictly function-oriented approach may result in the desired function, but with an arbitrary form. A strictly form-oriented approach may result in the desired form, but with an arbitrary function. Of course neither approach is typically, if ever, strictly adhered to. In almost all cases, some attention is given to both form and function; though this attention is likely to toggle between these concerns. Rarely is the focus simultaneously on form and function. At a high level, this is the purpose of the research represented by this dissertation: to present a paradigm in which form and function are seen as an integrated whole, and to see experiential media systems as systems constituted of these integrated wholes. I propose that such a paradigm will reveal new ways of seeing existing media systems, and may inspire modes of thinking and creating that do not isolate form and function as independent, relational variables, but see them as mutually defining variables.

The astute reader will protest that form and function are widely accepted and treated as an integrated whole, particularly in the field of architecture. I would argue that for many, especially those media designers without traditional art, design or architecture backgrounds, this integration may be more of a principle than a practice, but this is not my main point. I will clarify my meaning and use of terminology. I specifically introduce this topic using the terms ‘form’ and ‘function’ because I believe that these terms and the phrases ‘form and function’ and ‘form follows function’ (L. H. Sullivan, 1896) will be familiar and meaningful to most readers and that this initial understanding will serve as a bridge to my intended meaning.

The phrase I use in this dissertation to describe the integrated whole akin to that described in terms of ‘form and function’ is ‘structurally determined system’ (Maturana & Varela, 1980; Maturana, 1987, 2002). As a transitional step, one may consider the term ‘form’ to be replaced with ‘structure’ and ‘function’ with ‘organization’. These terms are not interchangeable and the differences will emerge throughout the body of this text, but I find the relations and distinctions between them quite useful in deepening my understanding of all of these terms. I derive this terminology and theoretical meaning of ‘structurally determined systems’, ‘structure’ and ‘organization’ from the biological and philosophical writings of Humberto Maturana and Francisco Varela (1980; 1987, 2002). I extensively cite Maturana’s 2002 summary of these ideas (2002) to capture his contemporary take on the subject matter, but recognize, as Maturana himself notes, that the origins of these ideas date significantly further back and represent collaborative thought and effort.

The story told in this dissertation starts with the asking of a profound and ultimately very fruitful question:

> In November 1960, a first year medical student asked me the question "What began three thousand eight hundred million years ago so that you can say now that living systems began then?" I realized that at that moment I could not properly answer that question." (Maturana, 2002, p. 6)

Maturana's (2002) quest for an answer to this question led to a significant epistemological and ontological shift in his thinking, and ultimately to his concept of autopoiesis as a characterization of living systems (Maturana, 2002, pp. 5–6). To answer the initial question posed to him, Maturana realized he had to answer the more fundamental question of: "What should happen in the manner of constitution of a system so that I see as a result of its operation a living system?" (Maturana, 2002, p. 5). A question in this spirit gradually took form in my mind as I reflected on my own production of experiential media systems. In a first iteration of this thought process I directly appropriated Maturana's (2002) words, asking: "What should happen in the manner of constitution of a system so that I see as a result of its operation an experiential media system?" Maturana’s statement was likely originally written in Spanish (Maturana, 2002, p. 23) and if not, certainly reflects this linguistic foundation. With additional thought, my emerging research question evolved to ask, “How do the relations of structure and organization, within and between systems, affect how we see the nature of these systems and their interactions?” This question, while central to my topic, is a reiteration and fusion of questions asked by Maturana (2002) and Simondon (1958). My research question is: *How is structure seen as determining the organization of systems, and making seen as a process in which the resulting structures of technical objects and the maker are co-determined?* I ask as a secondary question to focus this research to my domain: *How might an understanding of structure and organization be applied to the invention of contemporary experiential media systems?* I apply these questions to natural and technical objects, and modes of making. I consider how the results of these investigations may apply to a wide range of material and immaterial systems.

Fundamental to the essence of Maturana’s (2002) question, quoted above, is the phrase, "I see as". At a superficial level, this implies a subjective and individual exploration. At a more significant level, "I see as" implies a philosophical stance, a recognition that one can *only* see something *as* something (Wittgenstein, 1953). Varela and Maturana’s (1980; 2002; 1978) theory of structurally determined systems, which will be examined in depth in this document, defines these systems as organizationally closed. By this logic it is not possible to directly know an external system. If direct access is not possible, is there another means of knowing another? Structural coupling will be presented as a response to this question (Maturana & Varela, 1980; Maturana, 2002; Varela & Goguen, 1978).

This dissertation will start with a definition of structurally determined systems. This definition opens up questions of the mechanics of information and perception. These mechanics are seen as a process called ‘structural coupling’ (Maturana, 2002). After laying the groundwork for a general understanding of structurally determined systems, I show how man-made systems may be seen as structurally determined. This is done initially from a theoretical perspective, introducing Mechanology (Simondon, 1958), or the science of machines. Finally, I show that the practice and products of making can be seen as structurally determined. Projects from my own practice as a creator of art and experiential media systems illustrate the theory in practical examples. These examples are spread throughout the document, but feature prominently in the final portion. Throughout these examples I emphasize the materiality of these practices. I conclude this dissertation with a discussion of aspects of materiality and show how systems of all types can be seen in terms of these aspects of materiality. I identify the entirety of my research and writing process as a paradigm construction project and see the resulting document and media systems as snapshots of this dynamic process. A paradigm implies a point of observation. I stress that this point of observation is not singular or fixed, but is instead manifold and dynamic.

My primary research questions unfold into a series of questions, forming the structure of my dissertation. These questions start with those asked by Maturana (2002): How does structure determine the organization of a system? Is the organization of a system maintained when the structure of that system changes? How can organizationally closed systems interact with systems external to themselves? Questions asked by Simondon (1958) continue this sequence: Can technical objects be seen as natural objects? How can technical objects be seen in terms of their evolution? How can margins of indetermination in structurally determined systems be seen as opportunities for information transfer? My questions which follow, are strongly informed by Maturana's and Simondon's theories and philosophies, and underpinned by Wittgenstein's (1953) paradigm that when we see something, we always see it *as* something (Wittgenstein, 1953): How can making be seen as a structural coupling between a maker, her tools and her media? How does making result in a co-determination of the structure of the maker and the technical object produced? How can a maker know their material? How can structure and organization be employed as material computation? How can making and invention be seen as either industrial or artisanal modes of production? Are distinctions between modes of production still valid? In what ways do these modes of production inform and complement one another? How can my material practice illustrate and reveal the theoretical constructs of the philosophical basis of this dissertation? Can conceptual function be considered alongside physical function as an integral part of a structurally determined system? How can aspects of materiality shape the paradigms through which immaterial systems are viewed?

Significance of Problem

Excepting extremely rare examples, we are never separated from technology. Even the most basic, natural clothing we wear represents an embodiment of technology. As technology and society has progressed, our relationship to technology has evolved. Technology is less of a tool we consciously turn to for specific needs and occasions and more of a constant companion that we form a partnership with and coevolve with (Simondon, 1958). For this reason, finding a means of understanding the nature of technology is important, whether we are directly involved as a creators of technology or merely as a participants in the culture that technology shapes.

In the absence of genuine invention, technology tends to evolve slowly in a predictable linear progression. I use the phrase 'genuine invention' to refer to a conception of invention as a creative act requiring a "conditioning of the present by the future" (Simondon, 1958, p. 62). In other words, that which is invented cannot yet exist because the conditions for its viable existence do not yet exist. Imagination, which requires a sensitivity to the technicality (Simondon, 1958, p. 87) of the media with which one works, provides a cognitive scaffolding that allows invention to take place (Simondon, 1958). Simondon says,

> Imagination is not only a faculty for inventing or creating images beyond the bounds of sensation. It is also a capacity for perceiving in objects qualities that are not practical, qualities that are neither directly sensory nor wholly geometric, qualities that have to do neither with pure matter nor pure form but belong to the in-between level of systems. (Simondon, 1958, p. 87)

Sensitizing ourselves to the technicality of our media is essential to produce breakthrough inventions and experiential media systems.

My personal connection with the subject matter of this dissertation is through my practice as a media artist and engineer. At an immediate level, this connection is to the media itself: the physical material, electronic circuits, mechanical systems, and software. At an experiential level it is about discovering and defining relations between these materials. In a word, this can be called “making”. But it would be naïve to assume that this individual experience of interaction with material happens in a vacuum. There is a context for all of this, a context of culture. Any material I use, any form I create, has a cultural history and impact. It is never only one thing seen from one perspective but always a plurality. Even in the experience of an individual, William James (1912/1976) identifies a simultaneous objective and subjective reality (James, 1912/1976). McLuhan identifies the medium as the message, connecting everything to the culture in which it is created, and seeing that what is created transforms culture (McLuhan & Fiore, 1967). In this dissertation, through a review of literature and from personal experience, I identify aspects of materiality. I show how these aspects of materiality, seen in terms of their structure and organization, are of practical concern in a range of application domains, and speculate on their application in still more domains. Broadly speaking, I show how the work I present here may be applied to a study of what may be called “the materiality of culture.”

Scope of Research

The primary foundation for this theoretical perspective of experiential media systems as structurally determined systems (Maturana, 2002) is my own personal experience making and interacting with such systems. This foundation is subjective, in the sense that it is my individual experience, which cannot be directly experienced or verified by others, but is also simultaneously objective in the sense that, in James’ words, “experience plays the part of a thing known, of an objective 'content'” (James, 1976). My points of observation are but a few of the manifold points of observation of experiential media systems. In stepping back from the pure phenomena of making and experiencing the systems through interaction, and looking at these systems as systems, I am in effect approaching them from a diagrammatic perspective (Wittgenstein, 1953). By this I mean that I’m seeing the products and my experience from an abstract perspective, in the same sense that Wittgenstein suggests when he explains a picture-object (the original text includes an illustration of simple hand-drawn face),

> Here it is useful to introduce the idea of a picture-object. [This illustration] For instance would be a 'picture-face'. In some respects I stand towards it as I do towards a human face. I can study its expression, can react to it as to the expression of the human face. A child can talk to picture-men or picture-animals, can treat them as it treats dolls. I may, then, have seen the duck-rabbit simply as a picture-rabbit from the first. That is to say, if asked "What's that?" or "What do you see here?" I should have replied: "A picture-rabbit". If I had further been asked what that was, I should have explained by pointing to all sorts of pictures of rabbits, should perhaps have pointed to real rabbits, talked about their habits, or given an imitation of them. (Wittgenstein, 1953, p. 194)

By considering my work in terms of philosophical perspectives I am seeing my work as a picture-object. In this diagrammatic representation I can't help but, in Wittgenstein's (1953) terms, notice aspects that I may or may not have noticed before. As Wittgenstein emphasizes, through this aspect dependent perception, when I say I see something, I am necessarily “seeing it as” something (Wittgenstein, 1953, pp. 194, 195, 202, 213). What I see it as depends, in Maturana's (2002) terms, on *my* structure at that instant (Maturana, 2002, p. 6).

The major conceptual framework of this research, built on the foundations of my material practice, consists of philosophies of perception, information, material culture and technology. The work of this dissertation is finding convergent threads from these literary works, and from the knowledge from my material practice, and stitching them together into a larger cohesive fabric. My experience, as an artist, engineer, maker and scholar has determined my structure at the point of encounter with these bodies of knowledge and my structure changes, I learn (Maturana, 1987, pp. 74–75), as I am structurally coupled with these bodies of knowledge. Maturana (1987) emphasizes this meaning, stating, "languaging occurs in the concreteness of the doings of the observer in his or her actual living in the praxis of living itself" (Maturana, 2002, p. 32). The praxical knowledge, which I define as embodied knowledge that emerges through active engagement with the world and resists translation into symbolic representation, that I have from making experiential media systems, in significant part, determines what aspects of these philosophies I am drawn to, and reciprocally, the philosophy I study reshapes my perception of these media systems and my process of making them. It is in this way that I say that my reflection on my own creative process and products forms the foundations for this research and motivates this paradigm construction project. While it is useful to consider the application of this theory to processes and products significantly outside the scope of my personal experience, I do so only speculatively.

The philosophies and theories that I synthesize and expand on through this research constitute general principles. As such the theoretical content of this dissertation may inform any field of study or practice. However, my synthesis and interpretation of this theory is a product of my cognitive structure and organization as an individual. In more general terms, I see this theory from a certain perspective because of who I am, and who I am is a result of what I do.

I come to this research first and foremost as an artist. I am academically and professionally trained as a sculptor. My medium as a sculptor has evolved over the years and includes: wood, metals, plastics and other static materials; and electronics, mechanics, computation and other temporal and spatial media. For all of these media, I possess some level of engineering knowledge that allows me to effectively engage creatively with that media. This knowledge is not discretely divided into classes applicable only to a single form of media, but exists as an amorphous, mutually informing body of knowledge. Something that I learn from one specialized practice inevitably is applicable to another. I would not even draw a boundary between this media knowledge and what might be called "daily life" activities. Pruning a tree or cooking dinner is just as much informed by and informs my media practice. In other words, I do not approach this subject matter entirely from any specific domain. I do however illustrate the theories presented here with specific practical media examples, primarily with systems of my own individual or collaborative production, but also including works of others in related domains.

In this document I use the phrase ‘experiential media system’ to refer to a general category of interactive media as envisioned by ASU’s School of Arts, Media and Engineering. As stated on the school’s website, “The school's mission is to provide groundbreaking research and education on experiential media that integrate computation and digital media with the physical human experience.” (Arts Media and Engineering, 2015). As practiced in the School of Arts, Media and Engineering (AME), experiential media may take many forms. Media systems may be instantiated as websites, multimedia performances, medical therapy systems, and many other forms. A few of these forms are primarily what are commonly called ‘digital media’, but many extend to include the human body and/or physical media. The work I primarily produce in the context of my

AME research incorporates physical hardware with digital computational systems. The physical aspects of my work are fundamental to their function. I include a discussion in the “Open Questions” appendix of this document on the topic of the materiality of code. This discussion speculatively explores the application of theories founded on the concept of structural determinism (Maturana, 2002) to purely computational media, but my primary expertise and interest resides in systems in which a physical structure is an essential component. As I discuss experiential media systems in this document, I do so with these sorts of systems in mind and from the point of observation as a maker of physical-digital media systems.

Given the fact that the paradigm presented in this document is generated through the production of experiential media products produced by myself, as an individual (building on the works of many others), or by small collaborative groups, and that these products and practices primarily originate from an academic environment, the findings of this research would be most directly valid for individuals and groups that share some or all of these attributes; however the work may also be of significant value and validity for philosophers and theoreticians studying creativity, invention, mechanology, or any of the other subjects and fields that this research draws on, particularly for those who primarily approach the making of experiential media systems as outsiders.

Organization of Dissertation

Chapter 1, Introduction, begins by introducing the dissertation topic and presents arguments for the significance and scope of the research. This chapter introduces my personal studio practice as a foundation for the paradigm construction project presented in this dissertation. I state that the philosophies and theories presented in this research serve as the conceptual framework for this paradigm construction project.

Chapter 2, Methodology, describes my research methodology. I begin by contextualizing my methodology with an overview of the historical evolution of my research. I emphasize the nature of my research and how this led to me not using research methodologies that I initially pursued. I describe alternative perspectives on what constitutes research. I describe the abductive research methodology that I ultimately employ in this dissertation, emphasizing the strengths of this form of logical inference. I present thesis statements but emphasize that these are theories generated from the research, not starting questions.

Chapter 3, Literature Review, begins with an introduction of the major philosophers and theorists that I cite throughout this dissertation. I then present other key individuals who represent the cultural and artistic foundations of this research but are not featured in the main body of the dissertation. The Background chapter concludes with an extensive section on haptic systems, haptic musical interfaces and the perceptual fusion of multimodal information, contextualizing much of my practical experiential media system development work.

Chapter 4, Structure Determines Organization, introduces Maturana’s (2002) theories of structurally determined systems and structural coupling, which are key to the paradigm I develop through this dissertation project. I draw attention to Maturana's epistemological stance which requires him to "create a living system, either conceptually or practically in the laboratory" (Maturana, 2002, p. 6). I emphasize structure and organization as the fundamental defining features of structurally determined systems. I introduce Maturana’s concepts of organizational closure and interactional openness in defining the nature of structurally determined systems. This chapter explains how structural coupling can facilitate communication between organizationally closed systems (Maturana, 2002, pp. 16–17). In the context of this topic, parallel concepts from Simondon's (1958) mechanological theory and Reddy's (1979) linguistic theory are compared and explored.

Chapter 5, Determining Structure (In Theory), begins with an introduction of Gilbert Simondon's (1958) mechanological theory. The "technical object" is defined and discussed in depth in terms of its evolutionary stages and their associated characteristics (Simondon, 1958), including hypertelia, concretization and abstraction. The second major section of chapter 5 looks at connections between the biologically based theory of Maturana (2002) and Simondon's (1958) mechanological theory. The questions of how communication may be seen to occur and what makes a system viable are at the center of these discussions.

Chapter 6, Determining Structure (In Practice), considers the theoretical constructs described in the previous chapters from the perspective of the maker. This chapter starts with a consideration of roles humans can play in their interactions with technical objects (Simondon, 1958). I discuss the modes of production of technical objects as seen by Simondon and consider how these modes may complement and blend with one another in contemporary practice. I consider the nature of workmanship and the roles constraints play in the regulation of making. I argue that making can be seen as structural coupling, consider what it means to ‘know material,’ and present examples from my practice to illustrate the theory I present in this document. I introduce my theory of conceptual plurifunctionality as an extension to Simondon’s general theory of plurivalence/plurifunctionality. I conclude with a consideration of aspects of materiality showing the applicability of these aspects to material and immaterial systems in a wide range of domains.

Chapter 7, Conclusion, summarizes the major concepts developed through this dissertation project. I emphasize the generation of research questions through the abductive research methodology employed in the execution of this project. I discuss future research paths that this paradigm construction project illuminates.

Throughout this document, I make extensive use of mechanological terminology and concepts from Gilbert Simondon's (1958) *'Du Mode d'existence des objets techniques' (The Mode of Existence of Technical Objects)* (Simondon, 1958). Since an official English translation of this work has not been published and he is not widely cited in philosophical literature outside of a narrow, largely Continental, tradition, I will do my best to provide a clear introduction to the concepts and terminology that I build on. My advisor, Dr. Sha Xin Wei, introduced me to Simondon’s ideas and provided the unpublished translation of Simondon’s work that I cite. I do not claim to be a Simondon expert and cannot read his work in his native French language, so my interpretation of his work may not be wholly consistent with that of others. I am confident however that what meaning I have extracted from his work, resonates with me and is consistent with the way I see my thinking process as a maker and user of machines.

At the outset of this document, I want to make a statement regarding linguistic gender bias. Much of the source material for this dissertation contains phrases and terms that linguistically have a male gender bias. Examples include: the Latin phase, *Homo* *faber* (man as maker) (Sennett, 2008); the craftsman (Sennett, 2008); and workmanship (Pye, 1968). A quick search of Simondon's (1958) "On the Mode of Existence of Technical Objects", a key reference in this document, reveals no uses of the words "woman" or "women". "Man" features prominently as a general and generic term for either an individual human or humanity as a whole. While the subject matter of these texts, and of my work, is not directly about gender in any way, I find the linguistic bias somewhat troubling, however in the interest of clarity and consistency, I typically use the same terminology in the material I am quoting when discussing this material. In writing independent of these sources I strive for neutral and balanced language.

When I think about the community of makers in my life: my professors, my students, my colleagues in fine arts, sciences and engineering fields, I identify a highly diverse group of men and women, of various ages, races, and sexual orientations. The terms craftsmanship or workmanship do not honor this diverse community. In another dissertation I might take this on as battle to fight. In this instance, please simply know that I do not use such terms thoughtlessly and that they do not reflect a personal bias.

CHAPTER 2

METHODOLOGY

I employed an abductive research methodology in the research and writing of this dissertation. I emphasize the utility of this methodology and provide examples of the application of abduction in scientific research later in this chapter.

The production of generalizable, transferable knowledge can take many forms. As a PhD student, I’ve been introduced to a wide range of research methodologies. The range of research methodologies applicable to Arts, Media and Engineering research is likely broader than would be typically applied to a more historically established and narrowly focused research domain. Coming from a fine arts background, I experienced all of these structured methodologies as a new way of seeing, understanding and sharing the work I was doing. I recognize in retrospect that my fine arts work did take place with a research methodology, but one that was implicit and informally defined.

The process of formulating my dissertation research project was a long and complex journey. Early in this process I identified certain characteristics of media systems as fundamentally motivating: tangibility, real-time responsiveness, mechanically dynamic, and featuring a synthesis of real and simulated physics. I explored a range of application areas to capitalize on these characteristics, including: education, motivational systems, physical fitness, and artistic performance. From these explorations several core subject areas emerged. Prominent among these were: immersive media, embodied knowledge, haptic information channels, and material computation.

At the point of formally proposing my dissertation research project I had settled on conducting research on the importance of various modalities and applications of haptic information for musical performance with a hybrid physical-digital musical instrument. I proposed a mixed-methods research methodology that would include quantitative sensor, actuator and audio synthesis engine state data; coded qualitative performance data; and in-depth personal interviews with the participating musicians. My dissertation committee was generally supportive of my overall research questions and of the creative importance of my proposed project, but they also recognized fundamental limitations in the general knowledge that could be persuasively claimed from my planned research. The primary problem was that with a completely novel interface I had no way to establish a baseline for learning or performance. There were, by definition, no experts to define such a baseline and certainly not time for even one, let alone a statistically significant number of such players to mature. I could have run the studies as proposed and probably would have made some interesting observations, but these observations would only have had any validity for this individual instrument and these performers. I could have dramatically limited the variables in the system to produce a study that closely matched prior haptic feedback, or other, studies, and in so doing expand the generalizability of my research. However I was not interested in this path because the very complexity that made my system challenging to evaluate from traditional scientific research perspectives, was exactly what made it interesting research.

I began looking for other models of research, continued building more media systems, and began to think more broadly about the full spectrum of projects I had worked on throughout my career in the School of Arts, Media and Engineering. In this time period, I was invited to join the newly formed Synthesis Center at ASU (Sha, 2014) as a graduate researcher. Dr. Sha Xin Wei (2013; 2011, 2014), director of AME and the

Synthesis Center, introduced the concept of the atelier-laboratory as a research environment modeled on the artists' studio (Sha, 2011) and the general idea of art as research. I explored this and considered various ways art practice could be seen as research practice (Bolt, 2006; Hockey, 2003; Maarit, 2007; Seago & Dunne, 1999; G. Sullivan, 2006). Naturally these approaches have differences, but they share the perspective that the artistic practice provides a unique and valuable way of generating new knowledge and that the artifacts of these practices can provide a "a method for collecting and preserving information and understanding" (Maarit, 2007, p. 1). Sullivan (G. Sullivan, 2006) emphasizes a fundamental concern about arts practice as research:

> "A positivist legacy expounded so clearly as a research maxim or a mantra curriculum asserts, *if you don't know where you're going, how do you know when you get there?* The assumption is that clearly defined intentions, whether expressed as hypotheses, research questions, lesson objectives, or standard statements, position the purpose of educational acts within the context of what is already known"

Sullivan identifies this perspective as one that inherently limits the possible range of types of knowledge that can be generated by the research. He goes on to ask:

> "But, how do we construct theories of 'possibility'? An arts researcher would more than likely subscribe to the view that *if you don't know where you are going, then any road will get you there*. Rather than seeing inquiry as a linear procedure or an enclosing process, research acts can also be interactive and reflexive whereby imaginative insight is constructed from a creative and critical

> practice. Oftentimes what is known can limit the possibility of what is not and this requires a creative act to see things from a new view.

I embraced this perspective and began my own process of reflecting on my own creative process and products. For a while I focused on the relations between the traditional computational and material computational dimensions of my work. I was interested in physical-digital systems in which there was a strong, mutually dependent fusion between the physical and computational aspects of the system. I labeled these systems 'computational objects'. In systems of this nature, if either the computational or physical aspects of the system could be removed or altered without fundamentally altering the remaining part of the system, then I did not consider it a computational object.

For another phase of this exploratory research I looked at my systems as relations between sensors and motors. This paradigm encompassed both machine and human sensorimotor systems and looked at the topologies of these systems. I focused attention on the varying aspects that defined the relations between sensorimotor components and how changing these relationships fundamentally changed the nature of the systems.

The problem I kept running into with these lines of investigation was the problem of how to constrain the scope of the research without reducing the complexity and accompanying richness of the systems I was drawn to think about. Starting from the media systems themselves, I found exponentially expanding ways of investigating their nature. It was only by consciously reversing my research process, stepping back from these systems and turning my attention to philosophical and theoretical texts that I began to get a handle on a focused way to progress in my research. The difference is subtle, but prior to this, I had turned to literature as a way to find theoretical support for the creative work I was intrinsically motivated to produce. At this point I was instead reading the literature for itself and slowly began finding ways in which what I was reading seemed to be referring to my projects. By reading this way, the literature became the foundation of the research, not a theoretical justification for my media systems.

I present this history of my search for a definition of my research to set the stage for an understanding not only of the abductive methodological approach I ultimately used for this dissertation, but importantly to emphasize why I did not pursue the work through alternate methodologies. Traditional inductive scientific studies were not attractive because they would have required looking at the work in a simplified form that would not accurately represent the essence of the work as I conceived it. The material of my research, the philosophical material and the process and products my media production that I consider in light of these texts, did not lend themselves to alternative subjective methodologies such as the systematic application of grounded theory (Glaser & Strauss, 2009). The material that constitutes my subject of research is not clearly bounded and amenable to a systematic axial coding as I understand a grounded theory methodology requires.

In the research presented in this document I define the materiality of my practice, which emerges through an analysis of my photographic documentation, software, electronics and tangible products, and present aspects of materiality as a lens though which to view other systems. These systems include the biological and technical systems that are the topics of the foundational literature, as well as the cultural systems of industrial and artisanal makers, media culture and other intangible systems. I emphasize that the point of observation from which I present any of this content is but one of manifold points of observation. It is impossible for me to present this work from every point of observation and dilutes the value of the work if I try to approach the work from too many points of observation. To the degree that it is possible, I will declare the point of observation from which I'm considering the subject matter as the research is presented, but it is important to note that this point of observation can never truly be a singular, concrete point. It will always to some degree be manifold and in flux. My objective is to provide the reader with an enriched understanding of the theoretical content I present by illustrating these theories significantly from the points of observation of my personal paradigm and practice.

I identify my research as a 'paradigm construction project'. This identification emphasizes the dynamic nature of observation. I intend, through my presentation of this research, to promote active reflection on how we see things and to encourage active reconstitution of our paradigms to generate the worlds we want to experience.

I employ an abductive research methodology in the conduction of the research documented in this dissertation. Abductive reasoning, which is the foundation of abductive research, can be illustrated with the following example from Pierce (1935):

Rule: All the beans from this bag are white.

Result: These beans are white.

∴Case: These beans are from this bag (Peirce et al., 1935, vol. 2.623)

This canonical example illustrates that this form of logic does not operate in the way we typically think of logic. There is no claim of truth implied in the conclusion. In fact, a layman's term appropriate for describing this logic is 'guessing' (Patokorpi, 2009).

In scientific practice, abductive reasoning is a form of logic that is typically applied for theory creation, not theory testing. Importantly, it does not require complete knowledge, as is required by deductive logic, and does not require the control of variables required by inductive testing. Instead it operates as a practical approach to forming theories in complex systems in which all the factors can never be known or fully controlled and in which there likely is no single truth (Patokorpi, 2009).

> Josephson and Josephson (1996) explain one of the powers of abduction, "abductions are ampliative inferences; that is, at the end of an abductive process, having accepted a best explanation, we may have more information than we had before. The abduction transcends the information of its premises and generates new information that was not previously encoded there at all" (Josephson & Josephson, 1996, p. 10).

Josephson and Josephson (1996) continue, "Whereas valid deductive inferences cannot contain terms in their conclusions that do not occur in their premises, abductions can "interpret" the given data in a new vocabulary. Abductions can thus make the leap from "observation language" to "theory language" (Josephson & Josephson, 1996, p. 10).

A very important characteristic of abduction applied as a research methodology is what Josephson and Josephson call 'emergent certainty', "that is, the conclusion of an abduction can have, and be deserving of, more certainty than any of its premises" (Josephson & Josephson, 1996, p. 13). This is essential in the way I apply this methodology to my subject matter. I identify many patterns and parallels in the language and systems that I consider. Any of these individual associations could be considered relatively weak or the product of chance, but collectively they add up to a strong abductive argument.

I observed, when I first read Peirce's (1935) example of abductive reasoning, that this is how many magic tricks work. Our expectations cause us to see things in a way that we are surprised by. As I describe in the introduction to this document, Wittgenstein (1953) draws our attention to this experience of perception, noting that when we see something, we always "see it as" something. From this perspective, there is no truth to be observed, so the abductive approach is not flawed. In fact abduction is important for diagnosis (Josephson & Josephson, 1996, pp. 6–9), industrial network research (Dubois & Gadde, 2002), human-computer interaction studies (Patokorpi, 2009), implementations of neural networks (Abdelbar, Andrews, & Wunsch, 2003), and in Bayesian networks (Galán & Mengshoel, 2009), to cite just a few applications.

In my research, following the abductive method, I see existing theories and philosophies as a rule. I observe commonalities between the features of the systems considered in these theories and philosophies and the features of the systems of experiential media production and products. I conclude from the rule and observations that the experiential media systems are "from the same bag" as the systems on which the theories and philosophies of structural determinism and technical objects are founded. Considered at this simplified level which reduces all the incremental stages of this logical inference to a single step produces a result that may seem tautological. In practical terms, this logical flow, as applied to my research, is much more nuanced and iterative. It is only through the accumulative evidence of many inferential relations that the strength of the theory emerges. I also remind the reader that this paradigm production is a dynamic process in which I see one philosophy or theory as another, and see my material practice and products as instantiations of these philosophies and theories. My material practice and products in turn affect how I see the philosophies and theories when I return to them. These statements should be read with Wittgenstein's (1953) theory of "seeing it as", which I introduced in my introduction, in mind. Through this process I generate questions; questions that may inspire new ways of seeing and inventing experiential media systems and suggest new ways of seeing systems in general, including social and cultural systems.

In the early stage of this research, I was not seeing my making process and products as instantiations of theories and philosophies. It was the other way around; I was seeing these theories and philosophies as instantiations of my creative work. When I came across theories of structural coupling (Maturana, 2002) and recurrent causality (Simondon, 1958) I viewed these ideas through the lens of my haptic systems, and the philosophies of GaLLaG (Game as Life and Life as Game) systems (Lee, Garduño, Walker, & Burleson, 2013). Theories of structural determinism were seen in light of my experiences as a sculptor and in terms of my material computation approaches to media systems.

Thesis Statements

My research methodology is not designed to test, but rather to generate theory based on the available information. These statements were not starting points for this research. They are a consequence of the research and included here to offer the reader anchor points for a few of the core concepts discussed in this dissertation. This list is by no means a comprehensive list of all the theory generated in this document, but represents some of the major points.

Thesis 1: Maturana's foundational theories of autopoiesis apply to Simondon's theories of mechanology (Maturana, 2002; Simondon, 1958).

Thesis 2: Experiential media systems are a class of technical objects as defined by Simondon (Simondon, 1958).

Thesis 3: Making is a form of structural coupling and subject to the same rules as all structurally determined systems. (Maturana, 1987, 2002).

Thesis 4: Artistic, aesthetic and other conceptual information may be constructed in cognizing individuals as a result of structural coupling with systems external to themselves.

Thesis 5: The organizational dynamics (or technicalities) of systems should include a consideration of thesis 4 when the system's plurivalence or plurifunctionality is assessed (Simondon, 1958, p. 87). (In less precise terms: Conceptual as well as physical functions should be considered when the multiplicities of functions of a form or material are assessed.)

This concludes my discussion of my research methodology. I presented a history of my search for a cohesive and appropriately scoped research project to contextualize my choice of research methodology. I emphasized the functional and experiential complexity of the systems I developed and argued that these characteristics were an essential part of their nature and that if they were reduced to simpler systems for evaluation, they would not be the same systems; therefore methodologies requiring a strict constraint or coding of variables were inappropriate for evaluating these systems. I described abductive reasoning, presented examples of how it is used in science and research domains, and emphasized some of the strengths of this form of logical inference. I showed how this form of reasoning would apply to my research to reveal interrelations between philosophical theories of natural and technical objects and the products and processes of my media practice.

CHAPTER 3

LITERATURE REVIEW

The survey of related people and projects that I present here is far from comprehensive but it is focused and should serve as a highly practical resource for readers and for my own ongoing research. I will introduce the theoretical and philosophical scholars that I directly reference throughout this dissertation as well as additional intellectuals whose work and philosophies relates to my subject matter, including anthropologists, sociologists and artists. Finally, I will provide a thorough introduction to the theory and application of haptics, including a review of related theories of perception.

Several of the philosophers and theorists that are central to my work are relatively unknown outside of specific regions and domains. Simondon in particular is difficult because of the lack of translations of his work. I will do my best to provide enough introduction and connections to provide readers a point of access for these more obscure, but important, thinkers. In this background section, I will not provide significant details of the theoretical stances of the authors that I extensively cite in the remainder of this document.

This background will not only serve to provide a general understanding of the conceptual terrain of the document, but significantly, will help to define the observational points of the research. The observation points of the artist, the philosopher and the maker will all be more fully established through the contents of this chapter. I include myself as a key observer in this dissertation, but here am specifically emphasizing all the observers other than myself, whose points of observation are revealed through their creative work.

I will begin with an introduction of the theorists and philosophers that constitute the theoretical foundation of this research. This introduction will include Ludwig Wittgenstein, Humberto Maturana, Gilbert Simondon, David Pye, Richard Sennett and Michael Reddy. The next section will introduce anthropologists, sociologists and artists whose work is not directly referenced elsewhere in this research but is critical to its existence. Following this will be an extended section focusing on haptic information and perceptual fusion of multimodal information. Haptics are a key element in several of my media systems and this background section will be essential to contextualize that dimension of my work in preparation for later discussions of these systems. Integral to the discussion of haptics is a consideration of the experiential impact of our multiplicity of sensory modes.

Philosophical Foundations

Ludwig Wittgenstein (1953), who is primarily identified as a philosopher, was born in Vienna, Austria-Hungary in 1889 into an extremely wealthy, but troubled family. He gave away his fortune and pursued numerous career paths other than philosophy. His philosophical career, to the extent that it could be called a career, was framed by the two world wars. In spite of his prolific writing, he was not a well published writer in his lifetime but his posthumously published *Philosophical Investigations* (Wittgenstein, 1953) is considered a modern classic work of philosophy (Wikipedia, 2015f). His philosophy that I express in shorthand as "seeing it as" (Wittgenstein, 1953, pp. 194, 195, 202, 213), is fundamental to my dissertation. The proposition that anything that we perceive is always perceived as something, is simple on the surface but has tremendous ramifications. My paradigm construction project explicitly operates with the knowledge that what we see something as is always in flux and never singular.

Humberto Maturana (2002) provides way of seeing the mechanics of Wittgenstein's "seeing it as" philosophy. Maturana was born in 1928, in Santiago, Chile. He is identified as a biologist, cyberneticist, and philosopher. He is famous for the theory of autopoiesis, which describes what it is about a system that makes it a living system: a system of self-creation. Underlying this larger theory is the theory of structurally determined systems, which play a key role in my paradigm construction project. I emphasize the fundamental elements of structurally determined systems and structural coupling, relating these elements to technical objects (Simondon, 1958). Maturana went on to evolve his theories into biologically based explanations of cognitive processes. He argues, “Living systems are cognitive systems, and living as a process is a process of cognition. This statement is valid for all organisms, with or without a nervous system” (Maturana & Varela, 1980, p. 13).

Gilbert Simondon (1958) was a French philosopher, born in 1924, making him a contemporary of Maturana. His broad philosophical topic is individuation. I studied his "minor dissertation" *On the Mode of Existence of Technical Objects,* which focuses on mechanology or the science of machines. He defines technical objects in terms of their genesis, describing cycles of specialization, internal unification and convergence into ensembles, providing rich insights into the nature of technology and its existence as a core component of human culture. Miguel de Beistegui (2005) describes the ontological challenge that Simondon’s philosophy addresses:

> In the light of the event of science, philosophy must avoid a twofold trap: namely that of philosophising without taking into account the challenge of science for thought; and that of subordinating philosophical thought to scientific procedures and ''facts.'' In other words, it can be a question of neither blissfully ignoring such a challenge, nor turning it into the sole measure of thought and an unquestionable paradigm. The task, rather, consists in setting a new ambition for philosophical thought against the background of the event of contemporary science. It is a question, in short, of allowing thought to advance in and through a genuine dialogue with science. (Beistegui, 2005)

De Beistegui's (2005) consideration of the relation of scientific paradigm with philosophical ontology compares the perspectives of Maurice Merleau-Ponty and Simondon (Beistegui, 2005). De Boever (2012) describes the paradoxically close and distant relationship between the two philosophers,

> Simondon was Merleau-Ponty's doctoral student. Simondon's monumental doctoral thesis, however, does not reveal any traces of influence on the part of Merleau-Ponty. And Merleau-Ponty's comments on Simondon amount to virtually nothing. Does this mean that the two approaches are incompatible? Such would seem to be the case: where Merleau-Ponty insists that philosophical questioning be rooted in perception, and finds his impetus as well as his method in Husserlian phenomenology, Simondon simply ignores phenomenology. Yet a closer look at Merleau-Ponty's later thought, which aims to overcome the Cartesian dualism still present in Husserl, reveals a certain proximity to Simondon's problematic of pre-individual being. (De Boever, 2012)

Limited publication and translation of Simondon's work constrained its reach within his lifetime. His work is gaining attention; new publications and translations of his work are emerging and many articles make reference to his philosophy. A Google Scholar search for "Gilbert Simondon" with the search limited to results since 2011 shows about 1,490 results. Limiting this search to English results only reduces the number to about 684. While this is certainly not a vast number, and this is a crude, unscientific measure, within these results one finds plenty of evidence of energetic discussion of Simondon's work. His work had an early and notable impact on Deleuze's (1968, 1969, 2002) thinking. "Simondon's theory of individuation through transduction in a metastable environment was an important influence on the thought of Gilles Deleuze, whose *Différence et répétition* (1968), *Logique du sens* (1969) and *L'île déserte* (2002) make explicit reference to Simondon's work" (Wikipedia, 2015e).

David Pye (1968) is an unusual figure amidst the philosophers and scientists featured in this document. He is a highly articulate theorist and his work provides an important point of observation to relate to those of Simondon (1958) and Maturana (2002), but he is also a highly respected artist and craftsman (though he has something to say about the latter term and proposes an alternative phrase). Pye lived from 1914 –1993. He grew up in a family with historical connections to the Arts and Crafts movement. His aunt, father and great-uncle all had vocations and/or hobbies involving craft and making. Pye trained as an architect but ultimately turned his talents to commercial furniture design and artistic production of wooden objects, particularly carved and turned bowls and boxes. His theory of design, particularly his concept of the 'workmanship of risk' (discussed later in this document) grew out of his material practice, his teaching of furniture design at the Royal College of Art, and his philosophical reflection (Frost, 1993; Wikipedia, 2014b).

I cite Richard Sennett's (2008) book *The Craftsman* (2008), in my introduction to my chapter focused on determining structure (chapter 6). This book is one of three he wrote in which a consideration of *Homo faber* (man as maker) plays an important role in understanding society (Sennett, 2008, 2011, 2012). Sennett's early career aspiration was as a cellist and conductor (Wikipedia, 2015h). This training and experience as an artist clearly informed his later work as a sociologist. This influence is expressed in his use of musical performance examples in his discussions of craft. While I don't extensively explore Sennett's theories in my dissertation, his work played a pivotal role in the course of my research. My woodworking professor, Tom Eckert (2015) assigned *The Craftsman* as mandatory reading. He recognized that craft extended far beyond techniques, aesthetics or anything nostalgic, and represented a philosophy and way of being. I read this book while doing the primary physical fabrication of my *Vox Curio* instrument. Doing so primed my thoughts for the philosophy I would explore in the development of this dissertation.

Michael Reddy (1979) was identified as a linguist at the time he wrote *The conduit metaphor: A case of frame conflict in our language about language.* In this brief but highly influential article, Reddy identifies how the structure of our language reinforces what he considers to be a logically untenable metaphor of communication (Reddy, 1979). I discuss this theory and his proposed alternative in depth later in this document so I will not repeat it here. The most interesting thing about Reddy as an academic figure is that beyond this single document, he is virtually non-existent. He changed careers several times and now is a therapist, wellness coach and author.

Cultural and Artistic Perspectives

My paradigm construction project, particularly in the way that I consider the creation and use of tools, can be seen in terms of anthropological and sociological research. Simondon (1958), whose philosophy is central to my project, sees the technical as playing an essential intermediary role in human culture (Simondon, 1958). Franz Boas (Bashkow, 2004; Wikipedia, 2015d), Émile Durkheim (Durkheim, 2014; Wikipedia, 2015c), and Claude Lévi-Strauss (Lévi-Strauss, 2008; Wikipedia, 2015b) provide foundational insights into material objects and culture and show how they are dialectically created.

The theories expressed by Franz Boas (Bashkow, 2004; Wikipedia, 2015d) have important parallels to Simondon's (Simondon, 1958) views of how culture is shaped. Both see integrative and diffusive forces continuously at play (Bashkow, 2004; Simondon, 1958). Bashkow (2004) describes the Boasian perspective, "First, it was axiomatic to the Boasians that cultural boundaries were porous and permeable. Boasian anthropologists, whatever their differences, did not conceptualize cultural boundaries as walls or barriers to external influence" (Bashkow, 2004, p. 445). This view aligns with Maturana's (2002) and Varela's (1978) understanding of structurally determined systems as organizationally closed but interactionally open (Maturana, 2002; Varela & Goguen, 1978).

Claude Lévi-Strauss (1958/2008) formulated a structuralist view of anthropology, arguing that mental and social structures, of which we are generally unaware, shape human culture and that these structures are shared broadly by humanity (Lévi-Strauss, 1958/2008; Wikipedia, 2015b, 2015i). This paradigm, which opened up new ways of considering humans and human culture, shares the foundations of theories of structural determinism (Maturana, 2002).

Émile Durkheim's (1893/2014) structural functionalist theories strongly influenced Lévi-Strauss (1958/2008). He looked for what unified and maintained the stability of societies. He said,

> For if society lacks the unity that derives from the fact that the relationships between its parts are exactly regulated, that unity resulting from the harmonious articulation of its various functions assured by effective discipline and if, in addition, society lacks the unity based upon the commitment of men's wills to a common objective, then it is no more than a pile of sand that the least jolt or the slightest puff will suffice to scatter. (Allan, 2005, p. 136)

Unity, in this context, equates to viability. I discuss viability of natural and technical objects later in this document.

Durkheim (1893/2014) states, "The totality of beliefs and sentiments common to the average members of a society forms a determinate system with a life of its own. It can be termed the collective or common consciousness" (Durkheim, 1893/2014, p. 63). This notion of society seen as a determinant system resonates with my project of seeing experiential media systems as structurally determined.

In the upcoming section, Haptic Interface Technology, I highlight numerous researchers and artist who produce experiential media systems featuring haptic components. At the end of this current section on Associated Philosophy and Theory I highlight three sculptors who produce works significantly dependent on materiality as a key aspect of their conceptual and experiential impact. I identify this use of material as implicitly expressing philosophical theory. Many additional artists and craftspeople could be fruitfully referenced here. I select these three because of the clarity of the examples they provide and because of the personal resonance I feel with these fellow artists. Tim Hawkinson's (2007) and Tom Friedman's (Applin, 2008) work both exhibit a fusion of physical and conceptual functionality through their media choices and application of this media in their sculptures. Ned Kahn's (Mather, 2006) work helps to illustrate Maturana's (Maturana, 2002) theories of structurally determined systems.

Tim Hawkinson's (2007) sculptures frequently represent the human figure, but in forms and materials that are far from traditional. His works emphasize aspects of materiality in ways that generate a poetic dialog between the visual forms and culturally defined associations. He utilizes the elasticity of latex rubber to produce his *Balloon Self-Portrait.* In this piece he creates a full body life cast of his own body, inflates the resulting rubber skin and suspends it from the ceiling. Areas of the rubber skin with less complex structures, such as the torso, readily inflate while the remaining areas remain closer to original proportions, producing a strangely distorted figure with a very real internal pressure and skin tension. Another sculpture, *Self-Portrait (Height Determined by Weight),* is simply a lead casting of the artist's feet and most of his calves. In the same way that cubism may draw our attention to dynamism and multiple points of observation, Hawkinson's sculptures, mechanisms and installations elicit questions of temporality, materiality and the nature of the human body.

Tom Friedman (Applin, 2008) also challenges our preconceptions and invites socially driven meaning with his innovative repurposing of everyday materials. He carves micro scale figurative sculpture out of aspirin tablets, makes snow angels in circular piles of laundry detergent and generates formal, non-representational sculptures out of plastic cups and drinking straws. His work clearly owes something to the ready-mades and found object sculpture of earlier eras, but he manages to continue work in this tradition in a way that feels completely fresh and surprising. Any individual work by Friedman might come across as a one-liner, but the collective force of his work is far greater than the sum of the parts. Each work adds a piece to the puzzle and suggests a reconsideration of the previously viewed work. Both Friedman's (Applin, 2008) and Hawkinson's (Hawkinson et al., 2007) work inspire and illustrate my theory of conceptual plurifunctionality (Simondon, 1958).

Ned Kahn (Mather, 2006) exploits materiality to produce systems that replicate or make perceptible naturally occurring phenomena such as weather events. His tornado systems are classic examples of his work. He configures the structure of the systems so that the desired organization of the system can manifest. Maturana (2002) uses the tornado as an example to explain the relations of structure and organization in structurally determined systems. Kahn recognizes that his work straddles scientific and artistic realms and doesn't fully fit in either, but serves both.

This concludes my introduction of key philosophers, theorist and artists that inform my dissertation project. The next section introduces theory and practical research related to haptic systems and perceptual experience.

The Haptic Channel and Perceptual Fusion of Multimodal Information

The focused discussion of haptic systems and related perceptual topics in this section is important for contextualizing discussions of my *Vox Curio* musical instrument, which features multiple modes of haptic interaction. The concepts and specific research presented in this section also serve as examples for the upcoming discussions of structurally determined systems, structural coupling, technical objects and the nature of determining structure. I will make reference to some of these concepts in this background presentation. I do so knowing full well that I have not yet adequately introduced the terms and concepts, but feel it is better to draw the connections now, even if the full meaning may not emerge until the reader has progressed further in the document, rather than leave it to the reader to retrospectively make these connections.

The Haptic Channel

The importance of haptic information in our daily lives is undeniable but typically underappreciated. We likely take haptic information for granted to a much greater degree than we do our vision or hearing, both of which can be easily temporarily suppressed. Tactile, kinesthetic and proprioceptive senses, along with the motor control systems that are engaged when we interact with physical objects through touch are collectively described as the "haptic channel" (Hayward, Astley, Cruz-Hernandez, Grant, & Robles-De-La-Torre, 2004). An important feature of the haptic channel is its two-way nature: it incorporates both sensing and actuation as mutually dependent and inextricably linked components. Sensing through touch is dramatically impoverished without motor engagement in a process Gibson (1962) calls "active touch" (Gibson, 1962). Likewise, motor movements are severely hampered without the sensing dimensions of the haptic channel. One need only attempt to tie one's shoelaces while wearing gloves, or recall the experience of trying to drink a glass of water after one's mouth has been numbed at a dentist's office to begin to appreciate our dependence on haptic information for efficient and psychologically rich interactions with our environment. As more dimensions of our lives are augmented with computer-mediated interactions, the absence of tangible engagement with our virtual environments and media becomes an increasingly obvious void.

The haptic channel may be subdivided in multiple ways to clarify the roles of its various components. First, the haptic channel may be split into sensing and motor-action components. Second, haptic feedback can be subdivided according to the specific bioreceptors and cognitive systems involved in the sensing process. Doing so results in the major categories of tactile feedback and kinesthetic/proprioceptive feedback. Tactile feedback may be further broken down into texture, temperature, shape, vibration, hardness, and other material properties.

Kinesthetic/proprioceptive sensing involves the body in space and in motion. It includes the sense of the relative positions of individual body parts to others, the sense of the body in relation the external environment (particularly including the sense of balance) and the force required to move or to resist movement. Haptic interaction devices designed to engage the kinesthetic system are generally referred to as force feedback devices. The distinctions between kinesthetic and proprioceptive senses, when recognized at all, are often debated and defined differently by different professionals in different fields of study. Stillman (2002) strives to provide common definitions and describes kinesthesia as a component of the proprioceptive sense (Stillman, 2002). When the distinction is relevant to the discussion, the terms kinesthesia and proprioception (and their derivative forms) will be carefully selected. In broader discussion where the distinction is not significant, the more inclusive term proprioception will be used.

Properties such as weight and shape that involve muscular activation and changes in the configuration of the body (e.g. closing one's hand around a ball) may be considered tactile or kinesthetic. This classification may depend on the scale of the movements, the hierarchical importance of the various sensing receptors involved and the source of one's definition for these classifications. The point is that these subdivisions have blurry lines in natural interaction with the physical world. We receive information simultaneously from many sources and combine and integrate this information (Ernst & Bülthoff, 2004) to arrive at perceptions of our environment.

Tactile information frequently is transmitted through direct skin contact with the sensed object, but direct contact is not a requirement. Tactile information may be received through indirect contact, such as touching a surface with a tool or probe. Merleau-Ponty's example of the blind man's cane is relevant here:

> The blind man's stick has ceased to be an object for him, and is no longer perceived for itself; its point has become an area of sensitivity, extending the scope and active radius of touch, and providing a parallel to sight. (Merleau-Ponty, 1962, p. 165)

The nature of the tool may even reveal information that is not perceptible with direct skin contact. An example of this is the detection of fine cracks in a surface by probing with a sharp pointed tool. The tool tip will drop into the void of the crack, producing a resistance or impulse that is transmitted through the tool to the hand of the user. This principle of receiving haptic information through indirect contact is key to the functionality of computer haptic feedback devices. We are able to perceive virtual information in tangible terms through intermediate devices.

Motor-action is the component of the haptic channel involving the physical exploration and/or manipulation of the environment with our body. As will be described in more depth in an upcoming section, sensing and motor-action are naturally coupled and complementary. One might appropriately argue that any physical manipulation of our environment with our body is a haptic interaction, making a standard computer mouse a haptic interaction device. Strictly speaking this line of reasoning is perfectly valid. Moving the mouse and clicking the buttons results in kinesthetic and tactile information, however this information is solely dependent on the actions of the user. Clicking a mouse with no connection to a computer provides the same haptic experience as clicking on an icon that launches an application. This is not to discount the value of haptic information that results from the physical properties of the interaction device (e.g. typing on a mechanical keyboard is substantially different that typing on a flat touch screen).

This brief introduction has highlighted tactile perception, proprioception and motor action as components of the haptic channel. While there is value in considering each of these components individually to better understand the details of how they function, it is more important for the purposes of this research to focus on how they work together. The next section will do just that: introducing the concept of “active touch”.

Active Touch

Intuitively, there is a significant difference between actively exploring the texture, shape, and other material properties of an object through intentional interaction with that object and a passive transmission of this same information without agency or independent control of the touch experience. Researchers (individually cited in the upcoming examples) have defined, classified and quantified these differences, validating our intuitive understanding of these different forms of haptic experience.

I draw attention at this point in this introduction of haptic interaction to the main topic of this dissertation: seeing systems as structurally determined. As has been touched on in previous sections and will be elaborated on in the main body of this dissertation, systems may be seen as structurally determined, "that is a system in which all that happens with it and to it is determined at every instant by the way it is made (its structure) at that instant (Maturana, 2002, pp. 5–6). The concepts of such a system being 'organizationally closed' and 'interactionally open' (Maturana, 2002; Varela & Goguen, 1978) are helpful in appreciating the upcoming discussion which requires a defined interiority and exteriority for the perceiving individuals.

Gibson (1962) introduces the concept of active touch, differentiating "being touched" from "touching". He argues, and presents evidence to support the idea, that perception of objects through touch is dependent on a differentiation between what he terms exterospecific and propriospecific stimuli. Exterospecific stimuli are information whose source is external to the body. Propriospecific stimuli are information whose source is internal to the body. Actively scanning an object or environment through an active touching process presents both external stimuli and proprioceptive information. Through this process the observer is not cognizant of the patterns of stimulation, but rather, perceives the object itself. Passive presentation of the same object to the observer (a researcher touching the observer's hand with the object) results in an awareness of distinct stimuli, but minimal perception of the object as an object (Gibson, 1962).

Gibson (1962) notes that performatory movements (active transformation of an object, by hand or with a tool) represent yet another class of haptic interaction and communication beyond that of the exploratory movements that were the subject of this research (Gibson, 1962). This notion of performatory movements foreshadows my discussion, later in this document, of making as a form of structural coupling.

Fanselow and Nicolelis (1999) explore the topic of active touch at the neuroanatomical level. In their journal article, *Behavioral Modulation of Tactile Responses in the Rat Somatosensory System*, they demonstrate that the neural responses to stimulus are different when the rat is actively exploring an environment and when the rat is passive. Four levels of activity were investigated in this study. In these experiments, stimuli are delivered directly to nerve cells as brief electrical pulses. Responses are measured in populations of neurons via arrays of microwires implanted in the ventral posterior medial nucleus and the primary somatosensory cortex. Describing the motivation for the research, they refer to other studies indicating that, "… motor activity alters the characteristics of neural responses to tactile stimulation." The findings of this research imply that active touch is not merely a higher level cognitive process involving attention and other factors that may influence perception, but that at the lowest neural stimulus-response level, voluntary motor activity influences the raw electrical information in the rat's brain (Fanselow & Nicolelis, 1999). This research empirically demonstrates the interrelationships between the structure and the organization of an autopoetic (structurally determined) system (Maturana, 2002).

Two examples that I experienced first hand provide an opportunity to compare the experience of active touch and passive haptic feedback. The first example is an interactive system experienced several years ago in the Emerging Technologies venue at the SIGGRAPH (“SIGGRAPH,” 2015) conference (I have been unable to retroactively identify this system so it cannot be cited.). In this system the participant had small vibrotactile actuators attached to their index finger and thumb and were given an empty, clear, plastic box to hold between these fingers. A 3D rendering of the plastic box appeared on a small 2D video display in front of the participant. The virtual box moved to match the position and orientation of the physical box held by the participant. Next a virtual ball was dropped into the virtual plastic box displayed on the screen. The vibrotactile actuators energized in a synchronized response to the collisions of the virtual ball with the walls of the container. Simple audio feedback, replicating the acoustics of a ball in the plastic box, accompanied the vibrotactile feedback. The participant could tip the box, allowing the ball to roll from side to side and explore the resulting visual, sonic and haptic sensations. More virtual balls were added, increasing the complexity and density of feedback. Finally the participant was invited to dump all the balls out of the plastic box. It was remarkable how convincing the illusion was. It truly felt like physical balls were being added to the physical container. Most surprising was the sensation that the box weighed less after the virtual balls were dumped out.

The second example from Emerging Technologies at SIGGRAPH in 2012 was called *Ungrounded Haptic Rendering Device for Torque Simulation in Virtual Tennis* (Teck, Ling, Farbiz, & Zhiyong, 2012). This system utilized solenoids attached to a real tennis racket to provide haptic feedback. Like the previous example a visual display was used to show a virtual representation of the environment, in this case, a tennis court. Unlike the previous example this display was a large-screen, 3D image projection, utilizing head tracking to provide the appropriate perspective based on the participants location. The participant was instructed to hold the tennis racket out in front of them with the racquet face parallel to the ground. Virtual tennis balls were dropped onto the racket face, striking in the center and on the edges of the racket. High-quality sounds of these collisions accompanied the visual and haptic feedback, which generated torques consistent in angle, if not magnitude, with the simulated collisions. In spite of the rich multimedia feedback provided by the system I found the overall experience unconvincing, especially compared to the experience I had years earlier with the simple clear plastic box example described in the last paragraph. My first thought was that I had had more experience with haptic systems in the intervening years and that it was simply the novelty of the experience that have made it so convincing earlier. It was only upon further reflection that I realized the true problem. The tennis system did not allow any agency or active touch. One could only passively hold the racket and experience a preset feedback. There was no opportunity to alter the feedback by moving one’s hand up or down or rotating the racket to change the collisions with the balls as one could do in a real-life version of the same interaction. The lack of agency dramatically decreased the sense of immersion and realism in the haptic feedback.

Visell and Cooperstock (Visell & Cooperstock, 2010) produced an unusual computer mediated haptic experience in their *Haptic Floor* project. The characteristic that makes this system unusual is that it is primarily interacted with through one’s feet. Most haptic systems prioritize the hands and arms for interaction. The system they produced renders convincing haptic illusions of walking on a variety of surfaces (e.g. sand, cracking ice). It does so by sensing the force on the floor surface then replicating the physical reaction forces through a Lorentz force type inertial motor. They model the physics of the surfaces as fracture mechanics systems and actuate the physical surface of the floor in real time based on the measured force from the participant and the state of the physical model (Visell & Cooperstock, 2010). Vibrotactile haptic systems are often included as features of theme park entertainment systems, arcade video games and other similar systems, but these typically only produce predefined or minimally varied sensations regardless of the active interaction of the participant. What sets the *Haptic Floor* apart from these systems is the role of active touch. The participant has agency and can actively explore the virtual surface on which they are walking.

The observation that an active touch is different than passively received energy implies that the structure and organization of the perceiving individual is different when they are in an active state, thereby changing the structural changes they experience as a result of their structural coupling with systems external to themselves.

The discussion of active touch has emphasized the importance of volitional control of one's motor actions in the acquisition of haptic information. This implies a process by which raw sensory data from multiple sources (e.g. tactile receptors in one's foot, muscle tension in one's leg and a sense of balance and motion from one's inner ear) is somehow joined together to form a cohesive perception. The following section considers perceptual fusion.

Perceptual Fusion of Multimodal Information

The phrase “perceptual fusion of multimodal information” is used as an explicit way of defining the topic of how humans derive meaning from varying sensory channels. I use the term ‘information’ in this context as an abbreviated reference to the energy signals, the structural changes in the individual that these energy signals lead to, and the cognitive interpretation of these changes that takes place. I present a fuller examination of information later in this document, in a discussion on paradigms of communication (Reddy, 1979), and through discussions of structural coupling (Maturana, 2002).

The subject matter of this section is often discussed in the literature as “sensor fusion”, however the phrase “sensor fusion” can also refer to, among other things, the mathematical combination of electronic sensor data. The subject is introduced here with an emphasis on human perception, and although the research from cognitive science, psychology and physiology has inspired, informed and been validated through its application to artificial intelligence systems and robotics, the primary focus of the research here is with regard to human perception and action. The phrases “perceptual fusion of multimodal information” and “sensor fusion” will be used interchangeably in this text, largely based on the terminology used by the authors referenced herein, but will consistently refer to human perceptual processes as described above unless specifically stated to the contrary.

Perceptual fusion of multimodal information is not unique to haptics, which has been the focus up to this point. The concept applies broadly to all varieties of media and perceptual experiences. Perceptual fusion of multimodal information describes the connections created in our mind between two or more forms of sensory information, such as visual information and sonic information.

Murphy (1994) presents a model of sensor fusion based on prior research from the fields of cognitive science, neuroscience and artificial intelligence. Murphy proposes that sensor fusion can be explained as a perceptual schema (Murphy, 1994). A perceptual schema is generally defined as “A structured internal representation of an object or image acquired through perception” (Colman, 2012). Murphy emphasizes the significance of the relationships between perceptual schema and motor schema, or the actions that occur in relation to the perceived phenomena. Murphy’s model of sensor fusion also proposes that sensor fusion requires not only simple mathematical combinations of sensory information but also evidential reasoning regarding the reliability and significance of individual sensory channels in varying contexts (Murphy, 1994). The structured representations that Murphy and Colman propose can be seen as a consequence of the structure of a structurally determined system.

Ernst and Bülthoff (2004) separate the sensory fusion process into two types: combination and integration. They state, “‘Sensory combination’ describes interactions between sensory signals that are not redundant. That is, they may be in different units, coordinate systems, or about complementary aspects of the same environmental property.” Ernst and Bülthoff continue, “‘sensory integration’ describes interactions between redundant signals. That is, to be integrated, the sensory estimates must be in the same units, the same coordinates and about the same aspect of the environmental property.” Sensory information that has been combined can be then integrated to form a single cohesive percept of the environment or object. An important concept described in

Ernst and Bülthoff's article is a Bayesian "perception-action loop". This loop incorporates prior knowledge about the sensed environment and emphasizes the mutually dependent dimensions of sensing, perception and action (Ernst & Bülthoff, 2004). This perception-action loop parallels Gibson's (1962) concept of "active touch". I note here the Bayesian inference and remind the reader that this process is abductive (Galán & Mengshoel, 2009).

Helbig and Ernst (2007) confirm the automatic nature of bimodal sensory integration in a series of experiments in which participants estimated proportions of objects through visual and haptic inspection. They demonstrate that even in cases in which one sensory modality is available but explicitly excluded in the participant instructions, the excluded modality is not functioning completely independently and still significantly biases the perception of the object. They also find that sensory fusion is rarely complete but instead operates on a continuum. Only in cases in which the sensory information from both sources is completely congruent would they expect to find complete fusion. A key factor in promoting this sensory integration is a priori knowledge (or belief) that the source of the sensory information is the same source (Helbig & Ernst, 2007).

Specifically considering the perceptual fusion of audio and haptic data, Bresciani et al. (2005) demonstrate that audio signals can affect haptic perception, but only if the auditory signal occurs within a sufficiently small temporal window so as to make it cognitively cohesive with the haptic stimulus (Bresciani et al., 2005). This demonstrates an application of the theory described by Murphy (1994, 1996): sensory information is fused, producing a biasing effect when the evidence logically supports it, but the conflicting sensor data is disregarded when it does not. This finding is consistent with Helbig and Ernst's (2007) theory of the role of knowledge of a common source. As the temporal difference between information received in separate sensory modalities increases, the observer's belief in the unified source diminishes (Helbig & Ernst, 2007).

Robles-De-La-Torre & Hayward (2001) provide further and surprising evidence about the nature of the perceptual fusion of sensory information acquired through active touch (Gibson, 1962). They demonstrate that force cues (information from muscles regarding resistance to motion as a finger is moved across a surface) can supersede the kinesthetic information that describes the geometry of the surface. Simply described, they produce the illusion of a bump when the actively explored geometry was actually a hole and vice versa by providing force cues for the opposite geometry (Robles-De-La-Torre & Hayward, 2001). This example of sensory fusion in which one information source can induce a contradictory perception in another sensory modality and mask the true nature of the object illustrates the complexity of the cognitive process and the potential for creative applications of multimodal interactive systems. In naturally occurring environments such perceptual illusions are less common, but computer control of multimodal feedback as an augmentation of reality provides the opportunity for enhanced and entirely new experiences. These experiments emphasize the organizational closure of structurally determined systems (Maturana, 2002; Varela & Goguen, 1978) and the inherent challenges of what we consider information transfer (Reddy, 1979) through structural coupling (Maturana, 2002).

Kevin O'Regan (2011) extends the concept of active touch to all perception in his sensorimotor approach to explaining perception. His theory is based on psychological and physiological studies that demonstrate that our perception is not fundamentally determined by the sensory stimuli, but by how our experience of this stimuli predictably changes with our active bodily engagement with the stimuli (O'Regan, 2011). O'Regan emphasizes, citing Ned Block (1995), that consciousness is "Being Conscious of Something". This directly parallels Wittgenstein's (Wittgenstein, 1953) claim that when ever we see something, we always see it as something.

From the perspective of structurally determined systems, haptic interaction and perceptual fusion of multimodal information can be seen as structural coupling. With haptic interaction, structural coupling is readily understandable because of the inherent tangibility implicit in haptic interaction. Perceptual fusion of multimodal information involves a wider range of energetic modes, but is still explainable in terms of structural determinism. Extended discussions of structural coupling, information and communication in the upcoming chapters of this document may make this argument clearer, but it is not the focus of this research.

Stimulus-Response compatibility. Structural coupling between structurally determined systems depends on an interactional compatibility between the systems. In psychophysical and human-computer interaction research, the phrase 'stimulus-response compatibility' (S-R) is used when considering such relationships.

The earliest use of the phrase 'stimulus-response compatibility' was (as nearly as I can determine) in the paper by Fitts and Seeger in 1953 (1953). They offer this definition of S-R compatibility, "A task involves compatible S-R relations to the extent that the ensemble of stimulus and response combinations comprising the task results in a high rate of information transfer." The study described in this paper focuses on the relationship between the spatial characteristics of the visual display of information (the stimulus) and a spatial motor response to that stimulus. They found that in terms of response time and error rate, performances were better when the spatial relationships of the stimuli and the required responses aligned. The theory that they provide to explain this is that correspondences arise from our everyday interactions in the natural world and that limited experiences in any particular interaction environment will always be influenced by the cumulative effects of all those external experiences. They describe the relationship between the experimental conditions and the natural world conditions as interacting probability functions, with a stronger weighting produced by the probability from the natural world (Fitts & Seeger, 1953). Norman's (1988) seminal work, *The Psychology of Everyday Things* presents and extended look at the natural world interactions that Fitts and Seeger attribute to the S-R compatibility effects they observed (Fitts & Seeger, 1953; Norman, 1988).

Akamatsu et al. (1995) found that a haptic feedback condition provided a significant performance increase in a computer mouse target acquisition task compared to alternative feedback conditions. They compared normal (visual position feedback only), auditory, color, tactile and combined feedback. Specifically they found that users selected targets faster with tactile feedback. Akamatsu et al. conclude with an important guiding principle for the design of human-machine interfaces: the principle of Stimulus-Response (SR) compatibility. They state, "Tactile feedback for motor responses maintains SR compatibility and should be encouraged whenever its integration into the human-machine interface is possible." In the simplest terms, SR compatibility describes the compatibility between perceived information and action required based on that information. They note that even though the selection time difference in these tests were relatively small, they did not expect a large difference given the simplicity of the task tested and speculate that the performance increases would be significantly magnified in more complex interactive tasks (Akamatsu et al., 1995). Performing control gestures with a musical instrument, such as my *Vox Curio* instrument, described later in this document, is exactly the type of complex interactive task that is likely to benefit from high SR compatibility in the interface design.

Hasbroucq et al. (1990) build on Fitts and Deininger's (1954) earlier research to provide a detailed analysis and taxonomy of stimulus-response compatibility, decomposing the problem into categorical sets with potential "dimensional overlap" or commonalities (Fitts & Deininger, 1954; Hasbroucq & Kornblum, 1990). Returning to the claim made by Akamatsu et al. (1995) that tactile feedback should be provided when motor responses are required, we recognize that the commonality between the stimulus (the tactile feedback) and the response (the required motor action) is the common location of the hand which acts as both information receptor and actuator (Akamatsu et al., 1995). In Hasbroucq et al.'s (1990) terms, there is a strong dimensional overlap between the stimulus and response properties, improving reaction time and decreasing error rates (Hasbroucq & Kornblum, 1990).

Mudd (1963) describes experiments investigating the possible existence of common, spatially mapped, cognitive models of dimensions of sound. Stereotypical responses were found for frequency, intensity and direction of sound. The strongest stereotypical response was for frequency, which mapped to a vertical coordinate system. These findings provide a foundation for understanding potential dimensional overlaps for

S-R compatibility driven decisions when designing interactive systems involving audio information (Mudd, 1963).

Simon and Rudell (1967) investigated the effects of S-R compatibility with a semantic auditory stimulus and a corresponding motor-action response. They explored varying levels and types of S-R compatibility, changing which ear heard a “left” or “right” verbal cue and changing from a randomized ear stimulus state to a state in which participants knew in advance which ear they would be hearing the cue in. In all cases, response times were quickest when the semantic content of the cue corresponded to the location of the ear. Eliminating the random variability of the cue location improved performance, but not as significantly as when the compatibility was at its highest potential experimental state (Simon & Rudell, 1967).

Response-Effect compatibility. Response-effect (R-E) compatibility (Kunde, 2001) is the complement to stimulus-response compatibility. R-E compatibility refers to the relationship between an action (response) and the anticipated result (effect) of that action. When the actual effect matches the anticipated effect (determined by an existing mental model), the R-E relationship is said to be compatible. When the actual effect is contrary to the anticipated effect, the R-E relationship is said to be incompatible. The reason this compatibility is significant is founded in ideomotor theory. Shin et al. (Shin, Proctor, & Capaldi, 2010) summarize the concept this way, “A framework for action planning, called ideomotor theory, suggests that actions are represented by their perceivable effects. Thus, any activation of the effect image, either endogenously or exogenously, will trigger the corresponding action.” If incompatible effects disrupt this action planning process, the response is hindered. Keller and Koch (2008) demonstrated this effect in a music-like interaction scenario and found that trained musicians exhibited a stronger reaction to the compatibility effect than non-musicians, presumably because their musical training had developed and/or reinforced the relevant mental models of action and sonic effect. R-E compatibility has interesting implications for seeing cognition in terms of structural determinism. It suggests that the structure of a cognizing individual is modified through structural coupling with external systems and that when similar systems are encountered this previously modified structure somehow facilitates interaction with those systems. Importantly this facilitation apparently happens in advance of the primary energetic exchange that is described as the interaction. For it to affect planning, a secondary energetic response would have to trigger the structural change.

Spence (2011) provides an extensive summary of psychophysical research and theories attributed to the fusion and differentiation of sensory data. He focuses on theories explaining sensory integration that go beyond the basic, and earliest studied explanations of direct temporal or spatial correspondence between sensory stimulation sources. The crossmodal correspondences described in this paper may be of several different types. The author describes semantic correspondences, which are connections due to the conceptual meaning or identity attributed to the stimuli. Structural correspondences are attributed to what are thought to be common forms of sensory representation in the brain. Statistical correspondences are those formed by the associations naturally occurring due to the properties of entities in physical nature (Spence, 2011)

This concludes my presentation of the theoretical dimensions of haptic interactions and perceptual fusion of multimodal information. The next sections will present practical haptic technologies and implementations of systems with a significant haptic component.

Haptic Interface Technology

Haptic technologies can be classified according to the specific haptic senses they primarily address. In general terms, these can be reduced to two classes: tactile and proprioceptive/kinesthetic. Tactile haptic feedback devices produce signals with the objective of producing sensations of touch primarily at the skin level. Proprioceptive haptic feedback devices produce signals with the objective of producing sensations of touch primarily at the motor action level. Of course this classification scheme is a gross simplification. As noted in the prior discussions describing active touch, S-R compatibility and R-E compatibility, tactile sensing, proprioceptive sensing and motor control are intimately linked and mutually dependent. Nevertheless, these broad classes provide a useful structure for describing the most common haptic feedback technologies.

Tactile haptic systems. The goal of tactile haptic feedback systems is to render the somatic sensation of touching surfaces with varying textures, frictions, temperatures, hardness, or other physical surface properties. This is accomplished with technologies including: voice coils; eccentric mass rotational motors; piezoelectric crystals; arrays of physically actuated mechanical pins; shape memory alloys; Peltier heat pump systems; electroheological fluid; magnetorheological fluid; electroactive polymers; electromagnetic suspension systems; and skin deformation techniques (Benali-Khoudja, Hafez, Alexandre, & Kheddar, 2004). Of these, the voice coil and related actuator technologies used to produce vibrotactile sensations are likely the most common.

Control algorithms for tactile rendering vary greatly depending on the properties of the technology used, the qualities of the virtual material(s) being rendered, and the requirements of the application. Laycock and Day (2007) describe the history and state of the art of haptic rendering algorithms. Benali-Khoudja et al. (2004) provide an extensive survey of tactile interfaces.

One of the general principles for vibrotactile feedback, a common form of tactile rendering, is that our experience of touching physical objects can be described in terms of magnitude of force experienced and frequency of force experienced. If one slides one's finger over a textured surface, the physical dimensions of the texture, in proportion to the contact force and velocity of the hand movement will determine the amplitude and frequency of bumps felt. High frequency transient forces may also be rendered, increasing the realism of the tactile experience (Kuchenbecker, Fiene, Niemeyer, & Member, 2006).

Proprioceptive haptic systems. Haptic systems that engage the proprioceptive system are commonly known as "force feedback" devices. They typically operate by sensing position of, or force applied to, a physical mechanism with which the user interacts. A control model (often, but not necessarily physics based) uses this sensor data (potentially along with additional data) to calculate a responsive force or new position. This calculated information is used to drive one or more actuators. This sensing feedback loop is repeated continuously at a high frequency, ideally resulting in the sensation of interacting with a physical object or environment.

The sensors required for this feedback loop depend on the specific design specifications of the system. Resistive, optical, magnetic, accelerometer and gyroscope sensing devices are all commonly used for position sensing. Force sensing is achieved directly with force sensing resistors (FSR's), torque sensors, load cells and pressure sensors. Many combinations of mechanical systems with other forms of sensing hardware make the indirect sensing of force possible. Force and position sensors must meet the dimensional range, dynamic range, sensitivity, resolution, frequency, hysteresis and any other system requirements.

Actuators for proprioceptive haptic systems can be rotational motors (servo, stepper, DC gear motor, etc.), linear motors (pneumatic, hydraulic, electric) or any other mechanism capable of producing physical motion, controlled by computational means, in a distance and force range perceptible by humans as movement (as opposed to a tactile sensation of vibration).

In compliance with Newton's third law of motion, forces always occur in equal and opposite pairs. The nature of these pairs of forces forms a sub-classification scheme for proprioceptive haptic feedback devices (Winfree, Gewirtz, Mather, Fiene, & Kuchenbecker, 2009). Devices may be classified as: classically grounded; body grounded; and ungrounded. Classically grounded devices are attached to a relatively massive and stable object such as a table such that the forces generated by the device act on the user and the immobile base. Body grounded devices produce forces on two different parts of the human body (e.g. the finger tip and the wrist). This configuration relies on the relative differences in mass, anatomical stability and perceptual sensitivity between the individual body parts to produce useful and convincing haptic renderings

(Lederman & Klatzky, 2009; Winfree et al., 2009). Ungrounded haptic devices produce forces through gyroscopic, asymmetrical acceleration, and other mass - inertial effects.

Yano et al. (2003) and Winfree et al. (2009) produced and explored the engineering challenges and affordances of ungrounded gyroscopic force haptic feedback devices. These examples can be described as control moment gyroscope (CMG) systems, producing torque by changing the angle of a rotating flywheel.

GyroTab (Badshah, Gupta, Morris, Patel, & Tan, 2012) is another, more recent, example of an ungrounded haptic feedback system. This system would be commonly classified as a reaction wheel system. It produces variable torque by changing the accelerations of two parallel flywheels. The flywheels' orientations are not changed as those in the previous CMG style systems (Badshah et al., 2012).

Amemiya et al. (Amemiya, Ando, & Maeda, 2008) demonstrate a technique which produces an illusion of a constant translational force from one direction with an ungrounded haptic interface. Their system utilizes asymmetrical acceleration of a mass to produce this effect. The mass rapidly accelerates one direction and relatively slowly on a return path. Major engineering hurdles faced in the production of this system included minimizing forces other than the single force direction they intended the device to render and finding an operating frequency at which the cyclical forces perceptually merged into constant force without being experienced as a vibration (Amemiya et al., 2008).

Haptics and musical instrument design. A great many technological innovations have facilitated the development of new and varied musical instruments throughout the centuries. Of interest here are the changes in musical interfaces as a result of the emergence of electronics and computer technologies and in particular, the role haptic information plays in the performance characteristics of these instruments.

On the plus side, electronics and computers have tremendously expanded the pallet of sounds available to musicians. New sensing and modeling technologies facilitate new musical gestures and performance modes. Networked systems of performers and instruments expand the potential scale and complexity of musical events to unprecedented dimensions. However, there are also challenges presented by the evolution from purely acoustic instruments to ones built around these new technologies.

Cook (2004) describes the consequences of isolating the controller portion of a musical instrument from its synthesizer and sound production components. He summarizes the problem as a loss of intimacy between the performer and the instrument, specifying the loss of haptic feedback, reduction in interaction fidelity and loss of the sensation of the sound actually coming from the instrument as the fundamental problems resulting from this type of instrument design. He proposes a design and construction methodology that reintegrates the instrument controller systems with the synthesis, sound output and haptic feedback systems, thereby restoring the intimacy between the instrument and the musician. Importantly, Cook suggests that this methodology may lead to new controller designs that evolve out of the process of being co-designed with and integrated into the instrument's synthesis systems and vise versa (Cook, 2004). The integration Cook suggests echoes Simondon’s description of the concretization of technical objects and may benefit from the generation of plurifunctional structures.

Many researchers and instrument builders have recognized what they perceive as limitations of musical interfaces with impoverished interaction and feedback modalities and have produced a wide variety of new interfaces that address these deficiencies in creative ways.

One class of such interfaces is identified as “hyper-instruments” (Machover, 1992). Bowers and Archer (2005) discuss the terminology of, and concepts behind, hyper, meta, cyber and a new proposed class of infra-instruments. Hyper-instruments are traditional musical instruments augmented with additional sensing and computational systems, allowing the instruments to maintain their traditional expressive potential and interaction affordances and have expanded performance capabilities (Bowers & Archer, 2005). Tod Machover (1992) created the “Hyperinstrument Project” at the Media Lab at MIT. His work continues as the director of the “Opera of the Future” group at MIT.

Gyrotyre (Sinyor & Wanderley, 2005), a music controller, is similar in its conceptual motivation and technical dimensions to my *Vox Curio* instrument, which is discussed later in this document. *Gyrotyre* consists of a small bicycle wheel with an attached handle and a set of sensors to detect the motion of the device. The musician manually actuates the *Gyrotyre* wheel. The motion of the spinning wheel, and the motion of the overall device are sensed and used to drive audio synthesis and signal processing programs, resulting in varying sonic output from the instrument. The physical nature of the device, including forces resulting from the potentially spinning wheel provides haptic feedback to the musician (Sinyor & Wanderley, 2005). A fundamental difference between *Gyrotyre* and *Vox Curio* is that the *Gyrotyre’s* physical feedback cannot be computationally modulated. It is simply a one-way controller. Information is transferred to the computer from the interface, but no information is sent back to the controller from the software.

Bahn et al. (2001) consider the importance of the human body in musical performance. They emphasize not only the significant physical relationship between the performer and their instrument, but also social and cultural factors including what they observe as the vicarious experience of the audience listening to and visually observing the physical act of the musician's performance (Bahn et al., 2001). This emphasis on the importance of the physical character, visual presence and performance characteristics of the instrument significantly influenced the design of my *Vox Curio* instrument.

Chafe (1993) experimentally demonstrates the critical role haptic feedback plays in the control of a musical interface. A key principle of haptic interaction is demonstrated in this research, namely the value of feedback and control being spatially and temporally co-located. Vibrotactile feedback significantly improved the accuracy and control of the software instrument in which a lip tension parameter was controlled through a hand deflecting a flexible metal bar, with and without vibrotactile feedback (Chafe, 1993). This finding is predicted by the principle of S-R compatibility (Fitts & Seeger, 1953).

Marshall et al. (2006) provide a brief overview of the importance of haptic feedback for musical interfaces; summarize the requirements for vibrotactile feedback with reference to the human sensory system; describe a number of actuators appropriate for generating tactile haptic feedback; and finally, present two musical interfaces that incorporate the aforementioned principles and techniques. They emphasize the value of having the musical control gesture, haptic feedback and sonic production systems full integrated into a single instrument body to produce something that is perceived by musicians as a "musical instrument rather than a computer controller". Marshall et al. did not present evidence from any formal studies to evaluate their success in achieving this goal (Marshall et al., 2006).

Overholt et al. (2011) describe the affordances of actuated musical instruments (physical instruments which combine computer and human controlled actuation of the instrument). They outline potential extensions and enhancements to the musical performance experience that result from the synthesis of human and computational abilities. They emphasize the vital role of the physicality of the instruments and the haptic feedback loop they provide. The authors propose the following potential benefits of actuated musical instruments: decreasing cognitive load for the performer (since the computer is doing some of the work); enabling and/or stimulating new ways of interacting with the instrument; freeing the performer from the need to constantly input energy into the instrument (allowing them to instead modulate energy produced by the instrument); perform in collaborative ensembles in which instruments are networked and performance gestures and feedback can be shared; and allow the musician to experience computationally defined parameters of instruments as tangible properties. Overholt et al. present four instruments as examples of actuated instruments: the *Overtone Fiddle*, the *Feedback Resonance Guitar*, *Robothands*, the *Electromagnetically Prepared Piano* and the *Haptic Drum* (Overholt et al., 2011). Each of these instruments is unique in interaction and sonic affordances and provides lessons that can be applied the design of future instruments.

In his dissertation, *Playing by feel: incorporating haptic feedback into computer-based musical instruments*, O'Modhrain (2001) researched the utility of including haptic feedback in addition to sonic feedback for what he calls "virtual" musical instruments.

O’Modhrain found that the availability of haptic feedback (above and beyond the passive haptic feedback associated with basic human motor activity) did improve the learnability and playability of these instruments (O’Modhrain, 2001).

Ahmaniemi (2010) compared the use of static versus a dynamic plus static vibrotactile cues for interaction with a virtual instrument. In this study, participants were tasked with following a percussive rhythm. They struck a virtual percussive surface with a downward motion of a hand-held sensor-actuator device. In the static condition, a pulse of tactile vibration was synchronized with the sonic pulse associated with the crossing of a virtual control surface boundary. In the dynamic plus static condition, an additional ramped vibrotactile signal was added to the haptic feedback. The magnitude of this haptic signal increased in inverse proportion to the distance from the target surface. Ahmaniemi found a significant performance increase with the dynamic feedback condition in both timing accuracy and in velocity control (Ahmaniemi, 2010).

The role of haptic feedback is not limited to the use of external musical instruments. Sundberg (2013) discusses how singers use phonatory vibrations, resulting from their vocalizations and felt in their chest and face, as feedback to help them perform. Sundberg focuses on the questions surrounding the utility of this potential feedback mechanism, pointing out for example, how singers describe placing a tone in their nose or chest. Sundberg also notes the perceptual limitations of this form of feedback based on our understanding of human physiology and the physics of the vibrations involved (Sundberg, 2013).

This concludes my survey of background literature, theory and systems. This background set the stage for the heart of this dissertation, a paradigm construction project in which I see systems as structurally determined. The theories of perception, particularly theories of haptic interaction may be more richly understood seen from the perspective of structural determinism and structural coupling. The aspects of materiality that are observed in the coupling of structurally determined systems may be seen at play in social and cultural systems. Artists’ use of media may be seen in terms of structure and organization.

CHAPTER 4

STRUCTURE DETERMINES ORGANIZATION

Foundations of Structural Determinism

When Maturana (2002) embarked on his search for an answer to the question of what defined a living system as such, he framed his approach through this question: "What should happen in the manner of constitution of a system so that I see as a result of its operation a living system?" (Maturana, 2002, p. 5). He bluntly added, "to answer the question properly I would have to create a living system, either conceptually or practically in the laboratory" (Maturana, 2002, p. 6).

Maturana's (2002) approach to the problem, first espoused in the early 1980's, which we see directly echoed by Braitenberg (1986) in his conceptual synthesis of cognitive structures, led Maturana to the development of his concepts of structural determinism, structural coupling and autopoiesis. At the heart of these concepts is the notion that the organization and structure (two terms that Maturana carefully uses and differentiates) of a system is what ultimately matters in defining its existence. Specifically, Maturana defines a structure determined system as, "a system in which all that happens with it and to it is determined at every instant by the way it is made (its structure) at that instant" (Maturana, 2002, p. 6).

An important dimension of structural determinism, and one that was in contrast to the prevalent thinking of the time regarding the nature of living systems was the self-defined closure of the system. This closure was defined not by a material boundary, the system remained open and was dependent on a flow of energy and matter, but by its organization (Maturana, 2002, p. 7).

When Maturana (2002) speaks of the organization of a system, he is speaking unambiguously about the relations between the components that make up the system. Relations in this context mean the functional dynamics of the system. The structure, at every instance, determines the dynamics, and thereby the organization. The structure can change while maintaining a consistent organization or can change such that the organization also changes. The organization of the system defines the class of the system (Maturana, 2002, pp. 15–16).

An autopoetic system is a specific form of organization in which, in a circular pattern, a process (which spontaneously occurs as a result of the system's structure) produces a structure that spontaneously exhibits this same production process (Maturana, 2002, p. 7). This high level summary of Maturana’s definition does not capture the specificity and nuance of his meaning, and I encourage readers unfamiliar with these concepts to refer directly to Maturana's texts for a more thorough and refined explanation, but this will suffice for now in the context of my research. Autopoiesis, as a specific organizational possibility within and between structurally determined systems, is not directly related to my topic. Structural determinism and structural coupling, which will be addressed in greater depth soon, are fundamental to my conceptual investigation of the function and creation of experiential media systems. Ken Rinaldo’s (2000) kinetic, interactive sculpture entitled *Autopoiesis* (Rinaldo, 2000) is a good example of an experiential media system in which one can see the interplay of structure and organization.

Maturana (2002) emphasizes that, "what constitutes a dynamic system is its manner of dynamic composition, not the elements that compose it." (Maturana, 2002, p.

10). Again we are focused on the relations that are established between the elements, not on the elements themselves. Maturana uses a tornado as an example to illustrate his point. The dynamics of movement (in this example) are what are significant, not the material makeup of the object. In an upcoming section I will introduce in greater depth, the ideas of Gilbert Simondon (1958), but I include a quotation from him here to emphasize the clear links I find between the ways they see their subjects. Simondon says in his description of technical individuals (a specific class of technical objects defined later in this document),

> Therefore the technical individual should be imagined, that is to say, it should be assumed to be constructed, as an ensemble of organized technical systems. The individual is a stable system of technicalities of elements organized into an ensemble. What is organized is these technicalities; the elements also are organized, but only in so far as they are bearers of these technicalities and not because of anything that has to do with their own materiality. (Simondon, 1958, p. 87)

I draw particular attention to Simondon's (1958) use of the term "organized" and even more specifically to his emphasis that, "What is organized is these technicalities". He says directly here that the materiality is not what is important, paralleling Maturana's (2002) definition of organization. I must reemphasize here that structure, which significantly includes materiality, is absolutely critical to both Maturana's theory of autopoiesis and Simondon's theory of technical objects.

A simple example, not of a living, or even a biological system, that further illustrates the relation of structure and organization is an inflatable rubber ball. For this example, let us assume the ball has a diameter of 12 inches. The ball's structure changes as it is inflated or deflated. This claim may be debatable, but I argue that the air molecules contained in the ball are part of the structure of the ball because they are a fundamental part of what defines the organization of the system. Just as in Maturana's (2002) examples of biological cellular systems, material and energy may transfer in and out of these structures and be incorporated and unincorporated in the cell's structure (Maturana, 2002, p. 7). I also remind the reader that I am speaking of structure, which I differentiated from form in my introduction. By changing the structure of the ball, its organization is simultaneously changed. If we deflate it far enough, it no longer bounces and it no longer rolls. Our dog might now enjoy it because it can easily carry it around. The important question is: is it still a ball? If we define a ball by its organization, or dynamics, as proposed by Maturana (2002), at some point it stops being a ball. The exact point this occurs depends on what organizational characteristics we require in our individual definitions of a ball. Incidentally, from the dog's point of observation, the ball likely never ceases to be a ball. It smells the same, tastes the same and so forth.

A slightly more complex example of an experiential media system pushes the question further. Wii bowling, a game played with the Nintendo Wii game console as part of the Wii Sports package (wikipedia, 2015), simulates the physical game of bowling. The question is: is Wii bowling, bowling? Clearly there are structural differences between the video game and the traditional version of the game, but organizationally there are potentially many commonalities. From my personal experience playing Wii bowling, the best experiences involve multiple players, all of whom, to varying degrees, physically mimic the sequences of actions that would occur in a physical bowling alley.

They wait for their turn to bowl, perhaps sipping a beverage and chatting with their competitors. When it is their turn, they stand up, maneuver to a position in which they are centered in front of the alley (on the video display). They calm themselves; raise the ball (the Wii remote) in preparation for the gesture that will generate a virtual toss of the ball. They may take a step or two as they swing their arm and virtually release the ball. After the ball is rolling down the alley, they will often lean their body in an effort to remotely impart a change in the vector of the rolling ball. Depending on the outcome of their efforts, they may jump in celebration or slump back to their chair in defeat. Organizationally, Wii bowling may be very similar to the real thing, even if there are significant structural differences.

Wii golf (wikipedia, 2015) provides an interesting point of comparison to Wii bowling in terms of their respective organizational similarity with their physical analogs. Bowling takes place in a stationary location. The players of Wii bowling, in a living room may, for the most part, replicate the entirety of the movements of bowlers in a physical bowling alley. Golf takes place in a much larger physical environment, with no single focal point as exists in the simulated bowling alley. Virtual golfers cannot, with today's technology, in any practical, seamless way, mimic the movements and interactions of real golfers as they walk or ride from location to location. The stationary focal point of the bowling alley, by contrast, establishes a persistent extension of the physical space occupied by the Wii bowlers.

This discussion of embodied video game experiences is intended to illustrate the extent to which a structure of an experiential media system may vary while maintaining an organizational identity (Maturana, 2002, p. 16). Simondon (1958) says, "The machine is a result of organization and information" (p. 9), emphasizing a conceptually consistent way of seeing systems as defined by their organizational structure and open to information.

The next section, introducing the concept of structural coupling (Maturana, 2002), will focus on this informationally open aspect of structurally determined systems.

Structural Coupling

When the concept of a structure determined system (Maturana, 2002) is first introduced, a logical challenge seems to arise. If a system is defined as a closed system and this system defines its own boundaries, interaction with anything external to the system seems impossible. Maturana (2002) seems to reinforce this understanding when he claims,

> A living system as a molecular system is a structure determined system, and everything that happens in it or to it, happens in each moment determined by its structure at that moment. That is, nothing external to a living system can specify what happens in it. (Maturana, 2002, p. 12)

The important detail to recognize in this statement is the claim that the external system cannot "specify" what happens to it. A simple example helps clarify the difference that is presented here.

> The motion of a billiard ball struck by another billiard ball is sometimes seen as determined by the force and direction of the ball striking it, but it is actually determined by the structure of the ball being struck. If the ball had the structure of a tennis ball it would move very differently. The ball striking the other ball provides

> energy, but the structure of the ball being struck determines what happens to that energy. (Reid & Mgombelo, 2014, p. 3)

It is easy to imagine an endless array of such energetic exchanges between systems of differing structure. We can easily see how in these exchanges the structure of each involved system will be changed and how these changes will affect subsequent interactions. In more specific and formal language Maturana (2002) offers this as a definition, “I have called the dynamics of congruent structural changes that take place spontaneously between systems in recurrent (in fact recursive) interactions, as well as the coherent structural dynamics that result, structural coupling” (Maturana, 2002, pp. 16–17). These mutual energetic and even material exchanges provide a way for information to be shared. The next section considers the mechanics of this information sharing in greater detail.

Conduit or Toolmaker

This section takes the foundational principle of structural coupling, initially defined by Maturana (2002) in the context of living systems, and considers its implications and applicability in the larger context of machines and humans. This discussion presents ideas put forth by the linguist Michael Reddy (1979) and considers these ideas in the context of Gilbert Simondon’s (1958) mechanological way of seeing information.

I argued in the last section that structural coupling could be seen as way of sharing information. By what means is this information shared? Reddy's (1979) linguistic analysis and comparative metaphors for communication provide a way of interpreting the mechanism by which information may be said to transfer from one structurally closed, often heterogeneous, system to another (Reddy, 1979). Reddy presents two metaphors for communication. The first, a conduit metaphor, implies a direct transfer of information as a package that is created, packaged (in words, sentences, etc.) or simply released, and received, collected and unpacked by another. This metaphor assumes a direct replication of the information on the receiving side of the exchange (Reddy, 1979, pp. 286–292). The second metaphor, identified as the toolmaker metaphor, assumes no possibility of a direct transfer or replication of information. It instead assumes that energetic exchanges are possible, in the form of sound waves (vocalized utterances, words), mechanically generated marks (diagrams, text), or other means determined by the structural properties of the objects involved in the exchange. The response to energy received from another, is wholly dependent on the current structure of the receiving object. In Reddy's metaphorical terms, the receiver must build what they can, from their own repertoire of materials, to generate their unique version of the information. The information that generated the energy transfer on the transmitting end may have little to nothing in common with that interpretively reconstructed on the receiving end (Reddy, 1979, pp. 292–297).

Simondon (1958) states, "The real perfecting of machines ... relates to the fact that the functioning of the machine conceals a certain margin of indetermination. It is such a margin that allows for the machine's sensitivity to outside information" (Simondon, 1958, p. 4). I see Simondon's notion of the margins of indetermination in technical objects, as the variables or degrees of freedom that these objects present. These variables account for the potential for a changed structure, a response to external energy, and thereby a potential informational response, in the sense of Reddy’s (1979) toolmaker paradigm. I will return to this idea of variables, degrees of freedom, and constraints in chapter 6 when I discuss the making process and Pye's (1968) concept of regulation.

Reddy (1979) emphasizes the challenge of communication as understood through the toolmaker metaphor. He points out that it is a lot of work for communication to occur and that often many energetic exchanges must occur before any real information can be accurately interpretively regenerated (Reddy, 1979, pp. 295–296). This vision of the continuous nature of this process parallels the notion of Simondon's (1958) idea of recurrence of causality. Simondon says,

> For the reasons already outlined, we can rightly state that the individualization of technical beings is the essential condition for technical progress. Such individualization is possible because of the recurrence of causality in the environment which the technical being creates around itself, an environment which it influences and by which it is influenced. This environment, which is at the same time natural and technical, can be called the associated milieu. By means of this the technical being is conditioned in its operation. This is no fabricated milieu, or at least it is not wholly fabricated; it is a definite system of natural elements surrounding the technical object and it is linked to a definite system of elements which constitute the technical object. The associated milieu is the mediator of the relationship between manufactured technical elements and natural elements within which the technical being functions. (Simondon, 1958, pp. 60–61)

This persistent energetic exchange, as described by Reddy (1979) and Simondon (1958) is congruent with Maturana's (2002) definition of structural coupling. It provides a mode of communication between such heterogeneous objects as a human, a tool wielded by the human and a material modified by the tool. It provides a way of seeing how one can claim to ‘know their material’. This concept of ‘knowing material’ is further examined in Chapter 6.

Simondon (Simondon & Le Moyne, 1968) describes a basic example of an energetic exchange in the operating of an oil lamp, which self regulates its combustion by consuming the oxygen it is dependent on for combustion. He states, "its functioning implies something informational, as implied internally.” He continues, “the implicit information, allowing homeostasis and stability of the object, exists in a simple ancient oil lamp" (Simondon & Le Moyne, 1968). This example emphasizes the subtlety of potential structural couplings and hints at the organizational dynamics that lead to the unity systems, be they living systems (Maturana, 2002) or technical objects (Simondon & Le Moyne, 1968; Simondon, 1958).

Structural coupling, far from being a secondary theoretical offshoot of structural determinism, has been shown to be essential to its meaning, for without structural coupling, a structurally determined system would have a meaningless isolated existence (Maturana, 2002). These essential nature of structural coupling will emerge in greater detail as Simondon’s (Simondon, 1958) concepts of unity are examined in the next chapter, which continues to examine systems as structurally determined. In the next chapter the emphasis will shift from the foundations of structural coupling to seeing technical objects as structurally determined.

CHAPTER 5

DETERMINING STRUCTURE (IN THEORY)

The previous chapter introduced the theories of structural determinism and structural coupling as defined by Maturana (2002). I emphasized the importance of the interrelated concepts of 'structure' and 'organization' in understanding these theories (Maturana, 2002). The informational implications of structural coupling (Maturana, 1987, 2002) were examined through a discussion of communication featuring Reddy's (1979) competing framings of the mechanisms by which communication occurs. These framings are the "conduit metaphor" and the "toolmakers paradigm" (Reddy, 1979) the latter of which was shown to be consistent with Maturana's theory of structural coupling (Maturana, 2002) and Simondon's mechanological way of seeing information (Simondon & Le Moyne, 1968; Simondon, 1958). An understanding of these theories and their implications is important for interpreting the validity and utility of seeing experiential media systems as structurally determined systems.

Simondon's (1958) mechanological theory will now be examined in light of the theories introduced in the previous chapter. I look at Simondon's "technical objects" as structurally determined systems, using Maturana's (2002) language and concepts as a foundation for interpreting Simondon's concepts of unity and concretization. Concretization is examined as an evolutionary process (Simondon, 1958). Additional theoretical intersections of mechanology and biology are explored. The chapter culminates with a discussion of viability. The factors that determine the viability of systems are considered from biological and mechanological perspectives (Maturana, 2002; Simondon, 1958). Simondon's understanding of invention is considered with respect to these concepts of viability (Simondon, 1958). The subject matter of this chapter, which provides a way of seeing human made objects as structurally determined systems, establishes the foundation for the final chapter, which examines dimensions of making, or the practice of determining structure, from my vantage points as an artist, engineer and philosopher.

Mechanology

Mechanology is the "science of machines" (Simondon, 1958, p. ii). For Simondon (1958), the technical object is the heart of mechanology. A comprehensive definition of the technical object as envisioned by Simondon can only be acquired through his original texts. The summary explanation I provide can only scratch the surface of his full dissertation on the subject (Simondon, 1958), but it should be sufficient to carry my thesis forward.

Technical Object

First and foremost in Simondon's (1958) characterization of the technical object is the importance of recognizing the human presence in technical objects. He stresses that the technical is not separate from, or in opposition to culture, but is an essential component of it. The technical is shaped by humanity and shapes humanity, and serves as "the mediators between man and nature" (Simondon, 1958, p. 1). I included a short section on anthropologists and sociologists in my Background chapter and highlight immaterial systems, including cultural systems in my concluding discussion in chapter 6 on aspects of materiality, but at this stage in my career, the social/cultural dimension of this topic are not my focus. I approach this work, not from a modernist perspective, but from a perspective that does not prioritize an anthropocentric view of media systems.

Simondon (1958) defines the technical object “in terms of its genesis” (Simondon, 1958, p. 8). He does this specifically in opposition to classification systems based on specific characteristics and practical uses. This type of classification is easily done, but Simondon warns, “such specificity as this is illusory, for no fixed structure corresponds to its defined use” (Simondon, 1958, p. 11). Simondon turns his attention instead to the evolutionary forces and processes that shape and specialize technical objects, identifying this process as concretization (Simondon, 1958, p. 11).

Unity. Concretization describes the process of the specialization of a technical object (Simondon, 1958, p. 30). This gradual refinement happens as problems in earlier iterations of systems are addressed in later iterations. It is important to note that according to Simondon (1958), not every functional improvement to a system represents a concretization. If a change is made that fixes one problem, but adds others, Simondon would identify this as an abstraction (Simondon, 1958, pp. 30–31). Simondon specifies, “The concrete technical object is one which is no longer divided against itself, one in which no secondary effect either compromises the functioning of the whole or is omitted from that functioning” (Simondon, 1958, p. 30). So concretization implies a unity. I argue that Simondon’s definition of a concrete technical object directly parallels Maturana’s definition of an organizationally closed structurally determined system (Maturana, 2002; Simondon, 1958). These parallels will be further explored later in this chapter. For now, I will continue with additional details on the process and ramifications of concretization.

Hypertelia. As technical objects are concretized, their specialization results in varying levels of what Simondon (1958) calls “hypertelia”. He says, “ The evolution of technical objects manifests certain hypertelic phenomena which endow each technical object with specialization, which causes it to adapt badly to changes, however slight, in the conditions of its operation or manufacture” (Simondon, 1958, p. 51). Simondon also refers to this phenomena as “functional over-determination” (Simondon, 1958, p. 8) and uses the phrase “overadapted functionally” (Simondon, 1958, p. 51). A simple example is presented here to help the reader get a feel for this concept.

A basic glove might start as just the projection of a hand shape onto two pieces of fabric. These pieces are cut out and stitched into an enclosed form with an opening at the wrist for the hand to slide into. At this stage, either hand can fit equally well in the glove. The front and the back of the glove are defined by its use, by which hand it is on. This glove is highly versatile. It provides basic protection for the hand. It would be described as having a low level of hypertelia (Simondon, 1958, p. 51). This original glove may have some disadvantages in certain circumstances. Because it needs to be able to bend in either direction as the fingers are curled, depending on which hand is involved, it may have more length of fabric on the palm side of the glove to accommodate this than would otherwise be necessary. This extra fabric bunches up, is uncomfortable, and makes it difficult to grab things with the glove on. The glove could be remade and tailored to better fit the three-dimensional contour of the hand. At this point the glove has become more specialized. For practical purposes, it can only be worn on the hand it is made for. Hypertelia is essentially the compromise that comes with specialization. At this stage in our glove's evolution, it has become more hypertelic, but only minimally so. If we make a dramatic transformation in the form and material of our glove, making it out of leather for instance, adding a bunch of extra padding on the palm side, and connecting a pattern of leather webbing between the index finger and the thumb, we now have a glove that is highly specialized for catching balls of a certain size, but not a glove that will allow us to effectively use our hand for very many other operations. If we were looking for a general-purpose glove, we would describe this latest glove as over-determined (Simondon, 1958, p. 8). It is only good for one specialized activity. It is hypertelic (Simondon, 1958, p. 51). This does not mean this evolutionary result is negative. This example merely illustrates the dynamic relationships that are in play as structures are changed and the technical object increases or decreases in viability in relation to a particular intermediary function and environment in which it exists (Simondon, 1958, p. 51).

When we design experiential media systems, we are presented with the opportunity to define the degree of specialization of the system. There is always a temptation to refine a system so that it is an optimal fit for a specifically determined environment or envisioned interaction. This may work well if the system remains in these narrow parameters of use, but may be of little use if the environment changes or a person deviates from the intended mode of interaction. Sha, Freed and Navab (2013) address this concern in their designs of interactive media spaces by specifically not defining the interactions that may take place in these spaces from a human-centered perspective. They instead see the space as a structurally determined system with customizable organizational dynamics (Maturana, 2002) (these dynamics may be thought of as the physics of the space). This space may be structurally coupled with any other structurally determined system, which could be a person, a group of people, a robot, a shaft of sunlight, etc. The structure of the space is changed through this structural coupling. This structural change is manifest as varying changes in the media from which the space is constituted (i.e. energy we perceive as sound, light, tactile sensations) (Sha et al., 2013). This approach avoids hypertelia and affords rich interactional opportunities.

Stages/Classes of technical objects. As technical objects evolve they require varying levels of external support and are combined with or are independent of other technical objects, humans and the natural environment (Simondon, 1958, pp. ixx–xx). Simondon systematically classifies technical objects with respect to these variables. These classifications have little to no direct bearing on my application and synthesis of Simondon's theories so I will not address them in depth (and a very in depth examination would be required to unravel his use and meanings of these terms). I present them here, with very basic definitions, to provide the reader with some clarity when they arise in Simondon's quotations.

The first classification of a technical object is as a technical element. Technical elements can perhaps best be understood as man-made analogs to natural elements (Simondon, 1958, p. 61). Just as the function of a natural element can only be described with respect to other natural elements, the technical element is wholly dependent on relations with other elements for its purposeful existence (Simondon, 1958). An important distinction between natural elements and technical elements, is that new technical elements may be generated (Simondon, 1958, pp. 85–86) whereas new natural elements may not (although this limitation on natural elements may be argued, the distinction remains useful). Simondon presents a sewing needle as an example of a technical element that emerged as the product of a technical ensemble (an explanation of a technical ensemble is provided in the upcoming paragraphs of this section). He says, "At the element level, technicality is concretization" (Simondon, 1958, p. 86). In other words, all the technical knowledge and physical technology that made the manufacturing of the needle possible is embodied in the needle. It is important, to interpret this meaning, to recall that Simondon defines technical objects in terms of their genesis (Simondon, 1958, p. 8).

Technical individuals are the next in Simondon's (1958) classification scheme. A technical individual is best understood by comparison to a human being as an individual (Simondon, 1958, p. 8). Simondon states, "man can act as a substitute for the technical individual, and can join elements to ensembles in a era when the construction of technical individuals is not possible" (Simondon, 1958, p. 96). The defining characteristic of an individual is its functional independence. This definition parallels Maturana's (2002) definition of a structurally determined system, the boundaries of which are defined by its own organizational dynamics (Maturana, 2002). A laser cutter is an example of a technical individual. It consists of a combination of technical elements, which, as a result of their structure, define an organizational dynamic or function. The distinction between a technical element, a technical individual, and a technical ensemble (which will be described next) is not always clear, however when I am attempting this distinction, a useful question that sheds light on some examples is: does this object/system potentially replace man as a tool-bearer or organizer of technical or natural elements (Simondon, 1958, p. 8)? Simondon's philosophy never places technical elements or individuals in isolation. They always exist in the context of a milieu, or environment, which is both natural and technical (Simondon, 1958, p. 61). The final classification is constituted by this relationship.

The technical ensemble, the last of these three classifications, is defined by the relationships between individuals (Simondon, 1958, p. 68). Groups of individuals, be they technical individuals, human individuals or a combination thereof, may have organizational dynamics (Maturana, 2002) that define these groups as individuals themselves or as technical ensembles. Simondon (1958) describes the concept:

> The principle that recurrent causality individualizes a technical object in its associated milieu makes it possible for us to consider all the more clearly certain technical ensembles and to know whether we should treat them as technical individuals or as an organized collection of individuals. We may say that a technical individual is one having an associated milieu as a sine qua non condition of its functioning. The opposite is true of an ensemble. (Simondon, 1958, p. 68)

I gain clarity in my understanding of this quotation by focusing on Simondon's (1958) use of the phase 'recurrent causality' and seeing this from the perspective generated by Maturana's (2002) theory of autopoiesis. Just as the living system, through its organization, recursively generates the structure it requires to maintain its organization as a living system (Maturana, 2002), the technical individual (in this case consisting of a structure of other individuals) is dependent on its organization to create its milieu (Simondon, 1958).

The classifications of technical elements, individuals and ensembles arise from the evolutionary levels and character of the technical objects classified. This chapter continues with a deeper discussion of the concepts of concretization and abstraction as defined by Simondon (1958).

Concretization and abstraction. Simondon's (1958) use of the terms concrete and abstract do not match their more common usage. He is not differentiating between the idea of something and the actual physical instance of that thing. His meaning differentiates between the degrees of unification of a system. An abstract system is not unified whereas a concrete system is unified. In Simondon's terms, "The concrete technical object is one which is no longer divided against itself, one in which no secondary effect either compromises the functioning of the whole or is omitted from that functioning" (Simondon, 1958, p. 30).

Concretization implies not only a fitting of structures to functions, but the production of synergetic relations between these functions (Simondon, 1958, pp. 30–31). A primary way Simondon considers this to occur is through a "convergence of structures into a structural unity rather than with the seeking of compromises between conflicting requirements" (Simondon, 1958, pp. 15–16). Simondon uses the example of a rib that is formed as a continuous exterior feature on a cylinder in a combustion engine to illustrate this meaning. Multiple essential and complementary functions are fulfilled by this structural element. The rib provides structural integrity for the cylinder, countering the force of the expanding combusted fuel; it dissipates heat by increasing the surface area; and it decreases the overall weight of the vehicle by reducing the required mass of the cylinder and eliminating extra fasteners that would be required to attach external heat sinks (Simondon, 1958, pp. 15–16). Simondon labels structures that exhibit this multiplicity of functions in a single structure, plurifunctional or plurivalent (Simondon, 1958, pp. 16, 57, 58, 60, 84).

Plurifunctional structures are featured in my musical instrument, *Vox Curio*, the production of which is described in detail in Chapter 6. This instrument features a motorized flywheel that is used to provide ungrounded haptic feedback. A cylindrical array of magnets, embedded in the interior of the torus shaped flywheel serve several simultaneous complementary functions. They act as a magnetically coupled gear, driven by a motor with a mating array of magnets on its output shaft. The magnetic gear adds no physical friction to the mechanism, reducing undesirable noise and vibration. It also provides a margin of safety by naturally slipping if mechanical impedance is introduced. Finally, the magnets, whose positions are detected by a Hall effect sensor, serve as an encoder, allowing a measurement of the rotational speed of the flywheel, which serves an important feedback function for controlling the flywheel's driving motor.

Simondon (1958) equates increasing technical perfection with the refinement and convergence of structures for specific functions. This is identified as a form of increasing concretization (Simondon, 1958). We have however, already noted the potential downside of concretization in the manifestation of hypertelia. Abstraction can be desirable. General-purpose computers, while highly concrete technical individuals from a genetic evolutionary perspective, are in and of themselves, functionally abstract. As symbolic processing machines, they are inherently not specialized. Computers allow a common set of hardware to be dynamically fitted to a wide range of functions. This dynamic malleability allows a modular construction of virtual machines. The symbolic processing reduces all information to binary data streams, resulting in a naturally ambivalent form of information. The source of information, and the destination of that information are irrelevant within this symbolic structure. The affordances of digital computer systems are an invaluable asset in the realization of experiential media systems but their intrinsic nature, their structure and organization as a technical individual, biases their use in such systems, contributing to the development of characteristic modes of interaction. I argue that experiential media system designers should consciously utilize traditional computational technologies when needed but should look for computational solutions in other technical and natural objects. I emphasize this idea further in my discussion of material computation in Chapter 6. Next I present an example where an increased concretization is necessary in the system's evolutionary path.

PaperPhone (seen in Figure 1) is an interactive interface, simulating the functionality of a smart phone with a variety of apps (Lahey, Girouard, Burleson, & Vertegaal, 2011). This device was constructed using actual flexible display technology. We augmented the flexible display with an array of flex sensors to allow the investigation of bend gestures as a mode of interaction with the device. While this study was groundbreaking in its use of actual flexible display technology (similar prior research had simulated the display using video projection and other strategies) and represented an essential step forward in the research on Organic User Interfaces (Vertegaal & Poupyrev, 2008), the results were limited in depth and nuance by lack of sufficient concretization. Our prototype was, in Simondon's terms, highly abstract.

Figure 1. *PaperPhone* simulated smart phone with real flexible display.

The prototype interface exhibited extreme modularity and was not physically unified as an interactive object. The *PaperPhone* was conceived as a handheld smart phone with similar hand fitting proportions and scale. The display area itself reasonably matched these dimensional requirements, and had the added benefit of being as thin as a heavy weight paper stock. However, the display technology required additional signal processing hardware that extends the dimensions of the physical display by another third of the area of the display itself. It also required an external processor that is hardwired to the display through a ribbon cable. Beyond this, *PaperPhone* required a second hardwired microcontroller to handle the sensor systems. Finally the whole system was connected to a laptop computer that simulated the phone operating system, allowed for dynamic participant programming of bend gestures, and ran the software for the studies we conducted.

This accumulation of disparate components limited testing to a static lab environment and restricted the range of testable gestures. For example, an accelerometer was functionally integrated into an early prototype, but was deprecated in later iterations because the relatively short and potentially fragile connecting ribbon cables made larger gestures and rotations of the display impractical.

More significant still, for our testing, was the limited flexibility and inherent fragility in the hardware. The addition of bend sensors to the display contributed to the relative inflexibility of the display. We did what we could, within our means, to optimize this sensory augmentation, including printing a custom flexible circuit for the sensors, but the simple act of layering the already laminated display with the sensors and an additional protective layer to shield the sensors resulted in a relatively stiff device, relative to the initial flexibility of the display itself.

Finally, the display hardware itself exhibits a major limitation that can clearly be defined as an opportunity for concretization. The actual display technology itself, the portion of the flexible circuit in which images are rendered, has been proven through rigorous testing to be robust (A S U Flexible Display Center, 2012). It can withstand repeated bending and high impact forces. However the required supporting electronics, including the integrated circuits, the electronic traces that carry the power and signals, and the connections from these traces to the electrophoretic display are not as flexible. Specifically the transitions from flexible to rigid components proved to be highly vulnerable to damage from bending. The physics of this are simple to understand, the flexible component becomes a long lever with the rigid point as a fulcrum.

The result of this limitation, where rigid materials were destructively coupled with flexible ones, was a significant number of displays that were rendered unusable, additional physical layers of protection to reduce the likelihood of further damaged hardware, and modified instruction sets for study participants restricting their interactions with the displays. It should be emphasized at this point, that all of these challenges and limitations were, to some degree, predictable given the general nature of prototyping interactive systems with newly emergent technologies; and highly informative, revealing the state of the art and the opportunities for concretization.

I will not suggest every potential concretization that would need to occur to translate our prototype *PaperPhone* into a viable commercial product. I believe most of these will be obvious to the reader from my description of the challenges we faced, and also acknowledge that the required machine genesis would likely take a number of unanticipated leaps and turns as it progressed.

I will however highlight one potential area of convergence in this system. A display that is flexible has multiple affordances that differ from those of a rigid display. Many of these can be appreciated as passive material properties: a large display could be rolled up or folded, displays could be integrated into clothing where compliant movement is required, etc., however many more affordances depend on knowing the nature of the movements of the flexible device. For this reason, the integration of a high-resolution array of flex sensors into the display itself is a logical advancement. It is unclear to me whether there is any commonality in materials used in current or emerging sensors and displays that would readily present an opportunity for a plurifunctional convergence, but it seems clear that the form and production technologies for both would provide this opportunity at the higher technical level of the manufacturing machines used in their production.

I have presented explanations of concretization and abstraction, and have provided several examples exploring the utility and problems that may arise in systems of either nature. I now shift attention to some of the cross-fertilization that occurs between these theories in the fields of mechanology and biology.

Intersections of Mechanology and Biology

Valentino Braitenberg (1986) was inspired by his neuroanatomical studies, to present his perspective of the mechanics of cognition through the conceptual creation of mechanical vehicles (Braitenberg, 1986). Figure 2 shows a simple example of Braitenberg vehicles. He realized that when we, as external observers, observe the functions of a system, we are not able to conclude from those observations, what underlying structure is responsible for these functions and in most cases, overestimate the complexity of the structure. He proposed the “law of uphill analysis and downhill synthesis” claiming that it is easier to build a system that exhibits a complex behavior than to analyze a closed system and accurately estimate its structure. He demonstrated through his relatively simple conceptual mechanical vehicles, behaviors that convincingly replicated seemingly complex cognitive activity (Braitenberg, 1986). Braitenberg’s example starts from biological structures, which inspires mechanological structures, which provide a way of seeing biologically based cognitive systems. The next section continues the theme of the relation of biological and mechanological theories, providing additional depth to the already introduced concept of structural coupling.

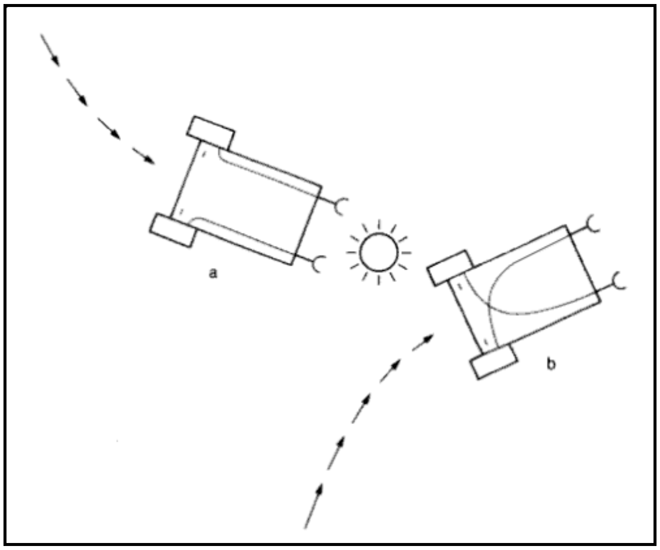

Figure 2. Variations of Braitenberg Vehicle 3, illustrating the relation of structure and organization as observed through behavioral difference, from *Vehicles: Experiments in synthetic psychology*. Copyright 1986 MIT press.

Communication and Information Flow: Structural Coupling

Structurally determined systems do not exist in isolation. They interact with other objects, systems, and their environment at large through a process Maturana (2002) labels "structural coupling". He defines it, saying, "I have called the dynamics of congruent structural changes that take place spontaneously between systems in recurrent (in fact recursive) interactions, as well as the coherent structural dynamics that result, structural coupling" (Maturana, 2002, pp. 16–17).

This is consistent with Simondon's (1958) concept of "recurrence of causality" as a condition for the existence of technical individuals. He states, "Such individualization is possible because of the recurrence of causality in the environment which the technical being creates around itself, an environment which it influences and by which it is influenced" (Simondon, 1958, pp. 60–61). In both the biological and mechanological contexts the meaning is the same. Systems can be organizationally closed, but interactionally open (Varela & Goguen, 1978). In humans, this openness to our environment provides the opportunity for structural coupling that we experience as perception. Varela et al. suggests a way of seeing perception as the result of energetic exchanges with our environment, stating,

> We can now give a preliminary formulation of what we mean by enaction. In a nutshell, the enactive approach consists of two points: (1) perception consists in perceptually guided action and (2) cognitive structures emerge from the recurrent sensorimotor patterns that enable action to be perceptually guided. (Varela et al. 1991, pp. 172–173) (as quoted in (Reid & Mgombelo, 2014)).

There is a common phrase used to describe the formation of structures in brains. It states, "neurons that fire together, wire together" (Miller, 1996). Varela's (1991) aforementioned theory is more inclusive in terms of the involved structures, but it is consistent with the commonly held belief about the results of concurrent neural activity.

This section elaborated on the theory of structural coupling and its implications for human perception. The next section concludes the focus on connections between biological and mechanological perspectives on structurally determined systems with a discussion regarding what accounts for the viability of systems.

Viability: Internal Unity and Relation to the External

Simondon (1958) says, "Technical objects which in their liaison with the natural world put into play what is essentially a recurrent causality must be invented rather than developed in stages, because such objects are the cause of their own condition of functioning" (Simondon, 1958, p. 61). This statement alludes to the question of the viability of a technical object. This section presents a dialogue, comparing Simondon’s and Maturana’s (2002) theoretical and philosophical stances on viability of the systems they study.

Maturana (2002) presents two laws that speak to the viability of biological systems. These are: "the law of conservation of organization (autopoiesis in the case of living systems) and the law of conservation of adaptation, that is operational congruence, with the medium in which a system (a living system in our case) exists" (Maturana, 2002, p. 10). The first of these laws focuses on the unity of the system as defined by its internal organization and determined by its structure (which may of course change). The second law focuses on the relations, the structural coupling between the system and its environment (anything external to its organizationally defined bounds). Again, a preliminary comparison between Maturana's (2002) and Simondon's (1958) perspectives is in order.

Simondon (1958) describes the process by which a technical object becomes viable as a technical individual:

> Little by little, as it develops in concretization, it becomes capable of doing without the artificial environment, and this is so because its internal coherence increases and its functioning system becomes closed by becoming organized. A concretized object is comparable to an object that is produced spontaneously. It becomes independent of the laboratory with which it is initially associated and incorporates it into itself dynamically in the performance of its functions. Its relationship with other objects, whether technical or natural, becomes the

> influence which regulates it and which makes it possible for the conditions of functioning to be self-sustaining. The object is, then, no longer isolated; either it becomes associated with other objects or is self-sufficient, whereas at the beginning it was isolated and heteronomous. (Simondon, 1958, pp. 47–48)

I present this quotation in an extended form to provide the reader a fuller context for and additional details of his meaning, but I point to a small portion of this text in particular. Simondon (1958) says, "its internal coherence increases and its functioning system becomes closed by becoming organized" (Simondon, 1958, pp. 47–48). Internal coherence and organizational closure precisely align with Maturana's (2002) "law of conservation of organization" (Maturana, 2002, p. 10). Simondon (1958) continues the thought a little further along in his text, "The technical being evolves by convergence and by adaption to itself; it is unified from within according to a principle of internal resonance" (Simondon, 1958, p. 13).

Simondon's (1958) discussion of topics related to Maturana's "law of conservation of adaptation" (Maturana, 2002, p. 10) is more complex and harder to draw direct parallels with individual quotations. This challenge is magnified by the varying levels at which he discusses technical objects (as elements, individuals, ensembles, and combined groupings, all with varying adaptations and associated milieux -- depending on the object in question). Simondon (1968) does however present the basic idea quite clearly in an interview in which he says,

> a technical object exists, is constituted, first as a unity, a solid unity, an intermediary between the world and man, an intermediary perhaps between two other technical objects, and that first stage of its development is, first of all, a

> stage of constitution of unity, a stage of constitution of solidity. (Simondon & Le Moyne, 1968)

This emphasizes the "conservation of organization" (Maturana, 2002, p. 10), but also directly alludes to the relation with the external environment in which it must exist. Simondon (1968) goes on to say,

> "the function of the tool is to establish a constant and non-fallacious relation between the body of the operator and the object on which he acts. There is an individuality, but an internally consistent individuality, of the object, even the tool" (Simondon & Le Moyne, 1968).

This example, while simple, illustrates a general philosophical perspective that I find consistent with Maturana's "conservation of adaptation" (Maturana, 2002, p. 10).

Another reference takes the concept a step further and emphasizes the dynamic interplay between technical objects and the other objects and environment with which they interact. Simondon (1958) says,

> "Technical objects which in their liaison with the natural world put into play what is essentially a recurrent causality must be invented rather than developed in stages, because such objects are the cause of their own condition of functioning. Such objects are viable only if the problem is resolved that is to say, only if they exist along with their associated milieu" (Simondon, 1958, pp. 61–62).

I've shown, through this dialog, fundamental parallels between Maturana's (2002) biologically based theories and Simondon's (1958) mechanologically based theories. This is sufficient evidence to arrive at the abductive conclusion that it is valid to, in Wittgenstein's terms, see one theory *as* the other.

This chapter has introduced technical objects and argued for seeing them as structurally determined systems. This was done primarily from a theoretical perspective, with a few practical examples. The next chapter will focus on the practical implications of and questions posed by this theoretical stance.

CHAPTER 6

DETERMINING STRUCTURE (IN PRACTICE)

In the previous chapters, I have introduced the general theories of structural determinism and structural coupling. The informational and communication implications of these theories were considered. I then showed how these theories apply to technical objects, emphasizing the fundamental parallels between the expressions of theory in the natural/biological domain and the technical/mechanological domain. I will now show how the practical domain of making can be seen from these theoretical perspectives, starting with a consideration of the role of the human in the technical ensemble.

The Human Role in the Technical Ensemble

Simondon (1958) regards the human individual as the original technical individual and argues that we should see the human in the technical (Simondon, 1958). According to Simondon, man is comfortable with his position as “tool-bearer,” as a human technical individual: organizer of technical elements. When human-made technical individuals emerge, the human sees them as a threat, fearing they will replace him/her. As technical ensembles of technical individuals grow in scale, complexity and ubiquity, the human’s role becomes as an assistant and/or supervisor. This can be experienced as problematic for humans as individuals and for society at large (Simondon, 1958, pp. 8, 92–94). Much of Simondon’s philosophy can be seen as addressing this concern by calling attention to the human in the technical and placing the technical not in opposition to, but as an essential part of a unified human culture (Simondon, 1958).

The ALERT (Active Learning Environment with Robotic Tangibles) system explicitly attempted to connect the human and the machine (Lahey et al., 2009). This system, which utilized tangible symbolic instructions for the programming of robots, required participants to occupy a shared physical space with the robots and encouraged them to think like the robot, planning their program by actively engaging in the space as they intended the robot to do (Lahey et al., 2009). ALERT systems are illustrated in Figure 3 and Figure 4.

Figure 3. An ALERT robot reacting to a tangible fiducial programming instruction.

Figure 4. Children learning to program an ALERT robot using tangible instruction objects.

Thor Magnusson (2009) emphasizes the often ignored human imprint on the technical object, focusing on the cognitive dimensions of musical instruments/interfaces. He differentiates between the embodied and hermeneutic relationships that are established in the structural coupling of musician and instrument, arguing that the former is dominant with traditional acoustic instruments, and that the later mode dominates with instruments that are fundamentally computer based (Magnusson, 2009). Magnusson introduces the idea of concretization as a variable in these systems, but he uses it to draw attention to the "black box" hidden nature of the systems that results from the concretization. I argue, in a way that I believe in no way contradicts Magnusson overall thesis, that the acoustic instrument is a highly individualized, concrete system, not in any way "divided against itself" (Simondon, 1958) and that the computer instrument is fundamentally more abstract, even if it's interactional affordances are fixed, because of the initial arbitrariness of their definitions. These examples serve as a prelude for the remainder of this chapter, which will focus on the human dimension of technical ensembles, in which the human serves as creator/maker/inventor.

An important concept to keep clear in this discussion is the difference between making a technical object (a machine, experiential media system, etc.) and the genesis of a technical object as it is understood by Simondon (1958). The genesis, in which concretization may, or may not, occur, refers to the evolution of a lineage of technical objects. It assumes the creation of multiple technical objects. A single technical object may be created, and may certainly be concrete in some greater or lesser degree, but concretization does not happen in the creation of a single technical object (Simondon, 1958). While it is tempting to claim concretization when plurifunctional structures are incorporated in the technical object (as I described in the magnetic gear mechanism of my *Vox Curio* instrument), this claim would be invalid by Simondon’s definition.

I can identify a technical genesis, though not necessarily yet with a high degree of concretization, in my series of balance board interfaces. The *Team Balance* game system (see Figure 5), *Physical Function* math learning tool (see Figure 6) and my *Snowboard Simulator* (see Figure 7), are all of a common lineage. A convergence of these independent systems, incorporating the degrees of freedom of the *Team Balance* interface, with the force feedback mechanics of the *Physical Function* interface, and the sensing and vibrotactile haptic capabilities of the *Snowboard Simulator* would result in a highly dynamic and versatile experiential media system. The technical requirements for such integration, even in an abstract form, are significant.

Figure 5. *Team Balance* physical interface hardware (left) and *Team Balance* game interaction (right).

Figure 6. *Physical Function* pneumatically actuated balance interface (left) and detail showing pneumatic and position sensor components (right).

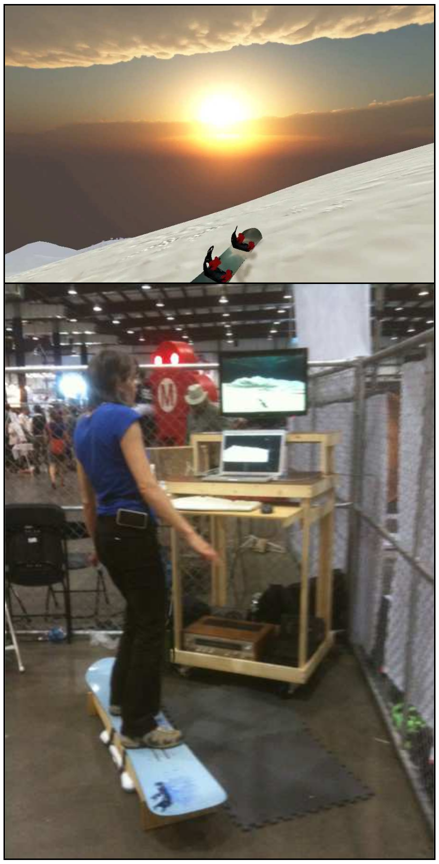

Figure 7. *Snowboard Simulator* game view (above) and haptic interface hardware being tested (below).

The preceding section introduced several important factors when considering the role of the human in the technical ensemble. I drew attention to the cultural role of the human as a technical individual. I introduced ways in which we can see the human in the technical. I emphasized the difference between the creations of individual systems from their genesis and illustrated this difference with references to systems of my own creation. The culture of making will be further considered in terms of the potential modes of production through which it occurs and the blurring of the boundaries between these modes.

Modes of Production

Modes of production are classified by Simondon (1958) as either industrial or artisanal. He summarizes these classifications saying, "The primitive artisanal phase is characterized by a weak correlation between the scientific and the technical, while the industrial phase is characterized by improved correlation" (Simondon, 1958, pp. 32–33). Industrial implies concretization. Artisanal implies abstraction. Simondon recognizes that there is an essential rhythmic oscillation in the evolution of technical elements, individuals and ensembles. He defines this process as “the law of relaxation”(Simondon, 1958, p. 75) (which is likely a reference to electronic relaxation oscillator circuits). This process involves a progressive increase in the technical, going from elements, to individuals, to ensembles. The process ends and restarts with the production of a new technical element. The presence of a new technical element requires concretization. Simondon explains,

> Industrial construction of a specific technical object is possible as soon as the object in question becomes concrete, which means that it is understood in an

> almost identical way from the point of view of design plan and scientific outlook. This explains why certain objects have been capable of being constructed industrially long before others. (Simondon, 1958, p. 33)

I suggest that the nature of the artisanal workshop has dramatically transformed in recent years and that the potential for concretization now is widely distributed. The next section describes my working studio and a vision for how such a studio may evolve in the near future.

Nature of a contemporary experiential media studio. As a contemporary media artist, my artisanal studio has many tools that were in relatively recent times, relegated to the industrial mode of production. The mechanism by which these tools became available may be described as an inductive transference of technicity: technical elements and individuals come into being as a result of tools and infrastructure with a higher level of concretization (Simondon, 1958). I identify the result of this process as a democratization of industrialization. Tools for concretization are now available to the individual maker and to small groups of makers.

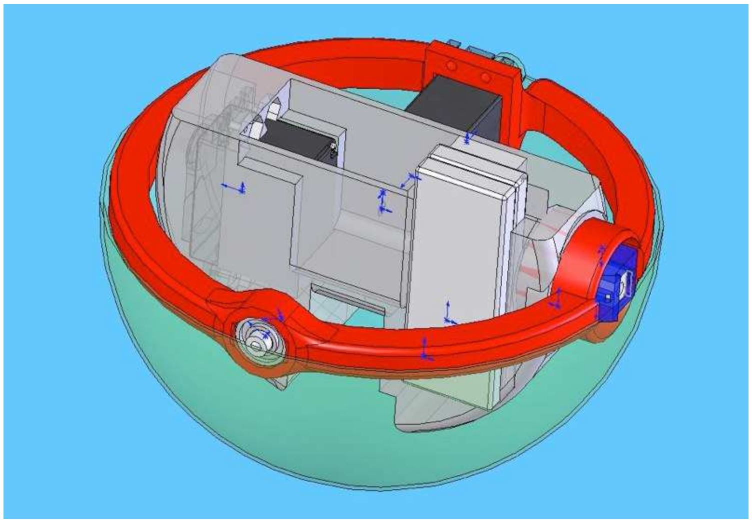

Figure 8. 3D model of *SphereBot* robot showing mechanical structure, motors and batteries.

The evolution of technology has compressed industrial processes into forms that are now accessible at the artisan workshop level. CAD (Computer Aided Design) and CAM (Computer Aided Manufacturing) tools allow for systems to be rapidly prototyped, allowing a true machine genesis. CAD tools, many available for free, allow systems to be virtually built and tested, with endless variations of forms and materials. With advanced tools, many of which are freely available to students, testing goes well beyond basic mechanics. It includes tools such as fluid and thermal dynamics, stress testing, and production feasibility evaluation. My *SphereBot* (an individual project) and *PeteBot* (a collaborative production) projects, shown in Figure 8 and Figure 9, demonstrate projects realized primarily through a CAD-CAM process. While it would have been possible to produce these projects without these design and fabrication tools, it would have been significantly more difficult to achieve the required mechanical relationships and precision of fitting. Most importantly however, producing these systems with these tools opens up potential for iterations and new systems, using components of these systems as foundations. This potential simply doesn’t exist on the same time scale in the absence of such tools.

Figure 9. Animatronic head of *PeteBot* featuring embedded audio/video sensors and servo motor actuators.

CAM tools allow virtual machines to be physically instantiated, allowing further iterative evolution. The laser cutter, a revolutionary technology in this domain, is a highly evolved technical ensemble, able to simulate an arbitrarily complex set of constraints to define a controlled cutting path. This technical ensemble facilitates the production of accurate and precise mechanical components, and generally does so far more quickly than other traditional tool processes. While in some cases, the parts produced by a laser cutter could be produced with relative ease (albeit requiring more time in most cases) by a simpler machine, in other cases the output of the laser cutter is virtually impossible to produce by other means, including most alternative CNC tools. The wings on my *OctoBoto* project, shown in figure XX, are a clear example of a component that is difficult to imagine producing with another tool. An important feature of the laser cutter is the ability to quickly and directly fabricate in final production materials, at a relatively large scale.

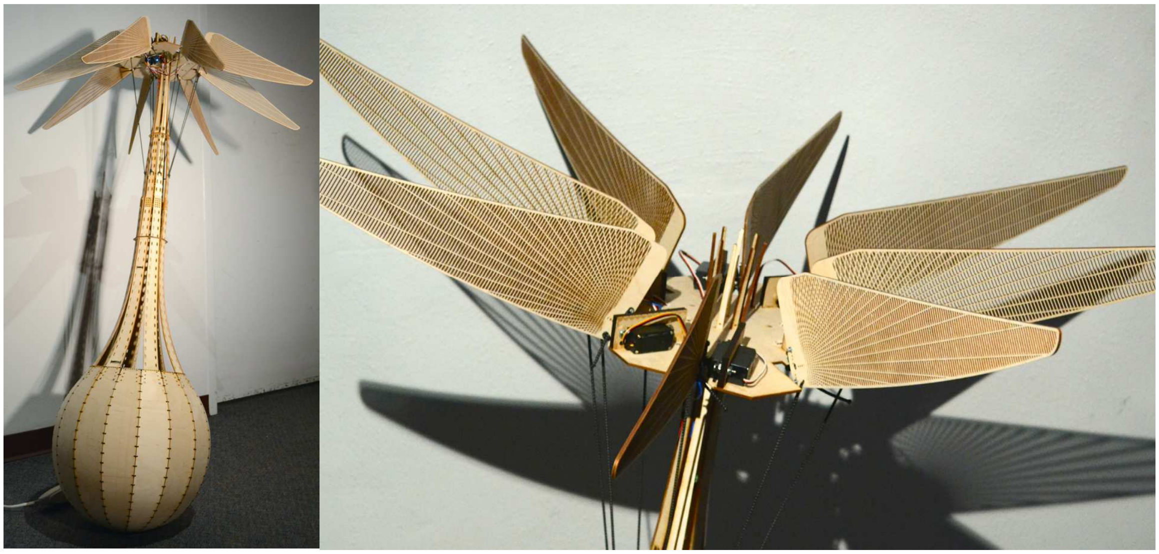

Figure 10. *OctoBoto* responsive kinetic sculpture featuring hand assembled, laser-cut domponents. Overall view (left), detail (right).

Technical elements such as microcontrollers, breakout boards, shields, and other components with high levels of embedded technical concretization are widely and affordably available. Just as in Simondon's example of the quality of a needle as a measure of the "degree of perfection of a nation's industry" (Simondon, 1958, p. 85), the integrated circuit, in all its rich variety, is an embodiment of tremendous technical achievement and provides versatile organizational dynamics. By themselves of course, they are inconsequential. They are only of consequence when structurally coupled with other technical and natural elements, individuals and ensembles.

Information networks, the Internet at large being the most prominent example, are prime examples of technical ensembles. The veracity of this claim could be measured by looking at the technical genesis and the structure of contemporary information networks, both big and small, but the strongest evidence in support of this claim is the cultural impact that information networks have had on our culture. Simondon argued in 1958 that,

> "Today, technicality tends to reside in ensembles. For this reason, it can become a foundation for culture, to which it will bring a unifying and stabilizing power, making culture respond to the reality which it expresses and which it governs" (Simondon, 1958, p. 9).

This quotation may be taken in with a sense of dread, exhilaration or something in between, but I suspect few readers in 2015 would deny that this accurately describes the magnitude of the Internet's impact on our culture. For the artisanal workshop, the Internet concentrates global knowledge on every subject and places it on the workbench next to the hammer and soldering iron.

Collectively the technicality embodied in these elements, individuals and ensembles brings many of the affordances of the industrial to the artisanal. Significant differences remain of course, the scale, capital resources, and the like are not present in the small workshop or studio, but the lines are blurred. I've painted a rosy picture of the affordances of the industrial modes of production that have populated studios like those I inhabit. It would be reasonable to ask, what's next, and is there anything left from the artisanal worth saving? These questions form the basis of the next topics.

Seeing making spaces as seeing spaces. Contemporary making spaces, even those equipped with the latest in CAD, CAM, motion capture, visualization and robotics systems may still be lacking something important. Bret Victor (2014) argues for the creation of "Seeing Spaces", as extensions of "Maker Spaces" (Victor, 2014). He identifies a trend in the types of systems that are made in maker spaces. He notes that many projects are not simple static objects, or even basic mechanical systems (which I observe may reveal their functional status through their tangible form), but instead are systems that include electronics and other computational hardware and software. These systems frequently have a dynamic interaction with the world, through relations of sensors and actuators (Victor, 2014).

Victor (2014) argues that the tools we have at our disposal in most shops, studios and maker spaces are all primarily designed for shaping and assembling things, not for understanding the things we have made. He proposes building maker spaces with an embedded suite of tools focused on seeing, in high functional detail, the status and behavior of what we build. Victor presents three levels, or dimensions of seeing: seeing inside, seeing across time and seeing across possibilities (Victor, 2014).

Victor (2014) separates types of making into three primary modes: tinkering, engineering and science. Tinkering happens without any theoretical understanding of the operational principles of the medium with which one is working. Engineering takes place when one understands the theoretical principles that define one's medium. Science is required when new theory is required. Victor argues that "seeing tools" allow a maker to work across all of these modes (Victor, 2014).

Victor's (2014) informal presentation of this theory frames his "seeing space" in conduit metaphor terms (Reddy, 1979). Taken in this sense, it is inconsistent with structural coupling theory (Maturana, 2002) and Reddy's tool maker paradigm (Reddy, 1979), but in fundamental ways, Victor's theory may be seen as strongly aligned with these theories. As I interpret Victor's intentions, he emphasizes the need for a continuous, immersive, multidimensional, multimodal, stream of data that is always available at a glance. A system of this sort could be seen as establishing a recurrent causality (Simondon, 1958), a structural coupling (Maturana, 2002), a persistent, bidirectional passing of signals that need to be interpreted through a building process with the limited materials we have at our disposal (Reddy, 1979). The persistence of signals that Victor proposes strongly differentiates his thinking from traditional engineering and scientific approaches that bring out a specific seeing tool (an oscilloscope for example) to look for a specific bit of data at a specific moment. This isolated look at a system leaves us with an impoverished understanding of the system. A continuous, multifaceted signal dialog offers far greater potential to "understand" a system.

Victor (2014) presents a vision for studios and laboratories of the future. What, if anything does the traditions of craft contribute to the advancement of experiential media and other technology? Is the act of making an act of thinking? These are the next topics.

Thinking to make and making to think. In John Hart's preface to Simondon's (1958) *On the Mode of Existence of Technical Objects*, he says,

> The crafts can act to provide continuity of meaning through direct knowledge of function made specific by the understanding of gesture. Nonverbal knowledge articulated by the hands and feet is the body's way of thinking just as the chiseling

> of words from sound is the mind's way of making contact. (Simondon, 1958, pp. xv–xvi)

He later notes,

> The studies of the crafts and of linguistics as prelude to mechanology take us closer to the centre of somatic reality. They have the effect of joining the distance that has long separated occidental man from the work of his hands. (Simondon, 1958, p. xxii)

I suggest that such studies, far from serving only as a prelude, should be, as I have in this document, considered in parallel and on equal grounds with mechanology.

Sennett (2008) introduces his book "The Craftsman" with a description of an encounter with his teacher Hannah Arendt. This encounter and conversation occurred just after the Cuban Missile Crisis and the threat of nuclear annihilation was in the forefront of her consciousness. Sennett said, "She wanted me to draw the right lesson: people who make things usually don't understand what they are doing" (Sennett, 2008, p. 1). Sennett explains, "In the working out of Greek culture, its peoples came increasingly to believe that Pandora stood for an element of their own natures; culture founded on man-made things risks continual self-harm" (Sennett, 2008, p. 2). He goes on, explaining her perspective, saying, "Technology itself can seem the enemy rather than simply a risk" (Sennett, 2008, p. 3). He continues to elaborate on the differences in their way of seeing the situation,

> *Animal laborens* is, as the name implies, the human being akin to a beast of burden, a drudge condemned to routine. ... *Animal laborens* takes the work as an end in itself. … By contrast, *Homo faber* is her image of men and women doing

> another kind of work, making a life in common. Again, Arendt enriched an inherited idea. The Latin tag *Homo faber* means simply "man as maker." ... *Homo faber* is the judge of material labor and practice, not *Animal laboren's* colleague but his superior. ... Whereas *Animal laborens* is fixated in the question "how?" *Homo faber* asks "Why?" ... For Arendt, the mind engages once labor is done. Another, more balanced view is that thinking and feeling are contained within the process of making. (Sennett, 2008, pp. 6–7)

Sennett suggests we ask, "what the process of making concrete things reveals about ourselves" (Sennett, 2008). (In this context, it seems clear that Sennett's (2008) use of the term concrete matches the more common use of the term, describing a real, materialized instant of something, as opposed to Simondon's (1958) more specialized use of the term to imply a reference to a genetic evolution of an object.) Sennett concludes, saying

> I want to make the case that my juvenile self could not then make to Arendt, that people can learn about themselves through the things they make, that material culture matters. … Craftsmanship names an enduring, basic human impulse, the desire to do a job well for its own sake. ... craftsmanship focuses on objective standards, on the thing in itself. (Sennett, 2008, pp. 8–9)

Just as Simondon (1958) identifies the technical, not as a force outside of, and in opposition to humanity and culture, but something fundamentally human and part of culture, Sennett recognizes material culture. He sees, as the essence of this culture, not merely material artifacts, but more significantly, the craftsmanship that persists in material and immaterial human activity. David Pye narrows in on the topic still further, identifying a particular mode of making and fundamental qualities that emerge from this mode. This next section provides a unique way of seeing what the industrial and concrete may be missing.

Artisanal process: what should not be lost. David Pye (Pye, 1968) says, "Design is what, for practical purposes, can be conveyed in words and by drawing: workmanship is what, for practical purposes, can not" (Pye, 1968, p. 17). These epistemological definitions which differentiate design and workmanship parallel my understanding of praxical knowledge, which I define as embodied knowledge that emerges through active engagement with the world and resists translation into symbolic representation. It also has important connections with Simondon's (1958) conception of the abstract and concrete. Simondon says, "Invention takes place on a middle level between the concrete and the abstract, the level of diagrams, which implies an earlier existence and a coherence for its representations" (Simondon, 1958, p. 86). This "earlier existence and coherence" is the primitive (fundamental) essence that workmanship provides. Pye continues,

> There is in the man-made world a whole domain of quality which is not the result of design and owes little to the designer. On the contrary, indeed, the designer is deep in its debt, for every card in his hand was put there originally by the workman ... Designers have on been able to exist by exploiting what workmen have evolved or invented. (Pye, 1968, p. 17)

In Simondon's (1958) terms, invention, the creation of the technical individual, cannot take place without technical elements (Simondon, 1958, p. 86), which at repeated points in the history of the technical, come into existence as a result of the human individuals and ensembles of human individuals working in the artisanal mode (Simondon, 1958, pp. 91–92).

Pye's (1968) thinking parallels that of Simondon's (1958) and Maturana's (2002) in other profound ways. Pye says,

> This domain of quality is usually talked of and thought of in terms of material. We talk as though the material itself conferred the quality. ... Only worked material has quality, and pieces of worked material are made to show their quality by men, or put together so that together they show a quality which singly they had not. "Good Material" is a myth. (Pye, 1968, p. 18)

This idea directly echoes Simondon, who says, "What is organized is these technicalities; the elements also are organized, but only in so far as they are bearers of these technicalities and not because of anything that has to do with their own materiality" (Simondon, 1958, p. 87). As both authors (Pye, 1968; Simondon, 1958) emphasize, it is not ultimately the material itself but the organization of this material that matters. Pye's proposition that materials put together may manifest a quality that was not present in the individual materials (Pye, 1968, p. 18) suggests that structural coupling is occurring, not only between the materials, but more importantly, between the composite system and a human who, as determined by their own structure, experiences the result (Maturana, 2002). This reading of these texts is further reinforced by Simondon's statement, "Usage brings together heterogeneous structures and functions in genres and species which get their meaning from the relationships between their particular functions and another function, that of the human being in action" (Simondon, 1958, pp. 11–12). It is in the refinement of materials, in the forming and structuring of the materials, and in the convergence of these materials with other materials that the qualities we prize emerge. This process of refinement, as described by Pye (1968), is akin to the concretization process described by Simondon (1958). Quality, seen from Pye's perspective may be seen as equating to viability, in Simondon's terms. I argue that an object becomes viable by non-self-destructively fulfilling its intermediary function. The workman makes a material viable for its intended functional and/or aesthetic/artistic purpose through their structural coupling with the material.

Comparisons between Pye's (1968) way of seeing traditions of workmanship and Simondon's (1958) view of the genesis of technical objects are revealing. Pye says, "In speaking of good material we are paying an unconscious tribute to the enormous strength of the traditions of workmanship still shaping the world even now (and still largely unwritten)" (Pye, 1968, p. 18). The "traditions of workmanship" of which Pye speaks, makes explicit a historical dimension, an evolutionary genesis of technique. Technical objects are defined in terms of their genesis (Simondon, 1958, pp. 8, 12). I argue that the tradition of continuous refinement and evolution of techniques that Pye discusses is an example of concretization.

I've introduced the significance of material culture as seen by Sennett (2008) and outlined strong parallels between Pye's (1968) philosophies of workmanship and Simondon's (1958) philosophies of the technical. While this indirectly addresses the importance of the artisanal process, these next discussions will provide more specificity.

Pye (1968) cuts to the heart of what he sees as a primary issue with the industrial mode of production,

> the greater part of all manufacture now is mass-production; in which, although there is some bad workmanship, much is excellent. Much of it has never been surpassed and some never equaled. The deterioration comes not because of bad workmanship in mass-production but because the range of qualities which mass-production is capable of just now is so dismally restricted; ... as if the same short tune of clear unmodulated notes were being endlessly repeated. (Pye, 1968, pp. 18–19)

Pye (1968) identifies the uniformity and consistency that results from the industrial mode of production as a blessing and a curse. He points to "the workmanship of risk" (Pye, 1968, p. 20), which incudes working with materials that fundamentally do not guarantee a successful outcome, as a making mode that by its nature avoids many of these negative qualities of the industrial mode.

Organic materials, or natural elements, offer an inherent complexity and richness that is often engineered out of refined materials, or technical elements. This complexity arises from the natural processes by which these organic materials come into being. In this text I use the word organic with the intended meaning of naturally developing, not man-made, not technical. I do not intend the meaning of carbon-based.

The processes by which organic materials come into being have an abundance of variables. In the case of plants, from which we derive the widely used material of wood, these variables include fluctuations of temperature, water, wind pressure, air quality, sunlight, soil quality, and interaction with other plants and animals. All of these variables, none of which are static, are recorded in the material of the plant as it grows (this is a form of memory in the context of material computation). The cellular structure is perceived in terms of porosity, grain patterns, color, hardness, shape, etc. All of these characteristics determine the physics of the material, and not just the physics as a homogenous mass, but variable physics at a microscopic level. In a technical element, these physics could be defined as a core part of the element's technicality (Simondon, 1958). The physics of these materials express themselves in the rich visual, sonic, tactile, olfactory and taste information that they have the potential to generate in an observer through structural coupling (Maturana, 2002).

The materials described in this discussion are useful examples to draw connections, and make distinctions, between natural and technical elements. Wood, a product of an autopoetic system, is a natural element. Maturana (2002) argues, " living systems are never out of place, or "more" or "less" adapted while living" (Maturana, 2002, p. 17). Maturana continues,

> it is precisely because a living system exists as a totality, through a molecular architectural dynamics and thus is realized moment after moment according to the operation of the local structural coherences of its molecular components, that there is no general organizational principle or force guiding the operation of the molecules that compose it in the integration of a whole. (Maturana, 2002, p. 17)

It is in this sense that Simondon (1958) separates technical objects from natural objects. He claims,

> There should be no confusing of a tendency towards concretization with a status of absolutely concrete existence. Though every technical object possesses to some

> degree aspects of residual abstraction, one cannot go to the extent of speaking of technical objects as if they were natural objects. (Simondon, 1958, p. 50)[1]

Technical elements, such as plywood and MDF, in contrast to Maturana's (2002) definition of natural elements, are structured with a "general organizational principle" (Maturana, 2002, p. 17). As discussed earlier, technical objects may exhibit varying levels of hypertelia (Simondon, 1958, p. 51) as a result of their specialization.

Of particular interest in my current work are the acoustical, structural, mechanical and aesthetic properties of natural wood, which I discuss in the upcoming section, Building Media Systems, which describes my experience creating several media systems. The next section provides additional details of Pye's (1968) theories of material and making, which are related to Simondon's (1958) ideas on the existence of technical objects.

Workmanship of risk, constraints, and self-jigging. Pye (1968) finds the word craftsmanship troubling in its ambiguity and culturally ascribed meanings. He addresses this concern and proposes and alternative phrase with a specific intended meaning. He says,

> If I shall ascribe a meaning to the word craftsmanship, I shall say as a first approximation that it means simply workmanship using any kind of technique or

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[1] I question the inclusion of the word 'Though', in the start of the second sentence of this quotation. This may be a slightly inappropriate artifact of the translation, though I am unable to read the original text to evaluate my assumption. I believe excluding this word makes the meaning more consistent in the context of this text.

> apparatus, in which the quality of the result is not predetermined, but depends on the judgment, dexterity and care which the maker exercises as he works. The essential idea is that the quality of the result is continually at risk during the process of making; and so I shall call this kind of workmanship 'The workmanship of risk'. (Pye, 1968, p. 20)

Pye's (1968) 'workmanship of risk' can be seen as a description of a particular type of structural coupling, one in which the coupled elements all have significant margins of indetermination (Simondon, 1958, p. 4). Pye clarifies his meaning of risk and suggests how to differentiate the 'workmanship of risk' from the 'workmanship of certainty', asking, "Is the result predetermined and unalterable once production begins?" (Pye, 1968, p. 22). The margins of indetermination in the human individual, the tools used and the material allow the entry of minute variations, nuance and other artifacts that are commonly identified as expressive and, indeed, individualizing.

The workmanship of risk may be thought of as a form of concretization. Pye explains,

> The first thing to be observed about printing, or any other representative example of the workmanship of certainty, is that it originally involves more of judgment, dexterity and care than writing does, not less ... all this judgment, dexterity, and care has been concentrated and stored up. (Pye, 1968, p. 21)

The concentrating and storing up of workmanship is a physically embodied record of concretized workmanship. This record is represented in the tools, machines and factories built by the workers. I choose the word 'represented' here intentionally. I do not intend the meaning of information transfer as exemplified by Reddy's (1979) conduit metaphor, but, mean precisely the structural re-presentation of information as expressed by his toolmaker paradigm.

The ‘workmanship of risk’ does not describe a constant freeform relationship that is completely uncontrolled. The degree of risk for any given operation can be moderated by a process Pye (1968) calls ‘regulation’ (Pye, 1968). Regulation may be thought of as limiting the “margins of indetermination” in a system (Simondon, 1958). According to Pye, this is done through dexterity, gradualness, and shape-determining systems. Shape determining systems are constraints (Pye, 1968, pp. 34–35). I will return to a particularly interesting mode of constraint Pye identifies as ‘self-jigging’ after presenting an extended consideration of the application of constraints and a consideration of constraints as they apply to a robotic system I produced.

Constraints. Constraints are fundamental to making. Let’s consider the simple act of drawing as a making activity. As I have previously described, all the systems involved in this activity (the human individual, and all the materials and tools) can be seen as structurally determined systems and interactions between these systems as structural coupling. The drawing surface establishes the first constraint. One may move a marking device near the surface without making any marks, but once the marking device intersects the drawing surface, a mark is made. Marking gestures frequently have what may be considered a ramp-up, or pre-flight period that establishes a particular energy and trajectory, producing a characteristic profile to the mark that is made. Similarly, marks may have a post-flight takeoff, an exit from the drawing surface. This exit may be at a shallow angle, resulting in a subtle, fading tail to the mark, or may take off at a sharp angle, leaving an abrupt ending, or even a slight backlash, to the mark. The drawing surface may be a rigid plane, or a soft, possibly contoured, form. The characteristics, the structures, of this constraint and the drawing medium, will significantly affect the resulting line qualities and the overall character of the drawing.

The anatomy, or structure, of the artist engaged in the drawing activity provides additional constraints. The wrist only moves so far, the elbow only has a single degree of freedom and is dependent on the shoulder for expanded ranges of motion. It is interesting to observe that throughout the human body, the pattern tends to be alternating joints with highly limited degrees of freedom (the elbow for example) with joints with more degrees of freedom (the wrist and elbow in this example). The same pattern can be seen going from ankle to knee, to hips. This structure determines the organization of the human body. These constraints, combined with the constraint of the drawing surface, can produce useful, and sometimes frustrating restrictions to the drawing gesture. These constraints may be considered soft constraints that can be consciously retrained and temporarily overridden. Drawing a circle requires coordinated movements of multiple joints. Drawing a consistent series of arc shaped marks may be accomplished with quick repetitive wrist motion and a slow retraction of the arm with a subtle bend of the elbow and movement at the shoulder. In this case, the elbow and shoulder are relatively static constraints for each mark in the series and the pivot of the wrist is a strong constraint, especially when combined with the constraint of the drawing surface.

What happens when the artist wants to draw a straight line, or a perfect circle? They may train their body to produce these shapes through a precisely choreographed movement of their joints, but in many cases, they decide it is time to call on external constraints and pick up a ruler, a compass, or another drawing template that will structurally couple with their drawing surface and their drawing tool to increase the regulation and accomplish the task with relative ease. This describes structural coupling with varying regulation of ‘degrees of indetermination’ involving humans and tools. I will now provide an example with a robotic system.

Camera Projector Robot. CPR (*Camera Projector Robot*) is relatively simple in terms of its basic components and operation. *Figure 11* shows the CPR system. It has a single camera and a single video projector mounted in a motorized pan-tilt mechanism. The camera and projector are arranged so that they face the same direction. The camera “sees” the same space that the projector produces an image in. Ideally these components would share the same optical nodal point so that they would have identical visual perspectives. As it is, they are close together, but the system exhibits parallax problems. This is a negligible issue with distant objects in the camera-projector view, but becomes more of an issue the closer objects are to CPR.

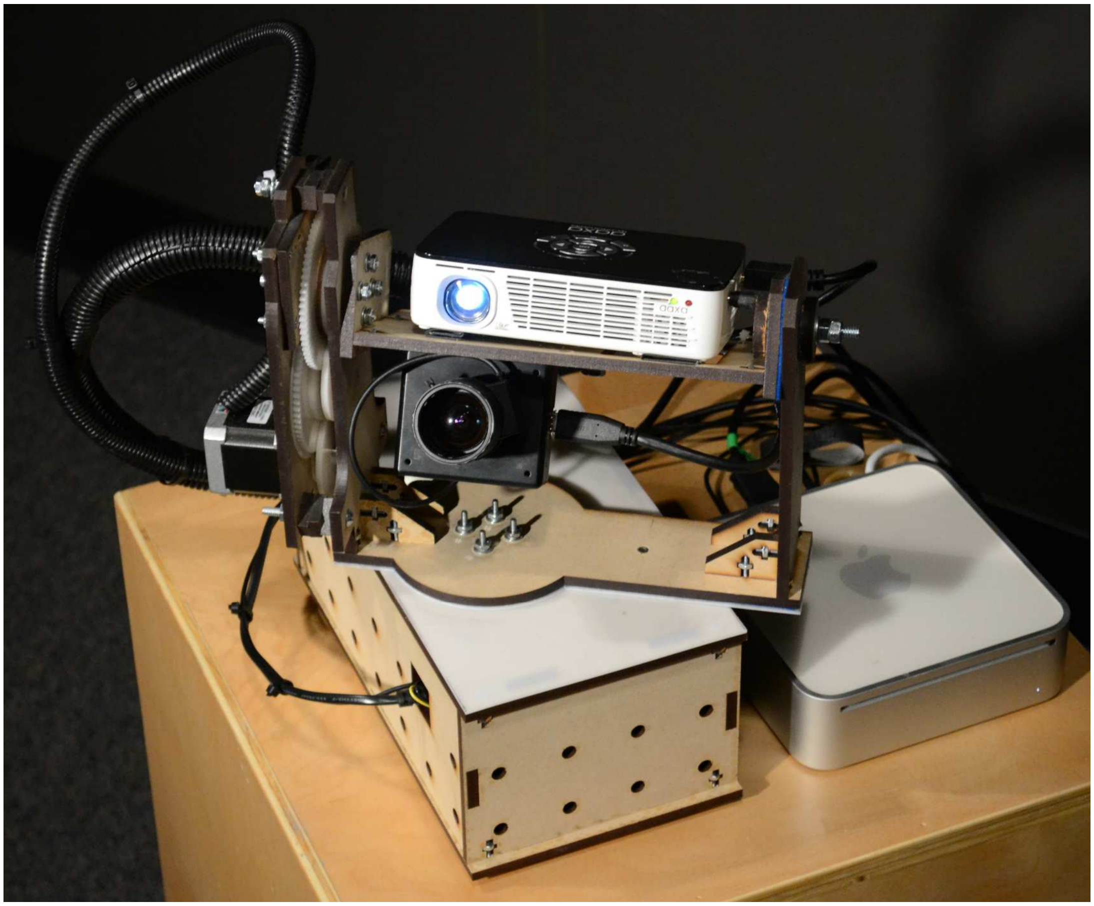

Figure 11. *Camera Projector Robot* (CPR) system.

The physical movements of the pan-tilt mechanism accentuate the parallax problem. Again, the ideal axes of the pan and tilt movements would align with the optical nodal points of the camera and the projector so that movements of the system would not result in changing foreground and background visual information. This performance would be very useful when attempting to augment a space with visual information based on the visual information received by the camera sensor. Aligning the visual information and maintaining common perspectives is facilitated by such a structural configuration of sensor and actuator elements. However there is a counter-argument that would suggest such a configuration might not be ideal.

Humans (and other animals) use parallax as part of their sensorimotor perceptual system to construct visual information from the raw light signals acquired by our eyes. Notice that the axes of rotation or the head, as determined by the location and mechanical characteristics of our spine, do not align with the nodal points of our eyes. Our eyes shift from side to side and move up and down when we tilt or rotate our head. This, combined with the binocular spacing of our eyes, insures that we do not have a stable relationship between foreground and background visual information, with very practical results of discriminating objects in our environment. The same opportunity exists for the CPR system. Theoretically it could learn about its body and external world by moving and receiving visual feedback during these movements. It has the additional capacity of projecting visual information into its environment and using the transformed feedback from this information as additional reference material with which to understand its world. A sensorimotor learning interaction similar to this is described by Philipona et al. (Philipona, O'Regan, & Nadal, 2003).

The arrangement of sensors and actuators in the CPR system are a major part of its structure and thereby significantly define its organization, which we experience as interaction affordances. The most interesting structural elements in CPR are not its tangible elements, but its intangible ones: it camera view and projection space. These elements may be seen as gradients, with sharp boundary edges, but as a property of their structure, with progressively less substance (to use a term typically reserved for tangible media) as the distance from the camera and projector increases. Due to the programming of the system, which can also be seen as a structural change, the camera view is experienced as a tangible structure, even though it is not physically tactile. The projector's projection of light provides an equally intangible structure. Taken collectively, the camera and projector constitute a system that is fully capable of structurally coupling with external structurally determined systems. The additional motorized, mechanical structure expands the dynamic organizational range of CPR. In its debut application, CPR allowed a projected image the Earth's moon to be pushed around through bodily interactions with the projected image. The description of CPR suggested the interesting possibility of seeing intangible elements in terms of their structure. I will now return to a description of tangible interactions with structurally determined systems with the presentation of a concept identified by Pye (1968) as self-jigging.

Self-jigging. Self-jigging (Pye, 1968, p. 35), which is illustrated in *Figure 12*, may be seen as a process in which one structurally determined system, which for this example we will identify as a chisel, is structurally coupled with another structurally determined system, which I will call the material. In this process, a human individual, who we will call the maker, is structurally coupled to the chisel. At the instant the structural coupling between the chisel and the material is initiated, the structure, and thereby the organization, of the maker is completely determining the structural coupling between the chisel and the material. The maker's organization must be sufficiently regulated (margins of indetermination minimized and prioritized) such that this initial coupling of the chisel and material matches her intent (which is determined by her structure at that instant). As the structural coupling between the chisel and the material continues, the structure of the chisel, the material and the maker all change. For now, the structural change of the maker will be disregarded, it is highly important, but not the focus of this topic. The structural change of the chisel will likely be microscopic in the course of a brief structural coupling with an appropriate, material, so it too will be disregarded for this example (although with different specific examples the changes could be more dramatic and instantaneous). The structural change of the material is of the utmost significance for this example. As the chisel progresses in the material, the structural coupling between the chisel and the material fundamentally changes. The channel cut by the chisel, now regulates its path. The maker, still essential for imparting energy into this system, is less critical in determining the relationship between the chisel and the material.

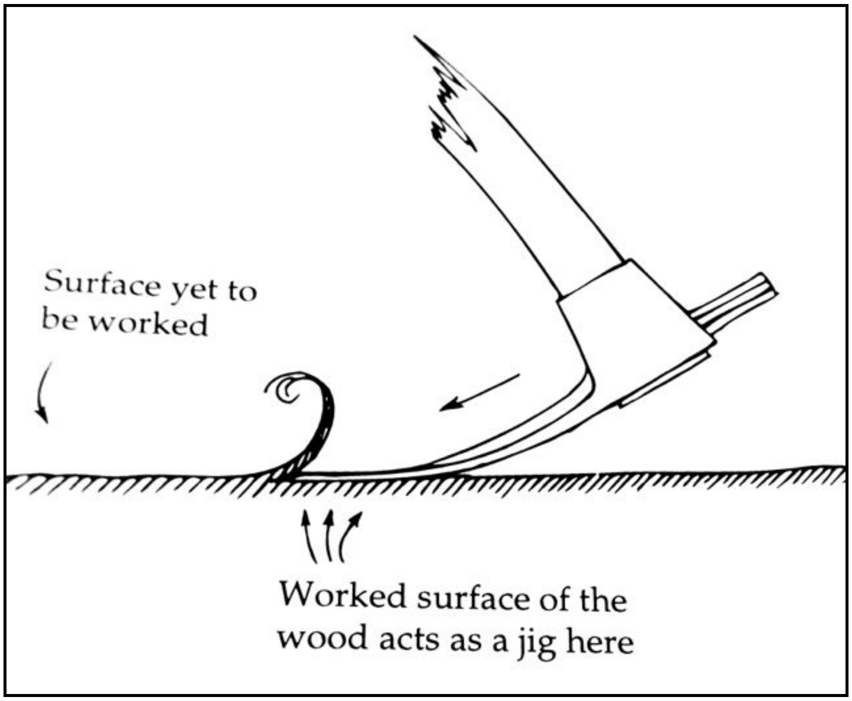

Figure 12. Self-jigging. From *The nature and art of workmanship*. Copyright 1968 by Cambridge UP.

Self-jigging (Pye, 1968) is also an essential form of structural coupling found in the operation of traditional mechanical shop tools. Shop tools provide a variety of constraints that are fundamental to their operation. These constraints are gradually integrated into the maker's cognitive structure in an embodied form "in the praxis of living" (Maturana, 2002, p. 32). These constraints are physical and in many cases are directly experienced by the maker as she uses these tools. I described the constraints as being fundamental to the operation of the tools. A couple of examples will help to clarify the meaning of this statement.

A table saw has a thin, essentially planar, blade with a circular array of teeth around the circumference of the blade. The planar shape of this blade is key to its use. When material initially comes in contact with the rotating blade, it may do so at any angle, however as soon as the cut is started the angle of the material in relation to the blade becomes constrained to that defined by the plane of the blade. If one attempts to deviate the trajectory of the material away from this constrained angle, the blade will bind with the material, creating a friction that will burn the material, throw it across the room, or cause other potentially disastrous results. Fortunately the table saw has constraining affordances beyond that established by the plane of the spinning blade. It has a fence that is arranged in a parallel configuration with the blade for the material to be moved along and tracks in the table surface, also arranged in parallel to the plane of the blade to allow for other sliding guides for the material. The tabletop of the table saw provides one of the most critical constraints of the whole system. The plane of the tabletop restricts the material from rotating away from the plane of the blade (providing a constraint orthogonal to that provided by the fence or tracks). When a maker uses the table saw she feeds material into blade, using the combined constraints provided by the system to safely cut the material. She feels the restricted planar motion as she pushes the material through the blade. Furthermore, she feels the tangible product of this planar motion in the form that is recorded in the material processed by the table saw. Although a table saw can be used to produce a variety of shapes and forms (even circles), the most characteristic products have two parallel sides (established by the relationship of the fence and the saw blade). This knowledge becomes part of the maker's pallet and is embodied in her memory as muscle memory (from the cutting process and through tangible interaction with the products of this process) and in the physical artifacts that populate her workspace.

The form and mechanical characteristics inherent in the tools may, through structural coupling, be instantiated in the materials they are used to process. In the case of the table saw, I identify the two parallel surfaces established by the relationship of the blade and the fence as the foundational, primitive, form. This form is transferred from the tool to the object produced and to the maker in the form of haptic/kinesthetic information. The resulting object possesses the capacity to recreate, again through structural coupling, this same formal (shape, mechanical, haptic) information to another object or person.

Up to this point in this chapter I have presented perspectives of the human role in the technical ensemble. I discussed modes of production as seen by Simondon (1958) and showed how the organizational boundaries of these modes may be seen as blurring. I introduced Victor's (2014) ideas maker spaces as 'seeing spaces'. I presented an in depth discussion of artisanal making, synthesizing Pye's (1968) theories with those theories previously discussed in this document. I used examples from my material studio practice to illustrate the points discussed. I wrapped up this section with a presentation of Pye's theory of self-jigging. The next section will build on these ideas, presenting a perspective of making as structural coupling, discussing what it means to know material, and considering how these concepts may lead to a vision of material computation.

Seeing Making as Structural Coupling

I argue that making can be seen as a unique form of structural coupling in which the maker intentionally alters the structure of the object or system they are making. Earlier discussions of structural coupling emphasized the mutual structural changes that occur to the involved structurally determined systems through this process (Maturana, 1987, 2002; Simondon, 1958). The addition here is the concept of intention. I argue that intention is not a mysterious entity requiring additional theory to come to terms with. What we call intention is merely the observable cognitive manifestation of a specific dynamic organization that is determined by the structure of the system (Maturana, 2002). Armstrong, citing Merleau-Ponty (1962) and Varela, Thompson and Rosch (1991), in his thesis *An Enactive Approach to Digital Musical Instrument Design,* states,

> Merleau-Ponty's concept of incorporation is consistent with the enactive model of cognition. In the enactive view, the systems and structures that play a determining role in the formation of cognitive patterns are in turn determined by the emergent patterns of interactional dynamics. Or to put it another way, at the same time that repetitive dispositions towards action and modes of perceiving are engendered within the agent's sensorimotor mechanisms, "cognitive structures emerge from the recurrent sensorimotor patterns that enable action to be perceptually guided (Varela, Thompson, and Rosch 1991: 172-173)." This formulation is essentially a latter day reworking of the fully recursive process, encompassing incorporating practices, that Merleau-Ponty defined as the *intentional arc*[4] (Merleau-Ponty [1945] 2004). (Armstrong, 2006, p. 21)

With respect to the maker, this argument implies that what can be made is determined by the structure of the maker, the structure of any tools used by the maker and the structure of the medium with which they are working, and all of these structurally determined systems continuously change structure (and potentially organization) through this structural coupling we observe as the making process. This leads to the question of what a maker means when they say that they ‘know their material’.

As a sculptor, I may claim to know my material. This expression of a sensitivity to, or understanding of my media, is not fundamentally about knowing its chemical composition or the manufacturing or processing that brought it forth. I may have some incidental understanding of these details, but what I’m really saying is that I understand its functional characteristics, or to phrase it more consistently with my perception of material as a structurally determined system, I say I understand its organization (Maturana, 2002). I know how it will respond to a variety of tools, whether or not it will polish to a glossy finish, how it will interact with other materials, how plastic it is at varying temperatures, how conductive or insulating it is, etc. In the next section I explore the relationships of structure and organization in materials I use to construct experiential media systems. This knowledge of materials is not limited to tangible media. It extends to electronics, code, and, as I shall further emphasize in upcoming arguments, conceptual media.

Simondon (1958) emphasizes the importance of understanding the structure and organization of media. He says,

> The technical imagination may be considered as defined by a particular sensitiveness to the technicality of elements that paves the way for the discovery

> of possible connections. The inventor does not proceed ex nihilo, beginning with matter to which he gives form; he begins with elements that are already technical and then discovers an individual being that is capable of incorporating them. The compatibility of individuals in a technical individual implies an associated milieu. Therefore the technical individual should be imagined, that is to say, it should be assumed to be constructed, as an ensemble of organized technical systems. The individual is a stable system of technicalities of elements organized into an ensemble. What is organized is these technicalities; the elements also are organized, but only in so far as they are bearers of these technicalities and not because of anything that has to do with their own materiality. (Simondon, 1958, p. 87)

Recognizing the inventor's sensitivity to the technicalities (Simondon, 1958, p. 87) of their media is an appropriate way of translating what we mean by knowing our material. Fundamentally it is not about the material in and of itself, it is about understanding the organizational dynamics (Maturana, 2002) of the material, and how it will couple with other natural and technical elements. I argue that from this perspective, we can see the invention process as a form of coding and the resulting systems as a form of computers. This way of seeing the coupling of structurally determined systems as computation may be labeled material computation.

Material Computation

Material computation may be thought of as a means of processing information through the physical characteristics of the medium. The entity that I identify in this section as 'information' should be seen as I have previously described it, as a structural change, in a structurally determined system, as a result of an energetic exchange, through structural coupling, with other structurally determined systems, as determined by the instantaneous structure of each coupled system (Maturana, 2002).

At a fundamental level, the systems we call digital, are no different than any other computational system. What sets them apart is the application of a threshold, defining on/off, or high/low, binary states. This artificial constraint, which abstracts, concretizes and renders generic the information it allows these systems to process, is extremely useful, as evidenced by the rich ecosystem of digital computational systems and applications we enjoy. Material computation, as I define it, does not utilize binary, or for that matter, necessarily any discrete states. In other words, it does not simply replicate the logical structure of digital/binary computer systems with alternative materials. It instead, takes advantage of the continuous and often inconsistent nature of the materials involved. Properties such as drift, bounce and hysteresis that are often actively engineered out of digital systems, may serve useful computational functions in material computational systems.

A common, and valid argument questioning the validity of material computation as a form of computation emphasizes the requirement for a computational system to be able to be programmed. I argue that one need only broaden their definition of what constitutes programming to recognize that non-digital, materials can be programmed. Take the simple example of a sheet of paper. Lets suspend that sheet of paper on a clothesline with two clothespins. The paper now processes input, e.g. air pressure from the wind, and outputs results, e.g. acoustic information, according to its current structural characteristics. If we change its structure, say for example by creating a crisp diagonal fold across its width, it will now process the same information differently and provide a different output. The sheet of paper has been programmed. Interestingly, this computer can also, in a sense, program itself. Left in the wind, its structure, its program, will gradually transform. Environmental variables, such as humidity, will result in program changes. Our computer has built in atmospheric sensors! Simondon (1958) states, “the functioning of the machine conceals a certain margin of indetermination. It is such a margin that allows for the machine's sensitivity to outside information” (Simondon, 1958, p. 4). Simondon continues,

> Modern calculating machines are not pure automata; they are technical beings which, over and above their automatic adding ability (or decision-making ability, which depends on the working of elementary switches possess a very great range of circuit-commutations which make it possible to program the working of the machine by limiting its margin of indetermination. (Simondon, 1958, p. 5)

We program material computational systems by modifying their structure and thereby modulating their margins of indetermination.

Material computational systems may offer advantages over their digital counterparts. They offer continuous rather than discrete operation, may be seen as passive and always on, provide material memory (with affordances dependent on the material), and may be simultaneously inherently simple and complex. Unpacking this statement would require a second dissertation. I offer a single example from my personal experience as a glimpse into the potential relations of material and digital computational systems.

OctoBoto. In a kinetic sculpture system I call *OctoBoto*, seen in **Figure 10**, I assembled a system of eight servomotors attached in a circular pattern on a wooden disk. Attached to each servomotor was a lightweight, wing shaped form. Immediately upon powering up the system, the wings started to vibrate in strong oscillating patterns, with apparent couplings of the vibrations of wings directly opposite each other. According to the software, the wings should have been held in fixed positions, waiting for movement commands. What was happening was simple, but completely dependent on the relationship between the electronic control system and the physical structure of the system. When the motors were first powered on, or moved to a new position, the structure would flex and spring back based on the material properties and mechanical characteristics (especially important was the length of the wings –the pendulums) of the physical structure. The force of this initial flex would result in a deviation from the software defined target position of the servos, which would energize to correct for the error. Because the frequency of the servo control signal closely matched the resonant frequency of the physical structures, small movements would quickly be magnified in a positive feedback loop to produce a strong sustained vibration. A gentle damping, in the form of placing ones hands gently on the wings, would suppress the vibration, but it would spontaneously return when the damping force was removed. My ultimate solution, which regulated, but did not fully eliminate this intrinsic behavior, which I considered desirable, in moderation, was a combination of material and digital programming. I attached elastic cords between each wing and the main body of the sculpture, adding a subtle biasing tension that damped the vibrations similarly to how placing one's hand on the wings did. I also edited the software to change the carrier frequency of the servo control signal, shifting it from the natural resonate frequency of the mechanical system. This interrelated structure and organization of physical matter and code is easy enough to see while building and testing a system (through downhill synthesis (Braitenberg, 1986)), but may be quite hidden to an external observer.

The preceding section addressed the idea of seeing making as structural coupling. This way of seeing making opened up questions about how a maker might know a material. From that another question emerged regarding the potential to see structurally determined systems as a means of conducting material computation. This continuous revealing of questions exposes the yields of the abductive research methodology. This chapter continues with an in depth description of my material practice of building experiential media systems.

Building Media Systems

In this section I illustrate seeing experiential media systems as structurally determined from my point of observation as the maker of these systems. I will illustrate how making can be seen as structural coupling, and how materials can be seen as structurally determined systems with specific examples from my practice as a maker. To be very clear, the perspective I provide with this example is from the point of observation of a sculptor engaging with physical material. Making could be seen in a very different light from a different point of observation. The first example I have in mind is the process I utilized to bend wood for the sides of my *Vox Curio* instrument.

Vox Curio. Wood, unless it is still very green must be made pliable before it can be bent. Depending on the specific wood, the shape and thickness of the pieces to be bent, and the ultimate end use of the product, this can be accomplished in a variety of ways. Extended soaking in water, and especially soaking in boiling water can dramatically soften the bonds of the wood fibers, making the wood extremely pliable. However this technique may lead to uncontrollable warping and permanent separation of wood fibers, making it a poor choice for the thin, acoustically active walls of a musical instrument. Even if this technique were successful in producing the desired form, I speculate that the resulting, possibly microscopic, structural changes would have negative acoustic impacts on the finished instrument.

Figure 13. Bending walnut panel over heated aluminum cylinder for body of *Vox Curio* instrument.

The technique I used to bend my walnut sides was the traditional luthier practice of heating the wood on a tubular metal form (see Figure 13). The heat causes molecularly trapped moisture in the wood to be released, effectively steaming the wood from within. If the wood has enough moisture, which depends on the variety of wood, its age and environmental conditions, no additional water will be required. Knowledge of the properties of the specific material, either from research or prior experience, may inform this process, but the authoritative information is constructed through haptic channels at the instant of every individual bend on every piece of material. This is structural coupling. The structure of the material and the structure of the maker are in a persistent, full-duplex dialog. You find out how soft the wood is getting, whether it needs a spritz of water to add moisture content and prevent scorching, whether an inconsistency in the grain pattern is going to make the wood likely to twist or cause fibers to separate, and a multitude of additional pieces of information as you coax (never demand) the wood into the desired form. You must also be sensitive to the dynamics of the wood as it is removed from the heat source and external pressure is released. It will spring back somewhat, and the degree to which it does will depend on how hot the material became and how long it was held at that temperature. This rebound may also not be consistent across the length or width of a bend. This too, cannot be corrected with force. If the shape is wrong after it cools, it must be reheated to make a correction. Bending wood by hand using this technique is a truly multisensory experience. Information is constructed from thermal energy (the temperature of the wood is felt with your hands), chemical interaction (smelling the wood as it rises in temperature and steams) and through mechanical force (haptic feedback through your hands, arms and body: feeling the initial springiness, eventual pliability, ultimate mechanical shape transformation of the material, and the same characteristics in inverse order.)

Figure 14 shows the bent walnut side pieces clamped into a rigid negative form. Traditional bar clamps are used in this process, as are less standardized clamping tools. In the lower left hand corner of the image on the left in Figure 14 a small piece of wood can be seen pressed into the tapered space between the walnut panels. This serves as a wedge, held in by friction and holding the panels in place in preparation for the gluing of brace joints. The image on the right side of Figure 14 shows a rubber ball being used for a similar purpose. In all these clamping examples interactions of materiality (structural couplings) are on display. With the bar clamps wood blocks are used to prevent leaving the material history of the clamping process that would result from the compressive force of the small surface area of the bare metal clamp head. The wood strip used as a wedge is relatively soft, allowing it to compress against the harder walnut and form a strong friction fit. The rubber ball, which can be increased or decreased in air pressure as needed to apply more or less clamping pressure, conforms to the bent walnut sides without any risk of marring their surface.

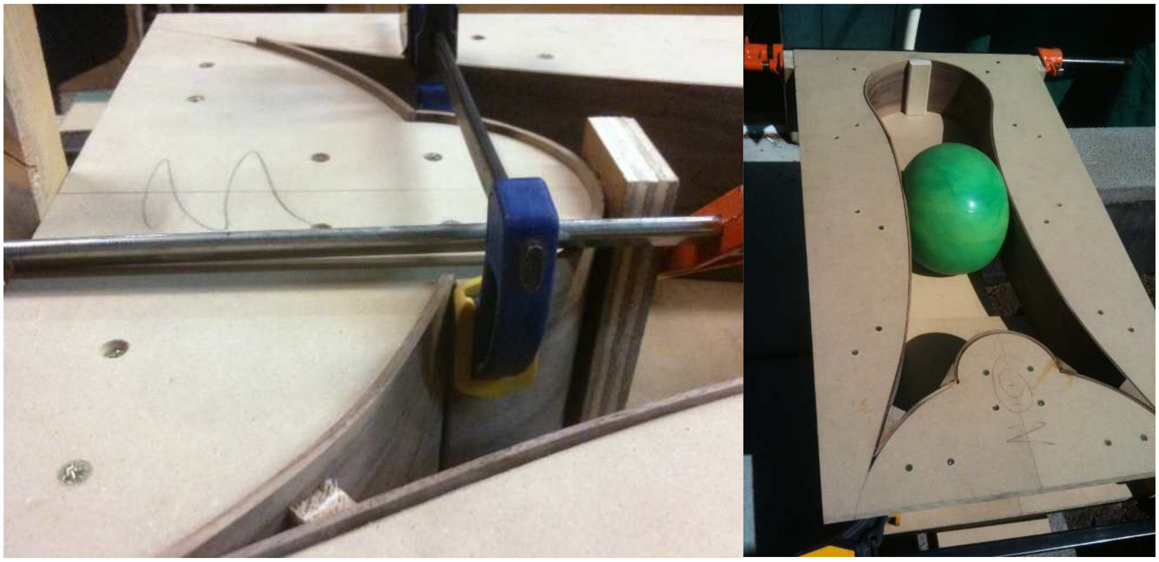

Figure 14. Bent wood pieces clamped in structurally defining form with bar clamps (left) and with rubber ball (right).

The knowledge required to successfully engage in the wood bending process I detailed here cannot be acquired without structurally coupling with the material as I described. Naturally I read and watched videos to learn about the process before trying it myself, and this process of acquiring knowledge was an essential part of my learning, but

I argue that my capacity to construct knowledge from these sources was dependent on my prior similar structural couplings with other materials. Experience breaking kindling for a fire, bending steel rod, bending glass, stepping on a water soaked log, and an uncountable number of other embodied learning experiences, gave me the bodily and cognitive structure to have a sympathetic response when I watched another person heating and bending wood.

Figure 15. Original, unfinished, flywheel that eventually broke. Maple crossbeam can be seen diagonally spanning the diameter of the flywheel.

The organic richness of materials formed under the influence of highly variable processes does not come without a trade off. The micro and macroscopic variations in material present significant challenges to the engineer and maker. The material may vary in strength at different locations and along different axes. It may split along a grain line. But perhaps the most consistent and pressing challenge, at least with wood, is the tendency of the material to swell, contract and warp with variations in temperature and humidity. In early iterations of the flywheel mechanism in *Vox Curio*, I experienced these challenges in dramatic form.

The first foreshadowing of troubles to come came as a tried to reassemble the crossbeam and the main flywheel mass, which can be seen in Figure 15. The ends of the crossbeam fit into precisely routed cavities in the flywheel. This fit was perfect the day I cut it. The next day I found myself needing to apply what seemed like an excessive amount of force to reinsert the crossbeam into the mating flywheel cavities. Fearing that this excessive force would crack the flywheel, I carefully sanded the mating surfaces until the parts once again slid together in a precisely fitting but low-pressure fit. I proceeded with work on other aspects of the instrument, thinking this stage of the fabrication was behind me. A day or so later when I went back to do some additional finishing work on the flywheel, I discovered that it was out of true and out of balance when I spun it. (This was wholly unacceptable since the flywheel needed to generate a controlled torque force, not act as a eccentric weight vibration motor!) Upon closer inspection I realized that the problem was not from my wood turning process, or from an inaccurately drilled axel hole. The problem was that the wheel had significantly warped. The crossbeam had restricted the movement of the sections of the flywheel that it was coupled with, but the free sections of the flywheel had shrunk and warped inward. Looking at the static flywheel, even under close inspection, you would not have noticed the problem, but when it was spinning the flat spots were painfully obvious. Upon reflection, I recognized several problems with my initial fabrication process.

First, I had done the initial shaping and fitting of the components on unusually wet Arizona desert days. The wood had absorbed extra moisture during these high humidity days, causing them to expand. When the weather shifted back to the typical dry environment of the desert, the wood dried out and shrunk back to its original dimensions.

The second problem was my material choices. I had selected maple, a wood traditionally favored for its hardness and stability, for the crossbeam. I used alder, a consistent, relatively easily carved, and reasonably affordable wood choice, for the flywheel. Alder, as I have now learned, is not as dimensionally stable as maple. The differences between the materials in their reaction the changing humidity accounted for a significant portion of the problems I observed.

Another factor that I had not taken into consideration was the difference in moisture absorption based on the shape of the material and the exposure of the end grain of the wood. The crossbeam only had exposed end grain at each end providing a relatively small surface area for moisture to readily be drawn into the wood. The flywheel, fabricated from sixteen mitered pieces of wood and turned to produce a compound curved surface, had much more variations of exposed grain across its surface, providing more opportunity for moisture absorption. Neither component had any sealer treatment at this stage to slow the effects of the humidity changes.

All of these collective factors led to the distortions and ultimate breaking of the original flywheel. The flywheel body, shown nearly finished in Figure 16, was refabricated in mahogany, a denser, more stable, and more costly, but aesthetically pleasing material. This version of the flywheel has held its form through several changes of season. Using the lathe to do the final shaping of the flywheel exemplifies the process of a highly concretized technical object transferring technicality to the objects it produces (Simondon, 1958).

Figure 16. Re-fabricated mahogany flywheel mounted in wood lathe.

When thin wood panels are joined at non-parallel angles to one another, the joint is often reinforced with a supporting transitional brace. This brace serves to increase the available gluing surface area and defines the angular relationship of the joint. When the panels to be joined are not straight, but bent as they are in my *Vox Curio* instrument (see Figure 17), the supporting braces must follow this contour. A simple, and traditional way of fabricating wooden braces to match a curved surface is to cut a pattern of thin slices, perpendicular to the length of the bracing material. The resulting structurally engineered material is called ‘kerfing’. A kerf is the void left in a material that has been cut by a saw blade. The width of the blade determines the width of the kerf. (Forgetting which side of a cut line to locate the kerf on is a common way to measure twice, cut once, and still end up with pieces of the wrong dimension.) When cutting kerfing, the cut is stopped at a precisely determined distance through the material. The depth of the cut is critical to the function of the kerfing. The function of this structurally engineered material may be seen as a consequence of the organization of a structurally determined system when it is structurally coupled with another system (Maturana, 2002). If the cut is too deep, the kerfing will be very fragile and difficult not to break while hurrying to get it clamped in place after applying glue. If the cut is too shallow, the kerfing will not be flexible enough and will require excessive force (which may break rather than bend the kerfing) or will require heating to bend it (dramatically reducing its utility). If the cut depths are not consistent across the length of the kerfing, some areas will not bend while others kink or break. For this reason a fixed stop-block that physically restricts the depth of the cut is typically used when manufacturing kerfing. The use of the stop-block also dramatically increases the speed at which kerfing can be cut. Cutting to a visually marked stop-line requires the cut velocity to be significantly decreased as the end of the cut approaches to minimize the risk of over or un-shooting the intended stopping point. Cutting with a tangible stop engages another sensory modality and practically guarantees a consistent result. Pye (1968) refers to this as a form of regulation, reducing the risk involved in the workmanship of risk (Pye, 1968). Pye’s theories will be discussed further in an upcoming section.

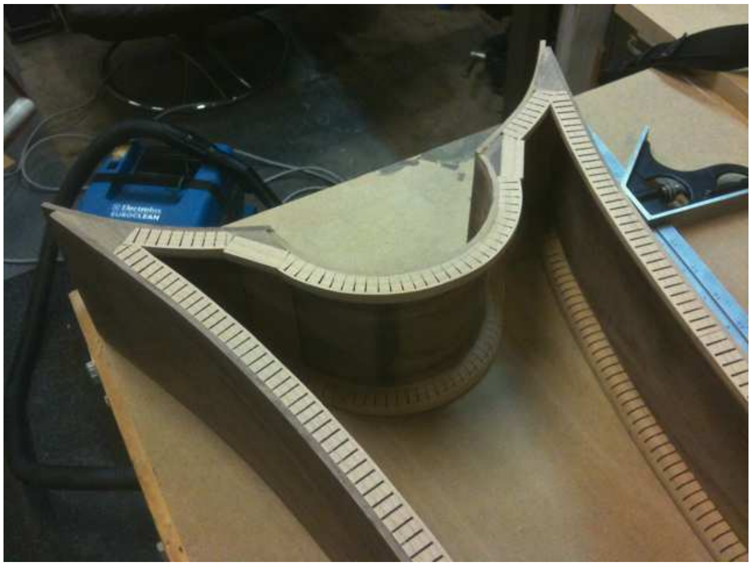

Figure 17. Kerfing installed on the interior edges of *Vox Curio* in preparation for the attachment of the top and back panels.

The slices in kerfing produce discrete bend points. The wood sections between the slices do not interpolate between these discrete points, so the spacing of the slices determines the resolution of the curve (or more accurately, sequence of angularly joined line segments). If the spacing is too wide for the curve it will be mated to, at best there will be significant gaps between the kerfing and the mating surface, and at worst the kerfing will not match the radius of the curve at all. If the spacing is too narrow, the kerfing will have a reduced structural capacity to define the mating angle of the joined panels, and will offer less contiguous planar surface area for the glue. These problems with too narrow of spacing are only likely to emerge with an extremely narrow spacing. The main reason not to cut extra narrowly spaced kerfs is simply to save time and effort. The relationship between the kerfing and the material may be seen as a structural coupling between an analog curve and a digital approximation of that curve. The fit only needs to be close enough to meet the larger structural and aesthetic requirements of the unified system.

Figure 18. Structural bracing installed on underside of top panel of *Vox Curio* instrument.

The body of *Vox Curio* was inspired by traditional acoustic guitar construction designs and techniques. Included in this design vocabulary is the use of bracing strips across the spans of the large flat areas of the thin top and bottom panels. Durability is a major motivating concern when engineering the shape and pattern of these braces, but this factor is by no means the only one. The thickness of the panel and the form and placement of the braces makes a significant difference in the acoustic performance of the instrument. The nuances of this engineering is beyond the scope of this document but it is not unrealistic to claim that the objective of the luthier is to produce a unified structure that represents, not a compromise between the desired acoustic characteristics and durability, but a synergetic relation between these structural requirements. Such a unified structure is described by Simondon (1958) as plurifunctional and represents a technical concretization (Simondon, 1958). I had such an ideal in mind when I engineered the braces for *Vox Curio* (seen in Figure 18), but since the shape of this body and the mode of acoustic excitation of the body are significantly different than that of any traditional guitar, I had no clear basis for my decisions. This being the case, I chose to prioritize durability for this prototype instrument.

The aesthetic and functional character of *Vox Curio* is a product of significant industrial concretization (Simondon, 1958) in the form of the software design tools and CNC fabrication hardware I used in its engineering and fabrication. Figure 19 shows an early design iteration of the instrument that eventually became *Vox Curio*. I was able to virtually iterate on different designs for the overall form of the instrument and specific components essential to its function with relative speed, ease and without added financial investment. This iterative cycle is in the spirit of the machine genesis that Simondon describes (Simondon, 1958).

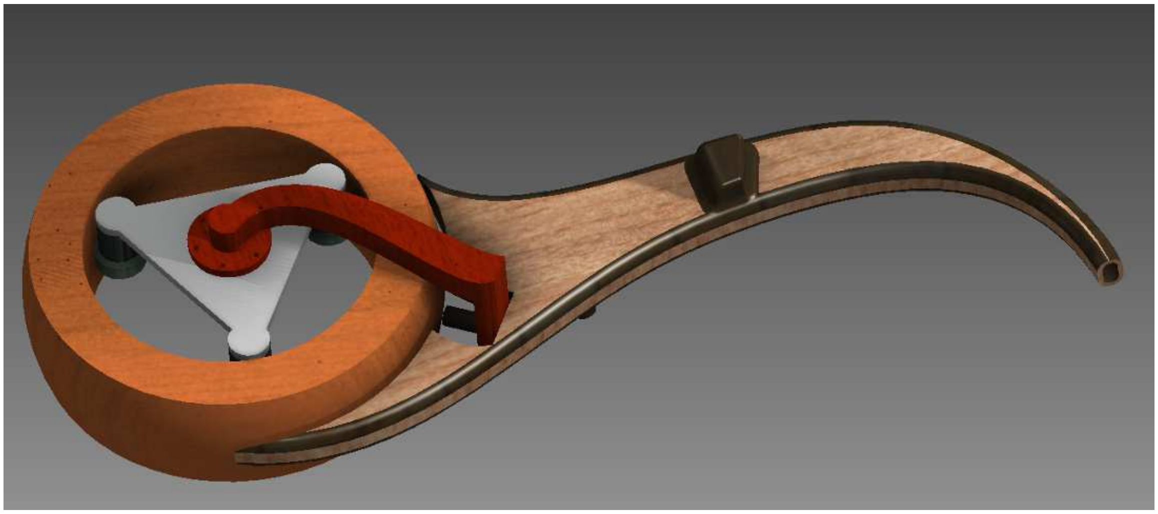

Figure 19. An early iteration, in 3D model form, of the *Vox Curio* instrument.

Figure 21 shows a 3D model of the flywheel and driving motor for the ungrounded haptic mechanism in *Vox Curio*. An important feature of this mechanism is the magnetic gear system that translates the motion of the rotary motor into the motion of the flywheel without a physical contact between the motor shaft and the flywheel. The real challenge of designing using contemporary software engineering tools is that virtually anything can be designed, but it may not be feasible to manufacture. I certainly keep manufacturability, with the tools I have at my disposal, in mind when designing systems, but I still run into challenges and need to make changes when translating my designs into actual products.

In this example I was focused on engineering a cylindrical array of magnets with a desired gear ratio and appropriate spacing between magnets to produce a smoothly magnetically meshed gear structure. The affordance of the software made this a manageable task, but I ended up designing parts that I could not easily and accurately manufacture without first building a machine for the job. I originally envisioned cutting slots in the interior of the flywheel body to embed the magnets in. The magnets would go in the center of these slots and filler wood pieces would close up the outsides of the slots. The difficulty was figuring out what tool could fit in the toroidal form of the flywheel, which by itself represented a great deal of labor, and how I would regulate and index the cutting process to achieve the perfect spacing required for smooth operation. I abandoned this original fabrication approach and instead split the flywheel into two halves and sandwiched a thin laser cut part in between these halves that could be quickly and easily recut if it didn't work perfectly on the first try.

Figure 20. Integration of hand built and laser cut subassemblies of *Vox Curio* instrument.

Vox Curio was produced using a blend of traditional luthier hand building tools and techniques and contemporary computer-driven design and fabrication technologies. Later in this chapter I discuss Simondon's (1958) way of seeing modes of production as either artisanal or industrial. I relate these perspectives to those of Pye (1968) who sees production techniques on a spectrum of risk (Pye, 1968). Figure 20 shows the integration of laser cut components with the hand fabricated bent wood body of my *Vox Curio* instrument. Although I utilized laser cut templates in the fabrication of the acoustic body of the instrument, subtle variations from this ideal form were the inevitable result of the organic variations in the natural wood and the compromises inherently required when bending and joining this wood. To integrate the hand built body with the laser cut components I had to carefully hand shape the laser cut parts to fit the body while maintaining the mechanical integrity of the laser cut components. For this reason, the laser cut panels could not be individually fit to the section of the body that they attached to, but had to be preassembled into a unit and fit to the body as a three-dimensional whole. At the point in history at which I am writing this document, computer controlled manufacturing technologies have significantly advanced and have become accessible to a wide range of makers. Individual components can be cut and printed with relatively high levels of accuracy and precision. However, assembling these components into a structurally determined system with an intended resulting organization still poses significant challenges, and these challenges are magnified if the maker employs natural rather than technical elements (Simondon, 1958).

Figure 21. *Vox Curio* flyweel 3D model (left) and detail of actual flywheel in production, showing array of embedded magnets.

Vox Curio is a unique musical instrument in many ways, but with little doubt, its most unusual feature is the flywheel mechanism that provides ungrounded force feedback. An early iteration of this system is shown in Figure 22. (Notice that in this prototype the gimbal gear only allows a 180-degree rotation of the flywheel.) In technical terms this mechanism is known as a ‘control moment gyroscope’ or a ‘control momentum gyroscope’. Wikipedia provides a succinct definition, “A control momentum gyroscope (CMG) is an attitude control device generally used in spacecraft attitude control systems. A CMG consists of a spinning rotor and one or more motorized gimbals that tilt the rotor’s angular momentum. As the rotor tilts, the changing angular momentum causes a gyroscopic torque that rotates the spacecraft” (Wikipedia, 2014a).

I discussed a general taxonomy of haptic feedback devices and presented additional examples of related ungrounded force feedback systems in the background chapter of this dissertation.

Figure 22. Assembled 'control moment gyroscope' head of *Vox Curio* instrument.

A significant motivation for the inclusion of a force feedback mechanism in *Vox Curio* came from my personal experience as an amateur musician playing acoustic and electric instruments (primarily guitar, trumpet and percussion instruments). The observations I present here are from my point of observation as an experienced, but relatively novice musician. I discuss my points of observation as a maker and musician in more detail later in this section. I considered the experience of playing these instruments in contrast to my experiences performing with the Laptop Orchestra of Arizona State (LORKAS) (LORKAS, 2015). While many differences between traditional musical instruments and the laptop computer as musical instrument can be enumerated, what stood out to me was the relationship of physical effort and sonic result. With the laptop such relations were arbitrarily determined through programming and choice of interaction modalities (e.g. key presses, touchpad swipes, accelerometer detected movement of the laptop body). With the traditional instruments the mappings of my physical efforts to sonic results were fundamentally a result of the structurally determined physics of the instruments structurally coupled to my body. A simple example of this is bending a guitar string to increase the pitch of the note. I observed, while learning to play guitar that I had to consciously minimize the force I exerted on the strings to avoid unintentionally shifting the pitch and playing out of tune, and that when intentionally bending notes I experienced the physical effort of doing so as not only a feedback that helped me consistently bend to a desired pitch, but importantly was intrinsically linked to my musical expression. I recognize that for more experienced and professionally trained musicians their experiences of playing may be different than my own and this haptic information may not be considered essential or even desirable (Paine, 2013, p. 80). Nevertheless I saw opportunities to explore this sensorimotor modality through this interface in which a substantial physical force could be programmatically modulated and implemented both as a feedback and as an assertive stimuli.

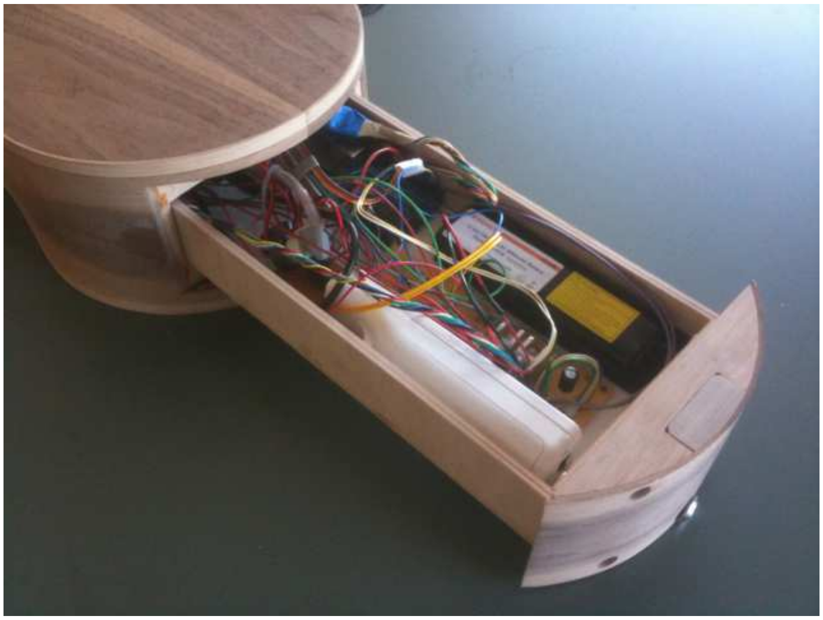

Figure 23. Electronics drawer partially inserted into *Vox Curio* instrument body.

An important relationship I wanted to explore in this system was the sensorimotor relationship established between the control moment gyroscope and the motion sensors that measure the movement of the instrument body. The suite of accelerometer, gyroscopic and magnetometer sensors are collectively identified as an Inertial Measurement Unit' (IMU). In the prototype set of electronics visible in Figure 23, I am using a Nintendo Wii Remote ™ (Wikipedia, 2015j). In the current iteration of *Vox Curio* I have upgraded this sensor to a x-OSC wireless I/O (input/output) board which incorporates a high-performance IMU sensor unit (x-io.co.uk, 2015).

The IMU allows for linear and rotational movements of the instrument body to be sensed, as well as an absolute orientation with respect to the magnetic field of the earth. IMU sensing is commonly used in musical interfaces (see Background chapter for examples), but what sets this interface apart from most is the potential for the control-moment gyroscope (CMG) to be actuated in response to IMU sensor information and for the movements of the instrument resulting from the CMG to be measured by the IMU. Both the system software and the musician, structurally coupled with the instrument, play an intermediary role in this potentially recurrent feedback loop.

Earlier in this chapter, in my discussion of David Pye's theories, which I see as describing structural coupling between makers, tools and materials, I discuss a concept Pye identifies as 'self-jigging'. Although I have not yet implemented a mapping of sensing, sound synthesis and actuation that effectively exhibits this characteristic, I think it may be fruitful to consider how I might see the relations I establish between the sensors, sound synthesis and actuation in *Vox Curio* as an opportunity to experience a form of self-jigging with sonic matter. In such a relationship the musician could instantiate or shape, through a physical movement of the instrument body, a sonic element. The CMG could be actuated such that it magnifies, or carries through, the physical gesture initiated by the musician. The inverse relation could also be explored, where the instrument resists, or redirects an initiated gesture. These modes of interaction could exist on a continuous spectrum rather than being implemented as discrete states. Such a variable response is not inconsistent with Maturana's (2002) definition of a structurally determined system. He says, " Accordingly, I thought then, whether a dog bites me or doesn't bite me, it is doing something that has to do with itself" (Maturana, 2002, p. 6).

Figure 24. Testing a vibrotactile actuator on the acoustic body of the *Vox Curio* instrument.

In addition to the control-moment gyroscope haptic system implemented in *Vox Curio*, it includes vibrotactile actuators that produce both haptically perceived energy and energy that excites the acoustic body of the instrument. This may be seen as a plurifunctional structure (Simondon, 1958). Figure 24 shows one of the actuators being tested on the outside of the instrument body (the actuators are ultimately installed in the interior of the acoustic body). In this test I was evaluating the coupling of the actuator to the body, varying the pressure of the actuator against the body and testing various materials for their damping effects and the resulting spectral response of the system. I was testing structures to see which structure provided the desired sonic and haptic organization for the system.

Figure 25. *Vox Curio* 'valve' pressure sensor/actuator assembly attached to instrument body.

Figure 26. *Vox Curio* 'valve' pressure sensors under construction. Copper tape and Velostat material are visible.

I drew on my experience as a trumpet player for inspiration for another interactional component of *Vox Curio*. I designed three pressure sensitive pads that I identify as ‘valves’ for the instrument. These can be seen in fully assembled, but still prototype form in Figure 25. Paired with a bite sensor, these three sensors can be used as a chording interface to generate a wide range of notes in the same way the valves of a trumpet and lip tension on the mouthpiece of the trumpet do so. I produced custom sensors for these valves using a combination of conductive copper tape and a material called Velostat, which is a carbon-impregnated plastic material. The electrical resistance of Velostat changes as it is compressed, making it an effective material for fabricating pressure sensors. Just as I have come to know the structure and organization of materials such as wood and steel, I have, to paraphrase Simondon (1958) become sensitized to the technicalities of these electrically relevant technical elements (Simondon, 1958, p. 87). I created my own sensors in this case rather than using commercially available pressure sensors because doing so allowed me to cost-effectively produce sensors that were custom fit and tuned for this application.

Figure 27. Detail of vibrotactile actuators on *Vox Curio* instrument 'valves'.

The main vibrotactile actuators installed in the body of *Vox Curio* serve a haptic and sonic function, and although *Vox Curio* can be externally amplified in addition to its internal acoustic amplification, I generally do not attempt to incorporate haptic feedback through these actuators other than that which directly translates to sound. Vibrotactile actuators integrated into the valve sensor system (seen in Figure 27) provide the opportunity to provide haptic feedback or assertive stimuli that is not directly part of the sonic signal. For example, I can produce feedback that corresponds to transitions across sensor threshold levels. For me, the most interesting feature of actual trumpet valves, modulating the flow of air through the instrument, is what happens when the valves are partially closed; the sonic slurring and muted tones that can be produced with the valves in these transitional zones. An implementation of such transitional interaction spaces is fully afforded by my hardware and is something I am eager to explore.

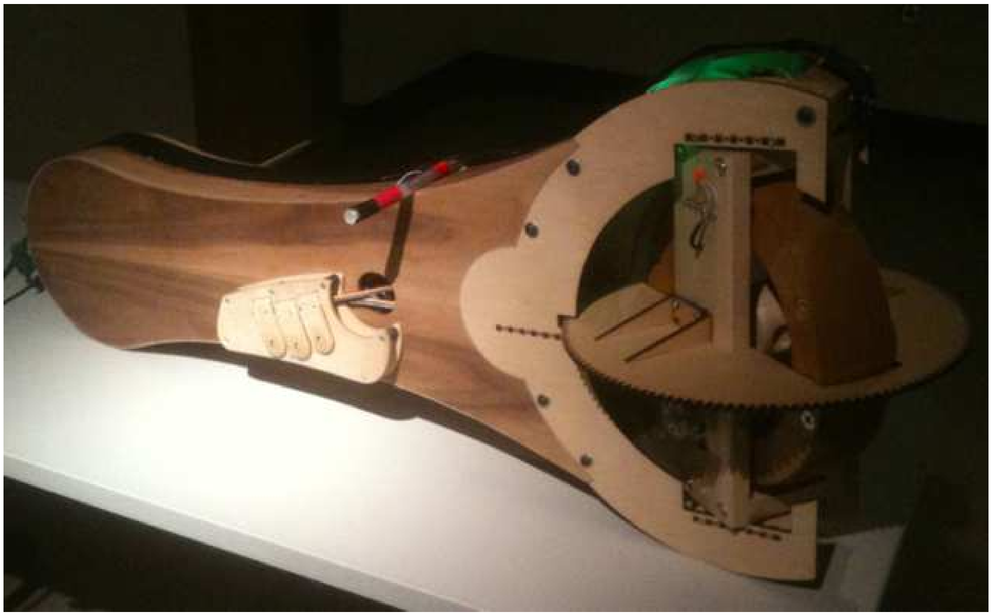

Figure 28. *Vox Curio* instrument fully assembled, powered up and ready to play.

Figure 28 shows *Vox Curio* powered up and ready to play. At this point I would like to make a subtle distinction regarding my point of observation while playing this instrument. First, it is clear that my experience of playing *Vox Curio* will likely always be something other that that of any other musician. As the maker of the instrument my perspective will always be informed by my knowledge of how I engineered its physical components and how I programmed its audio, haptic and sensory systems. But this is not the subtlety I'm referring to. The distinction I want to make is that I have not yet experienced *Vox Curio* from the point of observation of a musician. When I have played this instrument it has been as a maker. (Figure 29 shows me playing *Vox Curio*.) I offer an analogy to make my point clearer. When I am sculpting a limestone form, only a portion of my time is spent directly removing material from the object. A significant percentage of my time is spent stepping back and regarding the form. In this regarding I am on the cusp of a point of observation as a viewer experiencing a work of art, but I'm still fundamentally regarding the emerging sculpture from the point of observation as its maker. In the same way, when I am playing *Vox Curio*, I am momentarily regarding it from the point of observation of a musician, but I am fundamentally still regarding it as an emerging instrument, from the point of observation as its maker. I hope at some point I will be able to experience it fully from the point of observation of a musician, without any thought on how it was made or what needs to happen to improve its performance.

Figure 29. *Vox Curio* instrument being played.

I offer as a point of comparison a different experience of making and eventually playing an instrument in which I have been able to transition from observing it from the point of observation of a maker to that of a musician. I built a guitar and in spite of the fact that it still requires additional sanding and finishing, is missing volume and tone knobs, and still needs minor neck pocket adjustments, I was able to quickly transition to simply playing it and observing it from the point of observation as a musician. What is the essential difference between these two instruments that makes this dramatic experiential difference? The difference I see as significant is not the relative complexity of the two systems, although *Vox Curio* is dramatically more complex in many ways. The essential difference is that *Vox Curio* is a completely new instrument with no basis of comparison. I can easily see what I need to do to make the guitar "finished". There are millions of points of reference for this assessment. *Vox Curio* has no traditional performance repertoire or even an established musical pallet from which to draw. For a guitar a repertoire and pallet are firmly established. The guitar has a multitude of cultural reference points. *Vox Curio* only has the cultural reference point of being a new musical interface. So it is a simple matter, once a guitar is even vaguely playable, to begin to experience it as a musician. There are many cultural and musical anchor points available help form a performance relationship with the guitar and virtually none for *Vox Curio*. I'm certain that many others have come to the same conclusion when building and attempting to evaluate new musical interfaces, but I'm pleased that this does not remove the motivation to produce them. This will conclude the discussion of the production of *Vox Curio*. I will continue the discussion with an example from my experience building the aforementioned guitar.

Fabricating a guitar neck. I have learned a great deal about the structure and organization of structurally determined systems through my focused consideration of the materiality of natural elements while fabricating a guitar neck. This project was an exercise in the mode of production Pye (1968) identifies as the workmanship of risk (Pye, 1968).

Figure 30. Guitar neck in production, showing end grain orientation.

An important variable in many wood projects is the consistency and orientation of the wood grain. I selected a hard maple for the neck and a flat sawn orientation for the grain. Figure 30 shows the guitar neck in production with a clear view of the end grain pattern. Flat-sawn wood (looking at the end of the neck the grain pattern lies parallel with the fret board surface) provides lateral good stability but allows relatively easy flexing in the direction that the string tension will pull. Many builders choose quarter-sawn wood (looking at the end of the neck the grain pattern is perpendicular to the fret board) to maximize the resistance to the force produced by the string tension. I am working with the philosophy that the steel truss rod, a technical element, is there to counteract the string (also technical elements) tension force, and that the stability in the lateral orientation, which is not otherwise compensated for, is best provided by the structure of the wood.

Another variable in play in this decision is the orientation of the grain with regard to the arc of the grain. If (when) any warping force occurs, the wood will tend to bend away from the concave side of the grain arc. This tendency is a result of the anisotropic permeability of the wood grain. Exposed end-grain is more permeable than the relatively closed cellular structures of the other wood surfaces. I discuss anisotropy further at the end of this chapter in the section ‘Seeing it as Material’. I chose to orient the wood with the end grain (which is relatively flat as a flat-sawn board) in the direction of a smile (if one is looking at the heel end of the guitar neck) so that if any warping force is generated, it will be in opposition to the force of the strings. This allows the tension of the strings to continuously counteract the potential warping of the wood. Maintaining the necessary balance between the tuned string and truss rod tension should keep the neck appropriately flat. In this grain orientation, the natural warping tendency of the wood works in parallel with the tension of the truss rod. Of course aluminum, titanium, carbon fiber, or another technical element could be used as an alternative neck material to sidestep all these issues, but the familiar, desirable and traditional richness associated with the visual aesthetic and tone of the wood would be lost.

These discussions about wood grain, warping flywheels, and the building of guitar necks, may seem far afield from the overall topic of this dissertation, but I argue that, although the level of detail in the prior descriptions may not have been necessary, the core ideas are exactly aligned with my overall goal of promoting seeing systems as structurally determined, and seeing structure and organization as a unified whole. The structure of natural elements, as exemplified by wood in the aforementioned systems, determines their organization. Modifying this structure at the macro level, the maker may transform some aspects of this organization while maintaining others. This modification takes place through a structural coupling of maker, tool and material. Throughout this coupling, the maker is modifying the structure, but with a continual focus on both the structure and the desired organization of the final system, which will ultimately be coupled with a human individual, and so on in an outward expansion of structural couplings.

As the maker of systems determines the structures of these systems, the maker has the opportunity to generate plurifunctional structures (Simondon, 1958). In the next section I extend Simondon's (1958) notion of plurifunctionality.

Conceptual Plurifunctionality

When Simondon (1958) writes about plurifunctionality or plurivalence, he is specifically talking about physical functionality and structures (Simondon, 1958, pp. 16, 57–58, 60). Even electricity, prominent in Simondon's examples, can be seen as physical. While there are many strategies for generating plurifunctionality in this physical sense, such as employing sensors as actuators and actuators as sensors, I propose another way of seeing plurifunctionality, namely seeing the potential for conceptual plurifunctionality.

The notion of combining conceptual functions with physical functions is straightforward. Sculptors do it all the time, producing a structure that satisfies physical and mechanical requirements, while simultaneously visually or materially referencing an idea, or advancing an aesthetic. I suggest that such a fusion may not only serve poetic and artistic functions, but may also inspire invention by leading to non-obvious materials and forms. My theory of conceptual plurifunctionality is in early stages of production in my paradigm construction project. I will not, in the context of this dissertation, attempt a formal articulation and defense of this theory.

In my original written documentation of my idea of conceptual plurifunctionality, I used Simondon’s (1958) related term ‘plurivalence’ and wrote of conceptual plurivalence as an attribute of the system itself, as part of its organization, which is determined by its structure. I concluded that doing so posed a philosophical inconsistency with Maturana’s (2002) theory of structurally determined systems as organizationally closed. I realized upon further reflection, that the term ‘plurifunctionality’ was more accurate and was not inconsistent with the theory of structurally determined systems, because functionality is an abstraction from an external point of observation of structurally coupled, structurally determined systems (Maturana, 2002).

In my construction of a theory of conceptual plurifunctionality, I use Simondon's (1958) concepts as a starting point. I build on them, going beyond physical material and energetic functions to a consideration of artistic, aesthetic and conceptual functions in the same objects. While this deviates from Simondon’s application of plurifunctionality in his mechanological examples, I believe it is consistent with his interpretation of the process of invention. In an interview, Simondon was asked whether it was reasonable to compare his thought process with that of Gaston Bachelard (1958/1994), a French philosopher known especially for his philosophical application of phenomenology to architecture, in his book *La Poétique de l'Espace (The Poetics of Space)* (Bachelard, 1958/1994), which was first published the same year as Simondon's *Du mode d'existence des objets techniques* (On the Mode of Existence of Technical Objects) (Simondon, 1958). Simondon replied,

> I don't know. Bachelard is a poet., I don't really know his works well enough.. But I think we could just as well do a psychoanalysis of the technical object, as Bachelard has done a psychoanalysis of the elements. In particular, I think that each technical object can be treated as having an intention and an attitude. ... For me it is more than a symbol, rather a sort of gesture or intention or power, almost magical, a contemporary magic. ... That is a poetic aspect, an aspect of signification and of encounters of signification. ... We lack technological poets. (Simondon & Le Moyne, 1968)

I argue that we can see artistic practice as plurifunctional discovery and that conceptual, aesthetic and artistic functions can be seen as extensions to the concepts of functions in technical object theory. I point to the concept of the *objet trouvé* (found object) or ready-made, popularized by Marcel Duchamp (1973) as an act of an alternative "seeing it as" (Wittgenstein, 1953).

An example of my own art, a project called *Flight Lessons*, seen in Figure 31 and Figure 32, extends this act of "seeing it as" to encompass both physical and conceptual functionality. This project features a suspended speaker, which simultaneously functions as a sonic actuator, a symbol of communication and a magnetic lift. This same artwork includes a lead bird structure that can be seen as an icon of flight, a physical mass, a symbol of weight and a symbol of toxicity. The lead bird stands on steel stilts, magnetically supported by the speaker. These stilts can be seen as an augmentation to enhance stature and elevate, as crutches, and (because of their mode of suspension) as simultaneously grounded and floating. An audiotape loop with original source material from an audio tape of a motivational lecture on *The Seven Habits of Highly Effective People* (Covey, 1989) is modulated in speed, resulting in the human speech being heard as bird chirps, warbles and squawks. This single artwork has still more plurifunctional structures. I present this example to illustrate my theory of conceptual plurifunctionality from the point of observation of a sculptor.

Figure 31. Components of *Flight Lessons* sculpture by Byron Lahey. Lead bird on steel stilts supported by magnetic field of speaker (left) and wooden marionette suspended under mechanical system with audio playback system (right).

Figure 32. Overall view of *Flight Lessons* sculpture by Byron Lahey.

My primary purpose for suggesting such an extension of Simondon's philosophy is not to elevate artwork by associating it with the technical. My reason to suggest this conceptual extension is to encourage non-obvious thinking and thereby potentially enhance the process of invention, not to magnify the quantity of inventions, but to magnify the quality of inventions by promoting rapid cycles of concretization, individualization, the evolution of ensembles and the subsequent generation of more technical elements. I propose that the active, conscious inclusion of conceptual functions in the process of generating plurifunctional structures would encourage seeing the problems of systems in a new light. Designers and engineers take the first step in this operation many times, repurposing a random part from one system in another. The artistic application of this process extends the pallet of elements available for this process by seeing the problem not only in terms of physics, but also in terms of poetics. If you are looking for a spring, you will only find a spring. If your priorities are looking for an element that not only pushes objects apart but also conveys a poetic meaning, or has a particular aesthetic quality in harmony with, or juxtaposed with, other elements in the system, you are likely to be considering other options. Engineers may dismiss this idea as a waste of time and mental energy, but I'm not suggesting this for subtle, incremental improvements in systems that already exist. I'm talking about breakthrough inventions that require real creativity.

As a final note on this subject, I remind the reader that I am an artist, and I'm writing from that perspective. My expectation is not that the big industrial technology companies will take my advice and start rolling out systems that are not only truly innovative, but also poetic, though this would be a delightful impact to make. I'm more concerned whether my ideas resonate with my colleagues, professors, students and other artists and engineers inventing the future through the invention of experiential media systems. I will conclude this chapter with a deeper examination of materiality. Aspects of materiality have emerged throughout this document. This concluding section will look at these and other aspects of materiality and will consider how they apply to a variety of domains of knowledge and practice.

Seeing it as Material

I’ve introduced several aspects of materiality, primarily from my point of observation as a maker. In this section I present aspects of materiality in a cohesive, but by no means comprehensive, form. I argue that other systems, even systems as immaterial as social and cultural systems, can be seen as material. I make this argument with Wittgenstein’s (1953) concept of a “‘dawning’ of an aspect” (Wittgenstein, 1953, pp. 194, 206, 212) in mind. Specifically I am suggesting the meaning Wittgenstein proposes when he says, “ what I perceive in the dawning of an aspect is not a property of the object, but an internal relation between it and other objects” (Wittgenstein, 1953, p. 212).

The aspects of materiality that I mention in this section I classify under the general categories of: temporality, homogeneity/heterogeneity, symmetry/asymmetry, plasticity, tangibility, and autopoeticity. These categories themselves represent only one of a plurality of potential classification schemes for aspects of materiality. There is significant crossover between these categories and the aspects I place within each category may as easily find a home in another category. I do not present this scheme as a static formal framework, but rather as a snapshot of a dynamic paradigm construction project.

Temporality, as an aspect of materiality, describes, from the point of view of an external observer, how a material changes over time. I emphasize that temporality is an effect of the act of observation, not an inherent property of material itself, which I am seeing as a structurally determined system (Maturana, 2002). Maturana (2002) emphasizes the instantaneousness of structurally determined systems in his basic definition: “a system in which all that happens with it and to it is determined at every instant by the way it is made (its structure) at that instant” (Maturana, 2002, pp. 5–6). Temporality is nevertheless an extremely useful abstraction when considering materiality. The degree to which we see a material as static or dynamic depends of course on the time and spatial scale on which we observe it.

A consequence of seeing material as dynamic is the production of a material history. Hysteresis is the technical term that describes the effect that the history of a system has on its current state, and thereby on how it will respond while in that state. Hysteresis is observed in physical materials: foam rubber is seen as storing a record of prior structural couplings with materials that compress its form, aluminum may fold once but fracture with a subsequent attempt to replicate the same fold. Hysteresis is explicitly engineered into electronic devices such as thermostats and Schmitt triggers. It is observed in biological systems (Darlington & others, 1937; Rieger, Michaelis, Green, & others, 1976) and in economic systems (Ball, 2009; Blanchard & Summers, 1986). Hysteresis can be seen as a general from of memory in material computational systems. It can also function in culturally poetic forms as is exemplified by Willie Nelson and his guitar named Trigger. Michael Hall (2012) writes,

> Most guitars don’t have names. This one, of course, does. Trigger has a voice and a personality, and he bears a striking resemblance to his owner. Willie’s face is lined with age and his body is bent with experience. He’s been battered by divorce, the IRS, his son Billy’s suicide, and the loss of close friends like Waylon Jennings, Johnny Cash, and his longtime bass player Bee Spears. In the past decade, Willie has had carpal tunnel surgery on his left hand, torn a rotator cuff,

> and ruptured a bicep. The man of flesh and bone has a lot in common with the guitar of wire and wood. (Hall, 2012)

The script from a recent guitar advertisement summarizes a perspective from a cultural point of observation of the effects of history on Willie's guitar. It reads, "It left the factory perfect 46 years ago. Then it got better. Willie Nelson's beloved Martin N-20" (C F Martin & Co, 2014).

For any system that is observed as dynamic, one may ask whether its dynamics are reversible. Reversibility is a further abstraction from that of temporality and still a product of observation, not, properly speaking, an aspect of a structurally determined system. Setting aside the obvious, and important questions about what it would truly mean for something to be reversible, reversibility, as we generally conceive and experience it, is interesting to imagine as defining aspect of material. For autopoetic systems, at least observed on a macro-time scale, reversibility does not seem like a possibility. Water undergoing state changes from solid, to liquid to gas is, at least when viewed at a macro-spatial scale is reversible. Are cultural systems reversible? Are belief systems reversible? If reversibility is considered as an absolute, binary system that either is, or is not, such questions are not very fruitful, but if reversibility is considered as a spectrum of possibilities that can be partial, then these and similar questions become far more interesting. Thought of in this way, one can ask, in what ways a system can be observed as reversible? These questions are beyond the scope of the dissertation, but I pose them to emphasize the generalizability of seeing systems as material.

Another important aspect of materiality is its homogeneity or heterogeneity. This aspect of material may be genuinely considered as a fundamental description of the system's instantaneous structure (Maturana, 2002), not merely an abstraction constructed by an observer, however it is only through the organization that results from this structure that this aspect of structure becomes relevant. Earlier in this chapter I called attention to the differences between the characteristics of wood, a natural element, and MDF, a technical element, emphasizing the relatively high isotropy of MDF and the anisotropy of natural wood. The significance of homogeneity and heterogeneity depends on the specific example considered and the examples that could be provided to illustrate this aspect of material are endless, however I see this significance manifesting itself in two distinct, but interrelated levels. It may be considered in terms of how it, as an aspect of the structure of a structurally determined system, affects the organization of that system within the boundaries of that system. Or it may be considered in terms of how this structural characteristic manifests itself through structural couplings with other structurally determined systems. From the point of observation of an external observer, structural couplings take place over a span of time and space. The structural inconsistencies, in the case of a heterogeneous structure, may result in varying energetic interactions with and corresponding varying structural changes in a coupled system. I offer two examples, both music related, that illustrate homogeneity and heterogeneity as an aspect of materiality, in intangible systems.

The first of these examples are energy signals, which may be sonically perceived. I argue that a simple sinusoidal wave may be seen as a homogeneous material. This waveform is, by definition, fully consistent and predictable. By contrast, a complex signal, perhaps of the same fundamental frequency as the sinusoidal wave, that includes additional repeating and non-repeating waves of various frequencies and shapes may be seen as a heterogeneous material. Homogeneous and heterogeneous signals both have practical and aesthetic utility for artistic and engineering applications.

I present musical culture as my second example of intangible systems seen as homogeneous or heterogeneous material. Musical culture may be considered at many levels, from the structure of individual musical compositions, to marketing categorizations, to historically observed transformations of social groups linked to musical genres. A serious analysis of musical culture at any of these levels would require additional dissertations, but I argue, without supporting evidence, that in all of these dimensions of musical culture, heterogeneity plays in important role in providing contrasts, richness and evolutionary vitality.

The next aspect of materiality I will discuss is symmetry or asymmetry of systems. Symmetry may be an instantaneous structural characteristic of a structurally determined system, or it may be a product of observation of a system. I've already emphasized the structural asymmetry of natural wood in contrast to the relative symmetry of synthetic technical elements such as MDF. I described the significance of wood grain shape and orientation in my description of building a guitar neck, noting the anisotropic permeability of wood. Anisotropy also clearly plays a role in Pye's (1968) prototypical example of self-jigging, a wood surface shaped with an adze (Pye, 1968, pp. 34–35). The structure of wood, its grain orientation being a critical component of this structure, dramatically affects how it will respond to structural couplings with a chisel or other similar cutting tool.

Anisotropy is a significant factor in many other systems as well. It is a fundamental characteristic of polarized light and the technologies used to generate and manipulate it (Huard, 1997). It is essential for the functioning of certain types of biomedical imaging technologies which exploit the anisotropic characteristics of biological structures and magnetic fields (Basser, Mattiello, & LeBihan, 1994). LaLonde et al. (2007) show that social systems may exhibit anisotropy in their studies of the effects of "social dominance orientation" on attitudes towards interracial dating and adoption (Lalonde et al., 2007). Anisotropy is exhibited in ecological systems. Bélisle (2005) observes,

> Polarized or anisotropic flows of individuals may not only result from different abundances of dispersers that depend on the structure of the landscape, but also from variations in the ease of movement along the different axes and directions of movement. (Bélisle, 2005, p. 1991)

Chirality emphasizes a particular characteristic of some asymmetrical systems. Chirality is sometimes expressed as handedness, in reference to the qualities of our hands having a left and right form. I considered achiral forms for *Vox Curio* to remove handedness of musicians as a variable for research studies, but elected to proceed with a chiral form that could be, with some effort and additional production of components, be transformed from right-handed to left-handed form. Chirality is a fundamental aspect of nature with many examples from physics, chemistry, biology and mathematics (Wikipedia, 2015a). I will highlight an example from my personal experience and another from mathematics to emphasize the potential for this aspect to play an important role in immaterial domains.

The importance of chirality became clear in my early teenage years when I was working as a bicycle mechanic (although I did not learn the term chirality till many years later). The pedals on a bike are chiral forms. Pedals come in pairs with left-handed threads on one pedal and right-handed threads on the other. This chirality is necessitated by the presence of mechanical friction generated when the rider presses down on the pedals. If the left-hand pedal did not have a left-handed thread, the friction in the pedal would generate a mechanical force as the pedal was pushed down and around in a circular arc that would eventually loosen and unthread the pedal. This effect is easier to imagine if one envisions a solid cylindrical shaft as the pedal rather than the traditional pedal with bearings, which lessen, but by themselves do not fully eliminate the problem. The technical term for this effect is precession (Wikipedia, 2014c).

Brandom (1996) underscores the chirality inherent in complex numbers, noting, "Frege reminds us in the passage about the geometrical interpretation of complex numbers quoted above, multiplication by the imaginary basis i and its complex conjugate -i correspond to counterclockwise and clockwise rotations, respectively" (Brandom, 1996, p. 305). I remind the reader again of what Wittgenstein (1953) had to say about the dawning of an aspect. He said, “what I perceive in the dawning of an aspect is not a property of the object, but an internal relation between it and other objects” (Wittgenstein, 1953, p. 212). “-i ” is understood in relation to “i”. Chirality is meaningless without reference to a mirror image object.

The next aspect of materiality that I will discuss is plasticity. To be clear, I am referring to plasticity as it is defined in physics and material science domains. I do not intend any reference to the “plastic arts.” Plasticity refers generically to the ease with which a material may be reshaped without breaking. The physics definition of plasticity is more complex and far richer, emphasizing that “the physical mechanisms that cause plastic deformation can vary widely" (Wikipedia, 2015g). In my practice as a sculptor, understanding the relative plasticity of materials, and how to permanently or temporarily modify a material to change its plasticity, is essential for many operations. The example of bending wood that I detailed earlier in this chapter is a perfect example of this aspect of materiality. As a general principle, the concept of plasticity invites the question of: what conforms to what? The mode of conformance may not always be, in technical terms, a plastic deformation, but I find the general notion of a relative hardness and softness of a system and the consequences of this difference in their potential structural coupling a useful way of seeing systems. Simondon's use of the phrase "margin of indetermination" (Simondon, 1958, pp. 4–5, 24, 88) implies something akin to a plasticity or degree of conformance. This suggests a way of seeing concretization as a process of reducing plasticity of a system.

Tangibility is an aspect of materiality that is seemingly essential to haptic systems. I introduce tangibility as an aspect of materiality with the implied question of whether tangibility is essential for a haptic experience. I raise this question as a way of revisiting essential properties of structurally determined systems, the properties of being organizationally closed and interactionally open (Maturana, 2002; Varela & Goguen, 1978). I see our human experiences of interacting with physical, tangible objects as an example of structural coupling, and see the energetic exchanges from this structural coupling as modifying our structure. We learn how to interact with tangible objects and our haptic sensorimotor systems evolve. In the Background chapter of this dissertation I present many examples of haptic illusions and discuss the sensory fusion of multimodal information. These examples provide evidence that a haptic sensation is not essentially dependent on the structure of the object one interacts with; it is instead dependent on the structure of the person experiencing the sensation. This way of seeing tangibility has implications for several of the most interesting questions that have emerged from this research. These include: How soft can the boundaries of structurally determined systems be? What happens in the gradient areas of such systems? Is code material? Does self-jigging occur in non-physical media?

The final aspect of materiality that I present is autopoeticity. Simply stated, a material that is autopoetic is alive (Maturana & Varela, 1980; Maturana, 2002). Maturana recognized people's adoption of autopoiesis to describe social and other non-biological systems, but continues to argue that only living biological systems are truly autopoetic (Maturana, 2002). Living matter comes with a host of ethical, social, emotional, health, energetic and environmental concerns on top of any more basic physical engineering issues. As Marder (2013) points out however, these concerns are clearly on a sliding scale depending on the nature and perceived level of cognitive function of the living system in question (Marder, 2013). Autopoetic materials, in spite of the potential concerns with their use, offer characteristics that no non-living systems can match. They excel in self-assembly and self-organization (these attributes define them) and cognition is a result of this organization (Maturana & Varela, 1980; Maturana, 2002). Living systems inspire, among other things, materials, robots and artificial intelligence systems. Simondon (1958) identifies natural objects as the only purely concreted objects, objects not divided against themselves. In this respect, autopoiesis is the gold standard of aspects of materiality.

It is fitting that I end this chapter, and the main body of this dissertation where it began, with a consideration of living systems and what it is that makes a living system a living system (Maturana & Varela, 1980; Maturana, 2002). This chapter presented a view of technical objects, seen as structurally determined systems, from the perspective of their modes of determination. I considered the role and presence of the human in the technical ensemble and the characterization of modes of production as either industrial or artisanal. I discussed attributes of both of these modes of production and suggested ways in which they complement and merge with one another. I argued that making is a form of structural coupling, discussed material computation, and presented examples from my personal material studio practice to illustrate these points and illuminate other theories presented in this document. I outlined a theory of conceptual plurifunctionality and concluded with a presentation of aspects of materiality, showing how these aspects may reveal attributes of a wide range of material and immaterial systems.

CHAPTER 7

CONCLUSION

In this dissertation project, which I identify as a ‘paradigm construction project’, I asked as my primary research question: How is structure seen as determining the organization of systems, and making seen as a process in which the resulting structures of technical objects and the maker are co-determined? My secondary question was: How might an understanding of structure and organization be applied to the invention of contemporary experiential media systems? I identified a series of questions that emerged from these primary questions. I will address each of these questions individually in this chapter.

Maturana’s (2002), in his work on the theory of autopoiesis, defines systems as structurally determined. This definition poses the question I frame as: How does structure determine the organization of a system? Maturana’s answer to this question is complex and nuanced, but the essential definition is primarily rooted in the second question I pose: Is the organization of a system maintained when the structure of that system changes? According to Maturana’s definitions, the structure of a system may continuously change, with energy and matter coming and going from the system. These structural changes may occur such that the organization of the system is maintained or destroyed. It is the organization of the system, determined at every instant by the structure of the system that defines the class and bounds of the system. Maturana defines structurally determined systems as organizationally closed (Maturana, 2002). This leads to the next question: How can organizationally closed systems interact with systems external to themselves? As already stated, structurally determined systems are open to energetic and material exchanges, but these exchanges only occur as a result of the instantaneous structure of the system and the instantaneous structure of a system it is observed to interact with. The process by which this occurs is defined by Maturana as structural coupling (Maturana, 2002).

Maturana's (2002) theories, briefly summarized above, represent a paradigm, a useful paradigm, but only one of manifold possibilities. On my first reading of Maturana, my paradigm as a maker of physical-digital systems shaped my perception of his theories. I contemplated the systems of my own creation as structurally determined but recognized that Maturana's theories were based in biology, not in non-biological or technical systems. I turned to Simondon (1958) for a perspective on the technical and saw parallels in his theories with those of Maturana, and concluded that I could see technical objects as structurally determined as defined by Maturana. This led to a question that is addressed by Simondon: Can technical objects be seen as natural objects? Simondon defines technical elements, individuals and ensembles with reference to natural elements, individuals and ensembles, but does not see technical objects as natural objects (Simondon, 1958).

Simondon (1958) answers the question: How can technical objects be seen in terms of their evolution? He defines technical objects, not with respect to their characteristic attributes or functions, but in terms of their evolutionary genesis. Specifically he looks at this evolution in terms of what he calls, concretization or abstraction. Concretization is a unification of the system; abstraction implies a division within the system. Simondon claims that only natural objects are purely concrete (Simondon, 1958).

I identified, in Simondon’s (1958) writing, a concept that helped me see a mechanism by which the information exchange through structural coupling (Maturana, 2002) could be understood. Simondon proposed a “margin of indetermination” in technical objects and claimed, “It is such a margin that allows for the machine's sensitivity to outside information” (Simondon, 1958, p. 4). This suggests the question: How can margins of indetermination in structurally determined systems be seen as opportunities for information transfer? I argued that this was a general way of seeing variables and constraints in systems. I also presented an extended literary comparison of Reddy’s (1979) linguistic framings of information transfer and Simondon’s theories, concluding that Reddy’s toolmaker’s paradigm was consistent with Simondon’s and Maturana’s conceptions of information transfer (Maturana, 2002; Reddy, 1979; Simondon, 1958).

The topics represented in the previously addressed questions set the stage for the subsequent questions, which more fully represent my paradigm as a maker. I begin by asking: How can making be seen as a structural coupling between a maker, her tools and her media? I argue that each of the component systems in this relationship, as well as all those connected systems ignored in this simplified presentation of this relationship, can all be seen as structurally determined, as such any interactions between these systems must, by Maturana’s (Maturana, 2002) definition, be through structural coupling. My next question focuses on what I see as the most important ramification of this structural coupling between the maker, her tools and her media. That question is: How does making result in a co-determination of the structure of the maker and the technical object produced? This question is a major part of what I identify as my primary research question. Maturana provides a basic answer to this question in his definition of structural coupling. He says,

> As a consequence, in this process the structure of the living system and the structure of the medium change together congruently as a matter of course, and the general result is that the history of interactions between two or more structure determined systems becomes a history of spontaneous recursive structural changes in which all the participant systems change together congruently until they separate or disintegrate. (Maturana, 2002, p. 16)

As I describe in Chapter 6 in the section entitled *Seeing making as structural coupling*, for the maker, the structural changes they undergo may be described as learning. I describe in the section *Self-jigging*, in the same chapter, the result that structural changes to the material may have on the subsequent structural coupling of maker, tool and material. The learning that the maker may experience leads to the next question: How can a maker know their material?

I argue that a maker comes to know their material through their structural coupling with that material and with similar materials. I also argue that these making experiences prepare the maker to construct more significant information from indirect sources of knowledge about a making process such as listening to a description or watching a video of someone else engaging in the same process. I claim that what a maker comes to know is not merely how to modify the structure of a technical object. The maker, in Simondon's terms, develops a "sensitiveness to the technicality of elements" (Simondon, 1958, p. 87); they can be seen as understanding the organization of the system (Maturana, 2002).

If a maker can be said to know their material, as I have argued they can, we can ask: How can structure and organization be employed as material computation? In the section in Chapter 6 entitled *Material computation*, I claim that fundamentally, digital computational systems are no different than any other computational systems; they are simply constrained, through concretization, to binary states that enable the systems to function as symbolic processing systems. I argue that material computational systems can take advantage of attributes such as hysteresis and bounce that are engineered out of digital systems. I claim that modifying the structure of materials may be seen as a form of programming because it results in a changed response to a subsequent structural coupling.

I address at length the question: How can making and invention be seen as either industrial or artisanal modes of production? I describe Simondon's (1958) view of the artisanal mode of production as abstracting and the industrial mode as concretizing. I present evidence that a contemporary small group or individual studio, which would traditionally be seen as artisanal, provides the maker access to many tools that represent high levels of concretization and allow the worker to evolve system in a manner consistent with Simondon's view of the industrial mode of production (Simondon, 1958). This fact suggests an answer to my next question: Are distinctions between modes of production still valid? I do not directly answer this question in this dissertation, but suggest that such divisions are certainly less clearly bounded than they may have been in earlier times.

I argue that the important question to ask on the subject of modes of production is: In what ways do these modes of production inform and complement one another? I already emphasized the concretization that the industrial mode of production has brought to the artisanal studio. I offer Pye's (1968) theories on the 'workmanship of risk' as an important way in which the practices of the artisanal studio may positively impact the industrial mode of production.

In the context of this consideration of material practice, I ask: How can my material practice illustrate and reveal the theoretical constructs and philosophical basis of this dissertation? I present detailed descriptions of several stages of my production of my *Vox Curio* instrument. In these descriptions I explain the structures of the materials with which I am working and the organization that these structures produce. I describe why I define the relations between structures in the way that I do to achieve a desired structural coupling between technical elements. I also describe my structural coupling with these materials and explain how my structure is modified in these couplings and how these changes may be seen as learning.

From my point of observation as an artist, I see a potential extension to Simondon's (1958) theory of concretization through plurivalence or plurifunctionality. This potential is expressed in my question: Can conceptual function be considered alongside physical function as an integral part of a structurally determined system? I conclude, in the section entitled *Conceptual Plurifunctionality* that such an extension to Simondon's theory is valid but must be considered as a construction by the observer, dependent on their structure and the dynamic culturally defined meaning of the material or form that is considered from a conceptual, aesthetic or artistic perspective. I argue that conceptual plurifunctionality may enhance invention by suggesting non-obvious alternatives to problems.

Chapter 6 of this dissertation concludes with a discussion that addresses the question: How can aspects of materiality shape the paradigms through which immaterial systems are viewed? In this section I present descriptions of aspects of materiality, many of which emerged through my descriptions of my material practice. I offer examples of how these aspects of materiality inform a wide range of applied and theoretical domains of knowledge and practice. I state that this categorization of aspects of materiality represents a static snapshot of a singular point of observation, and is not presented as a formal framework. I again remind the reader that I have approached this research as a 'paradigm construction project' in the spirit of Wittgenstein's (1953) philosophical concepts of the 'dawning of an aspect' and 'seeing it as' (Wittgenstein, 1953). This philosophical paradigm is embedded in both the theory and the language of this dissertation.

A practical takeaway for experiential media system designers from my synthesis of theories and philosophies is the paradigm that when we create systems, it is the organization or technicality that through structural coupling, results in what we observe as functionality, but it is only the structure of systems that we can modify, therefore we should not focus on either structure or organization independently, but see them as a mutually dependent unity. I emphasize the intelligent selection of traditional and material computational solutions and remind makers of the potential advantages of natural elements, individuals and ensemble in addition to their technical brethren.

The bounds of my paradigm construction project do not stop at the boundaries of this document, but include the wide range of experiential media systems and technical elements that I produced throughout my career in the School of Arts, Media and

Engineering. I argue that these projects can be seen as an embodiment of my knowledge and my evolving paradigm. Each physical object, max patch and electronic circuit is a tangible record of a structural coupling I had with this media. Retracing their history would reveal my paradigm in various stages of construction, and perhaps, deconstruction. The making of these systems can be seen as changing my structure as a human individual, and providing the foundation for my reading and understanding of the theory and philosophy that I reference in this dissertation. On a practical level, these systems serve as research instruments for AME, Synthesis Center, Topological Media Lab, and a growing community of researchers.

When I described my abductive research methodology, I emphasized that the end result of abductive logic was a conclusion that was probable based on the evidence presented, and that this conclusion should be seen as a question to investigate, not a definitive answer to a question. The abductive logical structure seems absurd with simple examples like Peirce's bags of white beans, but it is perfectly appropriate and practical when the domain is complex and no single answer is expected. I generated questions through the application of this research methodology that I could not have postulated at the outset of this process. These questions include:

How soft can the boundaries of structurally determined systems be?

What happens in the gradient areas of such systems?

Is code material?

Does self-jigging occur in non-physical media?

Does structural determinism equate to a clockwork universe, or preclude free will?

Can Simondon’s theory of plurivalence be expanded to include conceptual, aesthetic and artistic functionality?

I present an informal discussion of some of these questions in Appendix A of this document.

Final Thoughts/Next Action

Many stimulating questions are raised by the modes of seeing that I present in this document. At the heart of the most compelling of these is what many consider to be Simondon’s main philosophical topic: the process of individuation (Simondon, 1964/1992, 1964/2005). When and how does something become an individual? What does it mean for something to be an individual? These questions promise to transition from pure philosophy, to practical concerns when we look at advances in robotics, prosthetics, augmented reality, artificial intelligence, wearable and implanted technology, and other rapidly evolving fields of study. Regardless of what one may think of his theories, it is difficult to deny that Raymond Kurzweil (2005) is on track with his use of the term ‘singularity’ to identify the essence of a real and significant technical and cultural process. Without significant study of Kurzweil’s theory, I can only speculate, but my instinct suggest that where his theory goes awry, and why it is often criticized, is that it ignores what Simondon (1958) labels the “law of relaxation”. Simondon believes that technical individuals and ensembles come and go, and that it is the technical elements that ultimately persist and continue the evolutionary process (Simondon, 1958, pp. 75–76). But this debate is an aside from my main point, that being, that the theory of individuation has much to tell us about our emerging reality.

I am particularly interested in the question of individuation as it applies to what are now frequently called digital-physical systems, or physical-computing systems. The hyphenated names suggest a conjunction, but in practice this conjunction is typically juxtaposition, not fusion. Synthesizing physical systems with computational systems in a manner consistent with Simondon's (1958) philosophical principles of concretization and individuation presents significant challenges, but challenges with significant promise. This philosophy, applied as a design methodology, runs in opposition to the current vogue of absolute universality and modularity (as typified in our smart phones with an app for every application). Concrete and individual physical-computing systems would be profoundly individualized in their purpose. Their structure would define their organization; plurifunctionality would be a guiding design specification; material computation would be their essence.

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APPENDIX A

OPEN QUESTIONS

In this appendix, I highlight some of the implications and big questions that emerge from this research. I submit these, not as well-structured propositions, but as freeform presentations of exciting research directions. I emphasize that these are unformed possibilities for future practical and philosophical investigation, not fully formed hypotheses stemming directly from my conclusions.

Is code material?

If code, by which I mean the symbolic language that exercises the affordances of computer hardware, is considered as a material, it should be subject to the same structurally determined mechanics as any other objects.

I answerer this question with an equivocation: I'm not confident that defining code as material allows a complete description of its nature. I'm not even sure a completeness of definition is possible. Seeing code as material is only one of many ways to see it and each way may reveal opportunities and attributes that are masked with others. That said, I don't find any logical inconsistency that would preclude identifying code as material. The obvious question is "What is material", or more to the point, "What do we see as material?" Does materiality imply tangibility? Can we touch it? Is oxygen a material? We may not be able to feel it as we feel the bark on a tree, but deprive us of it and we will quickly miss its material presence. Do we need to see material? Obviously we could use the same oxygen example to refute this requirement, but we may get smart and jump straight past the limitations of direct human perceptibility in forming our definition of material. If we exploit the full complement of scientific instruments to identify matter at every scale of physical and temporal dimension, at some point, matter itself disappears. Poof! It's gone! At this point I'm pushing past the limits of my understanding of theoretical physics, but it seems that we are left with probability fields and other mysterious phenomena that don't seem much like material in our everyday experience and understanding of it. If what we thought was material turns out to be nothing more than a particular composition of energy and probability, perhaps everything and nothing is material. In either case, the playing field is fairly level for what can be defined as material.

Stepping back a few steps in the line of reasoning, I point to a primary example of a technical object from Simondon's 'Mode of Existence of Technical Objects'. He used the electronic tube as an example of the concretization that happens through the convergence of functions in material structures. (Simondon, Du Mode, pg. 22) His description of the changing structural configurations and the additions of various anode-grid components are all emphasizing clearly material components. However for any of these components to have any meaning, an electrical current, a flow, or potential flow, of electrons, must be present. The electricity in a tube is every bit as material (or immaterial if you prefer) as that in the vast majority of our computing devices. The fact that we constrain, with great effort, the electrical energy to what we call off or on states doesn't change this in the least. It doesn't matter whether our code is ultimately instantiated and interacts through electricity, light, air pressure, or any other means of representation, if we accept Simondon's example as a technical object, we should accept code on equal terms.

Let us look at the question from another perspective. What if we assume that code doesn't have anything to do with its physical format, but instead is defined by the ideas that are symbolically represented? Lets also assume that the symbolic representation is arbitrary and can be discounted as part of the definition of code. If we are left with the ideas "contained" in the code as its essence, then we should now as what the idea is. If an idea requires a cognizing agent to generate it, then we must inquire about the nature of agent. We could take Braitenberg's (1986) theoretical journey of building artificial brains as an imagining of such possible agents. Or we could assume an immaterial cognizing agent, but this seems to lead to an endless recursion problem. Even if we only require an organization of energy to constitute the information of code, this constitution on some level, feels analogous to material.

The most compelling argument I can make at the moment in support of the proposition that code is material, is to reframe the question and ask: is code a structure determined system? I intend Maturana's definition of a structurally determined system (Maturana, 2002, pg. 5-6) as I pose this question. I suggest that his definition of a structure determined system is a very reasonable definition for material. Specifically I'm referring to his concept of "organizational closure", the idea that the dynamic relations within a system define the "operational boundaries" of the system (Maturana, 2002, pg. 14-15). Seeing code as a structurally determined system that is defined by its operational boundaries, we dismiss concerns about its representational format (whether we think of it in terms of a semantic structure, or as an electrical pattern, etc.). Its structure remains essential, for this is what determines, at every instant, its organizational dynamics, but, as Maturana argues, its structure can change, while its "organization is conserved" (Maturana, 2002, pg. 16).

My interest, finally, is pragmatic. I argue that seeing code as material may be useful. The utility of this perspective may include: discovering that we've only been using one type of material-code, identifying material properties in the material-code that we've overlooked or suppressed up to this point, discovering material combinations and alloys through the conjoining of varying types of material-code, and realizing the potential of a synthesis of material-code and physical material.

These suggested utilitarian functions of seeing code as material are fundamentally conceptual exercises. They invite new ways of thinking about code, but not merely from the perspective of generating more creative algorithms and frameworks with existing forms of code. They invite seeing the structure of code and its representational forms differently. For example, identifying different code-materials may suggest revisiting continuous, rather than discrete state systems of representation and logic. Suppressed material properties may include bouncing and hysteresis. We do sometimes "compress our code" and say, for example, that "my operating system froze." What would it mean for an operating system to boil, become saturated, to undergo a change of elastic modulus?

If we want to look for opportunities to develop material-code, in Simondon's terms, to increase its concretization, we need only look at all the existing abstract elements required to support the desired functionality of our existing code. In other words, look at the systems that are put in place to insure the viability of code that represent compromises, situations where you have to accept negative side effects of these life-support systems to enjoy their benefits. Our existing code is viable, but from the perspective of a highly evolved concrete object, just barely so. If we could start to find multiple structures in code that currently each fulfill only an individual function (which in many cases will only be to help maintain the viability of another part of the code) and find ways of merging these functional requirements into individual structural elements, we would be on our way to one of the fundamental characteristics of concrete objects, the presence of plurivalent or plurifunctional structures.

Does self-jigging occur in non-physical media?

The notion is simple enough; a system of structural coupling, once initiated more readily follows a trajectory of structural change that is established through this initiation, as a result of structural changes that occur in either or both systems. I can imagine coding a system that would simulate this, but am not sure it would match the definition I just spelled out (which may need refinement). More thought will be required on this one. Ideally an answer would not propose a system to be created to conform to these rules, but rather explain how an existing system is already such an example.

My advisors suggested interesting ways of seeing this question, suggesting auto-calibration and feedback loops as potential instances of self-jigging in non-physical media.

Does structural determinism equate to a clockwork universe?

From a practical standpoint, this is certainly not something we would directly perceive or be able to test, but more importantly, I also don't believe it theoretically follows if we accept the Heisenberg's uncertainty principle.

More interesting to me than a theoretical debate, on either physical or philosophical grounds, about the possibility of a clockwork universe existing as a consequence of structurally determined systems, is the role uncertainty is said to play in these very systems. Simondon identifies margins of indetermination as the enabling characteristic that allows for "sensitivity to outside information" (Simondon, 1958, p. 4).

In other words, we don't have to worry about the consequences of absolute structural determinism, because any fully structurally determined objects would exist as an anomaly. It would face a lonely existence, isolated completely from the environment in which it existed. Whether such an object could in some way exert change on its environment is an interesting question, but, if we accept Simondon's argument, and take it to the extreme, this object would not be able to be affected in any way by its environment. An object of this nature is more mysterious and thought provoking to me than a clockwork universe, in which everything interacts predictably, but at least interacts.