Material-based Design Computation

By
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ABSTRACT

The institutionalized separation between form, structure and material, deeply embedded in modernist design theory, paralleled by a methodological partitioning between modeling, analysis and fabrication, resulted in geometric-driven form generation. Such prioritization of form over material was carried into the development and design logic of CAD. Today, under the imperatives and growing recognition of the failures and environmental liabilities of this approach, modern design culture is experiencing a shift to material aware design.

Inspired by Nature's strategies where form generation is driven by maximal performance with minimal resources through local material property variation, the research reviews, proposes and develops models and processes for a material-based approach in computationally enabled form-generation.

Material-based Design Computation is developed and proposed as a set of computational strategies supporting the integration of form, material and structure by incorporating physical form-finding strategies with digital analysis and fabrication. In this approach, material precedes shape, and it is the structuring of material properties as a function of structural and environmental performance that generates design form. The thesis proposes a unique approach to computationally-enabled form-finding procedures, and experimentally investigates how such processes contribute to novel ways of creating, distributing and depositing material forms.

Variable Property Design is investigated as a theoretical and technical framework by which to model, analyze and fabricate objects with graduated properties designed to correspond to multiple and continuously varied functional constraints. The following methods were developed as the enabling mechanisms of Material Computation: *Tiling Behavior & Digital Anisotropy*, *Finite Element Synthesis*, and *Material Pixels*. In order to implement this approach as a fabrication process, a novel fabrication technology, termed *Variable Property Rapid Prototyping* has been developed, designed and patented.

Among the potential contributions is the achievement of a high degree of customization through material heterogeneity as compared to conventional design of components and assemblies. Experimental designs employing suggested theoretical and technical frameworks, methods and techniques are presented, discussed and demonstrated. They support product customization, rapid augmentation and variable property fabrication. Developed as approximations of natural formation processes, these design experiments demonstrate the contribution and the potential future of a new design and research field.

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Acknowledgements

To *imagine* is perhaps the most significant aspect of an architect's creative agenda. Much built work and many design artifacts occupy our environment but few stir and shuffle the domains of knowledge in a way so fundamental to cultural reorientation. Without imagination, innovation cannot be nurtured. I would first like to thank my thesis adviser and mentor, Prof. Bill Mitchell, who taught me that what is not surrounded by uncertainty, cannot be genuine and true; who encouraged me to take risk in defining my search as I question the preconceptions of an era. Thank you, Bill, for guiding me in a journey so charged with curiosity, and thank you for your consistently insightful input.

My thesis committee also included Prof. Lorna Gibson and Prof. Woodie Flowers from MIT. To them I owe the recognition of stepping with courage and grace inside my mind and helping direct my search for the origin of form from the point of view of their own respective disciplines. Lorna: I thank you for your patience and perseverance with my task to appropriate and implement concepts and methods from the physical sciences to the domain of digital design. You have provided me with scientific grounding coupled with a legitimacy to dream up my design ambitions; to me, you shall always remain a precious colleague and a dear friend. Woodie: you are a force of nature. I thank you for your unqualified support of the creative aspects in my search, and for recognizing the value of design and engineering research as an art form. With faith, you have shaped my thinking and given me courage to take risks driven by curiosity and curiosity alone.

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her friendship during the years that I have spent as a group member. Other faculty to whom I am in debt for creative and intellectual stimulus include Prof. Dennis Shelden, who was one of the very first faculty members in the department to present me with the mathematical foundations which later helped inspire a material-based approach to design vis-à-vis the "formalist project" so engrained in contemporary practice. Dennis, your lectures and works in the field of computational geometry have had an invaluable impact on my thinking, and I look forward, with enthusiasm, to future collaboration. I would also like to thank Prof. Larry Sass for his support and encouragement with regard to the experimental mentality which I have implemented in my work, and more specifically, its implications on the domain of digital fabrication and construction. Thank you also to Prof. Edith Ackerman with whom I have shared many engaging discussions in various contexts, and who has constantly questioned the cultural and humane significance of the production of artifacts.

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To Bill

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CHAPTER 1

NOTES ON THE SYNTHESIS OF MATERIAL FORM
An Introduction

> *"I believe in God, only I spell it Nature."*
> **– Frank Lloyd Wright**

> *"Buildings, too, are children of Earth and Sun."*
> **– Frank Lloyd Wright**

1.1 The Crisis of Form

Over the long trajectory of architectural design history, the design and production of artifacts has been characterized by the growing separation of form-making from its natural foundations in material conditions. In contradistinction to *craft production* (Sennett 2008) in which material and form are naturally intertwined into a tradition of making, modern design and production have historically evolved away from this integration towards the compartmentalization of form-making as a process independent of its sources in material knowledge. At least since the Renaissance, with the emergence of architectural theories, form-making, as the production of form inspired by theory, has become an autonomous body of knowledge. Within architecture and industrial design, the most culturally sensitive of the productive design fields, form has grown in both eminence and temporal precedence in the design process to the point that the condition of *form preceding materialization* has become normative and virtually intuitive in contemporary design culture. With the exception of few pioneering cases in contemporary design, the secularization and debasement of the material realm has become axiomatic. Materiality is, within the logic of the modernist tradition, an agency secondary to form.

The Industrial Revolution laid open the door to machine-based manufacturing and mass production. The creation of form was now to be conceived and created by the power of industrial automation; functionality took over as the leading standard and the principal ontology (Jencks 1984). Form was to *follow* function and ornament, so endemic to craft culture, became crime (Frampton and Futagawa 1980). The values promoted by ancient crafts, pronounced by the integration of material substance and construction methods, once within the province of the craftsman, were abandoned while in their place emerged a design practice based on values of mass production. Fast, cheap, repetitive and modular building types and parts were synonymous with Ford's visionary dream. Industry's victory aside, it seemed as if design's propinquity to ancient crafts and its design expressions as portrayed by vernacular forms of design was now doomed lost; and with it the intimate context of material technologies. Eventually, this non-material approach to the design and the automation of construction were to be reinforced under the command of computer aided design.

The digital revolution, which marked the change from analog to digital technology, has transformed the designer's drafting board into a digital canvas. Form, it seemed, was now divorced completely from the physical reality of its manifestation. Granted, these new design spaces afforded much liberation in terms of formal expression, but it has also broadened the gap between form and matter and made the hierarchical and sequential separation of modeling, analysis and fabrication processes infinitely more pronounced.

The implementation and broad absorption of enhanced computational design tools in architectural practice has, since the early nineties, motivated a renaissance of the *formalist project* in architecture; geometrically complex shapes became emblems of creativity in digital design environments and supported the design mastery of complex geometries in form generation. This formal and geometric design orientation has also addressed "free form" design and architecture along with their enabling technologies as part of the larger design phenomenon of the "mass customization" of "non-standard" form.

Today, perhaps under the imperatives of the growing recognition of the ecological failures of modern design, design culture is witnessing a *new materiality*. Within the last decade in both industrial design and architecture, a new body of knowledge is emerging through various industrial and academic research initiatives (Mitchell and McCullough 1991; Mitchell 2001; Shelden and Massachusetts Institute of Technology. Dept. of Architecture. 2002). Examples of the growing interest in the technological potential of innovative material usage and material innovation as a source of design generation are developments in biomaterials, mediated and responsive materials, as well as composite materials (McQuaid, Beesley et al. 2005). With the growing relevance of hybridized and mediated materialization, new frontiers of material science as a design science are supporting the emergence of new perspectives in architectural and industrial design. Thus the role of digital design research as the enabling environment of the transformation to a new age of material-based design in various design disciplines has become the cutting edge of computational design research. Here we are at the cusp of the emergence of a new field of research at the interaction of Materials Science & Engineering and Design Computation: *Material-based Design Computation*.

Accompanying the rise of what might be termed a *new materiality* as a phenomenon of the interactions between contemporary developments in scientific, technological and industrial design culture has been the recognition of the relevance of a unique body of precedents. New research into the forgotten pioneers of what is termed *form-finding processes*, that is, the exploitation of material properties and behavior as a source of form-generation in the pre-digital era (Otto, Glaeser et al. 1972; Otto, Herzog et al. 1990; Otto and Rasch 1995; Otto, Nerdinger et al. 2005), are now found to be of growing relevance. Processes in developmental biology and morphology, particularly in the areas of material characterizations of developmental processes, are studied as sources of principles for the design of innovative material structures (Thom 1975; Ruse and Hull 1989; Paton 1992; Goodwin 1994; Kauffman 2000; Kumar and Bentley 2003; Forbes 2004; Bar-Cohen 2006). More specifically, the notion of mimicking natural structures in the synthesis of new materials and processes has generated enormous interest in both the scientific and design communities. As this network of knowledge sources and resources develops, a new material sensibility in product and building scale is becoming crystallized and formulated. This new design sensibility carries with it certain potential ecological repercussions and intrinsic values that may be of significance in any future implementations of Material-based Design Computation.

Material-based Design Computation attempts to inculcate material properties and environmental conditions within the computational form-generation processes of design. The following, *Notes on the Synthesis of Material Form*, outlines the evolution of the scientific and research rationale of this thesis as well as the components, methods and results of its research. As a means of integrating precedents from diverse fields into a new unified field of design research, the exposition of the research rationale is divided into a multi-chapter structure. It is, perhaps, the *troika* structure of its theoretical resources which enlightens the proposal of Material-based Design Computation as a new research field:

Material-based Design Computation attempts to inculcate material properties and environmental conditions within the computational form-generation processes of design. The following, Notes on the Synthesis of Material Form, outlines the evolution of the scientific and research rationale of this thesis as well as the components, methods and results of its research. As a means of integrating precedents from diverse fields into a new unified field of design research, the exposition of the research rationale is divided into a multi-chapter structure. It is, perhaps, the troika structure of its theoretical resources which enlightens the proposal of Material-based Design Computation as a new research field:

- *Nature's Way*, or *Natural Design*, is seen through the perspectives of morphology Biomimetics. Both of these fields elucidate Nature's processes of design as design principles and morphological knowledge which are relevant to the generation of material form;
- *Material Science & Engineering* offers precedents and formalisms for the description of material form and structure. Such precedents, their descriptive formalisms, and their scientific exactitude provide the foundations for certain of the methods which are required for material-based computational processes;
- *Design Computation* provides models of computation and formalisms of computational representation that can be employed in the research in order to integrate analytical procedures with form generative processes to achieve an approach to design that incorporates material properties as a potential driver of form-generative processes.

The unique integration of these three bodies of scientific and design knowledge contributes to the development of the new field of Material-based Design Computation. They constitute the theoretical foundations and the methodological resources of the research which is explicated in Chapters 2, 3, and 4. In proposing an alternative approach to form generation in design, in general, and to architectural and industrial design form generation, in particular, and in demonstrating the potential for a profound transformation of content and methods in design computation, the research assumes as background certain of the core problems of design in an age of mediated technologies.

Axiomatic to the awesome proportions of this problem statement are, of course, the reciprocal advantages of the potential effects of this work. In recognizing and repeatedly referring in these pages to the phenomena of "a crisis of form" in architecture and design, the alternative culture of this work promotes *natural design* and the *new materiality* as one potential antidote to the "crisis of human environment". The potential ecological significance of this work is profound in its willingness to address certain of the root pathological conditions of the culture of waste by reconsidering the role of materials in design generation and production.

1.1.1 Organization and Structure of Thesis

The thesis is structured in 9 chapters. Following Chapter 1, Chapters 2, 3 and 4, provide for background concepts and ideas from the fields of Biology, Material Science & Engineering, and Design Computation respectively. Combined, these three chapters make up the background segment of the thesis, laying theoretical and technical foundations that appear to be useful and significant in support of its arguments. More specifically, Chapter 2 (entitled: *Nature's Way: Material Form and the Structuring of Difference*) provides a *general approach* to the thesis by considering the relation between form and matter in Nature as a model for design generation that is potentially more sustainable than conventional design processes of form-generation and production. Considering natural formation processes relevant to the thesis, this chapter reviews: the hierarchical structure and heterogeneity of properties of biological materials; growth response of biological materials to loading; and the role of anisotropy in biological materials. In Chapter 3 (entitled: *The New Materiality: Sources and Development of a Design Cultural Phenomenon*) approaches inspired by Nature pointing towards the potential integration between form and material in design are presented, and instrumental definitions from the domains of material science & engineering are given. Here, engineering materials are considered vis-á-vis *Nature's Way* as the potential substance to be recomposed and reformed according to principles and methods presented in the previous chapter. The review of engineering materials includes: cellular solids and composites; tiling; functionally graded materials; engineering shape optimization analysis; finite element analysis and biomimicking. Chapter 4 (entitled: *Design Computation: Digital Engines for the Structuring of Matter*) provides the technical means by which to consider, conceptualize and implement a new approach to design computation supporting the integration of physical properties within a form-generation environment. The aim here is to review state-of-the-art computational tools, techniques and technologies that carry the potential to support a new approach to design.

Chapters 5 through 8 provide the core chapters of the research description: they represent the body of knowledge and experimental frameworks associated with a new design approach entitled *Material-based Design Computation*. Chapter 5 (entitled: Design Computation: Digital Engines for the Structuring of Matter) lays out the theoretical and technical foundations for the approach, directly followed by Chapter 6 (entitled: *Material-based Design Computation: Methodological Frameworks*) which presents the methodological frameworks designed to explore some of the issues and questions raised in the previous chapter. Chapter 7 (entitled: *Natural Artifice: Experiments in Material-based Design Computation*) presents the collection of design experiments, design products and design tools demonstrating the approach of *Material-based Design Computation*. The designs and implementations presented demonstrate some of the ideas put forth in the earlier chapters of the thesis, especially the notion of material property and thickness variation within form-generation processes. Chapter 8 (entitled: *Natural Fabrication: Variable Property Rapid Prototyping Technology*) presents a novel technology, designed, developed, and patented to support the theoretical and technical ideas explored through the experiments. It describes a novel rapid prototyping machine allowing the deposition of material with continuous property variation coupled with improved control of material properties over a single fabrication. Chapter 9 (entitled: *Contributions: Material Computation: the Foundation of Material Ecology*) presents the conclusions, contributions and limitations of the thesis.

Combined, the thesis is comprised of three background chapters following the introduction (Ch. 2, 3, 4), four chapters devoted to *Material-based Design Computation* (Ch. 5, 6, 7, 8), and a concluding chapter(Ch. 9).

1.1.2 Organization and Structure of Introduction

The following introductory sections are organized according to the structure of this thesis; each section represents one out of the nine chapters that make up this work. Each section carries the title of its respective chapter and within it, a short summary.

1.2 Nature's Way: Material Form and the Structuring of Difference

Chapter 2 is set out as an explication of the intimate relation between material, structure and form in Nature, and ways by which such integration is achieved. Principles of natural form as a function of performance are reviewed and considered as potentially providing design guidelines. The main assertion is that in Nature, material is *heterogeneously* distributed to fit its structural and/or environmental performance, and that such structural heterogeneity (also termed *difference*, or *differentiation*) is made possible due to the integration between form, structure and material (Figure 1.1). Two case studies focusing on trees and bones, and representing classes of fiber-structures and cellular solids are reviewed, and related instrumental definitions are presented and discussed. The remodeling of bone tissue as it responds to functional demands of mechanical loading is presented alongside similar processes observed in a fully functioning wood tissue.

The advantages of material distribution and structural heterogeneity as observed in Nature are discussed and proposed as an alternative strategy to conventionalized design processes of form-making. This strategy stands in contrast to the current state of design of homogeneous components from lower level assemblies where a singular material lacking variation in thickness or proerty, is assigned to a given shape. Finally, some design dichotomies that are unpronounced in Nature (such as the dichotomy between structure and material) are discussed and speculations regarding their significance to design are presented.

The overarching principle brought forth is that contrary to a *form-first* approach in design, in Nature the typical hierarchical design sequence *form-structure-material* is typically inverted bottom-up as material informs structure which, in turn, informs the shape of "naturally designed" specimens (Vincent 1982). By the end of this chapter we ask: how can a *material first* approach, prioritizing environmental performance and material behavior over form, be accommodated by design, and in what stages of the design process can such an approach be implemented? What new design possibilities emerge, and what might their potential significance be?

1.3 The New Materiality: Sources and Development of a Design Cultural Phenomenon

The chapter begins by suggesting that the disintegration between form, material and structure, so emblematic of contemporary design has lead to a parallel disintegration in design method pronounced by the partitioning between modeling, analysis and fabrication. Such disintegration, as we shall claim, may potentially result in the prioritization of expressive shape over environmental performance.

Compared to Nature, our own material strategies appear to be much less effective, and generally quite wasteful. Since the industrialized age, the construction industry has been dependant on discrete solutions for distinct functions (Oxman 2008; Oxman 2008; Oxman 2008). Building skins are a great example of such a claim.

Steel and glass possess significantly different structural and environmental properties which relate to significantly different performance requirements. Diversity is achieved by sizing, rather than by substance variation, and it is typically mass produced, not customized. As far as material structuring is considered, in the artificial world, especially in the construction industry, one property fits all.

As we shall demonstrate, the assumption that discrete solids are made from single materials is deeply embedded in modernist design thinking, and typically unquestioned. Furthermore, it is enforced by the way that industrial supply chains work. At their lowest levels, supply chains are driven by component manufacturing processes performed by highly specialized machines operating on particular materials to produce low-level subassemblies. But can Nature's ability be emulated in the design of the artificial?

With the assistance of advances in structural and material engineering entering contemporary digital practice, design culture appears poised for transformation (Figure 1.2). Designers now seek to advance

Nature's strategies in structuring matter by designing synthetic multifunctional materials competing with evolutions unrestricted time-frame of design process. Fitness, not form, is what actually matters. In Chapter 3 the new materiality is recognized by proposing that in mimicking Nature's way, materials are to be designed for highly customized functions rather than simply be selected and assigned to preconceived shapes. This requires the transformation from a culture of material *selection* to one of material *design*, as well as the utilization of heterogeneous and variable properties that may potentially correspond to a given set of performance criteria.

The main aim of the chapter is to introduce certain design principles in material practice in which the control and structuring of material organization is informed by material performance constraints. Later we shall see how those principles may come to express themselves in the digital domain, and then to be further combined with shape-generation processes to foster seamless relations between material behavior and geometry.

Given Nature's way, which prioritizes the function of structural and environmental performance as the forces shaping matter into shape (and not the other way around), the chapter suggests ways in which to consider a *graduated properties approach* to materials characterized by structural heterogeneity across scales as it may correspond to various loads and constraints.

Designed anisotropy is suggested as the path into a more biologically inspired method for informed material distribution. This ability, it is proposed, will ultimately allow the designer to design materials that vary their properties in correspondence with the forces acting upon them. Indeed, the design world is swiftly catching up with Nature's secrets by engineering variable density materials. Such materials are responsive in the sense that their microstructure is optimized to specific performance requirements (such as mechanical loads) as demonstrated through the family of *functionally gradient materials*.

Moreover, there exist numerous examples of products and building components which have been fabricated and manufactured by means of varying material properties across volume sections to correspond with structural loads and other stimuli. This was the predominant method of all forms of craft throughout history. With the composites industry undergoing massive expansion, many industries are revisiting the role of materials in the shaping of products such as automobiles, airplanes, sail boats and so on. Case studies from both ancient and contemporary periods are reviewed and discussed in relation to their form-generation processes.

The dichotomy between overall structural shape and local material properties is addressed, alongside other dichotomies presented in Chapter 2. Finally, certain limitations of material-based design are addressed pointing towards the shift from material *selection* to material *design* and its potential significance in the digital domain as part of the form-generation process.

1.4 Design Computation: Digital Engines for the Structuring of Matter

The treatment of materiality by CAD follows from certain of the presuppositions presented in the previous chapters. In this light, traditional CAD and BIM systems are fundamentally limited in their capacity to represent graduated or continuously heterogeneous material properties. Their basic strategy is simply to assign a material property to a closed solid or a closed surface polygon. In this respect, such tools are rather limiting to designers who wish to explore and design with graduated properties.

Indeed, since its emergence in the 1960's, computer aided design (CAD) in its many transformations has afforded the designer with an almost effortless manipulation of shapes generally detached from their fabrication in material form (Figure 1.3). Such processes promote the application of material subsequent to the generation of form. Even when supported by high-fidelity analytical tools for analysis and optimization, these processes are predominantly linked to *geometrical* manipulations in three dimensions. Design culture now requires a shift from a geometric-centric to a material-based approach in computationally enabled form-generation.

The main argument presented in this chapter is that certain design conventions prior to the age of digital design have been preserved and re-appropriated in CAD. Such, for instance, is the notion that a product or a building is typically made up of lower level components and parts put together by higher-level assemblies. Each component is geometrically designed as a structural element (i.e. post, beam, or surface element) and then assigned its material.

The objective of Chapter 4 is to review the evolution of concepts and issues in design-computation that are relevant to the integration of physical parameters within digital form-generation, analysis and fabrication environments and explore their potential to support a seamless integration between matter and shape. Certain computational paradigms inspired by Nature and the physical world are proposed as relevant to this objective and their limitations presented.

Current methods for material representation in design are reviewed in both generative (modeling) and synthetic (analysis & fabrication) computational environments. Voxels, maxels, finite-elements, particles and vague-discrete modeling elements are presented as potential "digital units" that may incorporate local physical information as informed by environmental constraints.

The chapter concludes with the limitations presented by computational media to represent more than a singular physical property. In addition, and more significant to the research objectives, computational tools with physical orientation are currently mainly used for purposes of optimization rather than processes of form-generation. However, if such computational units could potentially represent variable properties and could also be assembled as a function of structural and environmental performance, a new approach to design supporting performance-oriented form-generation processes could be developed and implemented.

1.5 Material-based Design Computation 1: Theoretical and Technical Foundations

Defined as the process of computationally enabled form-finding, informed by material properties and environmental constraints, Material-based Design Computation promotes an integrated approach to design, whereby material properties inform the geometrical generation of three- dimensional form. Chapter 5 introduces the theoretical and technical foundations of Material-based Design Computation developed to support a new universal approach to the problem of digital form-generation with continuously varying material properties satisfying prescribed material conditions on a finite collection of material features and global constraints.

Research assumptions, goals, objectives and questions are defined and presented, addressing ways by which to achieve the integration of physical considerations within the generation of form in order to efficiently distribute materials and properties relative to the type of forces defined by the environment. This condition assumes a given material volumes to which are assigned various forces resulting in its reorganization of physical distribution and property variation.

Given the assumption that a graduated properties approach to the design of objects and buildings also appears to be of certain potential value to the emerging field of sustainable design in its promotion of environmental customization, we seek to define, explore, demonstrate and evaluate computational processes supporting such goals. The aim is to arrive at a design approach favoring high levels of customization over mass production; integrating between modeling, analysis and fabrication environments; utilizing a graduated property approach to the design of objects; and overall prioritizing material considerations over geometric expression.

1.6 Material-based Design Computation 2: Methodological Frameworks

Chapter 6 presents a set of methodological frameworks corresponding to the goals, aims, issues and questions introduced in the previous chapter. Experimental design methods and models are applied both to generate and to evaluate the design experiments illustrated in the following two chapters. These methodological frameworks focus on the two reoccurring themes that were identified as endemic to *natural design*: the achievement of the multi-functional / mass-customized artifacts through a graduated material property approach, and the exploitation of an integrated conception-construction process in order to achieve computationally-enabled form-finding environments. Both of these objectives are intimately related.

The methodological frameworks include the development of three concepts relevant and instrumental to the experimental work carried out and presented in Chapters 7 and 8. These concepts include a *variable-property modeling concept*, the concept of property, and distribution-driven digital anisotropy, and finally, the concept of computational material units, also entitled *material pixels*.

The *variable property design* environment (VPD) is a design approach, a methodology, and a technical framework, by which to model, simulate and fabricate material assemblies with varying properties designed to correspond to multiple and continuously varied functional constraints. Such capability is later also termed *synthetic anisotropy* pointing towards the designer's ability to strategically control the density and directionality of material substance in the generation of form. In this approach, material precedes shape, and it is the structuring of material properties as a function of performance that anticipates their form. The theoretical and technical foundations for this approach have been termed, Material-based Design Computation.

Material units are presented and defined per a given design environment: within modeling processes, the designer may consider tessellation strategies that are property-driven (as opposed to the now classical curvature-driven approach); within analytical processes, the designer may consider a mesh unit to correspond to more than one objective function (i.e. load and light); and, within fabrication processes, the designer may consider a "material pixel", also referred to in the literature as a "maxel", as a unit negotiating between digital modeling units and units of physical fabrication. These three environments (modeling, analysis and fabrication) correspond respectively to the methodological frameworks offered by *tiling behavior*, *finite synthesis method* and *variable property fabrication*.

Various definitions of material pixels are given as a function of the type of performance requirements that are considered (e.g. pressure maxels respond to load, thermal maxels to heat, light maxels to light, comfort maxels to physiological requirements, and so on).

1.7 Natural Artifice: Experiments in Material-based Design Computation

The mechanical response of physical forms driven by, and engineered with, spatial gradients (heterogeneity, or difference) in composition and structure appears to be of considerable significance in all sub disciplines of design: from architecture, to product design, to material design as well as to the technologies to fabricate and construct them. Chapter 7 illustrates a series of experiments in Material-based Design Computation in the design of various objects under diverse environmental conditions; these include as a culmination of the range of experiments the comprehensive design of two functional products. It is important to note that each project utilizes a particular methodological framework or some combination of multiple methods. The research is experimental, and various methods are experimentally implemented at various phases of the design process in order to systematically and comprehensively explore the research issues and questions presented.

The design experiments presented in this work are ordered and classified by the type of performance considerations which they address. *Monocoque*, *Cartesian Wax*, and *Stalasso* all prototypes for architectural structural skins, explore the generation of 3-D forms as they may be informed by loading conditions. *Subterrain* and *Fatemaps* are informed by heat; *Tropisms* and *Raycounting* explore the generation of form as it may be informed by light. The concluding and comprehensive experiments with design projects include Beast - a chaise lounge, the texture-form of which is informed by both loading and comfort constraints, and *Carpal Skin* a protective splint against carpal tunnel syndrome designed to control muscular movement and provide comfort.

Following the presentation of design experiments and projects, special focus is given to several key projects implementing relevant "methodological frameworks" in the previous chapter. A *tiling behavior* approach is demonstrated in the design of *Beast*; the *finite synthesis method* is demonstrated in the design of *Raycounting* and *Subterrain*. Following this, all design experiments and projects are classified according to the type of method and form-generation processes used.

1.8 Natural Fabrication: Variable Property Rapid Prototyping Technology

Chapter 8 is devoted to the development of a fabrication environment and technology designed to achieve *variable property fabrication*. The objective is to enable the direct connection between material design and fabrication, or, in other words, the link between materiality and materialization.

The design experiments and products developed and implemented in Chapter 7, all share in common the concept of gradual material variations informed by performance constraints. Instead of lower level components put together into higher level assemblies, and made from homogeneous parts, all projects exemplify the notion of property variation through the implementation of ideas such as structural heterogeneity and controlled material distribution. These experiments were supported by the Material-based Design Computation method and techniques allowing for the integration of material considerations as part of the form-generation process within the digital domain. However, all projects were eventually fabricated using existing rapid fabrication techniques.

Currently, in architectural design fabrication, there exists no rapid prototyping technology which allows for a continuous modification of material properties such as strength, stiffness, density and elasticity as continuous gradients across the surface and volume area of a functional component. Such variations are usually achieved as discrete changes in physical behavior by printing multiple components with different properties and distinct delineations between materials. In these cases, assembly typically begins only after the fabrication process has been completed. Such processes result in material waste and lack of functional precision. Variable Property Rapid Prototyping aims at implementing a novel material deposition 3-D printing technology which offers gradation control of multiple materials within one print to save weight and material quantity while reducing energy inputs. The result is a continuous gradient material structure, highly optimized to fit its structural performance with an efficient use of materials, reduction of waste and the production of highly customized features with added functionality. VPRP ultimately aims at significantly reducing material and energy waste in the design of products and buildings by constructing structures with varied properties using lighter, stronger materials and avoiding redundant deposition. The aim is that such products will be designed to use significantly less fossil fuel energy to construct and operate than they would typically consume.

The chapter briefly reviews current state-of-the-art fabrication technologies and their environmental disadvantages. Unlike Nature's way where high levels of environmental customization are achieved through property variation, contemporary design methods and products are characterized by material assemblies of homogeneous components. Current construction supports this logic.

The development of a new technology entitled *variable property rapid prototyping* (VPRP) is presented which allows the designer to print materials with varied properties (i.e. density, elasticity, etc). The ultimate aim is to combine such fabrication technology with a variable property modeling environment whereby computational units ("material pixels") and physical fabrication units are calibrated with, and according to, particular performance requirements (i.e. as is the case of bone).

Following a short survey, the *variable proper6ty fabrication* software environment is presented, where a color-coded control module represents the means by which to vary material properties continuously. Hardware modules are reviewed: general technical descriptions are given to the various parts of the machine. The chapter concludes with the technologys current limitations and future outlook towards a more *natural fabrication* inspired by Nature's way.

Finally, it is suggested that the VPRP as a pilot project aims at revisiting design fabrication technologies as approximations to natural formation processes that take in unformed raw materials and operate on them locally; using a single parameterized and digitally controlled process rather than many specialized processes, to produce formed solid objects. In this way, one is able to break free from the rigid logic of industrial supply chains and related CAD systems.

1.9 Contributions of Material-based Design Computation

Chapter 9 considers the theoretical, methodological and technical contributions of the thesis.

Theoretical contributions refer to the development, definitions and implications of Material-based Design Computation as a design method, technique and fabrication technology prioritizing materials and environmental performance over a purely geometrical rendition of shape. Unlike current design processes where form dominates matter, design based upon the interrelation between materials and performance promotes the design of objects with graduated properties perfectly distributed and highly customized to fit their function. It is anticipated that such an approach will offer new possibilites for design and potentially enhance a new sensibility to sustainable design as we know it.

Methodological contributions relate to the body of knowledge of Material-based Design Computation which aims at implementing the theoretical approach within a computational environment fostering material-informed form generation processes. More specifically, methodological contributions refer to the methods and technical means supporting this design approach through the introduction of design methods and environments included under the categories of *tiling behavior*, *finite element synthesis*, and *variable property fabrication*.

Through a series of design experiments, the thesis has demonstrated the integration of geometry, structure, and material not as separate elements of design, but rather as a multiplicity of design drivers acting together to generate form.

Beyond the developments of scripts and programs to realize the collection of design work presented in this thesis, technological contributions mainly refer to the development of a new fabrication technology entitled *variable-property rapid prototyping* enabling the distribution of material properties as continuous gradients within a 3-D printing environment.

Both variable property modeling and fabrication of materials with heterogeneous properties across a wide range of scales and applications holds a profound place in the future of design and engineering. The ability to synthetically engineer and fabricate materials using VPRP strategies appears to be incredibly promising as it increases the product's structural and environmental performance, enhances material efficiency, promotes material economy and optimizes material distribution. The fundamental technical contribution is a first-generation rapid manufacturing tool for depositing material with gradually varying physical properties such as density or elasticity per unit volume informed by structural and environmental fitness constraints.

The technical contributions of the thesis are summarized in Chapter 9 and include the analysis of forms allowing material property variation in response to mechanical, thermal, or lighting conditions; fabrication of forms with material property or thickness variation over a surface; and the development of a new device, the Variable Property Rapid Prototyping machine, for fabricating forms with varying material properties and thickness.

Following the main content of the chapter is an assessment of current limitations and future research. Certain fundamental question of "the origin of form" is re-addressed in the context of the design experiments presented. An important assumption underlying this research is that form may be generated without explicit *a priori* geometrical content, but rather as the byproduct of matching material parameters and environmental constraints. The main design model proposed in this thesis supports such a process by considering the landscape of design possibilities as the interaction between force and matter, and between energy and matter. Eco-maxels are conceived of as the units by which to technically achieve such a new concept of design.

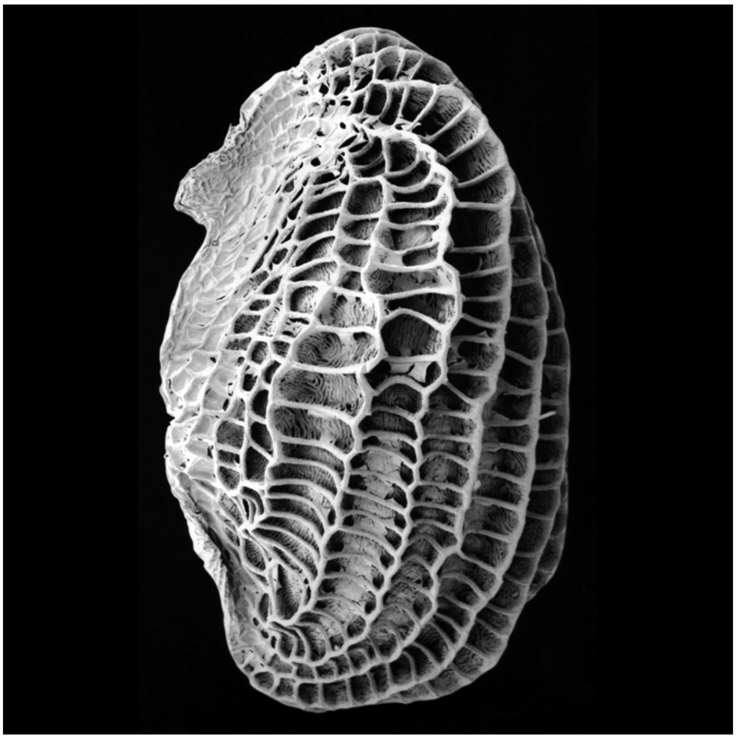

Figure 1.1: Orthocarpus Luteus (Yellow Owl's Clover) photographed by Rob Kesseler and Wolfgang Stuppy (Kesseler and Stuppy 2006). As demonstrated by the luteus, *Nature's Way* (chapter 2) will unfold Nature's form-generation strategies characterized by achieving high levels of environmental customization. In Nature one finds complete integration between shape, structure and material. Such integration, as we shall argue, is achieved by the assimilation between formal generation, adaptation and growth analogous to modeling, analysis and fabrication in the design of the artificial.

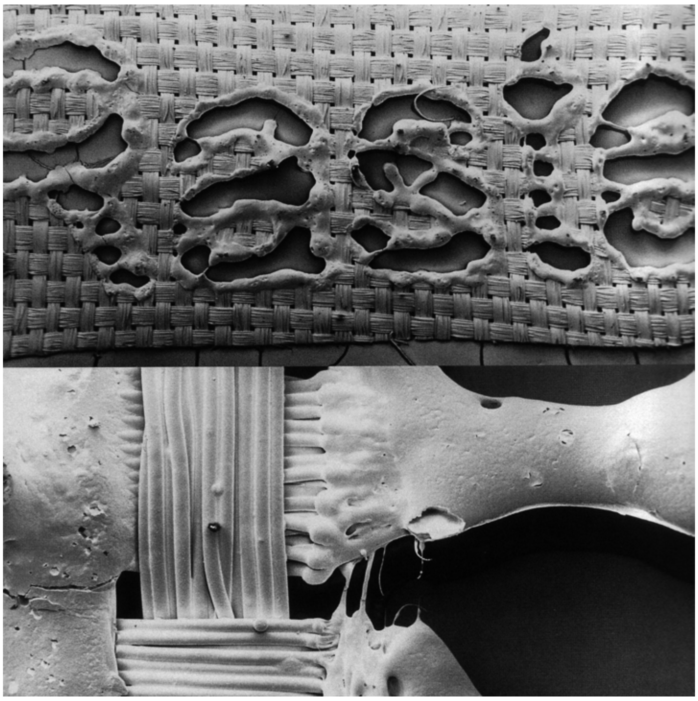

Figure 1.2: Laser-treated Polyamide. Image by Savithri Barlett (Braddock Clarke and OMahoney 2007). The two images are taken using Scanning Electron Microscope. Extreme laser heat is applied on fabric to reshape it at the polymer level (top). The fabric decomposes due to heightened temperatures and poor heat conduction by the polymer fibers (bottom). The New materiality (Chapter 3) will highlight advances in material processing currently available to designers on the way to achieving Natures design strategies.

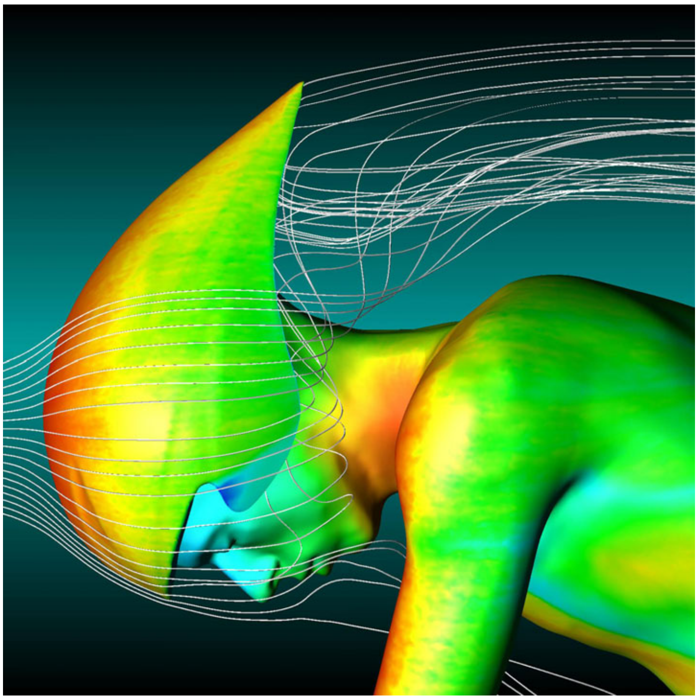

Figure 1.3: Computational Fluid Dynamics (CFD) analysis from scanned models help British Cycling Team sprint to Olympic medals. CFD analysis allows the designer to incorporate material and environmental constraints as part of the design process. Source: $http://legacy.ensight.com/news/british\_cycling.html$. *Design Computation* (Chapter 4) will introduce the state-of-the-art in computational strategies motivated by the physical world.

CHAPTER 2

NATURE’S WAY

Sources and Development of a Design Cultural Phenomenon

> *“In her (nature’s) inventions nothing is lacking, and nothing is superfluous.”*
> **— Leonardo da Vinci**

2.1 Why Nature?

Nature is demonstrably sustainable. Her challenges have been resolved over eons to enduring solutions with maximal performance using minimal resources. Unsurprisingly, Nature’s inventions have eternally inspired human achievements and have led to the creation of exceedingly effective and efficient materials and structures, as well as methods, tools, mechanisms and systems by which to design them. Insights gained from the study of natural materials are significant, not only from a scientific perspective, but also in the context of their application to the design of synthetic environments.

In this chapter we review and discuss the main characteristics of Nature’s forms. This is a challenging mission when carried out from the point of view of design, since the phenomenon of growth alone occupies such vast implications in considering form’s origins: we are yet to grow a building. Despite this, I aspire to examine Nature’s creations and to demonstrate that in Nature’s way there is always a direct relation between matter and energy, between form and environment, and between organ and function. When considering natural forms and materials from a design perspective, it is therefore important to note the strategies and mechanisms by which Nature goes about distributing materials and properties to account for its functions as she maintains the forms of life on earth.

2.2 Sustainable by Nature: Principles

2.2.1 Minimum Inventory Maximum Diversity

In *Structure in Nature Is a Strategy for Design* Peter Pearce presents a concept by which he elucidated Nature's sustainable ways. He refers to this as the concept of *Minimum Inventory - Maximum Diversity* (Pearce 1981) which underlies every natural system. Such systems are defined by Pearce as minimized inventories of component types, a kit of parts, along with rules by which to combine these components. The fit systems are those described by the contribution of their components to the maximization of different, though generically related, structural forms. Furthermore, in successful systems the rules of assemblage and the physical components themselves are seen as organically related such that the rules are seen to grow out of the parts, and the parts grow out of the rules.

2.2.1.1 Natural Systems

Snowflakes, for instance, exhibit great diversity of form, governed by certain physical, geometrical and chemical constraints. The snowflake is considered an archetype according to Pearce, of physio-geometric expression: within the six-fold form no snowflakes have ever been known to be exactly alike. The case of crystals is similar. Here one finds the expression of the diversity of form as a function of the least-energy internal arrangement of atomic arrays.

2.2.1.2 Biological Systems

In biological structures, the DNA molecule suggests a minimum inventory-maximum diversity principle from a biomechanical interaction point of view (Pearce 1981). Natural materials are made from a relatively small number of polymeric and ceramic components or building blocks, some of which are themselves composites (Vincent 1982). The solid part of most plants for example is made up of cellulose, lignin and hemi-cellulose, while animal tissue is largely made of collagen, keratin, chitin and minerals such as calcite, hydroxyapetite and aragonite. From these, Nature fabricates a remarkable range of structured composites (Vogel 2003). In these cases, as in many others, a singular generic system constrained by its inventory promotes maximum diversity.

2.2.2 Resource Conservation

The formative process in natural structures is typically characterized by least-energy responses. Such is the principle of closest packing, a principle common to both the animate and inanimate world. Interestingly, the principle of closest packing is equivalent to that of triangulation, and it is a well known fact that triangulated frameworks exhibit inherent geometric stability (Thompson 1942; Pearce 1981). Such properties enable framework structures to be built without moment joints, insuring axially loaded members. This, in turn, results in high strength per weight minimum energy structures[2.1]. Such a principle is of remarkable universality: it operates independently of scale or material with the same energetically conservative effect. Whether on the molecular level, the cellular level, or at the man-made structure level, its inherent stability always establishes a condition of minimum potential energy.

[2.1] In this context, consider Alexander Graham Bell's tetrahedral kites and space frames.

2.2.3 Minimum Energy

Nature creates forms and structures according to the requirements of minimum energy (Thompson 1942). She does so as a response to the forces and loads as she creates a great diversity of forms from an inventory of basic principles and a few materials. Furthermore, Thomson claims that the form of an object is analogous to the diagram of forces defining it. Such is a governing idea in the application of the minimum inventory-maximum diversity principle to building system design.

But, how are such principles implemented in the natural world from a materials perspective? There are many ways by which to consider Nature's material strategies. For the designer, there is particular interest in two of Nature's many various traits which are defined in the following section.

2.3 Sustainable by Design: Strategies

2.3.1 Integrated Multi-criteria Environmental Performance: Load, Light, and the Seasons

In considering Natural material usage, it is challenging to distinguish between structure and skin, since so many of Nature's forms assimilate between varied functions and their related materials and properties. Look at your skin and you will quickly realize that within one continuous tissue we are constantly in negotiation between seemingly contradictory functions as we consider the skin as both barrier and filter. Indeed, the skin has significant structural properties which allow it to fulfill its multiple functions. These functions include energy capture (i.e. insect compound eye), color generation (i.e. scales of butterfly wings), heat transfer (i.e. penguin feathers), mass transfer, drag reduction (i.e. shark skin), surface adhesion (i.e. contac splitting in gecko foot), surface repulsion, sensing, actuation, and so on. The one common denominator for all of these examples is that they are all constructed of complex fiber structures. Indeed, natural structures possess a high level of seamless integration and precision with which they serve their functions. A key distinguishing trait of nature's designs is the capability in the biological world to generate complex fiber structures of organic, or inorganic, multifunctional composites such as shells, pearls, corals, teeth, wood, silk, horn, collagen, and muscle fibers (Benyus,1997). Combined with extra-cellular matrices, these structural biomaterials form microstructures engineered to adapt to prearranged external constraints introduced into them during growth and/or throughout their life span (Vincent 1982). Such constraints generally include combinations of structural, environmental and corporeal performance criteria (Figure 2.1).

Since many biological materials are made of fibers, their multi-functionality often occurs at scales that are nano through macro and typically achieved by mapping performance requirements to strategies of material structuring and allocation. The *shape of matter* is therefore directly linked to the influences of force acting upon it (Vogel 2003). Material is concentrated in regions of high strength and dispersed in areas where stiffness is not required. It is a well known fact that in nature shape is cheaper than material, yet material is cheap because it is effectively shaped and efficiently structured.

Nature's ability to gradually distribute material properties by way of locally optimizing regions of varied external requirements, such as the bone's ability to remodel under altering mechanical loads (Figures 2.2, 2.3) or the wood's capacity to modify its shape by way of containing moisture, is facilitated, fundamentally, by its ability to simultaneously model, simulate and fabricate material structuring.

The structural properties of wood, for instance, not unlike most biological materials, can widely vary when measured with the growth grain or against it such that its hardness and strength may differ for a given sample when measured in different orientations (Figure 2.4, 2.5)[2.2].

[2.2] This property is known as *anisotropy* and it is due to *anisotropic structuring* that nature can create sustainable structures efficiently. We shall return to explain this trait in depth in the following chapter along with relevant examples.

2.3.2 Integrated Environmental Processes: Growth, Response, and Adaptation

Millions of years devoted to the fine-tuning of the relation between structure and function have resulted in Nature's remarkable solutions to complex structural-mechanical problems (Weiner and Wagner 1998)[2.3]. Moreover, natural material systems and structures are capable of changing their properties, shape, color, and load paths to account for varying structural and environmental constraints as well as to handle damage and promote repair. Their survival depends on Nature's ability to negotiate between multiple functions and evaluate their relative significance within a singular process integrating the mechanisms of growth, response and adaptation.

Furthermore, it turns out that rather than optimizing its resources for a single objective function, nature must instead negotiate multiple functions by means of one single material system. The survival of such systems depends on Nature's ability to manage and promote the economic viability of her constructions, as well as satisfying a set of desired mechanical properties such as strength, stiffness, toughness and resistance to impact. In addition to form-generation and response through analysis, one of the most unique features of biological systems is their capability to diagnose and repair localized damage to their structures. Clearly, such an attribute is desirable for man-made objects[2.4].

It is, however, important to state that natural processes of formal generation, analysis and fabrication are well integrated precisely because they can afford to be given the time-scales afforded by evolution. Gordon notes that both shape and material of any natural structure have evolved over a long period of time in a competitive world and represent an optimization with regard to the loads which it has to carry and to the financial, or the metabolic, cost (Gordon 1976). Still, it is our mission here to understand the relationship between generation, analysis and fabrication as it is applied to the formation of natural specimens in order that we might further speculate upon how such approaches may be implemented in design.

It is always thrilling to discover the extent of impact that the physical sciences had from the 1930's onward on modernist designers who found inspiration in the life sciences; more fascinating however is the acknowledgement of the converse condition in which the scope of impact that the design disciplines had on protagonists of the natural sciences is well celebrated. Such was the case of natural inclination that the ecologist Julian Huxley's had towards Walter Gropius, the former Bauhaus director who at that time fled Nazi Germany as he and fellow faculty relocated in London[2.5]. Alongside Gropius was László Moholy-Nagy former head of the school's metal workshop and renowned artist who, much like his fellow radical designers, who sought to unify the arts and the crafts with industrial universalism, found new voices as well as patrons in a community of biologists in London who adapted Bauhaus architecture and art as part of their scientific vision for the future (Anker 2006)[2.6].

[2.3] Here one has to bear in mind that despite evolution's unconstrained timeframe, biological structures are not always perfectly adapted to their function. This is partly due to the fact that beyond the mechanical function of materials, some, if not all, of them must fulfill other functions as well.

[2.4] However, using energy to increase stiffness is not always the most "natural" solution. Nature uses strain energy as a damage control mechanism by designing systems with large strain capabilities as compared to our modern constructs of steel, concrete, and graphite. Adaptation of structural impedance is perhaps the most fundamental and powerful concept of intelligent materials systems. By modifying the structural impedance of a system, we can change its vibration and acoustic behavior as well as change its resistance to damage.

[2.5] Julian Huxley was then secretary of the Zoological Society of London. He had an apartment at the zoo, which he used partly as a showroom for modernist design. Here, scientists, artists, architects, environmentalists and the science-fiction writer H. G. Wells regularly met for discussions about how to save humankind from environmental, economic and social destruction (Anker 2006).

[2.6] Bauhaus design was one of the group's chief passions, and Gropius looked to Huxley and his friends with hope and admiration. Traditional architecture and design reinforced an unfortunate dualism between people and nature, Huxley believed, whereas the Bauhaus approach promised a harmonious reunion. To Huxley, nothing less than the evolutionary survival of the

2.4 Inspired by Nature: Related Fields and Approaches

2.4.1 Biotechnik

In this circumstance Moholy-Nagy found a major source of inspiration in Raoul Francé. Francé is known to have founded the science of bionics with the motivation and claim that humans must learn how to copy Nature's inventions in order to survive on earth. This new science was first named Biotechnik - 'bio-technique' (Anker 2006).

Moholy-Nagy's students and fellow designers were instructed by him to view Nature as a "constructional model" and to search for "prototypes in nature" in order to better determine functional design. He proposed that all human technologies are based in natural technologies. Moholy-Nagy himself studied the works of Huxley and his colleagues and used it to generate his own principles, techniques and processes as they might be applied to human design. His 1935 film *In the Cradle of the Deep* documents the growth of lobsters and the fisherman's struggle to search them out. He argued that a "prehistoric animal shell is constructed in such a wonderful way that we could immediately adapt it to a fine Bakelite[2.7] or other molded plastic form". The point of the film was to show designers that observing the life of animals may well instruct designers how form follows function. Furthermore, Nagy's investigations into architecture and photography were also informed by the life sciences. He defined architecture "as an organic component of living" and argued that "architecture will be brought to its fullest realization only when the deepest knowledge of human life in the biological whole is available" (Anker 2006).

2.4.2 Biomimetics

With respect to this underlying motivation to translate natural, and particularly, growth, processes into design principles, Biomimetics is an emerging field the objective of which is to study design solutions to problems in the natural world as potentially relevant to contemporary design and engineering. According to Klein, B.M. Katz has defined the field as the study of natural processes and how they can be emulated to solve human problems in a life-friendly, waste-free way (Klein 2009). There it is stated that in contrast to genetic engineering which turns cellular organisms into factories for industrial production, biomimetics tries to turn society's productive resources into agents of nature. The natural world is treated as a library of ideas. J.F. Vincent, one of a small number of acknowledged experts in the field, defines it simply as, "the abstraction of good design from nature" (Vincent 1990). Although this sounds obvious, in fact, it involves much more complex intellectual and research-related processes.

Although the field of Biomimimetics can be traced to Leonardo da Vinci's work, it is considered to have been formulated in 1991 when the US Air Force Office of Scientific Research convened a group of researchers to consider the way in which nature produces and processes unique materials. Thus the original motivation was to achieve inspiration from natural materials and processes as a source of potential innovations in materials design that might be turned into practical applications. The field is also known by the term, *bionics*, as the copying of natural designs. The reference to bionics is also attributed to the US Air Force, but dated by Julian Vincent to the 1950's.

Despite the fact that the evolutionary time-frame of millions of years is of a completely different range of scales from that of contemporary engineering, product design, materials design and architecture, it was considered that the design objectives of these fields were often similar to those which underlies the evolutionary processes of nature. Among these are *functionality*, *optimization*, *energy efficiency* and *cost-effectiveness*. We now can study how nature has optimized the architecture of materials over the long

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human species was at stake (Anker 2006).

[2.7] Bakelite is an early plastic; a thermosetting phenol formaldehyde resin, formed from an elimination reaction of phenol with formaldehyde, usually with a wood flour filler. It was developed in 19071909 by Belgian chemist Dr. Leo Baekeland.

period of natural evolution. All of these factors are common to contemporary design and engineering fields. In studying how nature achieves optimization we concentrate on materials, structural properties, mechanical properties, functional integration, sensing and control systems, and other aspects of design that have general relevance for contemporary inventions and solutions.

In nature there is little emphasis on esoteric, or "expensive" materials. There are few chemical substances used in animal life, and they are generally constructed using relatively low-performance materials. Success from a design point of view depends not on what they are made of, but rather in how they are made. *Structure rather than energy*, is the general design principle of nature. It has been said that in nature, 'shape is cheaper than material', therefore we have much to learn from nature regarding effective and innovative approaches to the design parameters described above.

One of the classic studies which may be considered as among the foundations of the field is the work of D'Arcy Thompson, the Scottish naturalist and mathematician, who published the results of his research on natural forms in the *influential* work, *On Growth and Form* of 1917. Here, for one of the first occasions in human history, living things are treated as examples of the solution of engineering problems (Thompson 1942).

2.4.3 Biogenesis: Towards *Natural Design*

In this thesis we consider new approaches to form-generation inspired by nature from a materials perspective. The first serious engineering approach to the subject was made by A. G. M. Michell around 1900 in a publication entitled *The limits of economy of material in frame-structures* (Michell 1904). After that, *On Growth and Form* was the first general account of the influence of structural requirements on the shapes of plants and animals (Thompson 1942).

Other designers and engineers have further developed the fascination with biology and living nature in the context of form-finding. Among them were Frei Otto and his group at the *Institute for Lightweight Structures* at the University of Stuttgart during the 1970's. In a series of publications from that period, specifically IL-6 which marks the tenth year anniversary of the institute, Otto delivers an honest declaration about such associations and the productivity which they inspire: "Every material object has the ability of conveying forces. We are studying the capability to convey forces independent of form, material, and type of load... in all objects of organic and inorganic matter" (Otto, Trostel et al. 1973, p.5).

In this chapter we review structure-mechanical relations at various hierarchical levels of organization, highlighting wherever possible meaningful avenues in the generation and structuring of synthetic form.

2.5 Nature's Design Strategy: Structural Heterogeneity through Material Distribution

When compared to manmade fabricated materials, many natural materials, particularly in the plant kingdom, mechanically outperform some of the most common materials used by engineers and architects. Woods have strength per unit weight comparable with that of the strongest steels); shell, bone, and antler have toughness an order of magnitude greater than engineering ceramics; and mature bamboo stalks have slenderness ratios which are remarkable even by the standards of modern engineering (Ashby 1995). Yet Nature's materials are less than half as dense as many of these artificial materials and are characterized by very low weight and are functional for the plant to sustain[2.8] (Niklas 1992). What are the attributes that make natural materials so effective? In his *Plant Biomechanics: An Engineering Approach to Plant Form and Function*, Niklas determines that organisms live by the laws of physics and chemistry and as

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[2.8] Since vertical construction carries with it the design constraint of self-loading, in addition to being strong, materials should be light. In fact, for its density, cellulose is the strongest material known (Niklas, 1992).

such they have evolved and adapted to mechanical forces in a manner consistent with the limits set by the mechanical properties of their materials (Niklas 1992). Furthermore, in the plant world particularly it is often the case that material properties influence the plant's mechanical behavior[2.9]. Niklas demonstrates that the nutshell of the macadamia is as hard as annealed, commercial grade aluminum, resists twice the force necessary to fracture metals of various types, and is stronger than silicate glasses, concrete, porcelain, and domestic brick.

Biological materials are indeed very versatile: they can change their material properties to fit the age or the function of their immediate physiological condition[2.10]. Hence the mechanical behavior of any single biological material is defined by multiple properties, not all of which can be maximized. Each material is used according to its particular qualities and the types and magnitudes of the mechanical forces it must sustain.

In *The Mechanical Properties of Natural Materials*, Gibson explores various classes of natural materials as she examines the relation between their composite and cellular microstructures and their exceptionally high values of mechanical performance (Gibson 1995). The function of these natural materials exploits their exceptional structural properties: woods and palms resist bending and buckling, silk stores elastic strain energy, muscle stores and releases elastic strain energy during locomotion, and so on. Such relations have significant implications for the design of mechanically efficient engineering materials: when considering beams and plates of a given stiffness or strength, or columns of a given buckling resistance, woods, palms and bamboo are among the most efficient materials available (Gibson 1995). Gibson reviews four classes of natural materials: woods, palm and bamboo, stems and quills. The results of the analyses suggest novel microstructures for mechanically efficient engineering materials for bending stiffness and elastic buckling resistance achieved by optimizing micro-structural organization to fit performance requirements such that the cellular structure can enhance performance for loading parallel to the grain (Gibson 1995). Common to all these examples are the exceptional properties of natural materials arising mainly through novel microstructures for efficient engineering materials (Figure 2.6, 2.7). Nature's building blocks are therefore not as unique as their structuring in that it is not so much the material properties of the components as their arrangement within the natural composites which give rise to such a vast range of properties. Thus we may postulate that *Material Structure* is an important design property of natural design as well as a significant body of design knowledge.

2.6 Case Study 1 (Cellular Solids): Structural Heterogeneity in Bones

2.6.1 Macro (System) Scale: The Forces of Human Locomotion

In an inspiring essay, Benno Kummer discusses the work of the anatomist Von Meyer and the technician Culmann to comprehend bone matter as a system incorporating material and morphology as they are informed by structural performance (Otto, Herzog et al. 1990). The material, structure, and form of bone are all interrelated in its formation and behavior. Matter is distributed to fit stress paths in micro and macro scale such that the structural characteristics follow the behavior of the elements and fit their properties.

The basic building block of the bone family of materials is the mineralized collagen fibril. It is composed of the fibrous protein collagen in a structural form that is also present in skin, tendon, and a variety of

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[2.9] Given that the plant world is devoid of nervous systems, observations and examinations carried out regarding the relation between material properties and mechanical function are easily established.

[2.10] The responsiveness of plants to their immediate mechanical environment was recognized by botanists as early as the mid-nineteenth century when it was first discovered that young plant cell walls are ductile, while older cell walls tend to be much more elastic and resilient (Niklas, 1992).

other soft tissues. The collagen constitutes the main component of a three-dimensional matrix into which, and in some cases onto which, the mineral forms (Weiner and Wagner 1998).

The manner in which the building blocks are organized into higher order structures can also vary, and in fact, this is the basis for differentiating between the members of the bone family of biological materials. Furthermore, some such materials are composed of two or three different organizational structures such that the whole structure may be folded into even larger superstructures. The range of their orders and properties reflects many different variables: the diversity in structures, the orientation of the specimens, the variations in mineralization extent and porosity, the precise locations of the specimens, and so on. Thus the structures of these materials must be understood both in terms of the differences between family members, and most importantly according to hierarchical levels of organization (Weiner and Wagner 1998).

Understanding structure-function relations in these materials is therefore a challenge. The understanding of this subject requires sorting out the bulk mechanical behavior in terms of the contributions of the sub-structures at each hierarchical level. However, since many of these materials change their structure in time, and in turn affect the mechanical properties of the tissue[2.11].

Furthermore, specialized bone cells actively remove older bone and replace it with younger bone, which may even have a slightly different structure such that it is presumably optimized to function in the prevailing stress field at the time of its formation Weiner, S. and H. Wagner (1998). "The material bone: structure-mechanical function relations." This would still not be a valid analysis. Weiner and Wagner have chosen to organize their review according to the hierarchical levels of organization (Figure 2.8). They discuss 5 of the 7 hierarchical levels, which range in scale from nanometers to millimeters, in terms of their structures and mechanical properties (Weiner and Addadi 1997; Weiner and Wagner 1998).

2.6.2 Meso (Structure) Scale: Structure-Function Relations in 7 Hierarchical Levels of Organization

2.6.3 Micro (Material) Scale

The structure of skeletal elements is not the only feature which is adapted to the type of mechanical strain. This applies to the same extent for the density distribution of the bony material providing the mechanical strength. Today it is generally accepted that the density and anisotropy of cancellous bone depends on the magnitude and direction of the loads it experiences (Gibson 1984; Ashby 1995; Gibson and Ashby 1997).

Kummer and his fellow scientists at the institute devised graphical techniques, such as the *Material Mountain Ranges* (Figure 2.9), to quantify material distribution of bony matter as it relates to the distribution of strain, and assisted in the understanding that both the structure and the distribution of material in bone is adapted to the type and magnitude of mechanical strain. Cancellous bone has a cellular structure, and is considered to incorporate similar mechanical properties and structural behavior characteristic of the family of cellular solids (Gibson 1984; Ashby 1995; Gibson and Ashby 1997). Furthermore, it is probably one of the more classical examples for a system which organizes matter consistent with stress patterns across scales of both material and structure, a distinction that is at times vague and difficult to make.

[2.11] Some of these changes are in part thermodynamically driven, such as the increase in the sizes of the crystals, and some are also biologically mediated, such as the determination of the average proportions of collagen, mineral, and water in a given material.

2.7 Case Study 2 (Fiber Structures): Structural Heterogeneity in Trees

I have spent many hours gazing at trees. Beyond their extraordinary beauty, trees are the perfect example of systems which have been shaped by the forces of nature and as such, they represent Nature's strategies in regards to the growth, generation, adaptation and preservation of form.

Natural systems are shaped by, and exposed to the elements surrounding them. The range of loads to which a tree is exposed is vast and it includes forces of various magnitudes and directions, bending moments, torsional moments, and thermal stresses amongst others. If the tree is to resist the loads exerted upon it, these loads must be countered by a support applying equally large, but opposed, reaction loads against it.

In the engineering disciplines it is often the case that such force-form relations are simplified and abstracted as post beam models in order to predict physical deformation. However, Nature's strategies must not be merely reduced to geometrical abstraction, for in Nature the distribution of material substance relative to its guiding and shaping forces is as significant to the tree's structural stability as is its form itself. All in all, the case of the tree provides for a good starting point by which to understand the forces of Nature.

2.7.1 Macro (System) Scale: The Forces of Nature

2.7.1.1 Axial Forces

Axial forces are the most basic example. The mass of a tree's branches exerts (by its very own weight) an axial force on its trunk, thus causing compressive stress. The branches cause an elastic compression of the trunk in the axial direction resulting in a spatially uniform distribution of compressive stresses (Mattheck 1998). The soil below the tree's trunk must therefore exert an equally great but opposite force in order to avoid the hypothetical condition in which the post sinks into the soil. As a reaction, axial tensile forces would cause tensile stresses in the post. The situation is rather more complicated with eccentric loading.

2.7.1.2 Eccentric Loading

When dissecting a trunk horizontally, it is rather easy to trace the relative location of branches by establishing areas in the section more or less denser with tissue. In the case of eccentric loading, a uniform bending moment may be acting downwards in the entire trunk, compensated by the ground via the roots. Naturally, the bending moment in the side branch will cause much higher bending stresses than in the trunk. In this case, it may become quite apparent that in the central axis within the trunk and the branch neither tensile nor compressive stresses are present. Despite not being fully loaded, this zone within the tree constrains wood capable of bearing load. Furthermore, it is otherwise quite ineffective with regards to bending and thus rather wasteful from a materials perspective.

Nature tolerates this deficiency in a tree motionless and anchored in the soil. However in a mobile mammal one finds various bones that are hollow in the zones where fibers sustain neutral bending. In the animal kingdom it is thus the case that no material is placed where there is nothing to carry: in such regions bones are shaped simply as hollow tubes.

2.7.1.3 Lateral Loading

The tree arranges its material sensibly within the narrower limits of its possibilities: trees loaded laterally on one side by wind become elliptical in the wind direction. Thus, if the tree now deposits all its building materials in the zone of highest bending stress (tension side and compression side) by forming particularly wide annual rings there, this buildup goes into the third power of the large axis (the longitudinal axis describing the trunk), while a widening in the direction of the small axis is only linear. The tree thus forms a non-circular cross-section which is stiffest against the prevailing bending load, and is characterized by smaller stresses than a uniformly circular cross-section with an identical external bending moment. Root cross-sections may even assume nearly the shape of an I-beam, in which hardly any wood forms in the zone of neutral bending. Here the component is forced into an optimization of shape (Mattheck 1998).

2.7.1.4 Composite Loading

Besides tensile and compressive stresses resulting from axial tension or compression and the bending stresses (transition from tensile to compressive stresses with a defined spatial, usually linear, distribution) there are also the *shear stresses*. These are stresses acting tangentially in the shear-loaded plane, and prevent the bodies separated by it from sliding on each other. They are therefore qualitatively very different from the tension and bending stresses acting perpendicularly to a given reference plane. The *torsion* load causes, for example, a shear stress distribution in the cross-sectional plane of the twisted cylinder illustrated, which increases linearly from the center.

In our tree, a one-sided crown shape, with one branch extending far towards the light, could lead to a twisting of the trunk under wind pressure and cause the same shear stresses in the trunk. Each instance of loading is made up of a large composition of loading cases. Naturally, loading conditions are usually multi-axial and different stresses act in different directions.

2.7.2 Meso (Structure) Scale: Shape Adaptation in Fibrous Systems

2.7.2.1 Tension and Compression Wood

Reaction wood, also known by its scientific term *gravitropism*, is abnormal wood found in the trunks and branches of leaning trees resulting in abnormal rings wider on one side than the other. It is formed by the tree's response to directional stress and its attempt to counteract it. In hardwoods, reaction wood is also known as tension wood as it forms on the upper side of the lean. In softwoods, reaction wood is known as compression wood forms on the lower side of the leaning tree (Figure 2.10).

Although compression wood has a higher than-normal density, it is weak in some critical strength properties. The most serious drawback of compression wood is its abnormal drying behavior. When normal wood in the form of lumber dries, it shrinks in thickness and width (by predictable amounts). It shrinks very little (practically negligible) in length. Compression wood, however, shrinks in length by more than 10 times that of normal wood. This causes bowing and twisting of certain pieces of lumber.

2.7.2.2 Material Distribution through Optimization

Reaction wood is an interesting case of material formation informed by mechanical environmental stimuli that are external to the tree's genotype. In this sense, any material optimization processes occurring to counteract directional stress are relative to the tree's particular loading case. The tree's capacity to adapt itself to these external conditions is essential under conditions of uncertainty as far as future loading cases are considered.

Material optimization occurs as fiber structures within the woody tissue compute stimuli of morpho-mechanical nature and translate it into a process known as transduction, characterized by the movement of starch grains within the plant cell corresponding to the direction and magnitude of the load. A signaling regulation mechanism follows preceding the mechanical response. Shape adaptation is naturally dependant on the offset angle from the vertical axis as fiber reorientation emerges in time.

2.7.2.3 Hierarchical Levels of Shape Adaptation

The basic mechanism for shape-change in plants is based on the restructuring of fiber structures in multiple scales. Shape adaptation, characterized by incremental changes in curvature, occurs as non-symmetric tree laminates respond to external load forming compression and tension wood in the top and bottom areas of the tissue respectively. Local structural changes thus affect global curvature (Figure 2.11, 2.12).

Three hierarchical levels of shape adaptation may be observed as mechanical reorientation occurs on the cell walls (local level), the tissue (regional level) and the trunk (global level). In this case, geometrical manipulation is dependent on growth, deposition and reorientation of fiber structures.

2.7.3 Micro (Material) Scale

Tracheids in softwoods and fibers in hardwoods, for instance, provide the mechanical support for the tree. Gibson has idealized the cellular structure by modeling only the tracheids, or fibers, as a honeycomb. The models suggest the complexity of fiber orientation as larger numbers of fibers orient themselves more nearly, parallel to the axis of the cell than normal to it (Gibson 1995). Given the layup, the Young's modulus for the cell wall can be calculated from composite theory.

Another striking feature illustrated by Gibson are the relatively dense, fiber-like vascular bundles distributed throughout a "matrix" of parenchyma cells that make up the bulk of most non-woody structures. Longitudinal sections reveal fiber alignment relative to mechanical function. Some tissues on the other hand, such as palm stems have a non-uniform radial distribution of vascular bundles, with more bundles of larger diameter at the periphery than at the center. Unlike wood, palm lacks a cambium through which radial growth can occur to provide support with increasing height. Instead, palm stems rely largely on increasing the thickness and degree of lignifications of older cell walls leading to radial and longitudinal gradients in tissue density. The stem of bamboo has a radially varying volume fraction of "fibers", increasing its flexural rigidity (Gibson 1995). Plant stems resist both axial load (from their own mass) and bending moment (from wind loads): structurally, they act as beam-columns. Plant stems are axis-symmetric: their cylindrical tubes are able to resist wind blowing form any direction equally. Local buckling is accounted for by internal pressurization of the stem and support of a dense stiff outer shell by an elastic foundation of foam-like material (Gibson 1995).

More specifically, wood consists of cellulose fibers in a lignin, hemicellulose matrix, shaped to hollow prismatic cells. Skin, tendon and cartilage are all largely collagenous composites: in skin, the collagen is sandwiched between a basement membrane and an overlying keratinized epidermis; in tendon, the collagen fibers are aligned to form rope-like structures which make up most of the volume; and in cartilage, the collagen fibers are in a proteoglycan matrix with a small volume fraction of elastin fibers. Hair, nail, horn, wool, reptilian scales and hooves are made of keratin while insect cuticle is largely chitin. Bone, shell and antler are composites of calcite, hydroxyapatite or aragonite platelets dispersed in a helical matrix of collagen (Vogel 2003).

2.8 The Advantages of Material Distribution over Material Assembly

Fibers can be seen everywhere in Nature, and across multiple scales. Like engineering materials, natural materials can also be grouped into classes the common denominator of which is that all natural materials are made of fibers. They include: (1) Natural ceramic and ceramic composites include bone, shell, coral, antler, enamel and dentine. All are made up of ceramic particles such as hydroxyapatite, calcite or aragonite in a matrix of collagen; (2) Natural polymers and polymer composites include cellulose, chitin, silk, cuticle, collagen, keratin and tendon; (3) Natural elastomers such as skin, muscle, cartilage, artery, abduction, resilin, and elastin; (4) Natural cellular materials such as wood, cancellous bone, palm and cork all have low densities because of the high volume fractions of voids they contain. They are almost always anisotropic because of the shape and orientation of the cells and of the fibers they contain; the prismatic cells of wood, for instance, give a much greater stiffness and strength along the grain than across it.

Fibrous composite structures in nature are used mainly for three functions: (1) to introduce and exploit heterogeneity and anisotropy (locally and globally); (2) to modulate the tissue's physical properties; and, (3) to create functional architectures and shapes through structural hierarchies. All three functions are clearly interrelated.

Nature's capacity to structure its material organizations in a variety of different ways by which to efficiently and effectively correspond to multiple functions has various advantages in the natural world. They include (1) anisotropy, (2) heterogeneity and, (3) hierarchical structuring.

2.8.1 Anisotropy

Anisotropy is the property of being directionally dependent. It implies the heterogeneity of physical and mechanical properties relative to their functions. Anisotropy can be defined as a difference, when measured along different axes, in a material's physical property (absorbance, refractive index, density, etc.) Wood, as previously demonstrated, is a naturally anisotropic material. Its properties vary widely when measured with the growth grain or against it. For example, wood's strength and hardness will be different for the same sample if measured in differing orientation. The advantage in controlling the directionality of physical and mechanical properties results in highly efficient structures and forms customized to their environment and tailored to support the range of constraints introduced to them by their immediate environment.

2.8.2 Heterogeneity

Heterogeneity allows for the generation of position-dependent material properties. It is here considered as higher-level anisotropies accounting for non-homogeneous distribution of fibers with multiple directions (Figures 2.13, 2.14).

2.8.3 Hierarchical Structuring

The emergence of hierarchical structures in natural tissues and specimens is promoted by anisotropic material structuring resulting in heterogeneous organizations that, when superimposed, enhance the mechanical performance of the substrate. Bottom-up assemblies of structures and interfaces appear as multiple material organizations form super-structures in meso-, and macro-scales.

2.9 Natural Dichotomies on the Way to Design by Material Distribution

The distinction between materials and structures in the context of design is not a trivial one. It exists as a figure of measure related to scales of function and behavior. When we give scale to an object it acquires new meaning and gives meaning back to its environment. In this sense, scale allows us to go beyond formal representations which remain otherwise abstract in category: With scale comes a commitment to physics.

In his seminal essay *On Magnitude*, D'Arcy Thompson argues that any conception of form must be referred to in terms of magnitude and direction, "for the effect of scale depends not on a thing in itself but in relation to its whole environment or milieu" (Thompson 1952). Hence any manifestation of form must be examined not as mere representation but rather (and quite literally) as an entity embedded within its surroundings - whether physical or programmatic. Since we will be dealing with design artifacts which are physical in nature, the difference between "material" and "structure" is fundamental to the logic of material organization that is informed by performance.

In dealing with biology from an engineering point of view, Julian Vincent states that wood or leaf have obvious "structure" yet are mostly treated as materials. The resolution to this problem, according to Vincent, generally lies in behavior[2.12]: when dealing with a material, then it will have the same stiffness in tension, bending and compression in all directions. If it doesn't it is structure we're dealing with the stiffness which is being measured is not a material parameter (Vincent 1982). Materials are typically classified by charted properties such as strength, density, toughness, elongation, electrical resistively and energy content whereas structures are typically classified by behavior (Gordon 1976). For instance some structures are good for compressive loads (shells, frame structures) whereas others are good for tension loads (membranes, cable structures, etc.).

2.9.1 The Dichotomy between Shape and Size

Shape and size are of (traditional) concerns to the comparative and functional morphologist since they intrinsically define material form resulting from self-loading. The relation between shape and size is such that the size of an organism dictates the weight that must be sustained, while the shape of the organism defines the cross-sectional areas through which weight operates. Similarly, the spatial distribution of materials within an object which translates into the anatomy of a biological structure, defines the local strains resulting from a given load. Shape and size thus influence the relative magnitudes of stresses that develop within structural support members such as plant stems and tubular leaves. The importance of shape and size to biomechanics is self-evident when we consider engineering parameters called moments of area, which are mathematical descriptions of the spatial distribution of material within an object (Niklas 1992).

Furthermore, of the characteristics of organisms, only that of shape approaches size in terms of its variability; and shape proves far harder to reduce to one or a few numerical specifications. It has been a subliminal presence so far much avoided! Most of the slop in the data behind the scaling exponents comes probably from shape variability. How to deal with shape in our search for general rules of biological organization and operation? Some shape descriptions that have proven useful are: center of gravity (or, center of mass), moments of area, center of buoyancy (center of volume), fractal dimension, flatness index.

[2.12] There are also exceptions: single crystals can be anisotropic.

2.9.2 The Dichotomy between Structure and Material

Given that cost-effective and durable structures are the result of constraint negotiations carried over millennia, biological materials do not typically distinguish between material and structure (Rogers 1993). Furthermore, in Nature, the distinction between intelligent material systems and intelligent structures is basically irrelevant. Indeed, it may only be applied superficially in terms of the *scale* of a material's microstructure which governs its behavior, regardless of its size (Rogers 1993).

However, such distinction between structure and material has been repeatedly emphasized because the mechanical behavior of a structure can be understood only when its geometry and the material properties of its constituent solids or fluids are considered together. For instance, the geometry of the cell wall infrastructure within a plant tissue may in some cases supersede in importance the material properties of the infrastructure. Thus we can never disassociate the mechanical behavior of a tissue from it anatomical configuration (Niklas 1992).

The term bone refers to a family of materials, all of which are built up of mineralized collagen fibrils. They have highly complex structures, described in terms of up to 7 hierarchical levels of organization. These materials have evolved to fulfill a variety of mechanical functions, for which the structures are presumably fine-tuned. Matching structure to function is a challenge (Weiner and Wagner 1998).

2.9.3 The Dichotomy between Size and Scale

Organisms occupy an extensive size range in Nature of about a hundred million fold[2.13] : from the tiniest bacteria of about 0.3 micrometers long (a hundred thousandth of an inch) to whales of about 30 meters (110 feet) long. Vogel determines that when determining how size affects biological design, nothing is more significant than the relationship between surface area and volume (Vogel 2003). This is mainly due to the fact that any contact between an organism and its surroundings are a function of its surface, while its internal processes and structure depend predominantly on its volume[2.14]. However, in Nature, surface area and volume do not maintain a simple proportionality. In other words, one cannot simultaneously double both the surface area and the volume of a body without changing its shape[2.15] (Vogel 2003). In other words, an organism's shape determines the environmentally and functionally significant ratio between surface areas to volume.

Operational scales in biological systems have evolved to match natural scales and hierarchies of scales are often repeated in Nature. In a variety of mature adult lamellar bone[2.16] for instance, the interconnected bars known as trabeculae, and plates of bony tissue, are resized and reshaped by osteoclasts (bone-destroying cells) and osteoblasts (bone-forming cells). At the micrometer scale, there is a 'plywood' structure of layers (lamellae) of about 3 m bundles of collagen fibers. Bone salt crystals (impure carbonate apatite) fill much of the water space in the collagenous matrix as they form the bone's hierarchical structures. Similarly, when examined from the naked eye to the atomic force microscope, a piece of steel or ceramic will show a hierarchy of natural scales. In order of increasing magnification they include the sensed surface roughness, the observed grain structures with dislocations and inclusions of other phases, the space-charge regions or atmospheres of impurities around dislocations or segregated to interfaces, and, finally, atomic structures come into view. Mesoscopic features are those with characteristic scales between the atomic and macroscopic, and are crucial in how materials perform (Stoneham

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[2.13] The indicated range is equivalent to 8 orders of magnitude. When compared to the building industry one might consider a range equal to only 3 orders of magnitude from sand grain to brick.

[2.14] This is mostly true for buildings too.

[2.15] Here it is relevant to note that surfaces are proportional to the square of lengths; volumes are proportional to the cubes of lengths.

[2.16] Also known as spongy (cancellous or trabeculae) bone.

and Harding 2009).

This idea of an appropriate scale for a given system and property emerges repeatedly in natural systems. Furthermore, there might be several such scales, depending on the property. For a tree trunk, the appropriate scale for strength differs from the appropriate scale for water transport. For photochromic sunglasses, the scale for metal colloids contributing to darkening is much less than that for mechanical robustness. Identifying the right operational scales is a first step on the way to optimizing mesostructures by guiding a system to adopt the right scale.

2.10 Summary

Biological materials display exquisite hierarchical structural control designed for specific loading conditions, including the recurrent use of fundamental constituents, controlled crystallography, anisotropies and/or isotropy, orientation of structural elements, gradients, durable mechanically interlocking interfaces between dissimilar materials (compliant/ductile and rigid/hard), complex shapes/geometries, porosity, etc. (Vincent 1982; Wainwright 1982; Weiner and Addadi 1997; Weiner and Wagner 1998; Currey 2005; Ortiz and Boyce 2008)

The fundamental constituents of biological materials typically exhibit weak macro-scale mechanical properties (brittle biological ceramics and compliant macromolecules), and yet, they are able to achieve orders-of-magnitude increases in strength and toughness; this *"mechanical property amplification"* occurs in a non-additive manner that goes beyond the simple composite rule of mixture formulations (Wegst and Ashby 2004; Ortiz and Boyce 2008.

In this chapter I have chosen to focus on the structure-property relationships of co-continuous *meso-scale* composite microstructures inspired from designs observed in biology. We have seen that many natural systems assemble multiple layers of different porous microstructures together as they form higher order geometrical shapes culminating in macro-scale hierarchical designs that work together with the inherent material properties to achieve the required biomechanical function. In particular, we have focused on the strategies devised by Nature to promote heterogeneity and distribution at the *material level* (through anisotropy, heterogeneity and hierarchies), at *the structure level* (through shape adaptation along with dimensional and topological changes) and finally, at the *system level* (through emergent behavior and adaptation). We have also learned that such distinguishing traits between "material" and "structure" are at times quite elusive.

The design implications of the structuring of difference, or structural heterogeneity achieved through the informed distribution of fibers, holds significant implications from a design standpoint. Fiber structure orientation allows for an almost unlimited design space in terms of geometrical and topological variation, it promotes high levels of functional integration through the assignment of graduated properties, it supports the matching between material property distribution and continuous load paths, it allows the designer to consider the possibility of adaptive response, along with potential unlimited explorations of optimization strategies for robustness and a relatively easy integration of sensing functions.

As we have seen in previous examples as well as the detailed case studies into bones and trees, fibers represent physical line elements providing paths for transmitting, transferring and diffusing mechanical and chemical information into structures. Groups of fibres can be organised in one-, two-, and three-dimensions to create physical equivalents of lines, surfaces and solids such as those obtainable from textile technologies (which preserve fibre mobility) or composite technologies (where the fibrous networks are rigidified by bonding together fiber bundles).

As we move from the world of natural materials to artificial man-made materials in search for novel form-making strategies that comply with those of sustainable design, Nature's way will remain a revealing source of inspiration. Through the discussion in the following chapter of machine controlled braiding, filament winding, knitting, bending, twisting and nano-fiber production along with various other exciting nature-inspired design techniques, we will discover just how quickly the design world is catching up, and what major challenges remain unresolved, on the way to a more *Natural Design*.

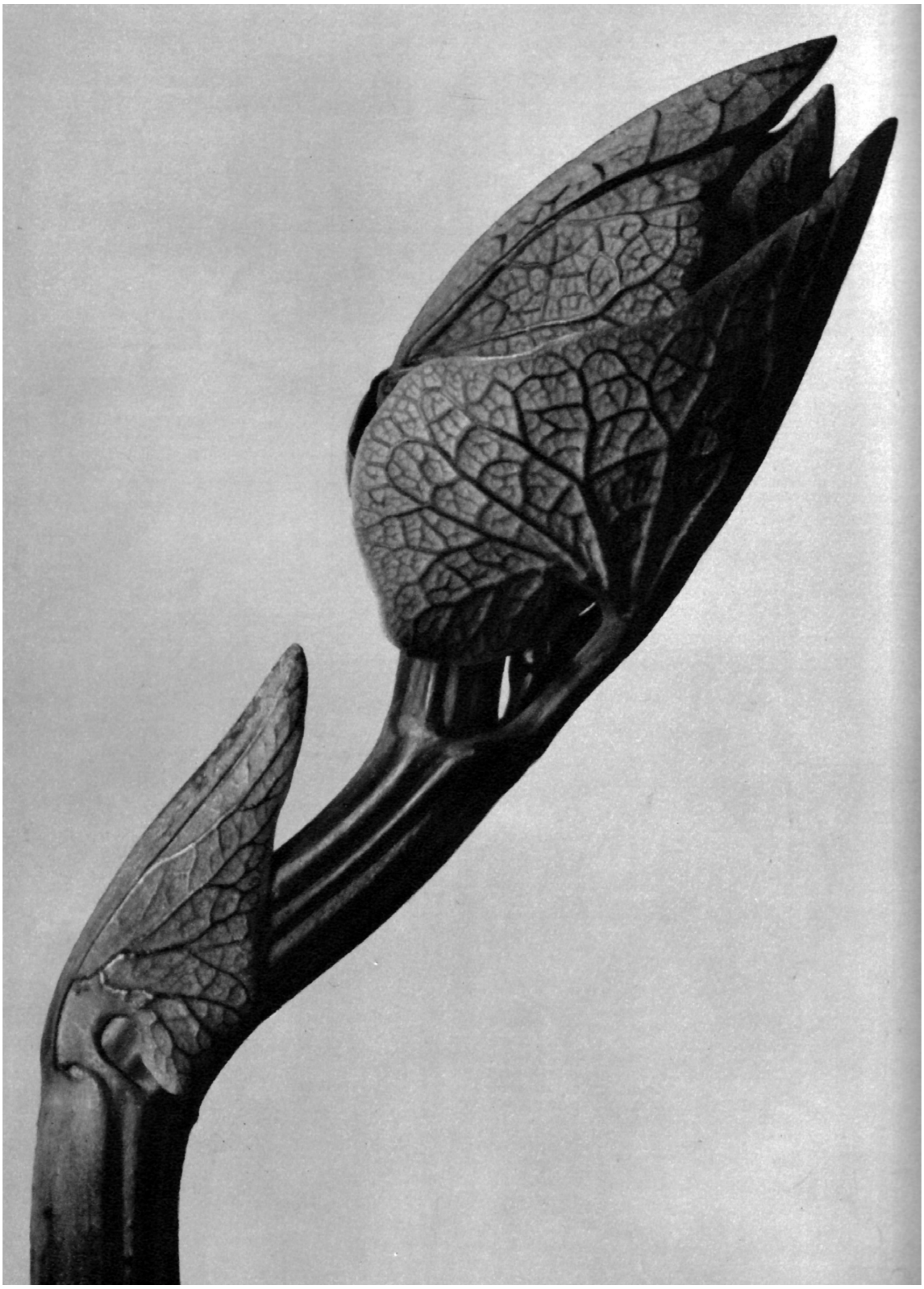


Figure 2.1: Aristolochia Clematitis by Karl Blossfeldt (Blossfeldt and Nierendorf 1982). Nature has achieved high levels of "environmental customization" by integrating multiple performance criteria. This condition is particularly evident in the plant kingdom where fiber structures are physically structured and spatially organized to combine structural functions (such as stability) with environmental functions (such as water transfer and heat absorption).

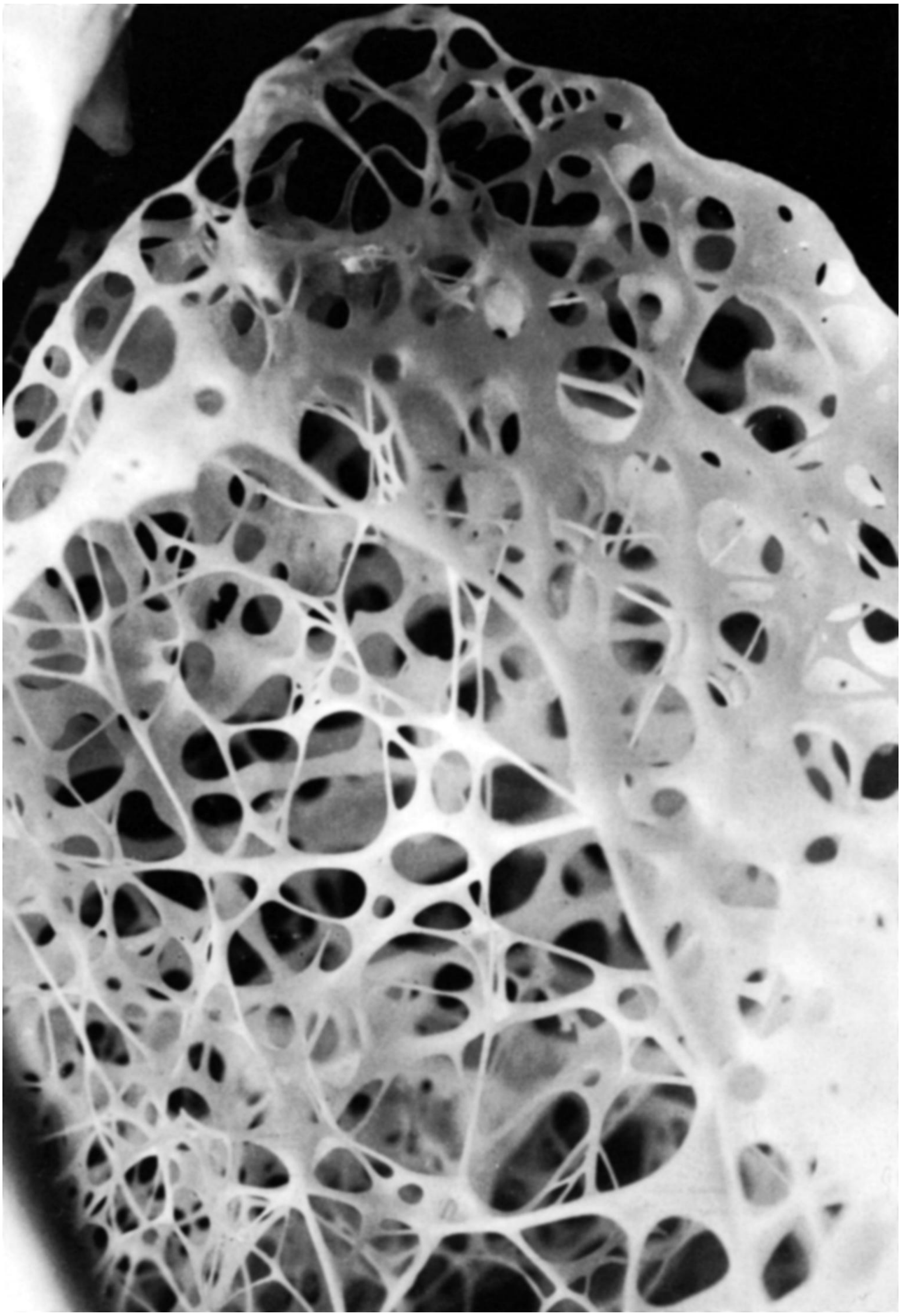


Figure 2.2: Close-up image of spongy bone from the human femur (although most femoral bone is typically denser). Photo credit: Klaus Bach, IL-archive. Nosebone of a saddle storck preparation: Paul Bhler, University of Hohenheim. Source: Otto F. et al. (1995). IL 35. Information of the Institute of Lightweight Structures (IL), Pneu and Bone. University of Stuttgart, Stuttgart, p. 243

Figure 2.3: Human femur in section revealing trabecular bone distributed along lines of tension and compression. (Reproduced from Thompson, D. W. 1992. On Growth and Form. The Complete Revised Edition. Dover Publ. NY.) Photo credit: Werner Nachtigall. Source: Nachtigall W., Blchel K., (2000). Das *große* Buch der Bionik, Neue Technologien nach dem Vorbild der Natur, Deutsche Verlags-Anstalt, München, p.243

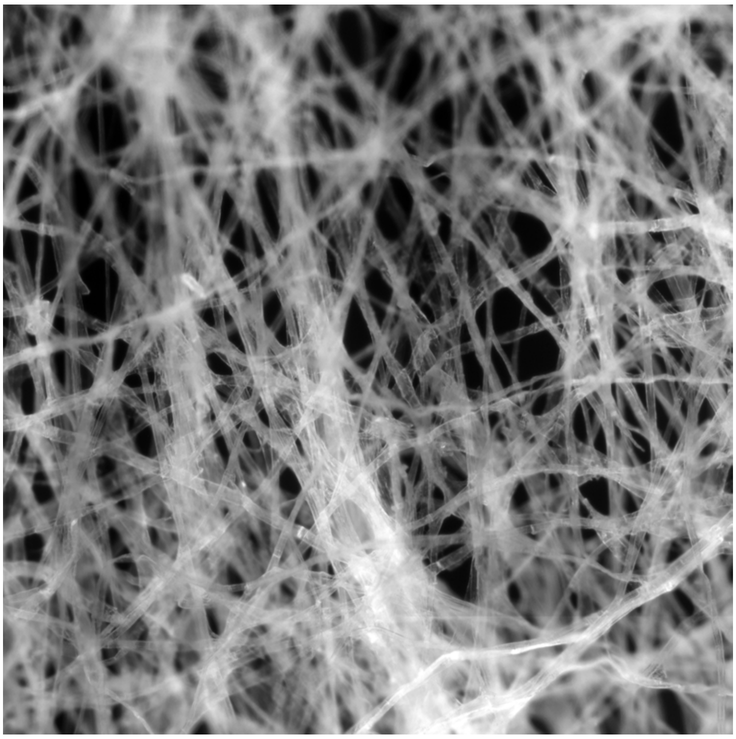


Figure 2.4: Wood fibers give the wood its anisotropic nature. By controlling fiber density and direction, material performance can be significantly modulated. Source: $http://reference.findtarget.com/search/Solid/$

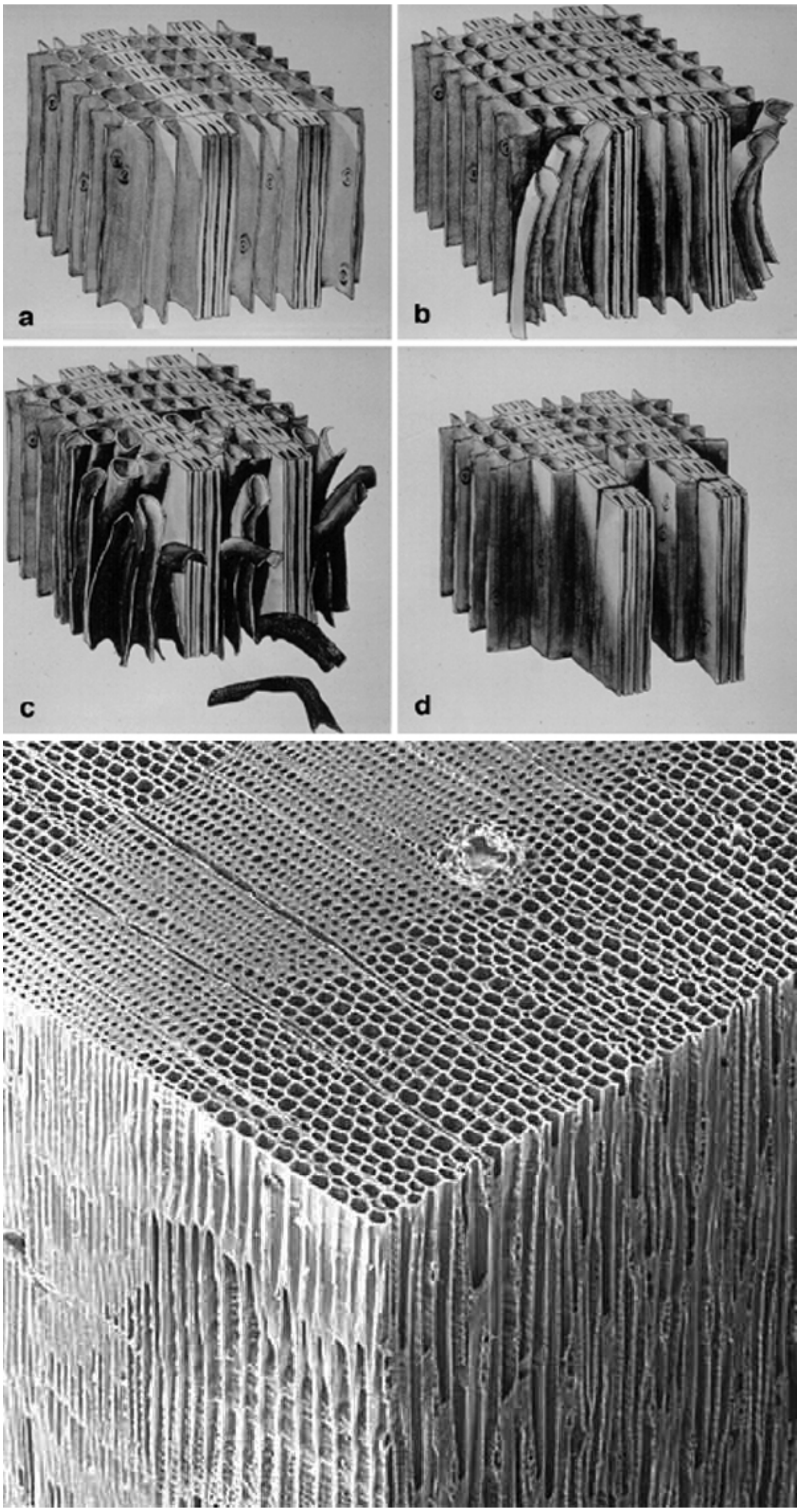


Figure 2.5: Wood fibers give the wood its anisotropic nature. By controlling fiber density and direction, material performance can be significantly modulated. Source: *http : //www.woodmagic.vt.edu/Images/activities/BigFiber.jpg*

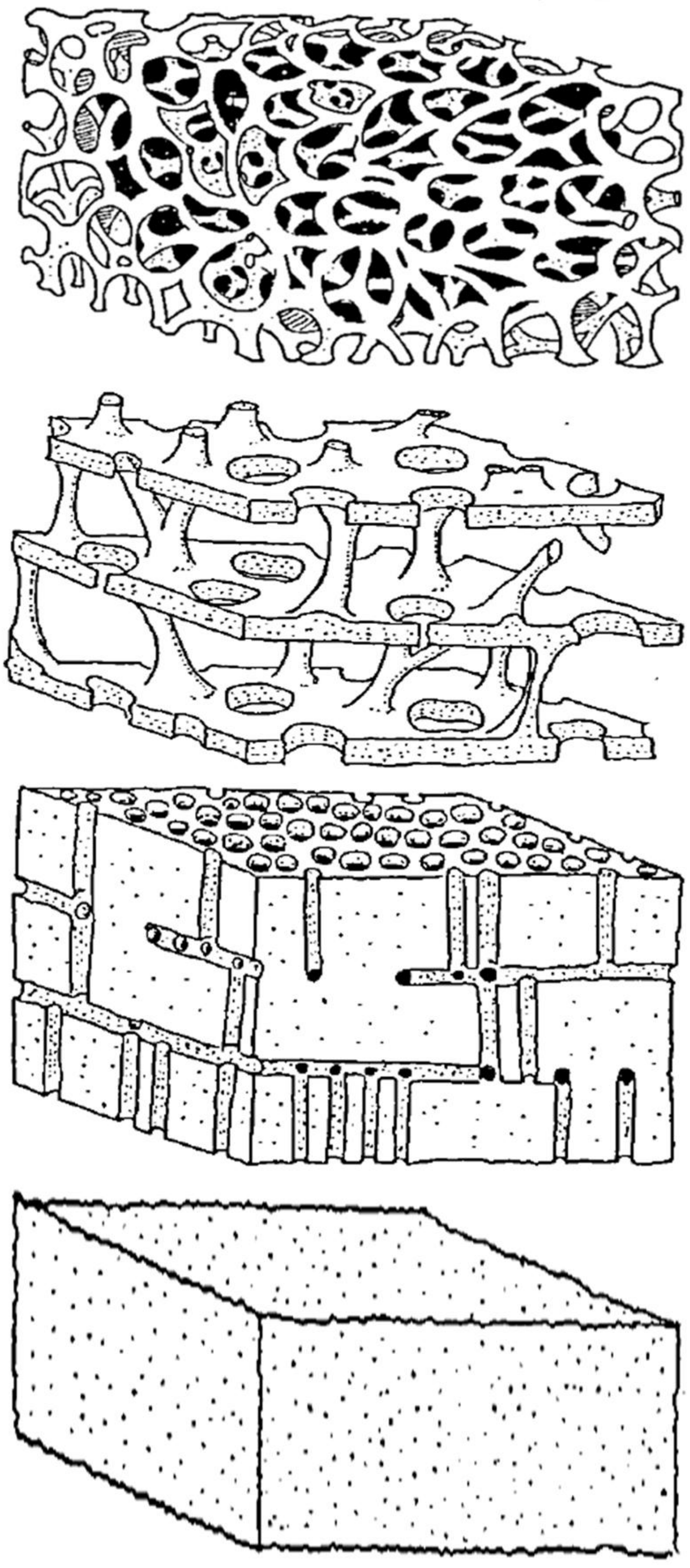


Figure 2.6: Schematics of various microstructures found in the tests and spines of sea urchins (Echinodermata). Organizational principle from top to bottom: labyrinthic, microperforate, imperforate (Smith 1980; Carnevali, Bonasoro et al. 1991).

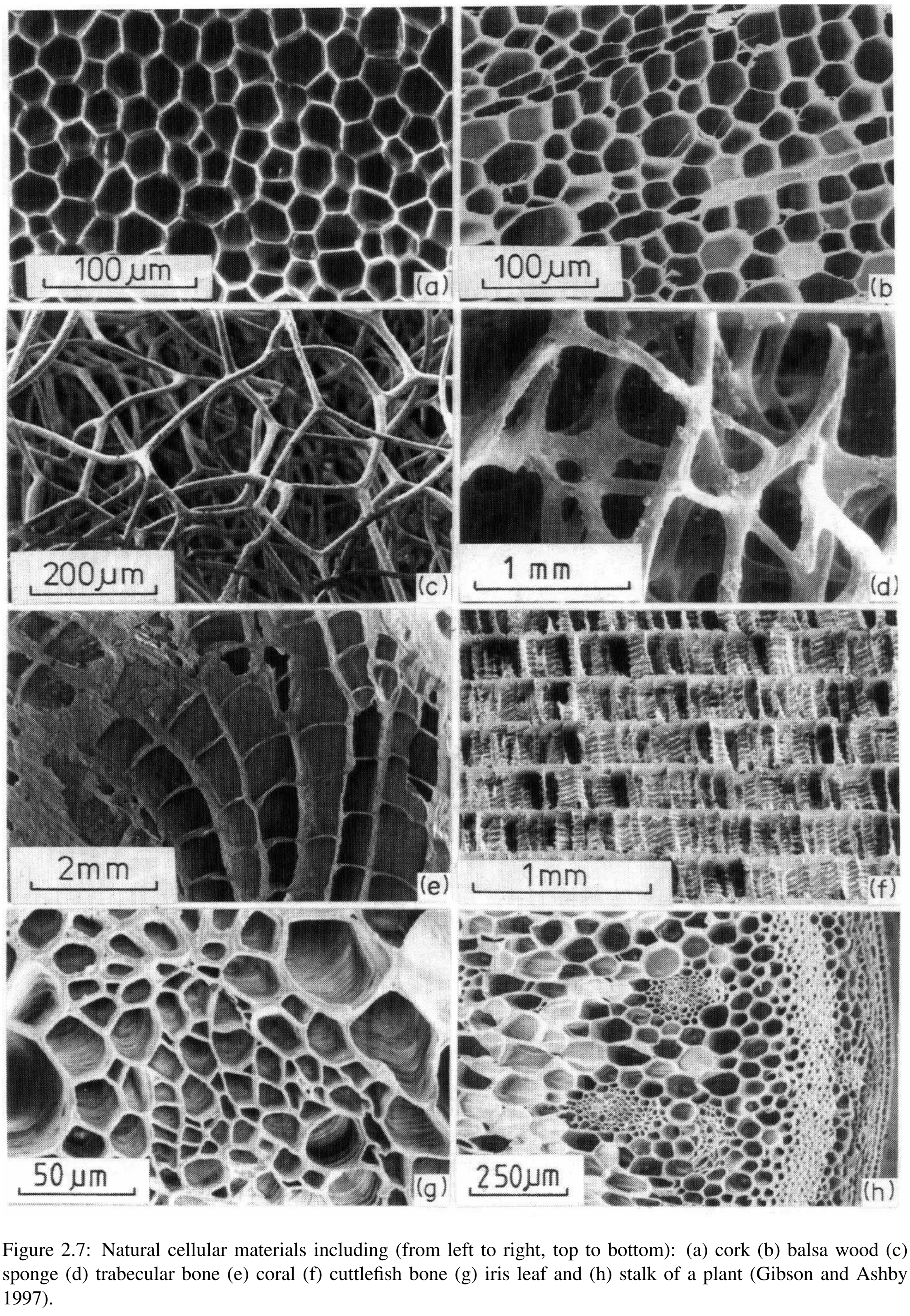
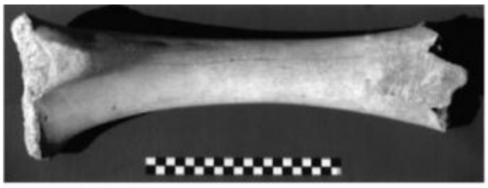
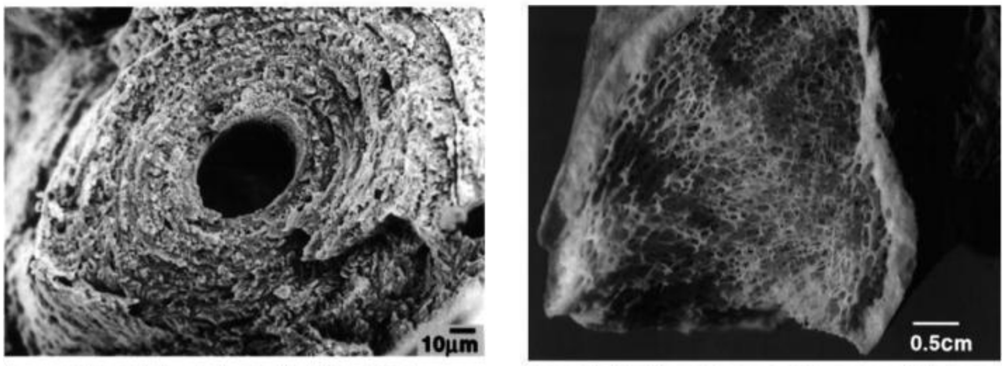


Figure 2.7: Natural cellular materials including (from left to right, top to bottom): (a) cork (b) balsa wood (c) sponge (d) trabecular bone (e) coral (f) cuttlefish bone (g) iris leaf and (h) stalk of a plant (Gibson and Ashby 1997).

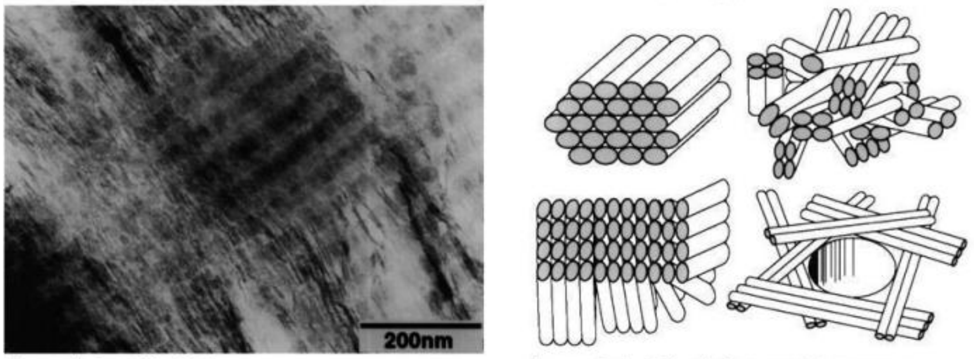


Level 7: Whole Bone



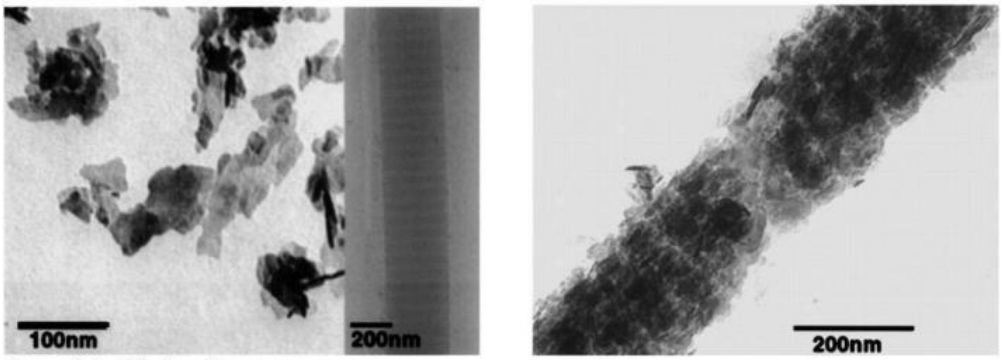
Level 5: Cylindrical Motifs: Osteons

Level 6: Spongy vs Compact Bone



Level 3: Fibril Array

Level 4: Fibril Array Patterns



Level 1: Major Components

Level 2: Mineralized Collagen Fibril

Figure 2.8: The 7 hierarchical levels of organization of the bone family of materials from. Level 1: Isolated calium phosphate mineral hydroxyapatite from human bone (*left side*) and part of an un-mineralized and unstained collagen fibril from turkey tendon observed in vitreous ice in the TEM (right side). Level 2: TEM micrograph of a mineralized collagen fibril from turkey tendon. Level 3: TEM micrograph of a thin section of mineralized turkey tendon. Level 4: Four fibril array patterns of organization found in the bone family of materials. Level 5: SEM micrograph of a single osteon from human bone. Level 6: Light micrograph of a fractured section through a fossilized (about 5500 years old) human femur. Level 7: Whole bovine bone (scale: 10 cm). (Weiner and Addadi 1997; Weiner and Wagner 1998).

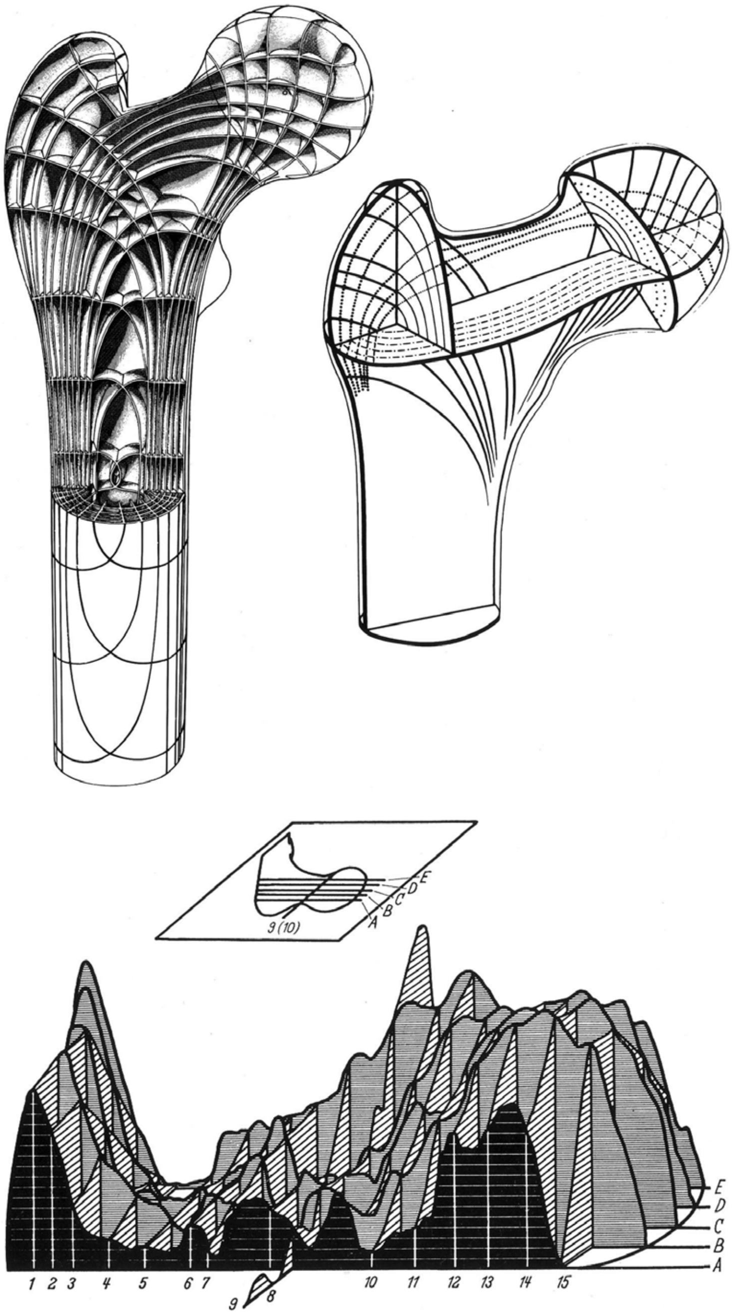


Figure 2.9: The *mountain range technique* was invented to illustrate calcium distribution in the bone as a function of the load applied. The top image represents the internal bone structure informed by load paths across the bone. The bottom image represents material distribution relative to the anatomical section examined (Otto, Herzog et al. 1990).

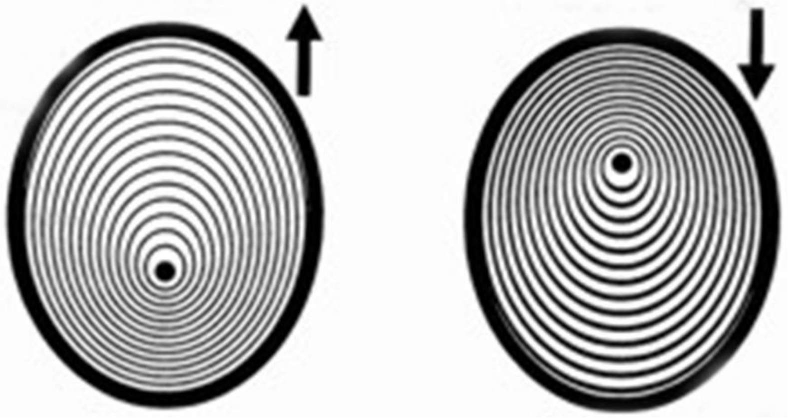


Figure 2.10: Tension wood (left) is formed on the upper side of leaning hardwood trees and is typically indicated by eccentric, or off-centre, growth rings. Known to have lower strength than normal wood, tension wood may cause warping during drying. Compression wood (right) is formed on the underside of leaning softwood trees, and is typically detected by annual rings on the underside that are wider than normal and appear to have a high proportion of summerwood. Arrows indicate leaning directions. Source: $http://www.forestry.gov.uk/fr/GGAE-5GGEJN$

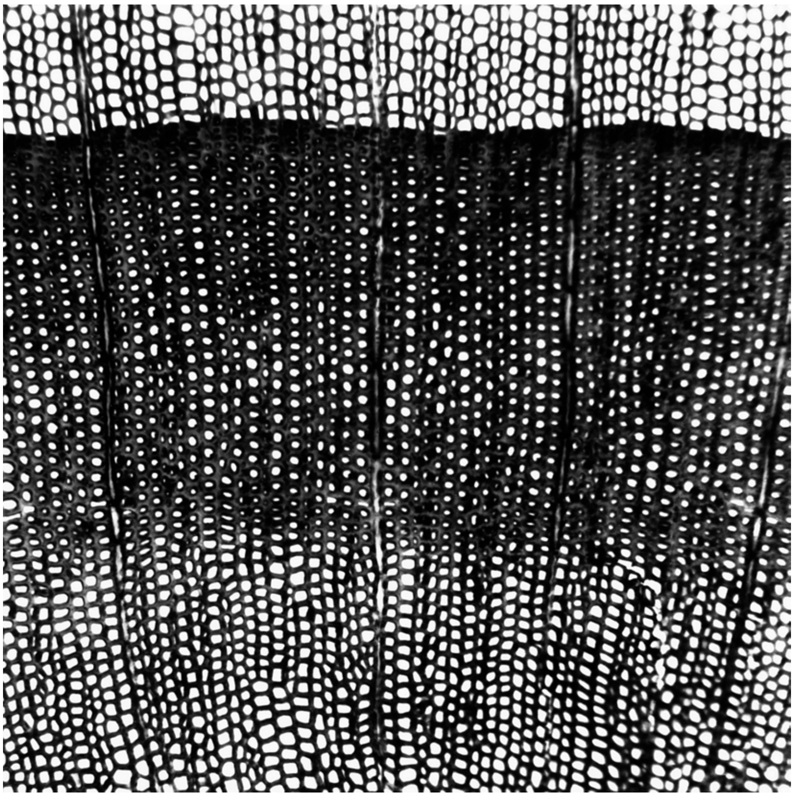


Figure 2.11: Density variation in compression wood from Juniperus spec. Source: $http://www.wsl.ch/staff/jan.esper/pics/anatomy5\_high.jpg$

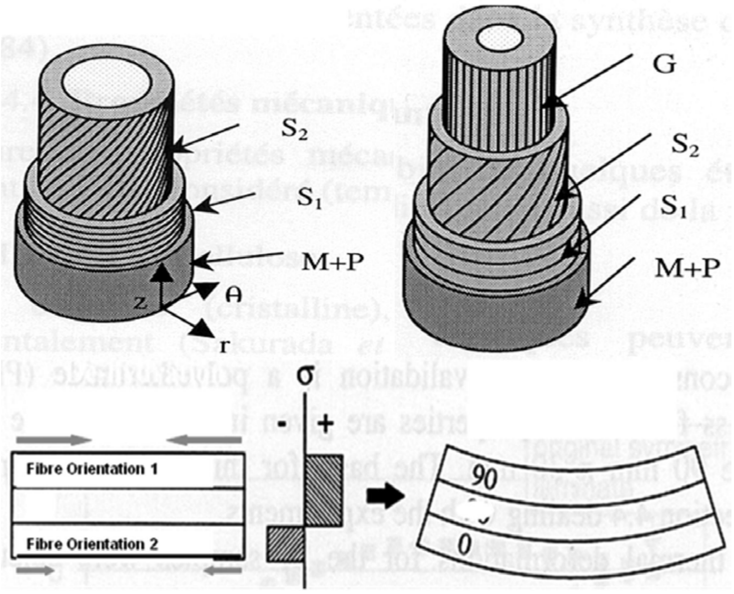


Figure 2.12: Tension wood (top right) shrinks more than normal wood (top left) during maturation (Clair and Thibaut 2001; Clair, Thibaut et al. 2005)

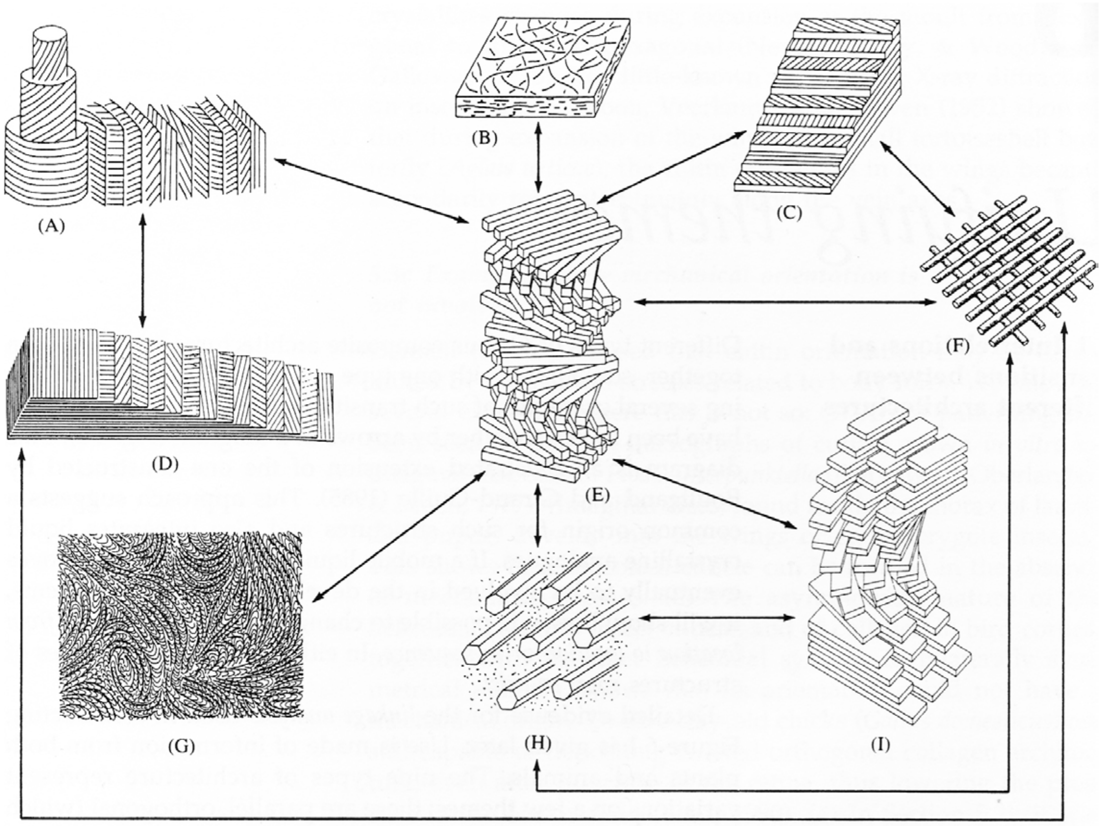


Figure 2.13: Evidence for a common origin of the diversity of fibrous composite architectures. (A) Cylindrical helicoidal (double twist) grading into planar helicoidal (single twist). Example: bone haversian system. (B) Planar random layer. Examples: parts of some plant cell walls. (C) 45 degrees helicoids. Example: dogfish eggcase. (D) Twisted orthogonal. Examples: fish scales. (E) Monodomain helicoidal (small rotation angle). Example: insect cuticles. (F) Orthogonal. Example: cuticles of cylindrical animals. (G) Polydomain helicoid. Example: mantis eggcase proteins. (H) Parallel (unidirectional). Example: tendons in arthropods. (I) Pseudo-orthogonal. Example: wood tracheids (Neville 1993)

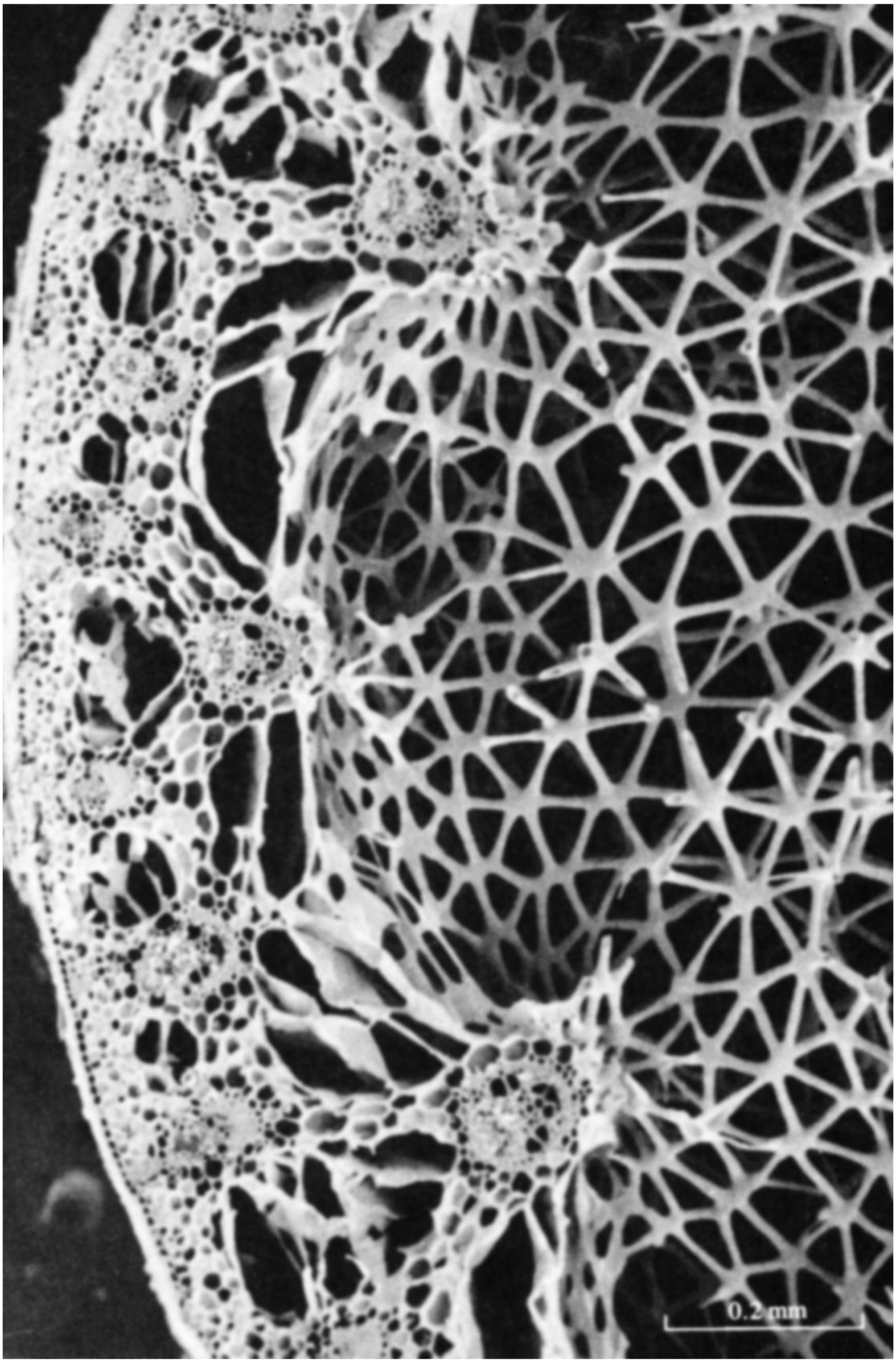


Figure 2.14: Scanning electron micrograph of a section through a stem of a rush (Juncus effesus). The pitch which fills the middle of the stem is made of a geodesic construction of tubular stellate cells, whose walls are known from arced patterning in transmission electron microscopy to be helicoidal. This image represents the dichotomies between shape, size, scale, structure and material in natural systems (Neville 1993).

CHAPTER 3

THE NEW MATERIALITY

Sources and Development of a Design Cultural Phenomenon

"Brick says: I like an arch"
— Louis Kahn

3.1 Shape over Matter: The Crisis of Form

As in Nature, when creation *begins* with matter, *morphogenesis*, or the generation of form, is a process engendered by the physical forces of Nature. Similarly, in the framework of this thesis, *Material* is not considered as a subordinate attribute of form, but rather as its progenitor. Such is the story of form told from the point of view of matter, and it begins, unsurprisingly, with form's crisis.

To paraphrase Darwin: there is more to the origin of form than the preservation of favorite expressions in the struggle for style. By way of practice we are educated to apply matter opportunistically to any given form. This inherent design methodology implicitly assumes the predominance of shape over matter in processes of form-generation. However, when the order is inverted, we find that starting with matter is not as straightforward a process as we might anticipate. Shape, it appears, (still) rules over matter.

3.1.1 Form First, Structure First, Material First: the Designer's Causality Dilemma

It is important to stress that despite momentous progress in material science, engineering and construction, material has remained inferior to shape across most scales and disciplines of design. Indeed, most literature in the realm of *materials in architectural design* has centered on questions relating to material selection rather than questions relating to material generation. Consequently, materials are traditionally pre-defined and classified as property pools in the process of design materialization. Until recently, the function of materials in design processes thus appears to be considered and persistently treated as secondary to form itself. This condition has indeed been amplified by the construction industry and digital fabrication processes which have exacerbated the tendency of the designer to materialize form by liberally accessing materials as a library of open and eclectic potential. However, this is anything but a new phenomenon. A brief historical review of early forms of craft as well as some of the most innovative, *au courant*, developments in material science and engineering, illuminates, yet again, the role of material as the substance of form, rather than form's progenitor.

In *Nature's Way* we have demonstrated an alternative path to the generation of form whereby the interaction between material properties and their environment is (naturally) prioritized and thus precedes and propagates the resulting shapes. Material behavior in Nature appears to be a prerequisite for the emergence of form, and yet in design, shape eternally comes first. Given our methods and technologies for design production, this condition is anything but coincidental. The tools that architects and designers use today in the processes of form representation and generation assume geometric form's instrumental superiority. In design, the process appears as simple and as straightforward as that: imagine, draw, apply and analyze; construction follows. Invert this process, and you will, again, arrive at Nature's Way.

3.1.2 Origins of a New Materiality in Design

To claim that the prioritizing of material in design is a recent discovery would be profoundly inaccurate. The history of material science and engineering is a testament to cultural production and a protocol of the way in which humans have interacted with their environment in their search for shelter, habitation and well-being (Ashby 1995). The significance of materials in the development of early civilizations is attested to by the way in which archaeology has divided technological progress into eras defined by materials endemic to them: the Stone Age, the Bronze Age and the Iron Age. Today's epoch may be described as the Materials Age, as a result of new developments in materials and technologies which have dramatically altered the way in which we make, build and live (Ashby 1995). Indeed, one of the most thrilling precedents in the design of materials to date is the evolution of composites in all classes and scales. Composites are a central chapter in the history of twentieth century technology as demonstrated in Antonelli's "Mutant Materials" exhibition at the Museum of Modern Art more than a decade ago (Antonelli 1995). Yet even with the testament of such emerging tendencies of a design culture of the material, the problem of material's inferiority complex to shape still lingers as a design cultural phenomenon characteristic of the theory and practice of modern design.

The literature concerning material in design is vast, though for the design researcher, it is also overwhelmingly fragmented. A survey of this open-ended field indicates the wide array of research areas representing, exploring, classifying and researching the topic. There are many scientific and design views of what may constitute the physical and behavioral characteristics of materials, and even more interpretations for each view. However, most importantly, each of these views may be useful to a particular construct of a given field and for a given application (Addington and Schodek 2005).

The breadth of interest and activity around new and innovative materials and material technologies today is one of the dominant influences upon contemporary architectural and industrial design. Kwinter has referred to material as "the new space" (Kwinter 2001). This tendency is so prominent, in fact, that the drive for material innovation in recent years has been broadly absorbed into the design and research of mainstream practice (Balmond, Smith et al. 2002; Addington and Schodek 2005). The design professions as a whole have experienced the renaissance in materials over the last few years. In addition to key publications and relevant excerpts from journal articles, leading exhibitions and publications highlight the role of materials in design. In particular, design interest and experimentation with composites and textile-like material design (McQuaid and Beesley 2005; Ritter 2007) has been abundant and exposed the need to consolidate our methods and our practices.

This *new materialism* appears to have a diverse and complex influence upon contemporary design. Historically there are two distinct ways of influencing design. The first quickly absorbed material as a stylistic and formal phenomenon, while the second is more profound in exploring the complex interrelations between science, technology and design that have only begun to emerge (Antonelli 1995; Antonelli 2008).

The literature on the topic of *smart*, or *intelligent*, materials, and *material systems* is vast and has accumulated over the last decade to include designations as varied as the disciplinary contexts in which they originated (Gordon 1976; Addington and Schodek 2005; McQuaid and Beesley 2005; McQuaid, Beesley et al. 2005; Braddock Clarke and OMahoney 2007; Ritter 2007). However, there exist two prevalent paradigms which may be used to classify most such designations (Rogers 1993). The first definition is based upon a *technological paradigm* and relates to the integration of actuators, sensors, and controls embedded within a material, or structural component. Such a definition specifies the elements comprising the material but avoids completely addressing its utility and the means by which it has been fabricated and assembled. The second definition is based upon a *science paradigm* and it attempts to relate predominantly to the material's micro-structure as a system capable of informing its functionality. Related sets of definitions in this paradigm include both the material's structural functionality its ability to reduce mass and adapt to changing energetic constraints, and the way in which it has been fabricated.

A detailed inspection of the relevant literary sources quickly communicates the well-known mentality in architectural-design whereby materials are typically selected, not designed. Several material selection routines and ways of classifying them have evolved over the years by and for different disciplines. The choice of material cannot be made independently from the choice of process by which the material is formed, joined, finished, and otherwise treated (Ashby 1995; Ashby 2005). Similarly, the revival of material consciousness in design is most likely associated with the fast rate at which fabrication technologies are entering contemporary discourse. As such tools develop, principles of material science and technology merge with other specialties such as engineering, chemistry, biotechnology, and information science (McQuaid and Beesley 2005). This interdisciplinary state of design knowledge is rapidly finding its way where the most pressing issues and questions concerning the generation of form arise.

This chapter focuses on the latter class of materials and explores the material's structure and behavior as defined by its properties devoid of the introduction of electronics. The aim is to explore the potential to reorganize matter from a purely physical perspective. Furthermore, it provides a critical review based on a survey of the state-of-the-art of materials in design. It will start by questioning material's role as shape filler, and point towards a potential shift in design process and thinking. It will highlight the roles materials currently possess as secondary to the generation of form itself, and in most cases tertiary to form's rationalization as structural entity by the engineer. On the basis of this introduction it will raise key research issues and will propose a novel definition of new materiality as a non-hierarchical association between form, structure and material.

3.2 The Component Syndrome: Expressions of a Design Cultural Crisis

3.2.1 Form as Iconic Shape

Architecturally speaking, when we think of "form" we think of the shape of a thing and how it might be described in terms of its geometry. For thousands of years, the largest structures on earth were the pyramids, but rarely does one refer to the distribution of load when describing the shape of a monumental tetrahedron. The nature of this claim remains consistent across the periods from ancient Egypt to Bilbao. Form is a category of description as opposed to a causal condition as it might be described in Nature.

Furthermore, it is a well accepted in architectural practice that preconceived spaces of various forms and shapes have been conventionally designated for generic classes of functions. To challenge this classical space-making tradition, architects have recently begun to exploit emergent technologies in the construction industry supported by a body of inventions in processes and materials. And, indeed, the general prevailing assumption amongst many architects and designers is that all that is imaginable is buildable. We are approaching an era in which this assumption is not too far from the truth. But coupled with it, are many less exciting consequences, particularly when considering the environment. This, the architect's passionate search for form, has prioritized formal expression and consequently deeply victimized environmental sustainability. A materials-based approach to design, potentially replacing this form syndrome with material sensibility, may be of significant impact in today's climate of environmental crisis.

3.2.2 Form as Assembly: Habitat as Machine for Producing Obsolescence

Building by components is everywhere. They are the prevalent means by which to describe and construct form's physical manifestation. Given that we cannot yet *grow* a design, as does Nature, we assemble it. Material assemblies have been around for many centuries. It was the industrial revolution however, in the late 18th century that has planted the seeds of componentization as the logic for the mass-produced product.

With mass-production came ideas in design that conceived human habitat mechanistically, that is as a living machine. Its advantages were clear and economically viable: all parts could be replicated, replaced and reassembled in adaptation to change. However, this conception carried with it certain serious disadvantages which were soon to damage the natural environment. Material redundancy and waste express only a small segment of what might be considered the condition of industrial pathology. The building industry may still be identified with the value system projected by the industrial revolution: standardization, homogenization, modularity, redundancy and repeatability. However, most or all of these characteristics of industrialization are antithetical to Nature's Way. Thus it comes as no surprise that the economy and design culture of obsolescence are in profound contradiction to the contemporary search for a more sustainable design practice.

Form driven by the design and control of materials across multiple scales may lead the way to a more environmentally responsible, structurally sound, and no-less formally expressive design approach.

3.3 The Selection Syndrome: Methodological Expressions of a Design Cultural Syndrome

Given material's typically secondary role in the expression of shape, the consideration of material as "shape filler" comes as no surprise. As such, material is characteristically selected from an array of potential matches between its properties and its hosting form. Ashby claims that the selection of a material and process cannot be separated from the choice of shape (Ashby 1995; Ashby 2005). Such a claim makes reasonable sense considering that each material presents the designer with its own set of properties as well as geometrical and structural constraints. However this logic maintains the continued priority of shape over matter.

3.3.1 Beyond Material as Shape Filler

There exist various ways by which to classify materials. Material science and engineering classifications typically deal with material composition and properties. Reflected in such classifications are insights that provide a way of describing specific properties or qualities such as hardness, electrical conductivity, etc. that characterize different materials[3.1]. Consequently, while the material scientist is occupied with

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[3.1] The Representative Volume Element (RVE) is one such way of classifying material properties within a singular volume element. This concept is central to the mechanics and physics of random heterogeneous materials with a view to predicting their effective properties. The RVE size is associated with the estimation of the desired overall property of a material relative the relationship between the structure of materials at atomic or molecular scales and their macroscopic *properties*, the structural engineer engages with material *behavior*. In selecting the optimal material for a given function, the engineer must weigh categories such as state, structure, processing techniques, environmental conditions, and applications (Addington and Schodek 2005).

Michael Ashby's material selection charts provide the designer and engineer with a highly efficient template of classification (Figure 3.1). In his *Material Selection in Mechanical Design* (Ashby 2005), Ashby introduces a design tool for materials selection in engineering. It provides a highly consistent and systematic compilation of materials, their properties and applications in design.

Ashby classifies the family of engineering materials as six families including metals, polymers, elastomers, ceramics, glasses, and hybrids (Ashby 2005). Family members have a number of features in common such as properties, processing routines, and, often, similar applications. The family of hybrids includes combinations of two or more materials in a pre-determined configuration and scale. They include fiber and particulate composites, sandwich structures, lattice structures, foams, cables and laminates. Fiber-reinforced composites are of course the most familiar and incredibly desirable for their combination of lightness, stiffness, strength and toughness.

Ashby's material property charts were developed as a response to the designer's need for an efficient materials selection process based on multiple criteria. Since it is almost always the case that the designer is interested in a combination of properties rather than a singular one, each material is presented as having a *set* of attributes. In this way, ratios of strength to weight, and weight to stiffness may be considered in plotting one property against another. The resulting charts are useful in that they condense a large body of information into compact and accessible form. They reveal correlations between material properties that aid in checking and estimating data along with a characteristic span of values (Ashby 1995; Ashby 2005).

3.3.2 From Selection to Formation

Materials by themselves, however, require the application of innovative technologies, tools, and techniques that process them into shapes desired to fit their functions. In other words, the way in which a material may be treated, directly affects its performance and its functional traits. The distinction between *material* and *matter* carries much relevance in this context, the latter being traditionally associated with the notion of an omnipotent substance that may be made into any desired shape (Smith 1980; Smith 1981). Such "making" or "structuring" of matter, involves a deep understanding of material properties and their capacity for physical manipulation.

Recent advancements in material science and engineering have introduced the notion of designing material behavior. The field of composite materials, specifically, the field of Material Science has enhanced the designer's capability to influence and control material behavior. All industries are equally inspired and affected by this climate while most design fields are contributing to the pool of exhilarating turn-of-the-century products; architecture, building construction, civil engineering, transportation, medicine, agriculture, sports and fashion are all imposing pressing challenges on the state of design in the reinterpretation of the role of materials. This is unquestionably the age of materials.

As tools for the generation, production and construction of form turn into integral parts of computational environments for design. Through the concept of material behavior the physical qualities of form itself

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to the number of realizations of a given volume V of microstructure that one is able to consider. It is shown to depend on the investigated morphological or physical property, its contrast compared to the materials' constituents, and their volume fractions. RVE sizes can be found for a range of physical properties including elastic strain energy and thermal conductivity, but also for geometrical properties such as volume faction Gusev, A. (1997). "Representative volume element size for elastic composites: a numerical study." Journal of the Mechanics and Physics of Solids **45**(9): 1449-1459.

is gaining new interpretations.

3.4 Nature's Way: Environmentally Informed Structural Heterogeneity

3.4.1 Anisotropy: Nature's Difference Engine

Traditionally, we tend to classify materials, along with their various properties, either as structural or as functional (Stoneham and Harding 2003). Structural materials are mainly exploited for their mechanical properties, while functional materials have some other purpose, in relation to electrical, thermal, optical properties, or combinations of them. In Nature, however, it is often quite challenging to distinguish between structural and functional materials as most biological materials such as wood can be both structural (supporting the branches of a tree) and functional (pumping water up to the leaves), with different scales for these different roles.

Nature achieves such integration by varying the material's properties and introducing in it directional (structural) changes relative to their functions. This ability is termed anisotropy and has been briefly described in the previous chapter. Generally speaking, anisotropy is defined as directional dependency. It is expressed as a given difference in a material's physical property (absorbance, refractive index, etc) when measured along different axes (Bar-Cohen 2006). Wood for instance, is a naturally anisotropic material. Its physical properties vary widely when measured along the growth grain or against it (in other words, there is a dependence of the Young's modulus on the direction of load. This is also the reason why wood's strength and hardness will be different for the same sample when measured in unique orientations. The directional dependency of a physical property is easily found in most natural materials. Fiber-reinforced composites and composite materials, in general, are highly anisotropic, displaying greater strength along the grain/fiber direction than across it.

Anisotropy is central to the structuring of materials and their behaviors. In the fields of Material Science and Engineering, the concept of anisotropy is tightly linked to a material's microstructure defined by its grain growth patterns and fiber orientation. However, beyond such scales, anisotropy may be utilized as a design strategy. In design, examples vary depending on the type of property being examined and the manufacturing technology applied to manipulate material organization. Over the last decade, advancements in textile design have proved, yet again, the distinctive role fibers play in the design of products and environments. High-performance textiles are everywhere: car-skins, skier's helmets, spacesuits, motorcycle racing gloves, sail boats, and ropes with integrated conductive fibers. Interestingly, some of these applications transcend the scale of the micro.

Finally, anisotropy is without a doubt one of the most important properties for a designer operating at the heart of contemporary design culture. Its many potential interpretations as a method for controlling material organizations seem incredibly promising in an age where developments in material science impact processes and products in design. Yet the extent to which anisotropy is explored as a generative means to create form is still rather limited and unexplored. If one were able to model anisotropy in digital space, prior to the actual production of form, what would it look like?

3.4.2 Towards an Artificial Anisotropy

Gordon's seminal book *The New Science of Strong Materials* or *Why You Don't Fall through the Floor* (Gordon 1976) proposes that a new science of strong materials is emerging as designers are able to modify and improve materials by understanding their behavior. Gordon predicts that the coming new engineering materials will resemble much improved versions of wood and bone more than they will the metals with which most contemporary engineers are familiar[3.2].

One may consider that this new age of engineering materials allows the architect to move from a culture of material selection to that of material design. Such is the case of textile-inspired building concepts that have been addressed recently by a number of design practitioners in the field. The FESTO company for example has been investing in research and development of extreme textiles for inflatable structures. Most recently, Philip Beesley and Sean Hanna have contributed to an important publication highlighting design achievements in extreme textiles as part of a major exhibition displayed at the Cooper Hewitt National Design Museum in 2005 (McQuaid and Beesley 2005). In the chapter "Transformed Architecture" (McQuaid and Beesley 2005), Beesley and Hanna identify the advantages of textile structures designating them as highly flexible, strong and lightweight. An example of the exploitation of these concepts are Peter Testa's carbon-fiber towers which offer a strategy to eliminate joints and abrupt changes in material by producing continuous extrusions of carbon-fiber composite cables.

3.5 The Promise of Composites: Towards a Natural Artifice

It is well accepted that the properties exhibited by structural materials are governed by their chemical composition and the spatial arrangements of their constituents across multiple scales. The quest for superior material properties has typically been dominated by sources of raw materials and discoveries in processing conditions. Significant improvements in material science and engineering, however, have afforded the designer with the ability to design microstructure-property relationships and processes by which to control material chemistry and microstructure.

With the introduction of composite materials, designers can finally prioritize material design over material selection. In the following section we review precedents from the world of craft as well as high-tech designs demonstrating the designer's ability to control material properties and relate them to some global function. In this way, a new design approach may be promoted in which material properties may vary continuously in order to correspond to external structural or environmental requirements.

3.5.1 Foams: Variable Property Density

Foams are cellular materials which hold large quantities of air. Almost any material can be foamed, and different techniques are applied in order to foam different types of solids. Amongst them are polymers, metals, ceramics, glasses, and composites (Gibson, Tonyan et al. 1992; Gibson 1995; Gibson and Ashby 1997). When foamed, these cellular solids become lighter. This process allows the designer control over other sufficient related properties such as density, thermal conductivity, Young's modulus and compressive strength. Foams are therefore often used as shock-absorbing materials, and heat or sound insulators. In this sense, foams significantly extend the range of properties available to the designer and engineer (Gibson, Ashby et al. 1987; Gibson and Ashby 1997)

Foams are frequently classified as rigid, semi-rigid and flexible. Their cells are either open or closed and, as a result, their capacity to absorb water or air, as well as their capacity to return to their initial shape after deformation, varies. There are so-called 'delayed' or 'memory' foams or viscoelastic foams, which return very slowly. Foams are commercially identified by their density (g/cm^3 or kg/m^3). Plastic foams are commonly obtained by the expansion of a gas liberated by a chemical process. Polyurethane foams are the most common: flexible (for mattresses, cushions, and chairs) or rigid (expanded foams used for insulation in buildings). There are latex foams at the higher end of the market but with an average mechanical strength which as a result need protection (covering or a polymer skin). Aluminum

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[3.2] In this context, Gordon introduces a profound overview of elasticity and the theory of strength, non-metallic materials (timer, cellulose, glue, plywood and composites), the metallic tradition and beam formulas.

foam very light cellular material very strong in compression is used as the core of a sandwich material or for its dramatic aesthetic aspects; copper foam for its electrical conductivity, recycled glass foam is used as an insulating covering material.

3.5.2 Composites: Variable Property Elasticity

Composites have been around for centuries. Artisans and craftsmen have throughout history exploited the diverse properties of materials as they mastered skillful techniques to combine and convert raw materials into objects of consumption and beauty (Smith 1981). Among the most primitive composite materials to have existed were straw and mud in the form of bricks for building construction.

Typically, there are two categories of constituent materials - matrix and reinforcement - which make up a composite. At least one portion of each type is required. The matrix material surrounds and supports the reinforcement materials by maintaining their relative position. The reinforcements impart their special mechanical and physical properties to enhance the matrix properties. Such synergy produces material properties that are superior to many natural materials. Due to the wide variety of matrix and reinforcement materials available, the design potential of composites is incredible.

3.5.3 Functional Gradient Materials: Variable Property Synthesis

The distribution of material properties as a function of their performance requirements at micro structural scale is elegantly exemplified with the development and application of Functional Gradient Materials (FGM's). The term was developed in the mid 1980's in Japan in the design of a hypersonic space plane project where a particular combination of materials used would be required to serve the purpose of a thermal barrier capable of withstanding a surface temperature of 2000K and a temperature gradient of 1000K across a 10mm section.

The general idea of structural gradients was initially proposed for composites and polymeric materials in 1972 (Miyamoto, Kaysser et al. 1999) but it was not until the 1980's when actual models investigating the design, fabrication and evaluation of graded structures were proposed (Figure 3.2).

Functionally graded materials are a new generation of engineering materials characterized by compositional and structural variation across their volume unit, resulting in property changes in the material such as mechanical shock resistance, thermal insulation, catalytic efficiency and relaxation of thermal stress (Miyamoto, Kaysser et al. 1999). Spatial variation is achieved through non-uniform distribution of reinforcement phases (regions of space with unique chemical uniform and physically distinct characteristics). Reinforcements are inserted with different properties, sizes, and shapes, as well as by interchanging the roles of the reinforcement and matrix phases in a continuous manner. The resultant microstructure is characterized by continuously or discretely changing its thermal and mechanical properties at the macroscopic or continuum scale. In this way materials can be designed for specific functions and applications.

Various approaches exist which are used to fabricate FGM's such as perform processing, layer processing and melt processing. The basic structural unit of an FGM resembles biological units such as cell and tissues, and is referred to as an *element* or a *material ingredient*. Bamboo, shell, tooth and bone are all made up of graded structures consisting of chemical, physical, geometrical and biological material ingredients.

The concept of FGMs is revolutionary in the areas of material science and mechanics as it allows one to fully integrate between material and structural considerations in the final design of structural components. FGMs are applicable to many fields. In the engineering applications it is applied to cutting tools, machine parts, and engine components. Various combinations of these ordinarily incompatible functions can be applied to create new materials for aerospace, chemical plants, and nuclear energy reactors. However, the application of FGMs in product and architectural design construction scale has not been thoroughly researched and developed.

Functionally graded materials stand out as a special class of materials characterized by the gradual variation in composition and structure over volume, resulting in corresponding structure-property relationships. Unlike any other class of materials, FGMs are "designed materials", assembled rather than selected for a particular function or application. Given the designer's freedom to define the material microstructure based on its properties, any composite material could be made simply by varying the microstructure from one material to another with a specific gradient. Such processes facilitate the designer with the possibility of combining the ultimate properties of each material into one. Generally approximated by means of a power series, the transition between the two materials is achieved by combining several discrete layers, each containing localized optimal properties. Here, the notion of "units" is relevant insofar as it defines the micro-structural property of the material relative to its attributed mechanical functions.

The basic unit for FGM representation is the *maxel* (Miyamoto, Kaysser et al. 1999). Its attributes include the location and volume fraction of individual material components. The term *maxel* is also used in the context of additive manufacturing processes to describe a physical voxel defining the build resolution of a rapid prototyping or rapid manufacturing process, or the resolution of a design produced by such fabrication means.

3.5.4 Blurring the Boundaries between "Material" and "Structure"

The parting between "material" and "structure" in the material world, material being associated with the artificial built environment, has been the direct result of the hierarchy implied by the design process itself. Material, in the traditional sense of the word and the concept, is theoretically reduced to act as the "filler of form". By practical extension, "material" has traditionally been regarded as homogeneous and consistent in properties, effects and appearance. Only recently, with advances in composite materials and other related developments of functionally gradient materials, has the term earned meaningful semantic significance.

Today, the term "material" might as well be reconsidered as the "microstructure" of a structural component. Since designers have now gained the ability to weave plastic fibers and layer wooden sheets in correspondence to particular mechanical requirements, the difference between "material" and "structure" amounts to functional scale.

As we have previously determined, the distinction between material and structure in the biological world, occupies indefinable territory that is at best elusive. In his book *Structural Biomaterials*, Julian Vincent claims that when dealing with biology from an engineering standpoint such distinctions are extremely challenging. Hair, horn, cuticle and wood all have "structure" and yet all of them are mostly treated as materials (Vincent 1982). Moreover, Vincent claims that only once a distinction has been made can such complex materials be scrutinized. According to Vincent, the conflict is resolved by a simple test: materials have the same stiffness in tension, bending and compression. If they don't, we must be dealing with a structure, and the measured stiffness is not a material parameter (Vincent 1982). But, could it be, that below a certain size level of the components one does not need to consider the structure of a material and may consider it as homogeneous?

According to Vincent, it is often possible to identify a size threshold below which the structure of a material does not affect its mechanical properties. The threshold changes depending on the size of the test piece and the conditions under which the test is carried out. By observing the response of the test piece, its deformation, and the size hierarchy at which the main interfacial influences occur, it is possible to determine, if we are looking at a material or a structure. A great example given by Vincent is the observation of bone fracture. In the well-mineralized bone, the functional unit is the osteon, whereas in the less-mineralized bone, the main functional unit is the collagen-hydroxyapatite fiber. The same could be applied to the design of products and buildings. In a groin vault for instance, structural failure may occur at the brick level (analog here to the osteon) and/or at the thrust line the line of action of the resulting compressive force connecting between the four vaults (Figure 3.3).

In the former case, the brick acts both as the material and as the structure (as its boundaries determine the location of failure) whereas in the latter case, the groin vault geometry is the structure, which also happens to be made up of bricks. As a result it is relatively straightforward to assume that structural failure assists in negotiating between the domains of structure and material, and that, eventually, the distinction boils down to the scale of the functional units.

Amongst other scientists who have referred to the distinction between structure and materials is Michael Ashby, is his book: *Material Selection in Mechanical Design* (Ashby 1995; Ashby 2005). In the chapter relating to the "selection of material and shape" (Chapter 11 in Ashby 1995), Ashby assets that natural shapes achieve structural efficiency through their microscopic shape.

Microstructures are extensive by their very nature as they repeat themselves. Due to this nature, they can be thought of as "materials" in their own right possessing their respective modulus, strength, and density (Ashby 1995; Ashby 2005). As reviewed in the previous chapter, many natural materials such as wood, bone, stalks and leaves may be characterized by their unique repeated microstructure. Ashby carries on by claiming that provided they are large enough compared with the size of their micro-structural cells; shapes can be cut from such materials that inherit their properties. Ashby employs the term "shape" to consist of the external, *macro-shape*, of a given material, and the internal, or *micro-shape*, of the same material (Ashby 2005). A cellular structure or a honeycomb are two good such examples demonstrating micro structural solid organization (Gibson and Ashby 1997).

Ashby's macro- and micro-shape diagrams are a great example of a very clear distinction between shape and material, following Vincent's logic and tests (Figures 3.4, 3.5). However, as we have previously seen in *Nature's Way*, that there exists an intermediate scale between shape and material which defines a certain relationship between them. For example, in order to increase its stiffness and its strength, wood's solid component made of cellulose, lignin and other polymers is shaped into very small prismatic cells which vary in density as they disperse the solids further from the axis of bending or twisting of the tree trunk and its branches (Ashby 1995). In other words, by controlling the variation of material properties as a function of the shape they relate to, Nature negotiates structure and material. Moreover, in Nature one would not be able to find cases of "material patching" such as the ones described in Ashby's diagrams above. Instead, the density of the shape's micro-structure would change in order to fit the function of its macro shape. A few examples may relate to the distribution of micro-structural patterns relative to the direction of load applied on the shape. For instance, 'I' beams would be constructed with denser patterns in the periphery and sparser ones in the center in order to account for potential buckling, bending and twisting, while also saving material. We shall refer to such strategy as a *Material Distribution Function*.

3.6 Slow Craft: Low-Tech Cases in Material-based Design

3.6.1 The Wavy Hamon, a Swordsmith's Dilemma: a Case in Material Conditioning

How does one create a sword both strong enough to hold a sharp edge and soft enough to bend? Beset with the finest details of material craft, Viking and medieval European swords have long had staying power as *objets d'art* and testimonies of engineering genius. Heated, welded, cut, forged, bent and twisted, such artifacts were designed as the very substance of warfare. Striking form and practical function are combined in skillful processes of material re-surfacing and structuring.

The finished sword's function and performance were determined by its shape, proportion, and its physical properties. The steel had just about the right combination of hardness and toughness as it was repeatedly welded to refine its structure before forging the blade (Figures 3.6-3.10). The shifting colors during heating indicated the temperature of the glowing steel. At the right moment and the optimal temperature, the blade was taken from the hearth quenched in water or oil. Finally it was tempered to eliminate brittleness. The blade, as a result, was hard enough to hold a keen edge but was still flexible enough not to break during use (Smith 1981).

Pristine in its entirety, yet the creation of the Samurai sword surmounted a technological impossibility: the blade has to be forged in order to hold a very sharp edge and, concurrently, not break in the ferocity of a dual. To create steel both brittle (it must be hard enough to take a sharp edge), and soft (it must not break) was an almost unfeasible metallurgical challenge.

In seeking to settle the swordsmith's dilemma, Japanese sword artisans used a combination of four metal bars each holding different properties. A soft iron bar guarded against the potential breaking of the blade, two hard iron bars prevented bending and a steel bar took a sharp cutting edge. All four bars were heated at a high temperature and then hammered together into a long rectangular bar that would become the sword blade. As the swordsmith ground the blade to sharpen it, the steel took the razor-sharp edge, while the softer metal ensured the blade would not break. This intricate forging process brought about the wavy hamon, or 'temper line' a major qualifier in judging a blade's artistic merit.

3.6.2 Great Mosque of Djenné and the First Composites: a Case in Material Composition

Adobe bricks are the earliest case of material composites known. They serve as a natural building material composed of sand mixed with water, straw and other organic materials shaped into bricks using wooden frames and dried evenly in the sun. The straw is useful in binding the brick together while allowing it to dry evenly. Bricks are made in an open frame, and the mixture is molded by the frame before its removal. After drying, the bricks are turned on edge to finish drying. The same mixture to make bricks, without the use of the straw, is used for mortar and often for plaster on interior and exterior walls. Some ancient cultures used lime-based cement for the plaster to protect against rain damage.

An adobe wall has major environmental effects as it can serve as a heat reservoir due to its relatively dense thermal mass; therefore this type of construction is most useful in tropical climates.

The Great Mosque of Djenné is the largest adobe building in the world and is considered by many to be one of the greatest achievements of the Sudano-Sahelian architectural style, with Islamic influences (Figure 3.11). Its walls are made of sun-baked mud bricks called *ferey*, a type of mud based mortar, and are coated with a mud plaster which gives the building its smooth, sculpted look. Wall thickness varies depending on its height: taller sections were traditionally built thicker because the base has to be wide enough to support the weight. Bundles of palm wood were included in the building to reduce cracking caused by frequent drastic changes in humidity and temperature and to serve as readymade scaffolding for annual repairs. The walls insulate the building from heat during the day and by nightfall have absorbed enough heat to keep the mosque warm through the night.

3.6.3 The Baidarka Kayak: a Case in Material Assembly

A Kayak is a hunter's boat, some of which are at least 4000 years old. The boat's primary purpose was to hunt animals on inland lakes, rivers and the sea. The Kayak was made of seal skins and wood (Figures 3.12, 3.13). The wood was driftwood that was collected from beaches, since many of the areas where kayaks were paddled are void of the land-based raw materials used in making birch bark or dugout canoes. The baidarka kayak is a special kayak. The word refers to the double and triple kayaks developed by the Alaskan Aleut. The baidarka kayak (Iceland, 1806) meshes small pieces of bone into a wooden superstructure in strategic zones requiring maximum flexibility. This technique illustrates an early example of a composite material with non-homogenous properties, since the combination of bone, wood, and leather contribute to the local variance of the boat's rigidity along its length. An exterior performance parameter, such as the floating of the boat on waves, becomes the incentive to manipulate not only its shape (as it happens in the design of all boats), but also its locally adjusted material composition (Class notes from MIT Class 4.195, Special Problems in Architectural Design, Alexandros Tsamis-Jimmy Shen, Exercise III: Material Deployment Investigation, 2005, based on Dyson, 2002).

The variety of skin-on-frame kayaks made by the Aleuts of Alaska is typically called "Baidarkas". The big advantage for the traditional builders of skin-on-frame kayaks, the Aleut and Inuit residents of the far north, is that they could be built with the materials on hand. The frame did not require big pieces of wood and could be made with material that drifts up on the beach. The skin was made from their primary food species, the seal. This set up an interesting chicken-and-egg situation, because they needed the kayak to catch seals and they need seals to make the kayak. The resulting boat was light weight, rugged, resilient and easy to maintain. Due to the construction technique and materials used, any *skin on frame* boat is inherently flexible. There is some thought that this hull flexibility also offers some efficiency advantages.

3.6.4 Weaving the First Hut: a Case in Material Organization

Weaving is an ancient textile craft that involves placing two sets of threads or yarn made of fiber on a loom and turning them into cloth. In general, weaving involves the interlacing of two sets of threads at right angles to each other: the warp and the weft. The warp are held taut and in parallel by means of a loom. The loom is warped (or dressed) with the warp threads passing through heddles on two or more harnesses. The warp threads are moved up or down by the harnesses creating a space called the shed. The weft thread is wound onto spools called bobbins. The bobbins are placed in a shuttle which carries the weft thread through the shed. The raising/lowering sequence of warp threads gives rise to many possible weave structures from the simplest plain weave, through complex computer-generated interlacings (Figure 3.14).

Both warp and weft can be visible in the final product. By spacing the warp more closely, it can completely cover the weft that binds it, giving a *warp faced* textile. Conversely, if the warp is spread out, the weft can slide down and completely cover the warp, giving a *weft faced* textile, such as a tapestry or a Kilim rug. There are a variety of loom styles for hand weaving and tapestry. In tapestry, the image is created by placing weft only in certain warp areas, rather than across the entire warp width.

The practice of hut and basket weaving demonstrate interesting ways by which fibers can be distributed to correspond with required local strength and flexibility.

3.7 Rapid Craft: High-Tech Cases in Material-based Design

The following case-studies - both from the domain of extreme sports - illustrate the significance of variable property design achieved by the development of high-end composites and their respective fabrication technologies.

3.7.1 Pole-vaulting: A Case Study in Stiffness Variation

If its novel, it's in the Olympics. The Olympic Games have traditionally constituted a major opportunity for the sports to celebrate advances in engineering. Such is the case with pole vaulting. Pole vaulting, as an athletic activity, dates back to the ancient Greeks and its development, as a bendable beam used for jumping, illustrates how the shift to composites resulted in major athletic performance improvements (Figure 3.15).

Beam stiffness is a significant concept for many types of structures, particularly those shaped with slender proportions, such as trees, skyscrapers, bones and chairs. Inadequate beam stiffness could lead to large deflections, high localized stresses and failure in a particular region. In addition to bending moments, such structures may be subjected to twisting and torsional moments (torques). Pole-vaults are a great example of stiffness variation designed to account for its special performance.

In pole-vaulting, the highest stresses occur on the outside of the bent beam. In addition, within the middle zone of the pole, positioned across its height and known as its neutral axis, there are minimum or no stresses at all. There is, therefore, no need to place any material mass down its center. Bamboo for instance, which is a naturally hollow material, is much lighter per unit length than a solid pole - yet provides the same maximum stress. Give that pole-vaulting essentially involves the conversion of the kinetic energy of the running athlete to the potential energy of the jump using strain energy stored in the pole (the energy stored in elastic deformation), a lighter pole enables an athlete carrying a bamboo pole to take a faster run-up or to use a slightly longer pole.

Poles were originally made out of solid wood, probably hickory. Slightly more flexible bamboo poles were introduced in the early 1900s and a sharp increase in the achievable height coincided with the advent of composite poles made of fiberglass, about 50 years ago. In its elastic recovery, these poles are sufficiently strong and flexible to allow substantial amounts of energy to be transformed into elastic strain energy stored in the deformed pole, and consequently transformed again into potential energy. The mechanics of beam bending is clearly integral to this phenomenon. The sharp increase in achievable height that coincided with the switch to composite poles was due to a change in the mechanics of pole vaulting. Bamboo or metal poles with sufficient flexibility to allow significant energy storage would, respectively, be likely to fracture or plastically deform. Today, pole vaults are made by wrapping pre-cut sheets of fiberglass around a metal mandrel to produce a slightly pre-bent pole that would bend easily under compression with the athlete's take-off. The weights, length and stiffness of the pole are a function of the density and directionality of carbon fibers as they are laid out on the composite sheets.

3.7.2 Extreme Sailing: A Case Study in Elastic Variation

Boat builders were amongst the very first to experiment with carbon-reinforced composites. As early as the 1970's the pioneering innovator Edward S. ("TED") Van Dusen discovered that most standard construction materials had about the same specific stiffness per unit weight. This led him to experimenting with composites and making the first carbon-fiber composite Advantage racing shells (McQuaid and Beesley 2005). Satin weaves made of glass fiber in complex twill afforded Van Dusen the opportunity to locally inform the physical behavior of the sail. Within the weave each weft may float over as many as seven warps. With fewer points of intersection, the fiber has less stability, but more fiber can be packed into the structure. The density minimizes the risk of pinholes forming in the composite, keeping the boat watertight. The dependency between the fibers' material properties and their structural geometry, and their ordering organizations, are all contributors to the performance of the sail (Figure 3.16).

The 1980's experienced exponential growth in the field of textile design when high-performance fibers such as aramids and carbon fibers have been a major force driving the markets and industries of aerospace and the military (McQuaid and Beesley 2005).

As composite reinforcements, textiles offer a high level of customization with regard to type and weight of fiber, use of combinations of fibers, and use of different weaves to maximize the density of fibers in a given direction (McQuaid and Beesley 2005). Fiber strength is greatest along the length. The strength of composite materials derives from the intentional use of this directional nature.

Fibers are considered high-performance, if they possess exceptional strength, strength-to-weight ratio, chemical or flame resistance, or range of operating temperatures. Weaving, braiding, knitting and embroidery have existed for centuries. However, combined with an ability to locally control reinforcement, high performance fibers are contributing to incredible leaps in the performance of products and buildings alike.

3.8 Design beyond Selection: Current Problems Limitations

3.8.1 Patch Hide: the Problem with Smart Materials

As new research avenues find practical expression within design and architectural practice, it is clear that the design of better, lighter, stronger, more effective and efficient materials will be moving the industry forward. The design and control of a material's micro-structure is seemingly coupled with any potential real-time behaviors that may be incorporated into its functional portrait. So significant and far-reaching is the progress occurring in the area of smart-materials that one finds it hard to avoid addressing its relevant and contribution in this context.

What distinguishes a smart material from a traditional one is that for both traditional and high-performance materials there is a mostly fixed response to external stimuli. In other words, for a traditional material, properties remain constant under standard conditions (Addington and Schodek 2005)[3.3]. Smart materials on the other hand, are either property changing or energy exchanging (or both). Property changing materials trigger intrinsic response variation that is specific to any given internal or external stimuli. Energy exchanging responses trigger extrinsic response variation that can be computationally controlled or enhanced. There also exist combinations of such classes of materials in smart devices and systems in which smart materials are embedded in devices or systems with intrinsic response variations and related computational enhancements to multiple internal or external stimuli or controls. Finally, intelligent environments combine intrinsic and cognitively guided response variations of whole environments comprised of smart devices and systems to use conditions and internal or external stimuli.

The main problem behind such environments is that they are typically patched atop an existing structural or architectural system. Such "patching" strategies result in functional assemblies and kinetically actuated facades and products which require much energy to operate, and are typically maintained by global control. It is an assumption of the research that next-generation construction materials may support dynamic (in addition to their currently, static) spatially-differentiated material compositions and structural forms. The aim is to combine structural, optical, and fluidic behaviors which are governed by the material architecture, as well as the interactions between materials and their environment. Such material architectures could simultaneously bear large structural load, change their transparency so as to control light levels within a building or vehicle, and open and close embedded pores so as to ventilate a space.

3.8.2 Fabricating Difference: the Problem of Material Scale

Achieving structural heterogeneity in micro-structural levels to accommodate for varying (anticipated) load conditions is promising insofar as it may be applied to projects of micro-structural scale. The main problem arises when we attempt to translate some of these meso-scale capabilities, as exemplified through the use of foams, composites and FGMs, into macro-scale architectural and engineering design problems. Imagine, for instance, that a singular beam or better yet, an entire building system, could be

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[3.3] Further technically disposed content is offered by Addington and Schodek's "Smart Materials and Technologies". The volume includes a comprehensive account of smart materials, their classification and characterization across various scales, as well as the inclusion of elements and control systems integrated into materials such as sensors and micro-electrical mechanical systems. The book concludes with a classification of components and assemblies applied to facades, lighting systems, energy systems and structural systems.

constructed out of variable-property concrete so as to modulate its density as a function of anticipated loading conditions.

Variable-property design at construction scale is yet to succeed in challenging conventional full-scale construction systems. Indeed, architectural building codes and standards often supersede performance criteria with an attempt to simplify the selection process and remove liability for performance failures (Addington and Schodek 2005). Frequently, this supersedes results in the simplification of material composition with the aim of homogenizing the construction process in order to subscribe to performance standards. In Nature however, as we have seen, "every tree is different". It logically follows then, that mechanisms for the production of difference in material performance must be integrated with industrial construction processes before we may achieve Nature's Way. To paraphrase, modern construction methods prioritize efficiency over effectiveness, whereas Nature combines efficiency and effectiveness in ingenious ways.

There are some relevant sources worth exploring in this context. One such case is John Fernandez' *Material Architecture* (Fernandez 2006) which inspires the conceptual, methodological and practical shift from the material scale to that of construction, not without responding to building codes promoting sustainable design methods. Accompanied by essays and studies profoundly geared towards topics of sustainable design and construction, the book highlights the role of emerging materials in contemporary practice and offers a comprehensive and synthetic understanding of the topic in architectural design today. It highlights the condition that general structures of materials behave quite differently at the micro and macro levels, and that such behaviors must be accounted for when translating from micro to macro scale as the structure of a material at each of these levels will strongly influence its final characteristics and properties. It is thus imperative to reconsider the mechanisms and technologies promoting structural heterogeneity in building scale.

3.8.3 Load over Light: The Problem of Disciplinary-based Parameterization

In the milieu of design, the concept of material performance encompasses many, and often conflicting, interpretations which vary as we have seen previously - with the type and method of property classification. Central to the definition and utilization of material performance parameters and their dimensions, is the distinction between criteria associated with architectural, or design performance and those associated with engineering performance.

While the engineering disciplines prioritize structural integrity and environmental soundness against building loads, seismic loads and wind loads, to name a few, the architect in her consideration of comfort and well-being searches for spatial qualities of, and in relation to spatial distribution, visibility, and occupant comfort. As a result, many parameters must be re-negotiated in order to account for the various families of constraints.

3.8.4 From Structuring Materials to Designing Form: The Problem of Structural Hierarchy

Last but not least is the question regarding the origin of form. It is relatively easy to imagine how certain of these ideas may apply to the structuring of an already existing form in terms of its physical or material expression. Clearly, the form of human bone is determined by anatomical constraints which, in turn, comply with the physiological and chemical process involved in the distribution of cancellous bone matter. In other words, the structural (and otherwise, environmental) distribution of matter per a given boundary condition defining global form is not too challenging to imagine. It is, however, quite a complex design mission to develop a process in which the generation of form goes hand in hand with its substance formation.

Granted, there are numerous approaches to the structuring of materials per a given form. However, the question still remains what are the implications of allowing form to emerge as a function of material properties and environmental constraints, and how might such an approach be facilitated in and by design? We will attempt to answer this question and the other problematic highlighted above in the following chapter.

3.9 Matter over Shape: Towards Material-based Design Computation

The implications of controlling material heterogeneity at building scales from a design perspective are immense, especially in terms of efficiencies and effectiveness of both products and processes and their capacity to respond to external local requirements and pressures. But how to move from substance variation to formal expression and from material to construction scale is among the core questions of this work.

We assume that if we were able to compute the distribution of matter as a function of structural and environmental performance, we would be able not only to control substance variation defined per a given boundary condition, but better still, we could utilize such methods for the generation of form itself. Given that we are now well aware of such an ambition, drawing from Nature's Way (Chapter 2); and given that the range of material possibilities with their various scales have been sufficiently reviewed in this chapter, we are now ready to explore the potential of computational process to computationally support and instrumentalize a material-based design approach.

The ability to strategically utilize and exploit relationships between the spatial arrangements of material constituents and their bulk properties across various length scales will make possible the future description of material properties in terms of architectural parameters and qualities. Moreover, as heterogeneity and multi-functionality (both of which are representations of morphological adaptation) become designable - as this thesis will demonstrate the ability to independently manipulate material properties and develop structural materials with vastly superior properties corresponding to their environmental surroundings will be achieved. Such exploitation of the architectural features of materials, structures and spaces will expand and enhance the design space as structural properties are negotiated with environmental ones without compromising functionality. Already, the applications of materials with such controlled micro-structural architectures are pervasive, and will result in breakthrough improvements in strength, stiffness, fracture toughness, energy absorption, thermal conductivity, thermal expansion and weight. Coupled with environmental constraints, controlled heterogeneity of material properties and effects may eventually reproduce Nature's Way.

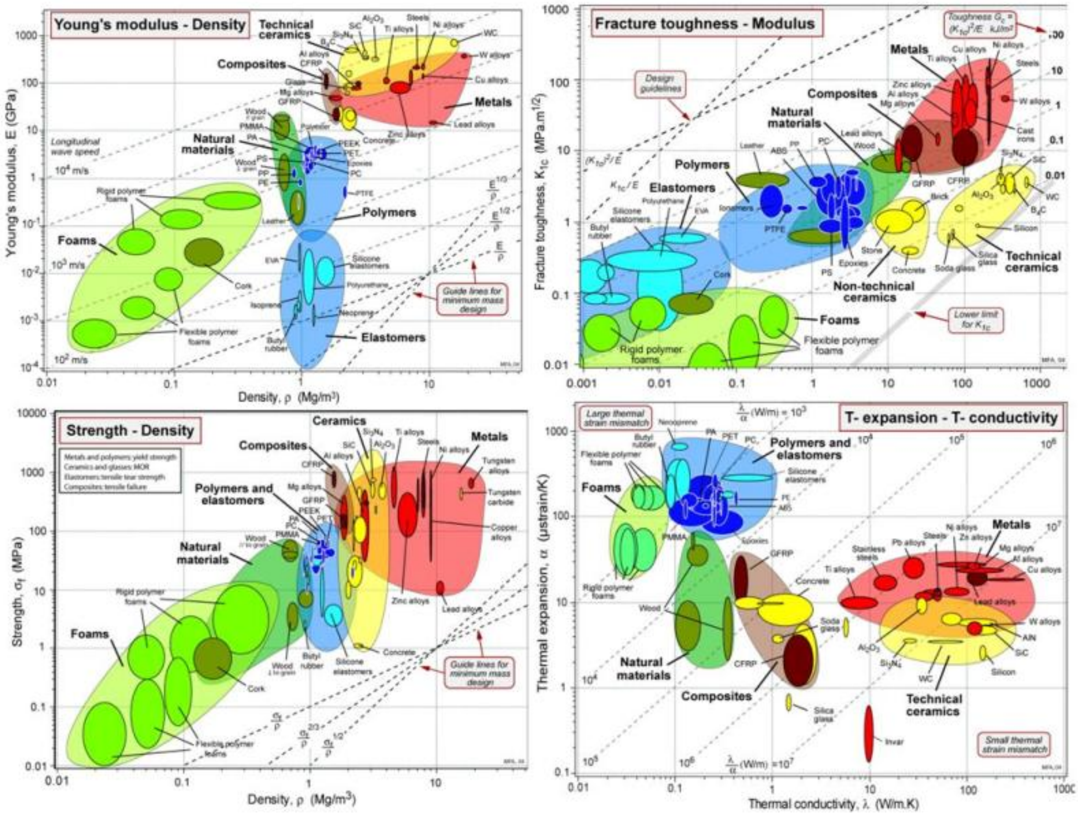
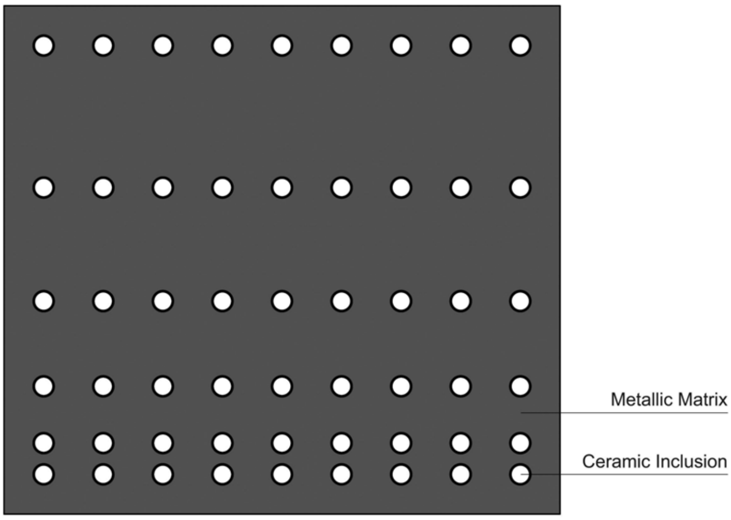
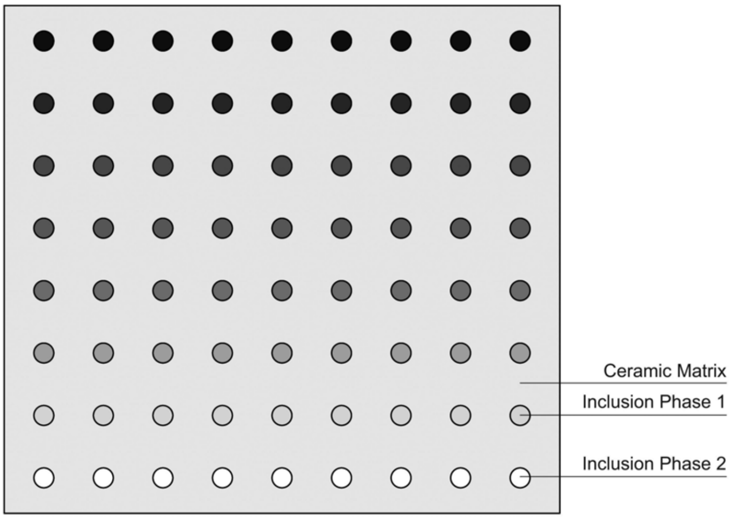


Figure 3.1: Michael Ashby's Material Selection Charts (from right to left, top to bottom): Young's modulus Density chart, Fracture toughness Modulus chart, Strength Density chart, T-expansion T-conductivity chart. Source: *http : //www.grantadesign.com/ashbycharts.htm*



Discretely graded microstructure



Multiphase graded microstructure

Figure 3.2: Graphic illustrations of discretely graded (left) and multiphase graded (right) microstructures of functionally gradient materials. Within FGMs, the different microstructural phases have different functions and the overall FGMs attain the multifunctional status from their property gradation enabling various multifunctional tasks by virtue of spatially tailored microstructures.

Figure 3.3: As in the main nave of St. Mary's church in Lübeck the brick groin vault has a distinct structure, defined by its geometry, and a distinct material (bricks). Being constructed from only one material however, the groin's structural stability is achieved by its geometrical arrangement. In the case where the point of failure occurs between neighboring bricks, one may refer to the material as the structural unit. Failure is defined by the size hierarchy at which the main interfacial influences occur.

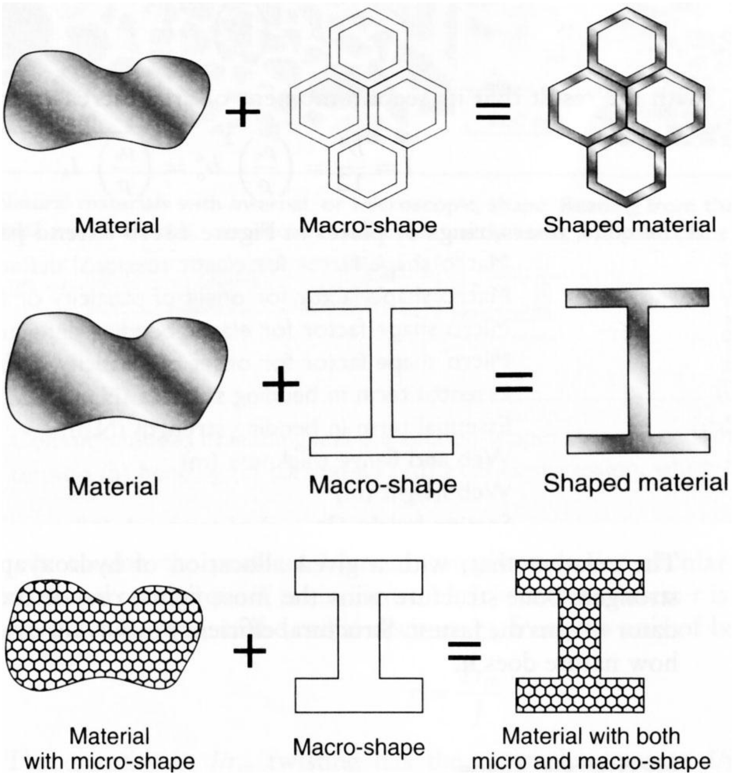


Figure 3.4: According to Ashby, mechanical efficiency is obtained by macroscopic shape with material macrostructure to result in efficient structures such that the overall shape factor is the product of the microscopic and macroscopic shape factors. The shape is characterized by a dimensionless shape factor, . The schematic is suggested by Parkhouse (1984). Source: Ashby, 1992, p. 285, 297, 298 (Ashby 2005).

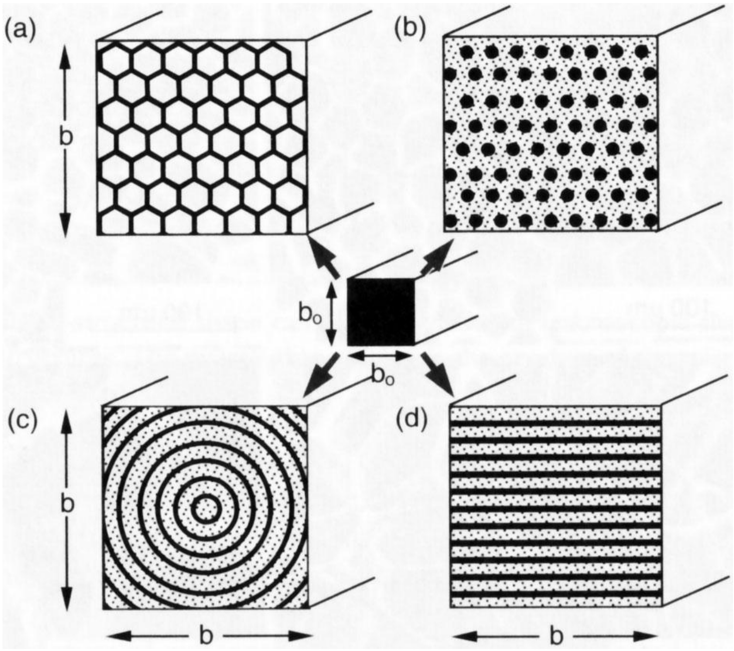


Figure 3.5: Four extensive mechanically efficient micro-structured materials: (a) prismatic cells, (b) fibers embedded in a foamed matrix, (c) concentric cylindrical shells with foam between, and (d) parallel plates separated by foamed spacers. Source: Ashby, 1992, p.300 (Ashby 2005).

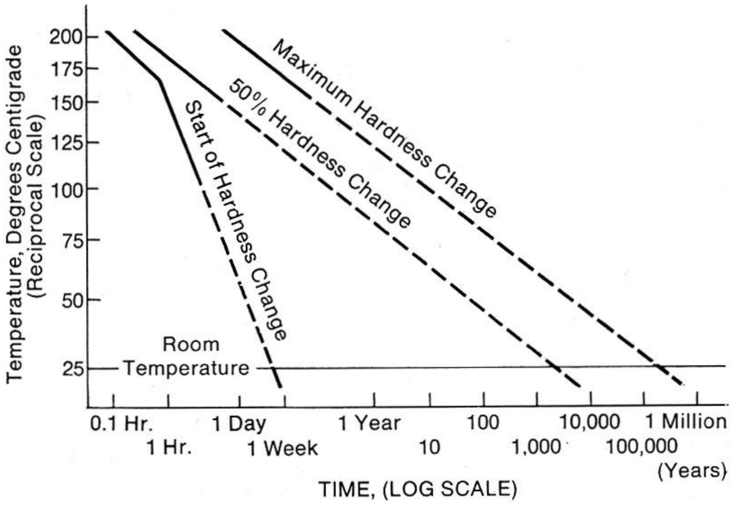


Figure 3.6: Curve showing the time required for change of hardness in a silver-copper alloy (8.75 percent silver) as a function of annealing temperature following quenching from 760. The dotted portions of the lines are extrapolations and are very uncertain (Smith 1981).

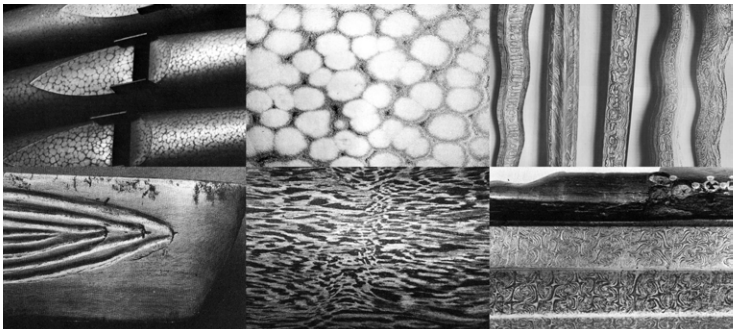


Figure 3.7: Images from left to right, top to bottom: (1) Spotted metal organ pipes in a church at Whitney, Oxfordshire (2) Modern spotted metal organ pipe. Surface of cast sheet of 52/48 lead-tin alloy about 1.5 mm thick. (3) blades of five Malayan *kris* photographed at the British Museum. (4) Sword from eastern Tibet, nineteenth century or earlier. Pattern of welded hairpins, developed by deep differential scraping. (5) Indo-Persian scimitar, first quarter nineteenth century or earlier (6) Patterns on barrel of a Turkish carbine, eighteenth century (Smith 1981).

Figure 3.8: Merovingian pattern-welded sword blade. Lorraine, sixth century. Corrosion products removed but otherwise untreated. The image shows the point of a pattern-welded sword, re-polished and etched (Smith 1981).

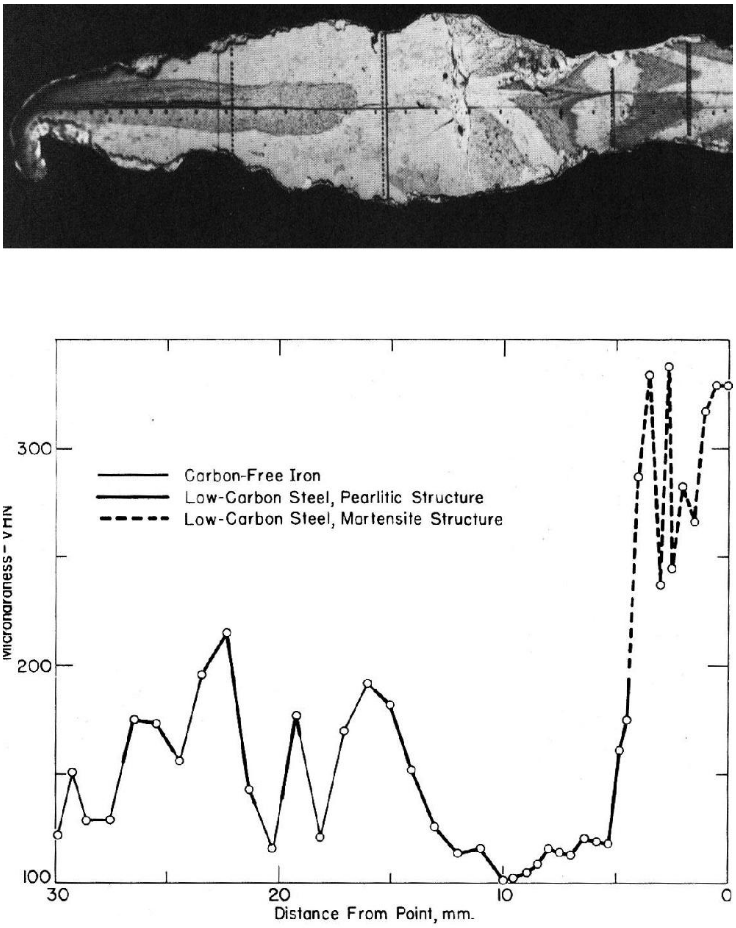


Figure 3.9: Top image: Merovingian pattern-welded sword blade. Lorraine, sixth century. Corrosion products removed but otherwise untreated. Bottom image: Variations of micro hardness along the center line of the sections shown in the previous figure (Smith 1981).

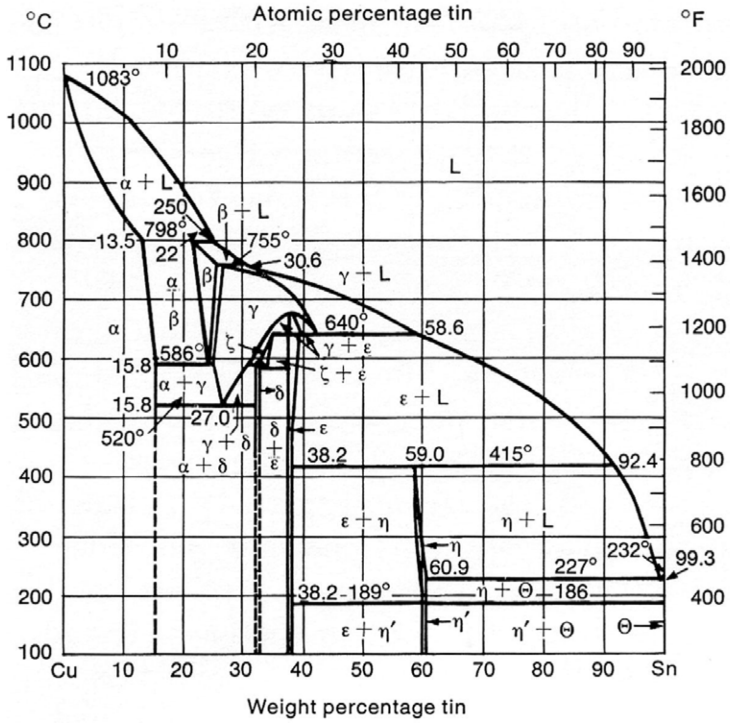


Figure 3.10: This phase diagram illustrates regions of temperature and composition wherein the alloys are liquid and where the different crystalline phases, marked alpha, beta, gamma, etc., exist. The dotted lines below 450 degrees Celsius show the conditions to be expected under normal metallurgical treatment (Smith 1981).

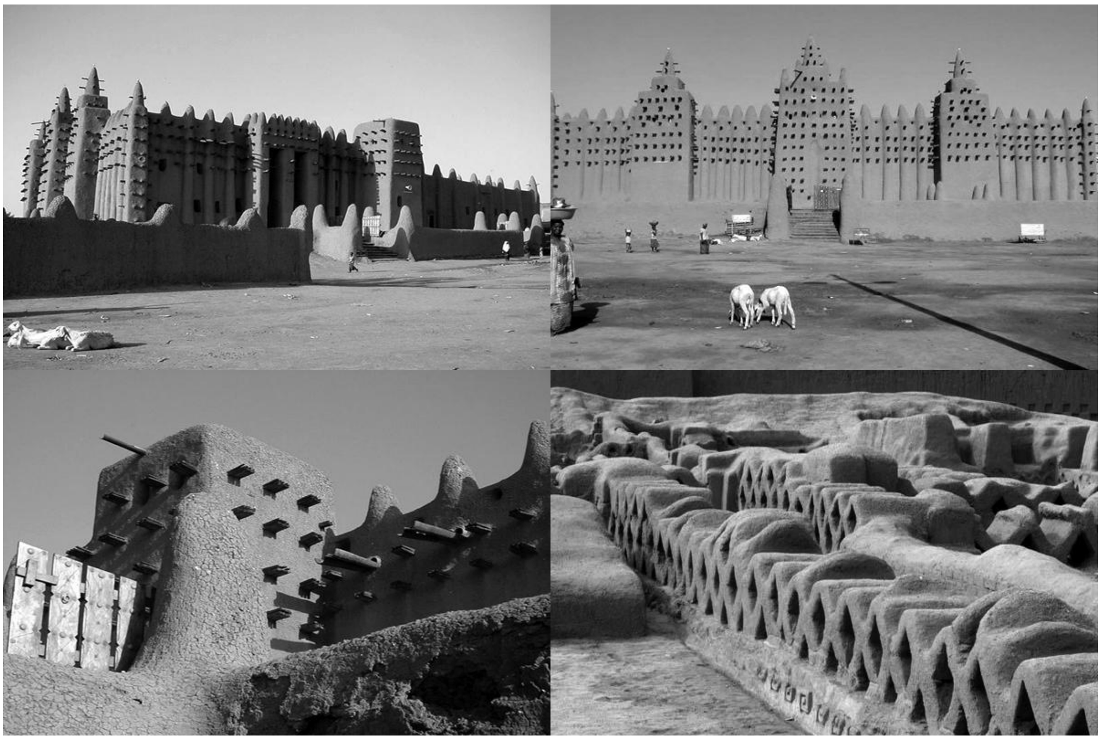


Figure 3.11: The Great Mosque of Djenné is the largest mud-brick (or adobe building) in the world and is considered by many architects to be one of the greatest achievements of the Sudano-Sahelian architectural style, with Islamic influences. Source: $http://en.wikipedia.org/wiki/Great_Mosque_of_Djenné$

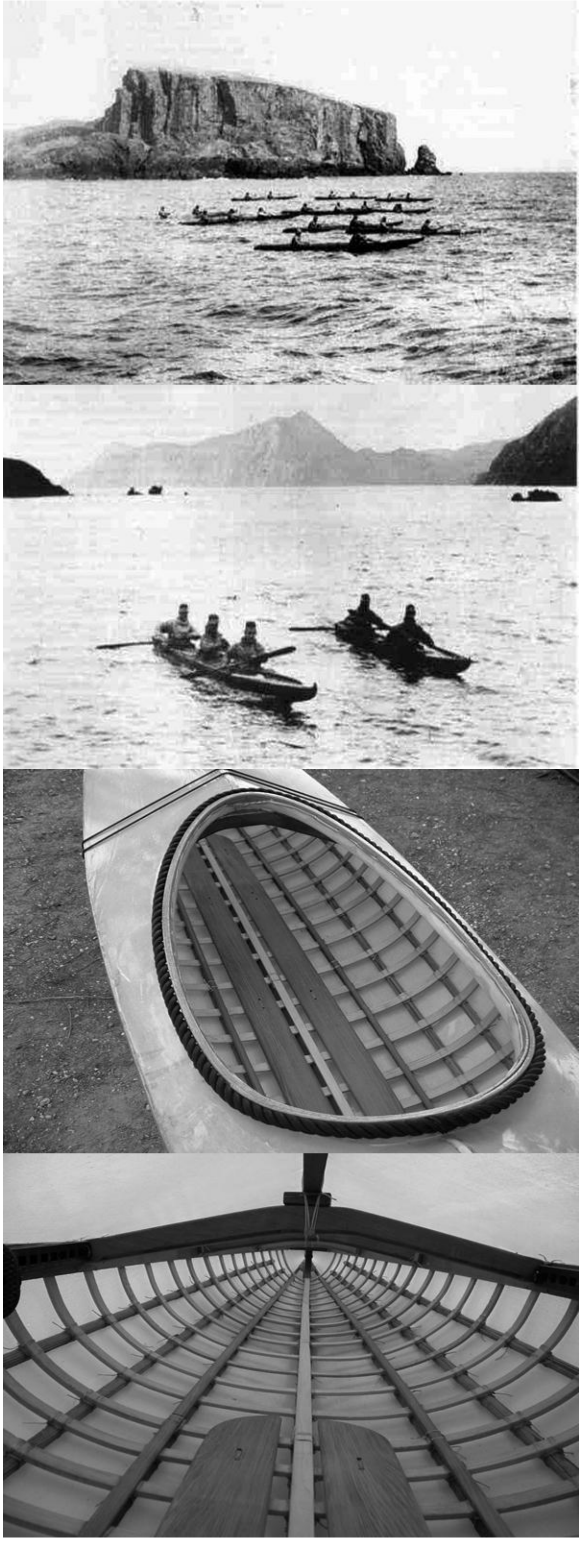


Figure 3.12: The Baidarka Kayak was made as an assembly of wood and bone construction for maximum strength and flexibility on local areas of the kayak. The “bifurcated” bow was one or the predominant features of such highly crafted constructions. Source: *http : //en.wikipedia.org/wiki/Baidarka*

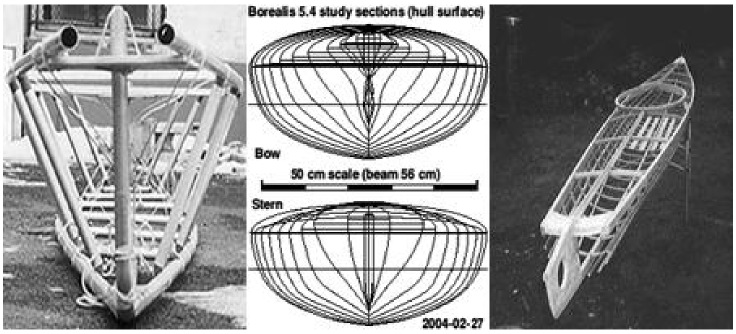


Figure 3.13: Rib forming of a Baidarka kayak: the “bifurcate” bow was one or the predominant features of such highly crafted constructions and served as the main structure upon which the intermediate rib structure rests. Source: *http : //en.wikipedia.org/wiki/Baidarka*

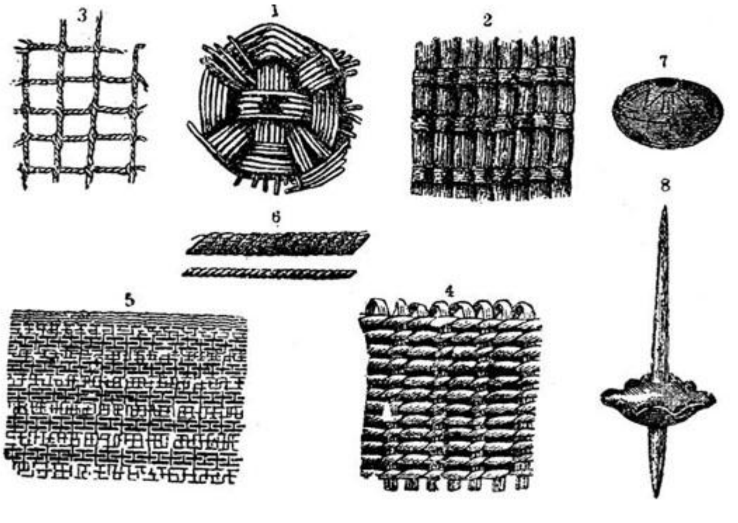


Figure 3.14: The use of a thatched structure (granary) to store maize is a traditional practice in the West African countries of Ivory Coast, Ghana, Togo, Benin and Nigeria. Detail of hut latticing - rope lattice made from “lukhasi” (Festuca costata), holding in thatching grass.

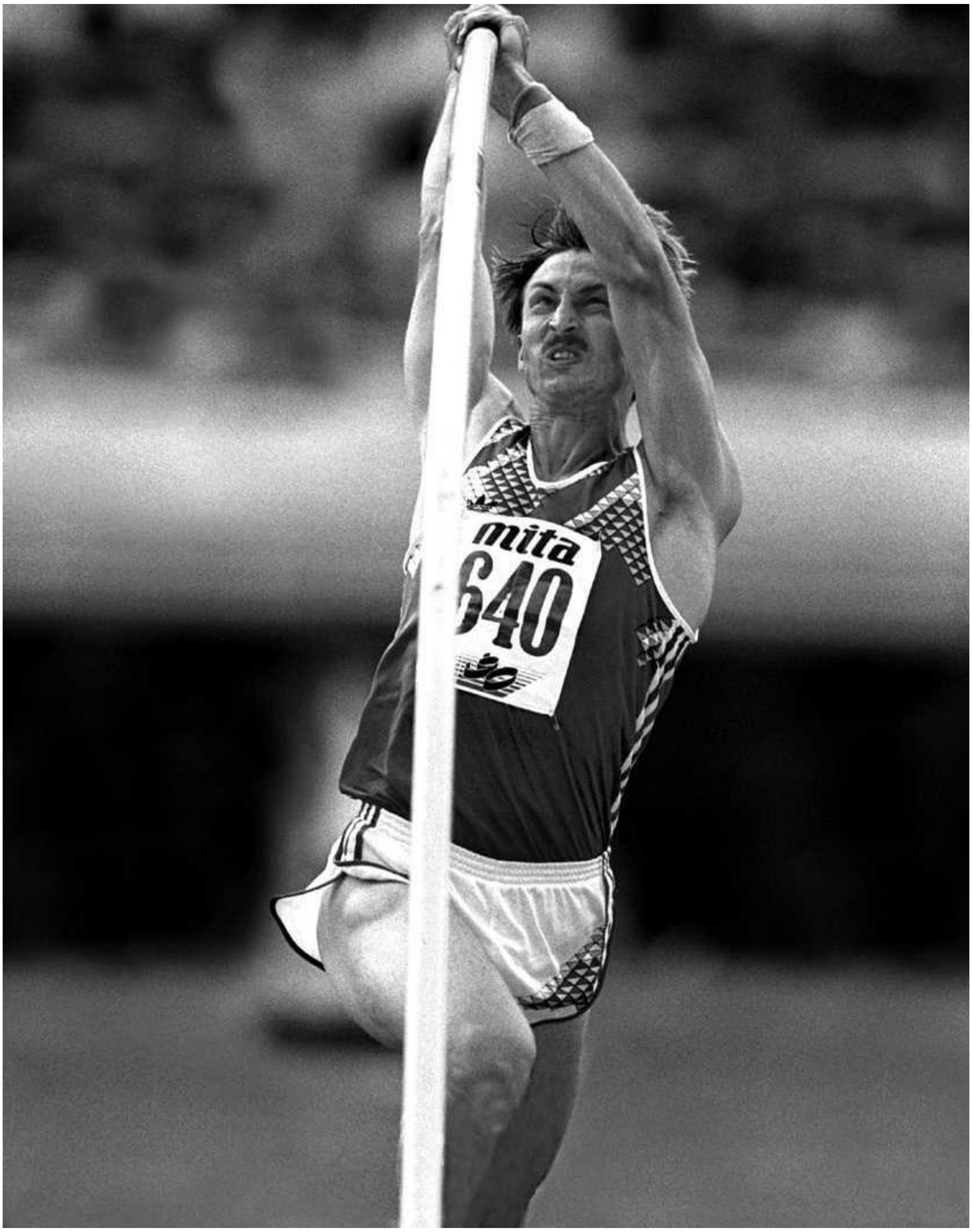


Figure 3.15: Pole vault design demonstrates the principle of variable-property design informed by structural performance and material properties. A typical vault is made of three layers: an external longitudinal fiberglass web and epoxy, a rougher fiber glass weave, and an internal layer made of glass fiber rings. Source: $http://www.sporting-heroes.net$

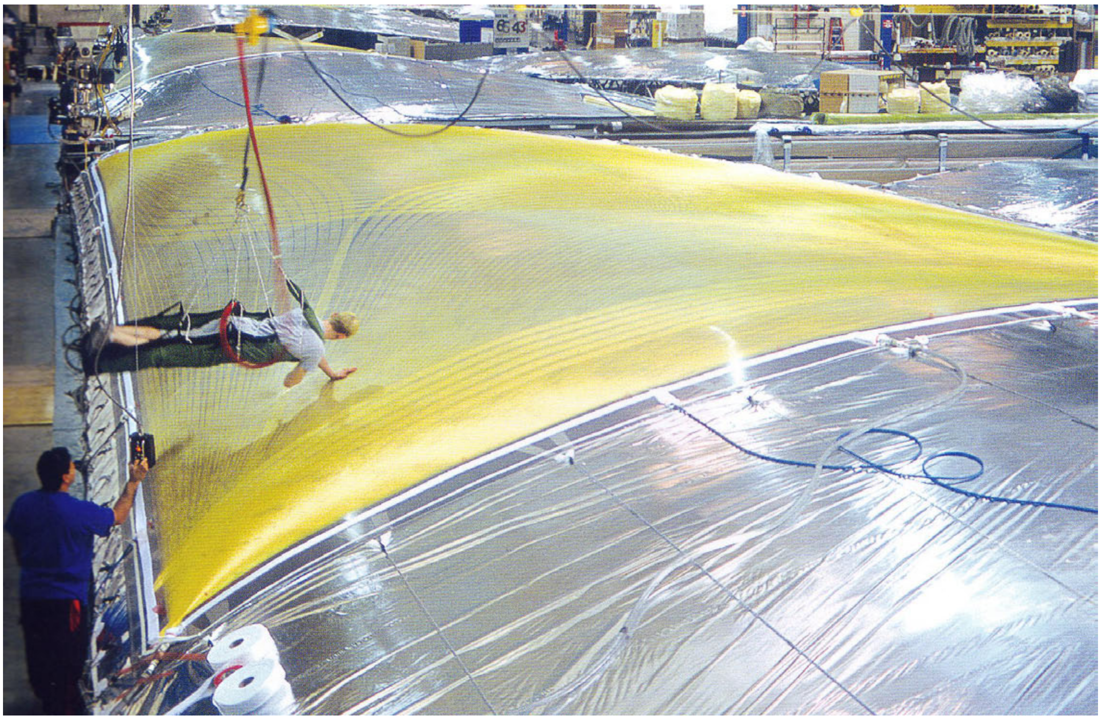


Figure 3.16: Aramid fiber sail on the mold table being inspected. Fiber thickness, orientation and density define the structural performance of the sail. Hence, by controlling the distribution of fibers, their thickness and spatial articulations, the designer can gradually control the membrane's structural and environmental performance (McQuaid, Beesley et al. 2005).

CHAPTER 4

DESIGN COMPUTATION
Digital Engines for the Structuring of Matter

> *"A set is a Many that allows itself to be thought of as a One."*
> **— Georg Cantor**

4.1 From Computer Aided-Design to Design Computation: an Introduction

The use of computer technology for the design of objects, real or virtual, has been supported by the plethora of applications associated with computer-aided design, also known as CAD. Developed primarily as a digital substitute for manual drafting of technical and engineering drawings, the output of CAD typically conveys symbolic information such as shape compositions, dimensions, and tolerances based on application-specific conventions. CAD is extensively used across various disciplines with many domain-specific applications including those for the automotive, shipbuilding, and aerospace industries, industrial and architectural design, among others. Within the field of architectural design, CAD is a major driving force for research in computational fields such as computational geometry, computer graphics and discrete differential geometry. Furthermore, CAD occupies a wide variety of design applications ranging from modeling (digital generation in the digital domain), to analysis (digital mapping of the physical domain), to digital fabrication (physical generation of the digital domain).

The ubiquitous and nearly pervasive use of computer-aided design, engineering and manufacturing (respectively known as CAD, CAE, and CAM) in architecture, frequently serves in current design practice as the facilitative technology by which to materialize the contemporary predilection for complex geometries and, so called, free-form design. In this sense such computer-aided environments might well be considered as the automated extension of traditional form description and form-making processes that preceded CAD's invention (Oxman 2007; Oxman 2007; Oxman 2008).

4.1.1 From Aid to Engine

Digital extensions of traditional, conventionalized design methodological processes have earned legitimacy and value as aids in supporting mediated design. Aiding the reformulation or pre-conceived form, such tools fall short of incorporating material properties and behavior constraints, as well as fabrication and construction processes inherent to them. Indeed, in dismissing the capacity of computational tools to support form-generation processes motivated by objectives *other than* the generation of form itself, computer-aided design appears as a whole to facilitate a status of "more of the same". As a result, the world of architectural design, now so saturated with excessive formal expression, continues to be dominated by top-down design decisions favoring form over material with their subsequent implications on the built environment. Looks, however, is not all that matters.

In cultivating design processes inspired by Nature's way we seek to employ alternative computational processes supporting the generation of form based on the interaction between material and environment. This entails a shift from computationally assistive processes to processes of a generative and performative nature. In other words, we aim to move from computer aided design to material-based design computation. This transformation potentially allows the designer to perform form generative processes while addressing material and environmental considerations. This new medium of performance and material-based generation also potentially allows the designer to achieve forms of a *material-ecological nature*, that is, a new vocabulary otherwise unattainable.

4.1.2 Objectives and Organization

The objective of this chapter is to review the evolution of concepts and issues in the field of design computation that are relevant to these general objectives and to characterize the emergence of a contemporary theoretical discourse and technical developments in Material-based Design Computation[4.1]. It is important to note that all prior research into physically related computation resulted from the objectives to capture, or trace, pre-generated form. Consequently there is no research dedicated to questions of how to design form based upon the properties of material. It will be demonstrated that such an approach will enable us to move from the digital manifestation of physical form to its physical manifestation of digital form in a unique computational design process.

The chapter includes a survey of relevant techniques in computational design that support form-generation processes within computational geometry environments. Examples of such techniques include particle systems, multi-agent systems, network analysis, and finite element methods among others. The aim here is to explore such computational design precedents and demonstrate how inherently related or removed are such techniques from the projected material processes of form-generation.

4.2 Natural Computing: Design Computing Inspired by Nature

Natural Computing is the terminology introduced by de Castro to encompass three approaches in the relationship between nature and computation (De Castro 2006). In these approaches, models of natural processes are used as a source of inspiration for the development of tools, techniques and technologies for solving complex problems in various domains from engineering to biology. Those three approaches may be classified according to the type of problems they attempt to deal with, among them: search, simulation, and physical processing.

[4.1] Early research in Material-based Design Computation pioneered the consolidation of disciplines such as material science, engineering and computation in the context of design and design process. Computational processes have been identified that integrate performance criteria with form-generation processes (Oxman, 2005; 2006; 2007 2008).

4.2.1 Search and Optimization

In this approach, algorithms are developed which take inspiration from Nature with regard to, and with the aim of, offering solutions for complex problems that cannot be otherwise solved using linear, non-linear and dynamic programming; the core idea here is to devise theoretical models which can be implemented in computers with a focus on problem solving rather than theoretical modeling. Such bio-inspired, or biologically motivated, computing techniques are comprised of highly abstract models, sometimes called metaphors (Paton 1992), and are designed to mimic particular features and mechanisms from biology. Examples include artificial neural networks and evolutionary algorithms, both of which are information processing systems for search and optimization inspired by models of the nervous system and evolutionary biology respectively with particular emphasis on problem solving. Ground-breaking work in the area of neural networks was pioneered by McCulloch and Pitts in a paper entitled: "A Logical Calculus of the Ideas Immanent in Nervous Activity" (McCulloch and Pitts 1943), which introduced the first mathematical model of a neuron giving rise to the field of artificial neural networks (Kohonen 1988; Fausett 1994; Haykin 1994; Bishop 1995). Evolutionary computation was pioneered in the mid 1960's with the works of I. Rechenberg, L. Fogel, A. Owens and JH Holland, and M. Walsh (Bck and Schwefel 1993; Fogel, Angeline et al. 1995; Frazer 1995; Spears 2000; Kallel, Naudts et al. 2001; Freitas 2002; Landweber, Winfree et al. 2002; Eiben and Smith 2003; Ghosh and Tsutsui 2003; Morrison 2004; Tomassini 2005; Fogel 2006) giving rise to the field of evolutionary computing. Most evolutionary algorithms are rooted in the neo-Darwinian theory of evolution which proposes that a population of individuals capable of reproducing and subject to genetic variation followed by natural selection result in new populations of individuals increasingly more fit to their environment. Evolutionary Algorithms (EAs), Swarm Intelligence and Artificial Immune Systems are also included within this category (De Castro 2006).

4.2.2 Simulation and Emulation

This approach includes the design of synthetic process aimed at creating patterns, forms, behaviors, and organisms that resemble life as we know it. With its products used to mimic various natural phenomena, it carries the potential of increasing our understanding of nature through computer models. De Castro specifies two main sub-approaches to the simulation and emulation of nature in computers which include the application of Artificial Life techniques or by using tools for studying the fractal geometry of nature. Artificial life systems have been created to study traffic jams (Resnick 1993); the behavior of synthetic biological systems (Ray 1994) and the simulation of collective behaviors (Reynolds 1993) amongst others. Its major concern is geared towards models of artificial life building life-like systems out of non-living parts.

4.2.3 Computing with Natural Materials

This approach corresponds to the use of natural materials to perform computation. It belongs to all nature-inspired hardware developments and thus it contributes to a truly novel computing paradigm that proposes to substitute, or supplement, current silicon-based computers. Computing with natural materials is geared towards new computing methods based on natural materials other than silicon. These methods result in non-standard computation that overcomes some of the limitations of standard, sequential von Neumann computers. Since bio-electronic devices can reach dimensions that are over one hundred times smaller than conventional silicon devices, bio-electronics can be harnessed for faster computer logic gates or light-activated switches (Forbes 2004). Given the assumption that any mathematical operation can be broken down into bits, and any logical function can be built using an AND and a NOT gate, any computable entity can be worked out by appropriately wired AND and NOT gates. Such independence from a specific representational system makes it possible to use new concepts for computational processes based on natural materials such as chemical reactions, DNA molecules, and quantum mechanical devices (De Castro 2006). Though still in its infancy, bio-electronics has the potential to provide significant advantages over traditional devices made with silicon. Design and construction of bio-electronics via genetic engineering or chemical synthesis can afford a much greater degree of control (Forbes 2004). Much related work is being carried out at MIT by Tom Knight, from MIT's AI Lab and Neil Gershenfeld from MIT's CBA[4.2]. I have recently read that Knight was working on molecular scale assembly of integrated circuits with the significant aim of programming bacteria in the same way a computer scientist might program a microprocessor (Forbes 2004).

4.2.4 The Problem with Natural Computation

Natural computation processes provide the designer with a new look at the natural world as it provides her with new ways to explore and understand processes that lie at the heart of the natural world. The main problem inherent in natural computing, however, remains its utilization in design through numeric and algorithmic techniques - merely for formalistic explorations that are, at times, divorced from real-world problems. In this light, one may often find that a network of leaf veins or the form of soap film is translated into building materials purely as geometrical forms, without necessarily understanding the structural and material logic inherent in their manifestation.

4.3 Computational Geometry 1: Synthesis without Analysis

4.3.1 Background: Problems and Issues

Design Computation aims to explore, develop and implement models of design generation (CAD), analysis (CAE) and fabrication (CAM) within the design process. Most of the important research carried out over the last decade and a half focuses on processes of parametric design based in associative geometry which are in most cases subjected to analysis, evaluation or optimization *post* the generation process (Figure 4.1).

Computational Geometry is the study of algorithms generated to solve problems *in terms of* geometry (Shelden and Massachusetts Institute of Technology. Dept. of Architecture. 2002). The field was developed parallel to advances in computer graphics and computer-aided design for purposes of data visualization and materialization. Recent advancements in computational geometry coupled with the expansion of CAD (computer-aided design) and CAE (computer-aided engineering) have expanded the designer's computational palette.

Traditional CAD applications typically allow for straightforward calculations of the absolute and relative location of features in Cartesian space. Such tools have now been expanded to include complex computational methods for non-Euclidian geometries such as B-Spline surfaces and NURBS curves[4.3].

In the following section problems associated with current approaches are raised and discussed.

[4.2] Center for Bits and Atoms, Massachusetts Institute of Technology

[4.3] Non-Uniform Rational B-Splines, are mathematical representations of 3-D geometry that can accurately describe any shape from a simple 2-D line, circle, arc, or curve to the most complex 3-D organic free-form surface or solid. Because of their flexibility and accuracy, NURBS models can be used in any process from illustration and animation to manufacturing.

4.3.1.1 The Problem of *Pre* and *Post* Geometry

Assuming a symbiotic relationship with geometry, design incorporates many issues that are independent of any specific formal configuration. These issues may be defined as the "parameter space" for a given design problem. Such "spaces" may be regarded as "pre-geometric" in nature; having arrived at a particular configuration, there exist potentially various alternative material interpretations of that particular configuration which may be regarded as "post-geometric" issues (Oxman 2007).

4.3.1.2 The Problem of Synthesis-Analysis Cycles

Computational geometry has customarily been used as a means for description and/or analysis of form. To a lesser extent it has been made instrumental for purposes of design generation. Given the significance of such tools to the exploration of shape and form, the limitation remains the partitioning between methodological models of description and models of, and for, generation. The integration of analytical tools and techniques as propositional rather than descriptive may potentially provide the user the capability to exploit work with computational geometry as a driver for the design process possessing *integrated built-in performance related considerations*.

The main objective of this work, as a central prerequisite to a potential paradigm shift in generative design, is to promote a novel methodology which supports the *seamless integration of geometry and performance*. Multi-objective representation where geometrical entities (or forms of description) promote speculations regarding the structural and/or environmental performance of the model endorses a design process that is generative in nature.

4.3.1.3 The Problem of Optimization

With regards to digital processes informed by physical constraints, much work has been done in design optimization which links performance evaluation to an already existing design. Prior research has been carried out which aims at assigning artificial intelligence to local discrete units such that each sub-domain may optimize itself according to presubscribed fitness criteria (Hanna and Mahdavi 2004; Hanna 2006). Under varied conditions of structural loading, each element as defined by the algorithm, modifies its thickness and orientation relative to local structural conditions. In micro structural scales, Haana perceives of an underlying repetitive modular system, the size of which correlates with that of the element sub-domain. Per a given element geometry, such changes occur as a response to environmental forces. Combined with Genetic Algorithms (GA's) and Machine Learning algorithms, the elements modify their geometrical and topological attributes. This research still lacks the incorporation of physical material properties as potential variables affecting the general distribution of matter and local shape to cater for local forces(Hanna and Mahdavi 2004; Hanna 2006).

Earlier research at MIT's Department of Mechanical Engineering combines the GA approach with an objective function such as strain energy to remove material where it is not needed (Shimada and Gossard 1998). This line of work overlaps with the Shape Optimization approach where the shape is optimized for optimal carrying of load. There are also "optimization" and work flow commercial packages such as "phoenix" and "insight" that can wrap the optimization code around the finite element simulation[4.4] to

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[4.4] Finite Element methods are included within a wide range of structural analysis methods (analytical method, strength of materials classical method, elasticity method etc) used for performance analysis. The Finite Element Method (FEM) is an analysis method primarily used within and across the engineering disciplines to allow for structural calculations of a given solid or fluid element. The overall shape of this solid may be incredibly difficult to analyze; however, the discretization of such shapes significantly reduces mathematical and physical (behavioral) complexity. The method was developed in the early 1940's by Alexander Hrennikoff and Richard Courant. Originating from the need for solving complex elasticity and structural analysis carry out shape optimization.

This research calls for the *elimination of procedural hierarchiess* which may potentially exist between "pre" and "post" geometrical design operations (i.e. form-generation first, material and/or performance evaluation later) and offer a new methodology for the *incorporation of material performance directly and explicitly into the geometric representation*. Some innovative work along these lines has been carried out which argues that models for design exploration promoting different forms of design representation should be bridged to support the discovery of novel designs (Kilian 2004).

The main objective of this work, as a central prerequisite to a potential paradigm shift in generative design, is to promote a novel methodology which supports the seamless integration of geometry and performance. Multi-objective representation where geometrical entities (or forms of description) promote speculations regarding the structural and/or environmental performance of the model endorses a design process that is generative in nature. In order to achieve seamless processes new forms of representation are required. These are introduced below.

4.3.2 Scalars, Vectors and Tensors: New Forms of Representation

Various mathematical qualities are made clearer employing visual tools and conceptual formulations rather than simply using numbers and functions. Visual learners frequently prefer the former method of elucidating such qualities. The concept of *tensors* is one such case, and given their considerable relevance to the understanding of material-based design computation, a rough illustration is provided below.

Numerically expressed entities such as prices and forces may be characterized by mathematical objects including quantities and/or directions. Such objects are termed scalars and vectors respectively. A scalar quantity can be represented by a single number (e.g. temperature, weight, volume, time and so on). A vector quantity represents a set of three scalar quantities, or numbers, collectively referred to as a vector. Combined, they share the description of a quantity which contains descriptions of magnitude and direction. Examples include force, velocity, acceleration, gradient of a scalar, and so on. All of these entities are described by some number and some direction indicating its path. In each of these cases, three numbers must be used to fully describe the quantity at hand. A specific coordinate is selected for describing a particular vector (Figure 4.2) such that if one chooses to describe a given force F in rectilinear coordinates, one would be required to specify the components of such force (Fx, Fy, Fz) for each of the three mutually perpendicular coordinates (Danielson and Noor 1997).

Tensors are geometric entities occupying the domains of mathematics and physics as they provide conceptual and technical extensions to scalars, vectors, and matrices. Multiple physical properties can be expressed as correspondences between two or more sets of vectors. Stress, for instance, takes one vector as input and produces another vector as output such that an expression between physical input and output is generated (Figure 4.3). It is due to their expressions of relationships between vectors, that tensors themselves are independent of a particular choice of a coordinate system. Furthermore, the tensor is a quality that obeys rules of tensor transformation. The coordinate-independent nature of the tensor makes the tensor take the form of a "co-variant" transformation law, meaning it relates between arrays computed in a one coordinate system to other arrays, computed in another coordinate system. Each array

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problems, the FEM offered a new approach promoting mesh discretization of a continuous domain (defined as the mathematical characterization of the analyzed object and/or environment) into a set of discrete sub-domains. Hrennikoff's work discretizes the domain by using a lattice analogy while Courant's approach divides the domain into finite triangular sub regions. The method was provided with a rigorous mathematical foundation during the 70's and has since been generalized into a branch of applied mathematics for numerical modeling of physical systems in a wide variety of engineering disciplines. In the field of structural mechanics, the FEM is often based on the *virtual work energy principle* or the minimum total potential energy principle which provides a general, intuitive and physical basis that has a great appeal to structural engineers.

is presented as a multi-dimensional matrix of numerical values. Elastic deformation and elastic stresses are examples of such tensors (Danielson and Noor 1997).

Each of the three mutually perpendicular faces of the cube represent three stress components, which collectively make up the tensor. Tensors have orders, or degrees, assigned to them which correspond to the dimensionality of the arrays representing them. By logical extension, a scalar might be regarded as a zero ordered tensor (its magnitude is its sole component, so it can be represented as a zero dimensional array) and a vector a one-ordered tensor (the vector is represented in coordinates as a one dimensional array of components). By this logic, a 3×3 matrix is a second-order tensor (being represented in a two-dimensional array and so on).

Tensors are very useful mathematical objects in the domains of physics and engineering. The medical imaging industry for instance, has rapidly developed over the last decade with the growing interest in Diffusion Tensor Magnetic Resonance Imaging (DT-MRI). In diffusion tensor imaging for example, scans of the human brain are produced by expressing the differential permeability of organs to water in varying directions using tensor quantities. Tensors thus provide a powerful framework to model the anatomical variability of the brain. They are also widely used in mechanics, for example with strain or stress tensors, and are becoming a common tool in numerical analysis to generate adapted meshes to reduce the computational cost of solving partial differential equations (PDE's) in 3D (Figure 4.4).

Diffusion tensor magnetic resonance imaging can be used to reconstruct whole heart geometry, as well as its fiber and laminar structure at a high resolution. In this technique, a tensor representing 3D diffusion of water in each image voxel is estimated such that it is aligned with the heart's cardiac fiber structure. In this way it is relatively easy to determine the occurrence of heart muscle disease (Helm, Beg et al. 2005).

Several frameworks exist in which tensor computations can be converted into Euclidean ones as tensors are transformed into their matrix logarithms, which makes classical Euclidean processing particularly straightforward to recycle.

4.3.3 Tensors on Canvas: Towards the Physical Representation of Material Properties

Most surface and solid modelers are achieved by using boundary representations such that the definition of 3-D form is the result of some preconceived boundary condition (Oxman 2007). Such forms are then created, edited and optimized using high-level constructive methods that rely on parameterized Boolean set operations and feature-based techniques (Biswas, Shapiro et al. 2004). Downstream applications often require optimization of integral-valued performance measures over such models that include volume, mass, and energy properties, as well as more general distributed fields (stress, temperature, etc.)[4.5]. Such properties, coupled with additional geometrical data may potentially be incorporated into the form-generation process so as to support the description of form as material substance using tensor indices.

Seldom is the architect driven by the need or by the desire to develop a design using tensors. This is partly due to the fact that tensor math is simply too hard to handle; but it is mostly due to their role as *analytical* functions that their *generative* potential in the field of architectural design has hardly been considered.

Currently, the design space of the architect includes the three dimensions of space (x, y and z). Cartesian space in 3D environments is the architect's canvas as every point in any given position may be described by its location in Euclidean space using those three coordinates. Such forms of representation appear to be sufficient for the architect who is traditionally engaged with geometrical manipulation as her means for both deriving and describing form. Physics and its analytics are left for the engineer, and any property to be optimized or simulated must first be explicated as an expression in 3D space.

[4.5] A key computational utility in all such applications is the computation of the sensitivity of the performance measure with respect to the parameters in the solid's construction history (Biswas, 2004).

Consider, however, the extension of Cartesian space to include the physical dimensions of matter and energy. In this thesis it is proposed that the geometric representation of form is not sufficient when considering material properties and their physical interaction with the environment. These aspects of the design process are frequently left for the structural or environmental engineer to analyze and predict. This introduces the following question: what if, instead of designing form with its physical properties emerging as byproducts of analysis and optimization, we would be designing directly with form's properties such that form itself would emerge as a tensor field informed by such constraints as thermal and mechanical conditions?

4.3.4 Points, Lines, Surfaces, Solids and Galaxies: The Problem of Hierarchies

Learning CAD is not unlike learning a new programming language: "you know one, you know them all". Occupying the designer's digital canvas is the world of geometry, governed by an eminent universal coordinate system (CS) referencing the (0, 0, 0) point for each new creation. Drop down menus containing functions, methods and various shape-generating tools accompany the main window into which new forms are drawn (yes drawn!) as points combine to create lines and as curves are lofted to create three-dimensional surfaces.

In this Euclidian universe, each point making up the design includes X, Y and Z values corresponding with its universal location relative to the CS. Things become straightforward once one has arrived at an understanding of the hierarchies of geometrically driven design. Points make lines (or curves), lines make surfaces, and surfaces make solids. While such representations of space suffice for basic Euclidean primitives, representation becomes challenging for more complicated spatial elements.

In the natural world, the generation of form appears to typically skip the steps required by the designer: lines and zero-thickness surfaces are too intricate to trace or, rather, such entities barely exist in nature. The physical world may well be described and reconstructed by the decree and the dictate of geometry, but there is more to shape than shape itself. Consider, for instance, the creation of bone tissue. Lines or curves would not suffice in the description or formulation of the tissue as a function of the changing loads it carries. The same applies for the growth of trees or the formation of muscle tissue and so on.

4.3.5 Material-assigned Geometry vs. Geometry-assigned Material

Few treatises in the field of architectural design computation have been devoted to the topic of physical representation through digital tools. Certainly, Dennis Sheldon's work entitled "Digital Surface Representation and the Constructability of Gehry's Architecture" (Shelden and Massachusetts Institute of Technology. Dept. of Architecture. 2002) holds relevance and is well-deserved of inclusion in this review. In his thesis, Sheldon presents work devoted to the development of computational tools describing Gehry's architectural forms with special focus on the digital representation of surface geometry and its capacity for describing constructability. Sheldon's objects of inquiry, much in-line with Gehry's design language, are surface materials such as paper and sheet metal. All the while, Sheldon is interested in the relationship between geometry and constructability. Subsequently, with an already existing formal expression, Sheldon successfully develops "generative strategies for the rationalization of surface form into constructible configurations" (Shelden and Massachusetts Institute of Technology. Dept. of Architecture. 2002). The generation of form is beside the point here; as a result, the role of materials occupies the scope of construction and materialization rather that of form-generation.

In this context however, it is essential to differentiate Sheldon's approach to the role of materials from the one presented here. To Gehry, as to Sheldon, the role of materials predominantly (and stylistically) restricted to the class of paper-like surface structures lies in their capability to describe geometry. In other words, in Sheldon's case, material is assigned to geometry. By contrast, it is here proposed that geometrical representations can potentially result from material properties and processes.

For Sheldon, as most naturally for Gehry himself as chief architect, the success of any computational tool is determined by its ability to seemingly trace the physical object, while any discrepancies between the digital and physical domains are attributed to descriptive failure. Tight conformance between the physical object (and it's already agreed upon form) and its digital portrayal is central to the role of computational process as assistive to the construction process.

Despite Sheldon's concern with the final stages of the design process (namely construction and materialization), its relevance to us lies in computational routines that occupy the space between the digital and the physical renditions of form.

Sheldon asserts: "The digital constructs of curved surfaces do not in themselves exhibit any affinity with the behaviors and characteristics of project materials" (Shelden and Massachusetts Institute of Technology. Dept. of Architecture. 2002). In other words, contrasting the robust alignment between rigid sheet materials and planar geometries, there typically exist little or no NURBS surface nets to describe Gehry's forms. This is peculiar, particularly considering that the impetus behind the early development of spline mathematics which was in fact developed to approximate the physically founded behavior of ship splines (Pottmann and Farin 1995; Shelden and Massachusetts Institute of Technology. Dept. of Architecture. 2002). In this process, thin metal strips were used in the delineation of ship hull forms, whose curvature was generated by materials bending, and only loosely approximated the corresponding bending of wooden laths on the ship hull. Meanwhile, it seems that the development of digital curved surface representation has diverged from this original material nature to one more reductive and abstract, guided by the feasibility of operations on the mathematical formulations themselves. Paper-like shapes, that are the central focus of Sheldon's line of inquiry, lie in-between the "highly constrained class of planar geometries and the general class of curved surface forms" (Shelden and Massachusetts Institute of Technology. Dept. of Architecture. 2002). Moreover, surface modeling techniques may impose constraints on the digital surface forms that differ from those of physical prototypes and their fabricated counterparts. Either way, the dichotomy between physical objects and their descriptive digital counterparts appears to be as challenging today as it has been throughout the brief history of digital design. Such a dichotomy emphasizes, yet again, that form generation processes may belong to one out of two potential classes: the first class being digital form-generation followed by physical fabrication, and the second class being physical form-generation, described, analyzed and simulated in the digital domain prior to construction. In both classes, material appears to be consistently secondary to geometry.

4.4 Computational Geometry 2: Analysis-driven Synthesis through Tessellation

From natural objects to manmade artifacts, tiling is all around us: it is the act of rationalizing highly complex form by breaking it up into smaller, continuous components. If well pursued, tiled objects can be easily designed and assembled. However, a geometric-centric view of tiling, whereby a predefined form determines the shape, size, and organization of tiles, has prejudiced the evolution of the field of digital design.

Precedents pointing towards *Material-based Tiling* exist mostly as procedural protocols written for the analysis and optimization of form after it has been generated. Such computational research is generally found in the areas of optimization and visualization (DeHaemer Jr and Zyda 1991) and focuses on issues of shape interpolation, namely, on the development of robust methods for connecting new vertices over given surface representations, and on methods for smoothly interpolating between models that represent the same object at different levels of detail (Turk 1992). The key notion is that of a *re-tiling procedure* that involves the creation of intermediate models, called the *mutual tessellation* of a surface, that contain both the vertices from the original model and the new points that are to become vertices in the re-tiled surface (Turk 1992).

Related work in computer science and visualization includes vector-field visualization and segmentation using centroidal Voronoi tessellation (Du and Wang 2004). In this method, the generators of the Voronoi regions in the tessellation are also the centers of mass with respect to a prescribed density. A distance function in spatial and vector spaces is developed to measure the similarity of spatially distributed vector fields. In this case, the tessellation assists in the analysis, simplification, and visualization of an existing material substance and its related vector fields. The method offers the generation of tessellated patterns a-priori or in parallel to form generation such that geometrical properties inform physical attributes and vice versa.

Specialists in the field of computer science had previously reviewed a large body of literature on automatic mesh generation for use in Finite Element techniques(Ho-Le 1988). In most of the cases examined, the aim was to subdivide the surface area or volume of a given object to provide a mesh over which some physical properties of the material, such as heat dissipation, could be simulated. Here, once more, the application of physical properties is applied for the purpose of analysis rather than the synthesis of form.

The field of computational geometry has also seen a good amount of work dedicated to tiling problems (Du and Wang 2004). Specifically, the properties of Voronoi regions and the associated Delaunay triangulation are relevant to establishing heterogeneous sizing hierarchies between triangular elements in the depiction of highly complex 3-D form (De Floriani 1989).

Digital design as a whole has experienced a renaissance in tiling through advancements in computational geometry and implementation of associative modeling strategies in design (Kaijima and Michalatos 2008). However, the question of how to extend the function of tiling beyond its role as a post-rationalizing strategy in the geometrical domain remains ill-developed.

I propose four discrete approaches to surface tessellation, defined by the guiding content for the tessellation. Such classification includes curvature-based tessellation, performance-based tessellation, assembly-based tessellation, and material-based tessellation.

4.4.1 Curvature-based Tessellation

Curvature-based tessellations are tessellations informed by the geometrical features of the surface. Examples include the transformation of polygonal-size variation as a function of the type and degree of curvature: smaller polygons are allocated in regions of high curvature, whereas larger cells are allocated in regions of low curvature (Figure 4.5).

4.4.2 Performance-based Tessellation

Performance-based tessellations are tessellations informed by a set of governing performance criteria such as the type and magnitude of mechanical loads or heat flux. In this case, the variation of cell size and density is a function of force vectors that emulate the magnitude and direction of the structural load. Geometrical features on the hosting surface demonstrate such functions. For instance, smaller polygons are allocated in regions of higher stress in order to increase the surface area that connects the elements, and larger polygons are allocated in regions of lower stress.

4.4.3 Assembly-based Tessellation

Fabrication constraints define assembly-based tessellation: in the case of repetitive fabrication, in which the size of each polygon edge is equal to all others, the polygonal tiling would be symmetrical across all directions. In other cases, the number of discrete measurements defined by the logic of assembly informs cell size and distribution.

4.4.4 Material-based Tessellation

Material-based tessellation assigns physical features to geometrical entities such as stress, strain, temperature flux, etc. In this case, mechanical material properties govern the relative form, size, and density of the cells. This class is different from all other classes[4.6] as it relates to the substance of the surface as a heterogeneous curvature domain. The location of a finite set of heterogeneities, defined by mechanical behavior, informs the tessellation. Each heterogeneous group has a polygon, or a group of polygons, associated with it. The mechanical properties as defined by the user, inform the spatial distribution of heterogeneities.

4.5 Computational Geometry 3: Analysis-driven Synthesis through Finite Element Methods

The following section presents the theoretical basis that can potentially support design that is driven by material properties. It introduces concepts related to the microstructure of materials and their relevance to design. A novel object-oriented finite element analysis method is presented and discussed which is relevant to the development of Material-based Design Computation.

4.5.1 The Promise of Reductive Approach to Physical Modeling

Like fingerprints, the structures of materials tell the story of their growth (by natural or artificial processes) and form (behavior). A composition of polycrystalline grains, second phases, cracks, pores, and various other features occurring on length scales that are large when compared to atomic sizes, the micro-structure of materials represents an intricate design (Carter, Langer et al. 1998; WC 2001; Carter 2010).

Simply put, an Object Oriented Finite Element approach to microstructures is designed to answer questions regarding the prediction of material behavior when forces of various types and magnitude are applied. In this way, the material scientist for whom the program is intended may visualize the location of stress and its distribution relative to "external" manipulation (such as temperature or load increase).

The typical, widely accepted approach for examining micro-structural behavior is based on the abstraction and reduction of a material sample from which a model is formulated to explain and predict its behavior. The advantages of such a reductive approach are clear: it facilitates a general case which may be repeatedly applied on, and refined by, cases of similar conditions; it simplifies and reduces the representation of complex structures into a finite pool of parameters. This defines a pilot case against which similar cases may be compared. For example, any given microstructure may be characterized by its grain size or porosity. Such parameters typically defer between one sample and the other, hence once generalized, some information is lost which may otherwise hold significant relevance for a particular case. As useful as reductive models may be, given their predictable nature, such information may be crucial for the design process. In other words, it is when physical properties depend on micro-structural particulars (such as the spatial correlation of crystallite orientation, the shapes and dispersion of second

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[4.6] Naturally, there could also be combinations of the classifications above, whereby a polygonal map, for instance, is defined by both the surface's curvature degree and its assembly logic. Mathematically, we know of three regular tessellations composed of regular polygons that can symmetrically tile a plane. Tessellations of the plane by two or more convex regular polygons, such that the same polygons in the same order surround each polygon vertex, are called semi-regular tessellations, or sometimes, Archimedean tessellations. In the plane, there are eight such tessellations. Simple and relatively known examples of surface tessellation are square and hexagonal tiling. Examples that are more complex include Penrose tiling; randomly colored, uniform polygon tiles; or hexagons and pentagons that compose a Buckminster sphere. In Chapter 4 we have distinguished between tiling of regular polygons (in 2-D), polyhedrals (in 3-D) and polytopes (for *n* dimensions).

phases, extreme figures of statistical distributions, local anisotropies and so on), that such a reductive approach is often futile (Carter, Langer et al. 1998; WC 2001; Carter 2010).

4.5.2 Object Oriented Finite Element Analysis (OOF) as Case Study

On the other side of the spectrum lies a non-reductive approach promoted by object-oriented methods. Such methods are unique in treating any microstructure as a special case devoid of the need to reduce any details characteristic of its behavior.

OOF (Object Oriented Finite Element Method) for Materials Science and Engineering is designed to simulate and predict the physical and mechanical macroscopic properties of complex materials microstructures. The code allows the designer to map material micro-structures onto finite element meshes in order to calculate local stress states, thermal behavior and so on. An integrated computational environment for multi-scale materials design, OOF is extendible to a range of problems such as elasticity, plasticity, thermal conductivity, and mass diffusion (Carter, Langer et al. 1998; WC 2001; Carter 2010).

Supported by the U.S Department of Energy, the development of OOF was led by Craig Carter (Department of Materials Science and Engineering, MIT), Ed Fuller, Andy Roosen and Stephen Langer (Information Tech. Lab, National Institute of Standards and Technology).

Commercial FE packages are frequently developed for, and applied to, large scale structural systems with regularly shaped components. Alternatively, systems of materials and their micro-structures are small scale and disordered. In the OOF environment, physics and Finite Element class structure are more closely tied to the underlying mathematics as well as allowing more physics and more types of finite elements (Carter, Langer et al. 1998; WC 2001; Carter 2010).

OOF is a Finite-Element Method based application designed from a materials science (rather than structural design) perspective. The motivation for its development was driven by the need to include, demonstrate, and utilize the role of heterogeneous, stochastic micro-structures on bulk physical properties and micro-structural damage propagation. As a result, the physical properties of materials can now be correlated with their various micro-structures in the process of design to shorten the materials development cycle, to improve material properties and their related processing and to promote design processes that are more reliable.

The core approach was guided by the need to develop computational tools for simulating multifunctional properties as well as clarifying and demonstrating the influences of stochastic, anisotropic microstructural features on the physical properties of materials.

The reductive, as-is knowledge of the physical and mechanical properties of multifunctional materials appears to be essential to their reliability as the substance from which design components are made. Not unlike fingerprints, no component is precisely the same as another when manufactured using natural materials. Such property measurements however are tremendously time-consuming and expertise-dependent. Furthermore, many measurements are essential in order to qualify new materials. Consequently, the development cycle for the design and validation of new materials has not yet caught up with the development cycle of structural components. Computational tools, such as OOF promote the shortening of material and process development without compromising diagnostic accuracy[4.7].

[4.7] Current capabilities include: modifying images, selecting pixels, assigning material properties to pixels, creating unstructured 2-D triangular meshes, adapting meshes to material boundaries (refining elements, moving edges, swapping edges), defining element and pixel groups, defining "active areas" to localize operations. Other capabilities include: solving unstructured 2-D triangular meshes, linear elasticity with thermal expansion, thermal conductivity, any crystal symmetry (isotropic, hexagonal etc), plane stress or plane strain, simple models of fracture, designer elements, boundary conditions (such as: fixed displacement, temperature, free, constrained motion, any combination of the above), distortions (applied displacement, temperature, applied force, heat flux), mesh creation (unstructured mesh, generative uniform mesh, modify material properties of existing mesh), output: maps of stress, strain, temperature, energy density), statistics of stress, strain etc for a whole mesh or

4.5.3 OOF: the Computational Process as Applied to Design

The computational process is based on an already existing digitized image of some micro-structure on top of which a data structure is then computed. Tools provide the user with the ability to graphically select features in the micro structural image and specify their properties such that the micro-structural data is composed of the visual image coupled with property data.

Virtual experiments simulating the material's behavior under various forms of loadings are then performed, visualized and quantified. A mesh is then fitted to pixel boundaries with the aim of minimizing (i.e. reducing) an energy function of the mesh, *E* (Figure 4.6, 4.7).

$$E = (1 - \alpha)Eshape + \alpha Ehomogeneity)$$

The set of operations applied to reduce the energy function of the mesh thus include fitting the mesh to pixel boundaries, generating the initial coarse mesh, refining the mesh's elements, applying a Monte Carlo method for node motion and edge swapping, and finally generating the final mesh (Carter, Langer et al. 1998; WC 2001; Carter 2010).

Further than its function as a materials computation and simulation environment, OOF turns out to be extremely useful in predicting thermal conductivity as in the design of material coatings and thermal barriers. In this case, OOF allows for the prediction of the thermal conductivity of a ceramic thermal barrier coating for a turbine blade which, when properly designed, will allow jet engine blades to operate at higher temperatures (Carter, Langer et al. 1998; WC 2001; Carter 2010).

OOF's framework serves as an exemplar of a *non-reductionist approach to analysis-driven design*. It does so by creating models of behavior prediction based on real-world cases that are more efficient and effective than prior approaches by excluding abstract modeling and simplification. Research into image-driven calculations is not a new idea (Edward Garboczi and colleagues at NIST have used this approach to investigate the behavior of cements and porous media, while researchers at Alcoa have developed finite element models of textured materials); however, its implementation as an open domain software, providing generic tools for calculating micro-structure-property relations is of great significance in the field of Materials Science and Engineering. Current limitations appear to relate to the need to model three-dimensional microstructure, a restriction currently being addressed by the team at NIST and MIT (Carter, Langer et al. 1998; WC 2001; Carter 2010).

4.6 Finite Element Methods: Problems and Issues in Design Applications

4.6.1 Background

Evolution is to nature what optimization processes are to the designer. Implemented across the fields of mathematics and computer science, the term optimization and its many manifestations refer to processes of solution refinement and guided choice. In the simplest, most elementary cases, optimization processes solve problems in which one seeks to minimize or maximize some function by systematically searching and choosing values that fit a given pool of constraints. Such is demonstrated by the Finite Element Method in the milieu of engineering and structural optimization. The Finite Element Method (FEM), also referred to as Finite Element Analysis (FEA) is defined as a numerical technique for finding numerically stable approximate solutions by eliminating ones that do not fit the domain of the objective function. The objective function is defined as the function determining the objective of a given optimization process

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element group, plot of stress, strain, etc along a cross section, stress, strain, etc at selected elements, forces at selected nodes, controlled from graphical user interface or script menu driven, commands in tree of submenus (Carter, Langer et al. 1998; WC 2001; Carter 2010).

which is also considered the function to be maximized or minimized in optimization theory. Various techniques are used as mathematical procedures for solving the equations defined by the FEM. They are also known as explicit methods for numerical integration of ordinary differential equations and include Euler's method as well as the Runge-Kutta method (Reddy 1984; Reddy 1984).

The Finite Element Method was developed by Alexander Hrennikof (1941) and Richard Courant (1942) and was motivated by the need for solving complex elasticity and structural analysis problems in civil and aeronautical engineering. Other approaches also exist which all share one essential characteristic of mesh discretization. Mesh discretization allows the designer to subdivide a continuous mathematical domain into a set of discrete sub-domains referred to as elements. Lattices and triangulation are offered by Hrennikof and Courant respectively (Reddy 1984; Reddy 1984). The engineering disciplines (mechanical, aeronautical, biomechanical, and automotive industries) frequently implement the method in the design and development of products. In addition to structural analysis capabilities, contemporary applications now include working environments for thermal, electromagnetic, and fluid simulation problems.

In the context of structural design and optimization, the method offers the designer the ability to increase stiffness and strength as well as to minimize weight, cost and optimize material selection. Detailed visualizations indicating the distribution of stresses and displacements aid the designer in determining where structures bend, twist or buckle. Finally, FEM software provides for a vast range of simulation options for controlling the complexities involved in the analysis of structural and environmental performances.

Over the last decade, further applications have emerged that examine the relation between search and choice by combining the Finite Element Method with other computational approaches already reviewed in this section, such as Genetic Algorithms (GA-FEM). In offering efficient search algorithms, GA-FEM approaches have proved successful in resolving complex structural problems (Hojjat Adeli 1993).

4.6.2 Finite Element Methods: Problems and Issues in Design Applications

The amalgamation of computer-aided design (CAD) tools and the finite element method (FEM) has greatly enhanced the engineer's ability to evaluate potential designs (Camacho, Hopper et al. 1997). For the designer, however, analysis unaided by synthesis appears to restrict the design space and limit possibilities for formal manipulation. Consequently, shape optimization methods have become increasingly popular, particularly for problems of structural design (Yang and Chuang 1994). However, for shape optimization methods to be fully accepted by the design community they must first be integrated with CAD systems that afford and promote formal operations. *In particular, the challenge central to the integration of CAD and shape optimization methods appears to be the inability to conform the finite element nodal coordinates to the CAD solid model dimensions.*

Some feature-based modeling environments have been developed that respond to such challenges using feature-based representations over-ruling the need to work directly with geometrical representations and instead operating on individual features defining these geometries (Chen, Freytag et al. 2008).

Related state of the art research at MIT's Department of Mechanical Engineering combines the GA approach with an objective function such as strain energy to remove material where it is not needed (Shimada and Gossard 1998). This line of work overlaps with the Shape Optimization approach where the shape is optimized for optimal carrying of load. There are also "optimization" and work flow commercial packages such as "Phoenix" and "Insight" that can wrap the optimization code around the finite element simulation to carry out shape optimization.

4.6.3 Nature Inspired Finite Element Methods

In the field of architecture, prior research has been carried out which aims to assign artificial intelligence to local discrete units such that each sub-domain may optimize itself according to presubscribed fitness criteria (Hanna and Mahdavi 2004; Hanna 2006). Under varied conditions of structural loading, each element as defined by the algorithm, modifies its thickness and orientation relative to local structural conditions. In micro-structural scales, Haana perceives of an underlying repetitive modular system, the size of which correlates with that of the element sub-domain. Per a given element geometry, such changes occur as a response to environmental forces. Combined with Genetic Algorithms (GA's) and Machine Learning algorithms, the elements modify their geometrical and topological attributes. This research still lacks the incorporation of physical material properties as potential variables affecting the general distribution of matter and local shape to cater for local forces.

Structural optimization is typically handled by iterative methods repeatedly computing a given model which includes physical parameters regarding its material composition and mechanical durability. Given a parameterized component along with a set of loading conditions, various optimization algorithms can be used to design effective shapes to counter a given load. Search procedures including gradient descent (GD) and genetic algorithms (GA) make repeated evaluations of the strength of different structures to do this (Hanna and Mahdavi 2004; Hanna 2006). The optimal structure will change under changing conditions of load as a new shape emerges. A structural component under complex loading conditions exhibits differing stresses at various points across its volume. If these stresses are sampled at the location of one of the unit cubes, they can be used to optimize the module of structure within that cube. The vector of stresses in the three (x, y and z) axes represents a loading condition for the structure in that cube, and for each stress vector there is an optimal set of node point positions and strut thicknesses to best resist that load. Both genetic algorithms and gradient descent (Hanna and Mahdavi 2004; Hanna 2006) have been used to find this optimal, using the finite element method to simulate the effects of loading.

4.7 Soft-Kill Optimization: Towards Biomimetic Design

4.7.1 Background and Relevance

Similar advancements in optimization have been developed in the field of Biomimetics as engineers reveal Nature's unique capacities for the design and optimization of its products. Within this scope, significant work has been carried out by Prof. Claus Mattheck, director of the Research Center at Karlsruhe. Mattheck embarked on the mission of simulating knot healing processes in trees. Knots are usually attributed to dormant buds or cut side branches and are generally considered as imperfections in the wood which greatly affect its mechanical properties.

Taking an in inspiration from Nature, Mattheck's aim was to develop processes to mimic growth and refinement and further implement them as computational routines in the field of shape optimization. More specifically, the task is to shape any given object so that it may be as light as possible without compromising its durability. In this process, both the external shape and its internal composition are modulated in a subtractive manner. In other words, the process of optimization is based on reducing access matter in specific locations that do not act as load bearing regions. Holes and recesses are incorporated in regions of unloaded zones. The following steps describe this optimization process which has been termed Soft Kill Optimization (SKO).

4.7.2 Computational Routines

1. A rough design draft is created for the desired form. Its external dimensions are set not to exceed the limits prescribed by the following function and are therefore preferably larger than smaller. This goes in line with the subtraction method: material can be eliminated, but not added i.e. the design draft may be continuously reduced, but not enlarged. A finite element mesh is then applied to the draft and the initial optimization process begins (Figure 4.8).

2. The initial elastic finite element analysis calculation is carried out taking into account the working load expected in service along with any presubscribed supports, restraints and guides, all of which will affect the distribution of stresses in the component. Mises reference stress[4.8] is generally also included in this initial calculation. In special cases, the normal principle stress s is also included.

3. In this step the local elastic modulus is set much larger than the stress calculated at any particular place $(E \gg \sigma)$. As a result, the more highly loaded zones become harder occupying more elements per more surface area, and the less loaded zones become softer, occupying fewer elements per less surface area. Interestingly, the initial homogenized material emerges as non-homogeneous as regions of stiff and soft matter appear. The new component may now characterized by its E-modulus variation across the initially uniform finite element mesh which was assigned to it in the very first step.

4. Given the newly defined non-homogeneous structure, a new finite-element stress calculation is carried out in which the load bearing zones of the component now carry even less load. This causes a sharper contouring of the entire structure. Steps 2 and 3 are reapplied repeatedly as the stresses in the non-load bearing zone bellow a certain minimum value are set at zero. The iteration method terminates when there is no longer visually and mechanically significant change in the component design.

Such automated process for the mechanically informed shaping of a structural component has generated a design perfectly fit to suit its structural requirements. The draft is predicted based on material constraints mapped to the actual load bearing locations in which the value of the modulus of elasticity vary locally. The overall modulus reappears as constant as the overall material has transitioned to its original homogeneous state. This pre-optimized light weight design may still require additional optimization routines in which areas remaining under loaded are shrunk away and notch stresses are reduced. The SKO method may be executed using local or global increment methods. The size of the increments refers to the amount of material being subtracted from the component per iteration, relative to the component's overall size.

4.7.3 Stress Increment Control Methods

The increment control method allows for further refinement of the structural component following the implementation of the SKO method. The first run of this procedure appears to be identical to the initiating step described in the stress controlled method ("step 1"). In the following iteration steps the calculated

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[4.8] Von Mises is a criteria used in predicting the onset of yield in ductile materials. The von Mises stress/equivalent stress/distortional strain energy is given by the relation:

$$\sigma_{eq} = \sqrt{I_1^2 - 3I_2} = \sqrt{\sigma_{11}^2 + \sigma_{22}^2 + \sigma_{33}^2 - \sigma_{11}\sigma_{22} - \sigma_{22}\sigma_{33} - \sigma_{33}\sigma_{11} + 3\sigma_{12}^2 + 3\sigma_{23}^2 + 3\sigma_{31}^2}$$

stress is no longer set equal to the local E-modulus, but rather to the local stress increment i.e. the $(n) - th$ to the $(n+1) - th$ FEM run is set equal to one increment of the E-modulus such that:

$$\Delta\sigma = \Delta E$$

Prior to any further run, this increment is then added to the existing E-modulus distribution such that:

$$E_{n+1} = E_n + \Delta\sigma_n$$

The newly defined E-modulus distribution now allows for repeated iterations to compute which will eventually eliminate any remaining non-load bearing zones in the design draft. The main advantage behind the local increment method is its rapid effectiveness even with when computed using relatively very few iterations. The disadvantage of the method lies in its potential to produce porous structures that are very challenging to compute and complicated to manufacture. To resolve this problematic, a *global* stress-increment controlled method was proposed by Dr Lothar Harzheim which results in fewer holes and notches in the final design draft.

4.7.4 Summary

The SKO method initiates by setting the initial approximate limiting dimensions ("bounding box") of the component. External loads are then applied as well as any limiting conditions such as clamping, support and guides. The FEM numerical tool is then applied to derive the calculations for stress and strain displacements in the component. Following the FEM application, the SKO method is then applied with the aim of eliminating any non load-bearing zones as it delivers a pre optimized light weight design draft. Any remaining notch stresses are then removed by the application of the CAIO (Computer Aided Internal Optimization) method. With Notch stresses are reduced by simulating biological growth facilitated by the removal of notches by shrinking any still remaining non-load bearing zones. The combination of FEM, SKO and CAO promotes the realization of the axiom of uniform stress and create durable and ultra lightweight components with maximum durability.

To summarize, the removal of low stress regions using evolutionary structural optimization is made possible by the trio of several methods developed by Mattheck and his team. The steps required for both external (-shape) and internal (-material) optimization include the following routines:

- Computer Aided Optimization (CAO) methods such as the Finite Element Method (FEM) previously described for the initial analysis of the component and the application of a FE mesh on which to perform further computation.
- Soft Kill Optimization (SKO) method for reduction of material substance corresponding to regions of high and low load.
- Computer Aided Internal Optimization (CAIO) for shaping holes and openings to correspond to the force trajectories applied on the homogeneous material.

4.8 The Element: the Discretization Technique as applied in FEM

A *discretization* technique is used in FEM in order to subdivide any given mathematical domain into a series of smaller regions within which equations are approximately solved. The determination of anticipated mechanical behaviors over the entire domain is determined by assembling sets of equations for each region, also known as an *element*. Multiple elements are connected between them through nodes making up a continuous mesh describing the surface area of the object. Common boundaries of adjacent elements within the mesh allow a continuous solution to be applied within the domain.

Solutions are determined per element and assembled to predict the overall functional behavior of the structural part. This process is achieved by measuring the displacement of elements at the nodes when load is simulated. Solutions are determined in terms of discrete values representing the displacements per each node (e.g. displacements in x, y and z directions). The degree of freedom at a given node is defined by the number of unknown primary field variables. The solution for the overall domain emerges as a piecewise approximation, expressed in terms of nodal values.

Strain is defined as the measure of the relative deformation of the solid body. In a Cartesian system, the components of strain are calculated as functions ("strain displacement equations") of the u, v and w displacement components. The normal strains Σx, Σy, and Σz are defined as the unit elongation of the body at a point in the direction of the respective x, y and z coordinate axes[4.9]. The shearing strains measure the distortion of the angle between the various planes. Additional material properties, such as piezoelectric properties can be included by additional terms in the stress-strain relationship equations.

For a given displacement function computed by FEM, strains can be calculated throughout the body from which stresses are derived using constitutive laws[4.10]. Clearly, an infinite number of geometrically possible displacement functions exist for a given object but only a singular unique displacement function will physically describe the deformation due to a set of forces and satisfy the equilibrium of forces. This unique function is determined according to the principle of minimum potential energy[4.11].

4.8.1 Shape Optimization vs. Topological Optimization

It is no surprise that most of the advancements in computational modeling and analysis have developed in the related disciplines of structural design and engineering. This is perhaps due to the fact that once form is provided, there are many ways of going about its evaluation and assessment in regard to its functional purpose. Such evaluation routines belong to the field of shape optimization. Problems typical to this field include finding shapes which are optimal in that they minimize a certain functional while satisfying given constrains. In many such cases, the functional being solved depends on the variable domain[4.12]. By logical extension to problems of shape optimization, problems of topology optimization are concerned with the number of connected components, or boundaries, belonging to the domain. Topological optimization techniques can assist working around the limitations of shape optimization problems which must have, by definition, fixed topological properties (such as a fixed number of holes in them).

4.8.2 Optimization Methods and their Relevance to Form-Generation

Problems relating to shape and topological optimization are of incredible relevance to the designer using performance-oriented modeling and analysis methods due to their ability to parametrically link formal constraints to functional ones. Once generated, the modeled form can be modified geometrically or topologically according to any functional limitations defined by the designer and/or by the environment.

[4.9] The strain is relative to some initial length

[4.10] Constitutive equations are used to relate between two physical quantities (often described by tensors) that are specific to a material or substance, and approximates the response of that material to external forces. It is combined with other equations governing physical laws to solve physical problems, like the flow of a fluid in a pipe, or the response of a crystal to an electric field.

[4.11] The principle of minimum energy follows from the second law of thermodynamics. It states that for a closed system with constant external parameters and entropy, the internal energy will decrease and approach a minimum value at equilibrium.

[4.12] The variable domain refers to a set of values that a variable can assume. For instance, when considering the bending stiffness of a tree trunk the variable domain contains all data related to possible and potential wind load conditions.

Given the designer's ability to manipulate the already modeled form in order to increase its fitness, the question arises as to whether or not such an approach can be generalized to include problems of form-generation. In other words, if one is given a set of constraints, an objective function[4.13], and some material parameters can form emerge?

4.8.3 Homogenization Methods and their Relevance to Form-Generation

Optimal shape design of structural elements based on boundary variations results in final designs that are topologically equivalent to the initial choice of design. This can be considered a drawback regarding the possibility of larger ranges of design solutions. Another limitation of shape optimization methods is that it typically introduces some meshing errors to the final element approximation of the analysis problem (Bendsøe and Sigmund 2003). The *homogenization method* first introduced and developed by Prof. Kikuchi from the University of Michigan, presents a methodology for optimal shape design where both of these limitations can be avoided. The great advantage of this method lies in its relation to modern production techniques[4.14] and consists of computing the optimal distribution in space of an anisotropic material[4.15]. This material is modeled by introducing an infimum[4.16] of periodically distributed small holes in a given homogeneous, isotropic material, with the requirement that the resulting structure can carry any given load combinations as well as satisfy other design requirements (Bendsøe and Sigmund 2003). Current shape optimization techniques operate by generating boundary variations for any given form while the homogenization method promotes directional changes in the material's microstructure generated by optimal topological variation corresponding to structural performance requirements.

4.8.4 Computational Issues in Homogenization Methods

Shape optimization of linearly elastic structures has been studied for over fifteen years and has reached a level of maturity that makes it possible to implement the methods in CAE (computer aided engineering) systems for production use (Bendse and Sigmund 2003).

One of the major challenges that lie at the core of shape optimization is the difficulty in modifying the topology of a structure during the design process. This challenge has resulted in thorough studies carried out in various settings that define the mathematical foundations for optimal shape design and design sensitivity analysis in boundary variation method.

Since change of topology cannot be executed in the design process, the state of the art today for shape design is that shape optimization is possible under the assumption that the initial topology is fixed during the iterative design optimization. In order to tackle the problem of topological variation, one must consider the possibility of representing a given shape without the use of shape functions (as is usually the case with boundary variation and sensitivity methods). The homogenization method was introduced by Kikuchi in the late 80's as such possible approach in shape optimization. It does so by transforming any given shape optimization problem to a material distribution problem using composite materials. The method considers two material constituents defined as substance and void. Instead of using the typical

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[4.13] The function determining the objective of a given optimization process which is also considered the function to be maximized or minimized in optimization theory.

[4.14] Such production technique include numerically controlled milling and plastic forming with controlled porosity through controlled cooling

[4.15] The term anisotropy is used here to describe direction-dependent properties of materials. For a more detailed description, please refer to the second chapter of this thesis.

[4.16] In mathematics, particularly set theory, the **infimum** (plural **infima**) of a subset of some set is the greatest element (not necessarily in the subset) that is less than or equal to all elements of the subset.

boundary variation methods for shape optimization, the homogenization method is applied to determine macroscopic constitutive equations[4.17] for the material with microscopic material constituents.

Problems of optimal structural design have been previously researched from a material perspective (Olhoff, Rønholt et al. 1998), and the computational approaches that have been developed in this context have great relevance for design processes informed by material behavior. The problem of thickness distribution as a function of variable load conditions, for example, has been previously examined for elastic plates and other generic structural components . Thickness distribution may be regarded as a problem of shape optimization dealt with from the point of view of constraints described by the shape and its contours. However, in introducing a material's micro-structure in the formulation of optimal-design problems, the work of Olhoff and Cheng has forged the way to a series of works exploring the role of topology on optimization. In this case, topological order is defined by micro-structural manipulations that give directionality to the shape or geometry at hand (Olhoff, Rønholt et al. 1998).

Problems of optimization can therefore be classified as belonging to either sizing problems, or shape design problems. The plate design problem, focused on the plate's contour as a function of the load applied on the shape naturally falls under the rubric of sizing problems, even when material composition is considered. Such is the classic case where calculations are applied on a plate constructed from two dissimilar materials in a given volume fraction. Conversely, the design of a torsion bar where one must consider the inclusion of a weak material in a strong one is considered a shape design problem. Interestingly, both of these typical cases suggest that laminated structures, made of two or more materials composed together, yield more efficient designs. This requires that the designer move from a shape-centric approach to a material-centric approach where material composition may be included in problems of optimal shape design. In other words, micro-structures must be designed in order to obtain the strongest structures. This effort requires a consistent way of computing effective materials properties for materials with micro-structures which is at the heart of the homogenization method (Bendsøe and Sigmund 2003). Optimal design of structures is therefore closely related to studies of micro-structures and the problem of finding optimal bounds on the effective material properties for composites. In mathematical terms the introduction of micro-structures in the formulation of structural design problems corresponds to a relaxation of the variation problem that can be formulated for the design optimization (Bendsøe and Sigmund 2003).

The computational approach at the basis of the homogenization method considers any given structural element[4.18] to be a spatial object defined purely by the loads it is meant to carry, its volume, and its design requirements including stress and strain limitations. A rough block is then assumed[4.19], the material of which is gradually removed according to the loading conditions based on finite-element approximations. The following steps of this method include traditional boundary variation optimization based on the design as it was computed in the initial phase.

The following steps are used to characterize the homogenization problem:

1. A reference domain is chosen, which allows the designer to define surface tractions[4.20] and fixed boundaries.

2. A composite material is chosen. This composite is constructed by periodic repetition of a unit cell consisting of the chosen material with one or more holes. The effective material properties of the

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[4.17] Constitutive equations are typically used in physics to describe the relation between two physical quantities (or tensors) that are particular to a given material or substance, and approximate the response its response to external forces. In structural analysis, constitutive relations link between stresses or forces to strains or deformations. The stress-strain constitutive relation for linear materials is commonly known as Hooke's law.

[4.18] The method assumes linear elastic members only.

[4.19] A "fixed domain".

[4.20] Referring to the adhesive friction between two surfaces in the case of a shape composed of two materials or more designed as a laminated structure.

composite are computed using the homogenization theory (Bendse and Sigmund 2003) . This step provides a functional relationship between the density of the composite (defined by the sizes of its holes) and its effective material properties.

3. The optimal distribution of the composite material is computed in the reference domain. This step allows to treat the optimization problem as a sizing problem with the density as the sizing variable.
4. The optimal distribution of material as defining a shape is interpreted, in the sense of the general shape design formulation.

The proposed homogenization method can thus provide the optimal shape as well as the topology of a mechanical element. The method is a material distribution method, based on the use of an artificial composite material with microscopic voids.

4.9 Material Representation in Digital Design

4.9.1 Binary Materials

Questions regarding the emulation of natural processes via computational logic, tools and technologies are a real challenge to multiple fields in many different ways. Computer scientists, biologists, and chemists amongst others, are all attempting to unveil the mysteries of nature's "computational" paradigms as they convert nature's logic to binary code. Over the last decade, more than a few MIT theses have sprung out of a frustration with existing computational paradigms (and their related fabrication technologies) combined with a fascination with nature. Biomolecular self-assembly has been researched by giants in the fields of computer science and artificial intelligence. In the Media Lab, such challenging design trajectories have been directed by Neil Gershenfeld of the Center for Bits and Atoms, and by Joseph Jacobson, director of the Molecular Machines group. The work of Saul Griffith, *Growing Machines*, is of relevance (Griffith 2004) as well as pioneering work by Manu Prakash - *Microfluidic Bubble Logic* - which offers new computing paradigms where bits can simultaneously transport and manipulate materials and information (Gershenfeld and Prakash 2008).

What appears at the core of all works related to any association between the natural and the digital is the quest for units. Moreover: questions regarding the challenge to emulate biology constantly boil down to questions regarding calibration. Each knowledge domain is concerned with its own set of units: protons, atoms, molecules, nucleotides, chromosomes, cells, material grains are all different ways by which to examine any given natural objet. Yet while a biologist is primarily concerned with the specimen's cellular functions, a material scientist is interested in scales that range between chemical composition and mechanical behavior. The computer scientist, on the other hand, is traditionally engaged with bits the basic units of information which exist in two distinct states and are interpreted as the logical values "1" and "0".

In digital imaging, the smallest unit available for visual manipulation is the pixel. The pixel is defined as a picture element, a single point in a raster image[4.21]. Represented by dots or squares, pixels are generally arranged in a two-dimensional grid. Each pixel represents a sample of the original image, where more samples typically provide more accurate representations of the original image. The intensity of each pixel is variable as well as its color definition, typically combined of red, green and blue values.

[4.21] In computer graphics, a raster graphics image or bitmap is a data structure representing a generally rectangular grid of pixels, or points of color, viewable via a monitor, paper, or other display medium. Raster images are stored in image files with varying formats.

Current CAD applications do not support the descriptions of internal material composition. However, some options exist which employ digital entities capable to describe micro-scale physical properties of materials and internal composition. Such entities include:

4.9.1.1 Voxels

Voxels are digital volume elements analogous to 2D pixels whose position is defined by their proximity to other voxels in 3D space. Voxels are good at representing regularly-sampled spaces that are non-homogeneously filled and are often used in the visualization and analysis of medical and scientific data. The origin of the voxel has its roots in the medical industry. Voxels are frequently used in the visualization and analysis of medical data. These processes are generally associated with morphometrics the field concerned with variation in the form of organisms.

4.9.1.2 Maxels

The basic unit for functional gradient materials (FGM) representation is the *maxel*[4.22] . The attributes of maxel include the location and volume fraction of individual material components. A maxel is also used in the context of the additive manufacturing processes (such as stereolithography, selective laser sintering, fused deposition modeling, etc.) to describe a physical voxel (a portmanteau of the words ‘material’ and ‘voxel’), which defines the build resolution of either a rapid prototyping or rapid manufacturing process, or the resolution of a design produced by such fabrication means.

4.9.1.3 Finite-Elements (FEM/FEA)

The Finite Element Method (FEM) is a numerical technique for solving partial differential or integral equations over complex domains (such as cars, pipelines, complex building skins). The aim is to simulate physical behavior under structural and/or environmental loading cases. The method operates by applying a mesh discretization of a continuous domain into a set of discrete sub-domains, usually called elements. Elements are predominantly small triangular features comprising the surface area of the simulated domain and can be individually analyzed.

4.9.1.4 Particle System Elements

A particle system is a computer graphics technique to simulate physical fuzzy phenomena that are almost impossible to reproduce using conventional rendering techniques (such as the simulation of some, moving water, dust and hair). Particles are typically controlled by emitters, which acts as the particle’s source and determines it location and motion in 3D space. The emitter has attached to it a set of particle behavior parameters including spawning rates (determining how many particles are generated per time unit), its initial velocity vector (emittance direction upon creation), lifetime, color and more.

4.9.1.5 Vague Discrete Modeling Elements (VDM)

Vague Discrete Modeling is a technique which supports the modeling of features, functions and methods of geometrical objects in associative modeling environments such that every feature is defined as a rule, capable of modifying its representation. The technique is *vague* in the sense that multiple objects are represented by one interval model, and that multiple shape instances can be generated based on certain

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[4.22] The term was introduced in 2005 by Rajeev Dwivedi and Radovan Kovacevic at Research Center for Advanced Manufacturing (RCAM).

instantiation rules. This allows the definition of an object's global shape while remaining the possibility to modify the shape in relation to constructive, functional, ergonomic or aesthetic constraints. The model is represented by 3D points representing its geometrical boundaries as sets of instances of object clusters. The outcome is a nominal discrete shape that is defined in terms of its typology, but its geometry is transformable depending on parameters defined by the user.

4.9.1.6 Summary

The common denominator for these four methods is the representation of physical behavior and/or material properties by assigning properties to discrete features comprising the model, whether by using voxels, elements, particles or point-sets. One major disadvantage of all entities mentioned above is their consumption of computational power in calculations. Also, the editing of such formats is made difficult by the lack of a robust method to relate between them in order to combine and integrate modeling and analysis routines.

4.9.2 Non-Binary Material Representation

Computational approaches supporting the representation of physical matter, whether through elements, particles or voxels have the major advantage of describing 3-D forms with varied material properties, such that the rate of graduation is informed by the granularity of the representational technique. This introduces one of the main questions repeatedly highlighted in this research regarding the smallest unit of matter. Such a "material unit" must be small enough to support material property graduation as a function of structural and environmental performance, and yet big enough to be physically constructed. But what computational environment support such design processes?

Various recent developments operating at the intersection between natural sciences and computation have explored alternative approaches to rapid fabrication processes supporting a graduated materials approach. Indeed, the question of generating form from scratch has not yet been resolved in these applications; however, they hold great relevance for its conceptualization.

One such project originated in the field of Computer Aided Tissue Engineering, or CATE (Sun, Starly et al. 2004). Computer Aided Tissue Engineering enables a systematic application of computer-aided technologies, i.e., computer aided design (CAD), image processing, computer-aided manufacturing (CAM), and solid freeform fabrication (SFF) for modeling, designing, simulating, and manufacturing of biological tissue and organ substitutes. Through the use of CATE, the design and fabrication of intricate three dimensional architecture of scaffold can be realized with reproducible accuracy to assist biologists in studying complex tissue engineering problems (Sun, Starly et al. 2004). Most importantly, this approach points towards the ability to analyze and fabricate natural specimens utilizing a voxel-based approach.

4.10 Material Fabrication in Digital Design

Current rapid fabrication technologies are designed as software and hardware packages separate from modeling and analytical environments. Since we are dealing with form-generation processes that may carry the potential to integrate physical material properties within the design process, a quick review of current state-of-the-art fabrication technologies seems appropriate.

4.10.1 Discrete Parts, Disintegrated Processes: The Limitations of CAM

A wide range of manufacturing technologies supporting rapid prototyping (RP) processes have recently made their appearance in both academic institutions and industrial corporations. Such technologies collectively serve the goal of fabricating parts and prototypes by laying down material in a gradual, controlled way, and in contrast to traditional manufacturing methods based on removing material (i.e. milling, turning) or deforming material (i.e. casting, molding). They include layered manufacturing, additive manufacturing and stereolithography. To date, software efforts in this area have focused on achieving compatibility between existing CAD tools and RP manufacturing processes. Geared toward the design of parts manufactured by traditional methods, current RP technologies do not facilitate designers with the exploitation of the expanded design space offered by layered manufacturing (LM) technologies (Chandru, Manohar et al. 1995).

4.10.2 From Discrete to Gradual Rapid-Fabrication Methods

A typical form-generation process in the design and architectural practice involves the geometrical representation of shapes and their fabrication first as models and then as full scale constructions[4.23]. The current range of rapid prototyping machines can be broadly classified based on the way they add material to an object under fabrication (Vijay and Edmond 1995):

1. Sequential vector-based systems create layers by the sequential formation solidification or deposition of the contours in the object's cross sections. Solid interiors are obtained with a hatching or filling-in operation.
2. Parallel image-based system use masks to create successive layers of the component. Either a light source solidifies a photopolymer or a sprayer deposits a material on surfaces exposed by the mask.

The advantage of the former approach is that geometric complexity does not affect the time it takes to complete a layer. Each mask is simply a slice of the object essentially, the image of the object's cross section.

For computational environments that support the integration of physical parameters, whether through voxels, particles or any other approach to the discretization of 3-D form, a similar approach to fabrication seems only suitable and reported to be well suited to parallel systems (Vijay and Edmond 1995).

4.10.3 Advantages of utilizing a Voxel-based Approach to Fabrication

4.10.3.1 Integrated Interface

However, such systems require a new geometric modeling approach uniquely customized to support it. Whereas traditional geometry based modelers displays a smooth, shaded object that gives the designer no feedback on the actual surface finish of the object after fabrication, a voxel based modeling approach naturally provides the designer with a WYSIWYG interface relating not only to the contours of the 3-D form but also to its substance representation.

4.10.3.2 Smooth Transition between File Types

A voxel-based approach to fabrication carries the advantage of supporting a relatively smooth transition between file types. The component is modeled, and then analyzed using a finite-element analysis module. The design is then iterated to account for the analysis results and the model is output in a given format (e.g. .STL) for fabrication. Digital fabrication equipment, such as layered manufacturing technologies

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[4.23] Since this thesis will mostly focus on digital fabrication technologies and their potential interface with modeling and analysis environments, we will consider the construction of physical matter as products of digital fabrication, and more specifically, layered manufacturing technologies.

for instance, then accepts the .STL file and generates a set of slices by orienting the object based on constraints and process parameters unique to a given fabrication technology. Because of the discretization inherent to LM the resulting component could have properties different from what the CAD analysis predicted. A voxel-based approach, in contrast, eliminates the need for an intermediate format as well as for a post processing step beyond the designer's control (Vijay and Edmond 1995).

4.10.3.3 Direct Fabrication

Image-based layered manufacturing (LM) systems do not require a slicing step with the voxel based approach, since the slices in three orthogonal directions are directly available from the voxel volume. However, vector based LM equipment requires a translation step to extract contours and enclosed regions from the image data of each slice. The obvious drawback is the size of the data, but image compression techniques can mitigate this problem.

4.10.3.4 Voxel-Maxel Relationships

In a voxel-based approach there exist a direct relationship between a voxel and the basic additive resolution of the LM equipment. The relationship implies that the surface area of the resulting object can be estimated by identifying the exposed voxels in the model, adding the area contributed by the voxel faces on the boundary, and using suitable filters to simulate the effects of merging and coagulation behaviors in the real material. Properties such as friction coefficients, surface roughness, and contact area between interacting parts to be estimated (Vijay and Edmond 1995).

4.10.3.5 Printing Composites

A voxel-based approach carries the potential to exploit a major capability of layered manufacturing (LM) equipment by considering the stacking of material layers with varied discrete properties. From here it is relatively easy to imagine the potential of this approach in the design and fabrication of composite materials. The range of materials that current commercial LM systems handle is limited but growing (Vijay and Edmond 1995).

4.10.4 Summary

The voxel-based approach for geometric modeling offers a powerful methodology for the new rapid prototyping technologies. It has several advantages over conventional modeling methods, stemming chiefly from the close resemblance between a voxel model of an object and the object fabricated using an LM technology.

4.11 Towards Material-based Design Computation

Before the integration of computer-aided design (CAD) in architecture, the architect would initiate a design process by generating some geometric form which would later be assigned a set of materials along with some structural and environmental analysis. This process entails that we begin with form. CAD was typically developed to support processes of design automation, but interestingly, it did not challenge the design process itself; it only made it easier, and better still faster.

We have previously seen that Nature and the world of natural materials operate quite differently, as form is merely a byproduct of assigning material parameters to environmental processes. In the previous two chapters we have characterized natural forms and materials by their ability to negotiate between multiple performance-criteria in order to generate objects that are highly customized to fit their environment. In addition, they are characterized by the lack of separation between processes of form-generation, evaluation and fabrication.

Given the obvious values rooted in Nature's processes and products (i.e. material efficiency and high levels of customization), it is imperative that the world of design considers alternative computational approaches to design that promote and sustain such values.

As we move away from the world of computational geometry and into applications from structural and material engineering, we find that in these disciplines form is closely related to physical properties, behaviors and anticipated functions. Amongst the various applications supporting physical simulation of sorts (i.e. finite element methods) we also find novel expressions for combining such applications with novel form-generation processes (i.e. cellular automata and genetic algorithms combined with some finite-element method). The problem with such experimental design methods still remains the disparity between the actual form generated by the script or the program, and its material properties and behavior relative to their anticipated functions. As we aim to unite between generation, evaluation and eventually fabrication, we must look beyond current approaches in design computation that support and promote seamless integration between the digital and the physical domains.

In the following chapter a methodological framework entitled *Material-based Design Computation* will be introduced. It was developed to support a new universal approach to the problem of digital form-generation with continuously varying material properties satisfying prescribed material conditions on a finite collection of material features and global constraints.

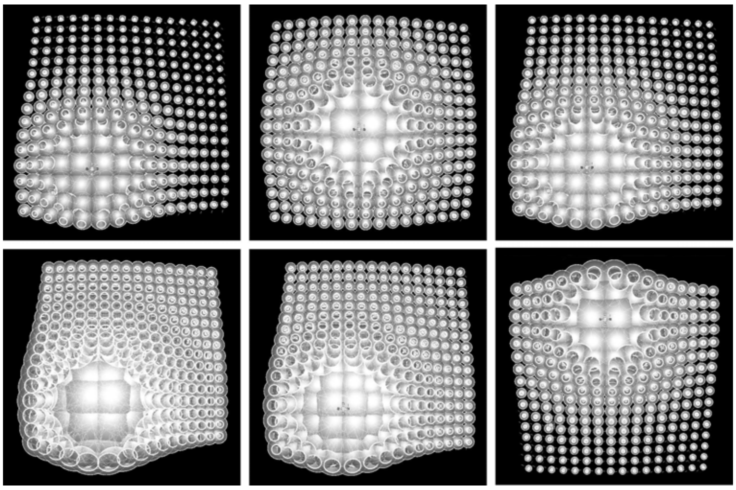

Figure 4.1: Parametric design exercise exploring the relationship between a singular parametric component and its "hosting" environment. In this case, one point feature defines the overall organization of all other components defined as partial spheres. Parametric design explorations such as this are initially informed by geometrical constraints. However, it is clear that in such cases computational routines inform the final shape rather than aiding some preconceived architecture. Programmed and represented in the *Generative Components* software, 2007.

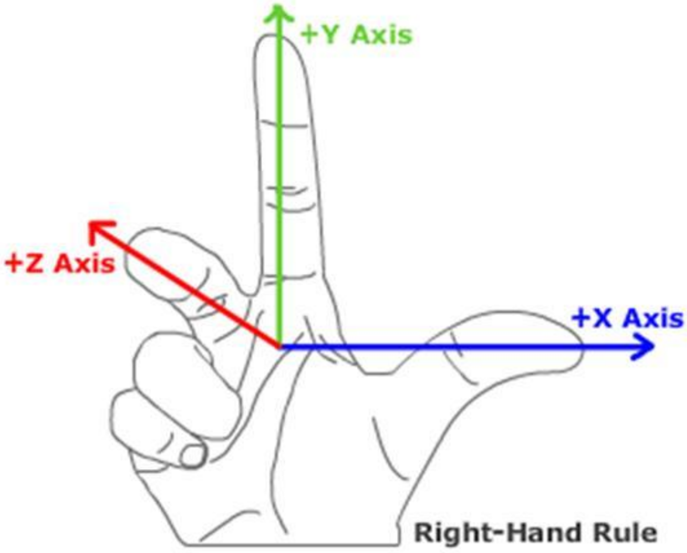

Figure 4.2: The right-hand rule in mathematics and physics is a common mnemonic for the expression of notation conventions for vectors in 3 dimensions.

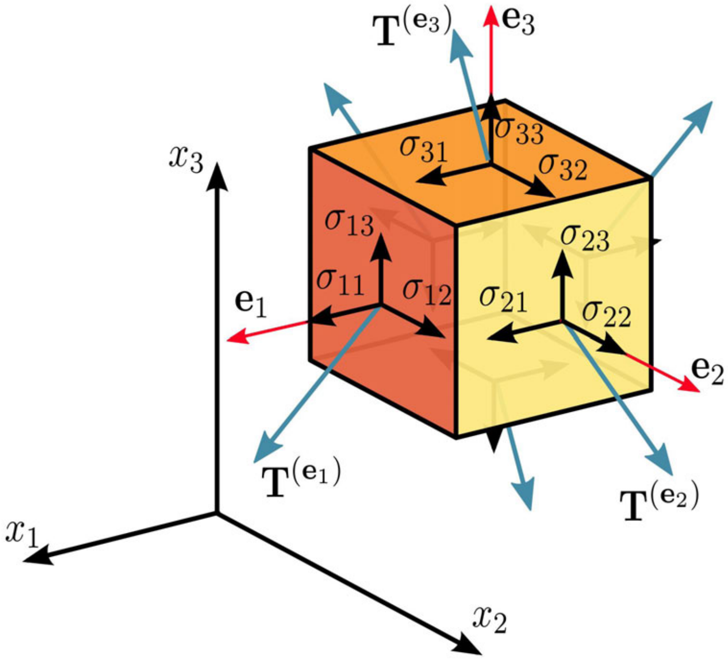

Figure 4.3: Unlike vectors, tensors relate to more than 3 dimensions such as the case for expressing stresses or strains. The tensor may have an arbitrary number of indices relating to various physical characteristics and constraints. The stress tensor illustrated in the images abive is an example of a second order tensor. Since we are generally operating in 3 dimensions, the stress tensor has 9 elements. The first index i stands for the surface on which the stress is taken to be acting and the second index j is representative of the direction of the force. The elements

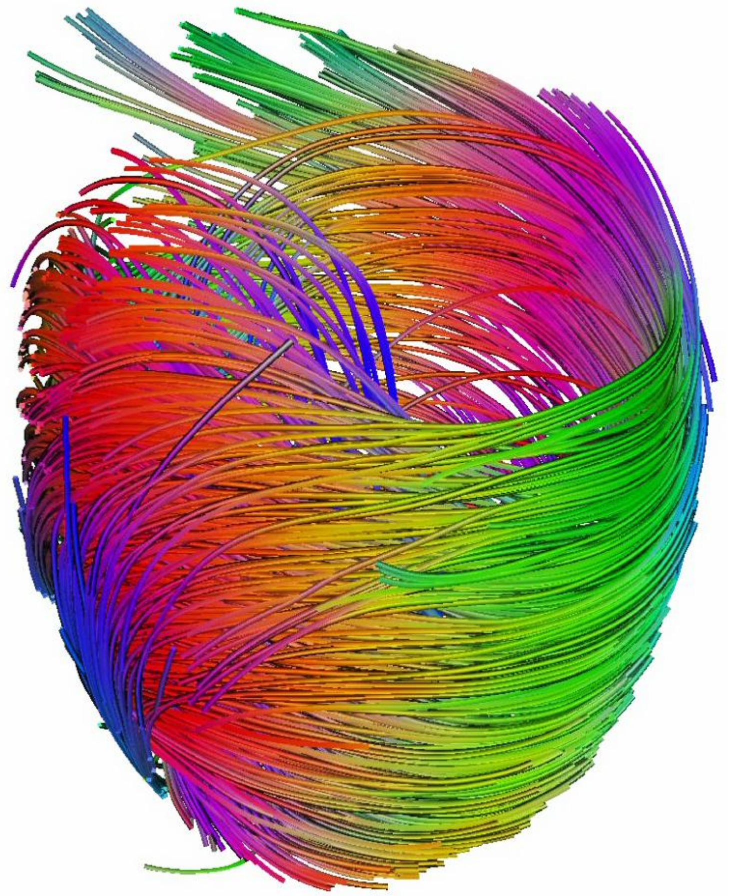

Figure 4.4: The image was generated from an MRI scan of a heart, using Diffusion Tensor Imaging. The scan tracks the movement of water molecules throughout the heart muscle as it reveals how the muscle cells are aligned. The lines represent the orientation of muscle fibers in the heart's biggest chamber, the left ventricle. Tensor-oriented representation techniques allow the practitioner to visualize physical behavioral data in addition to geometrical formalisms. Source: $http$: $//www.ox.ac.uk/media/science_blog/100209_1.html$

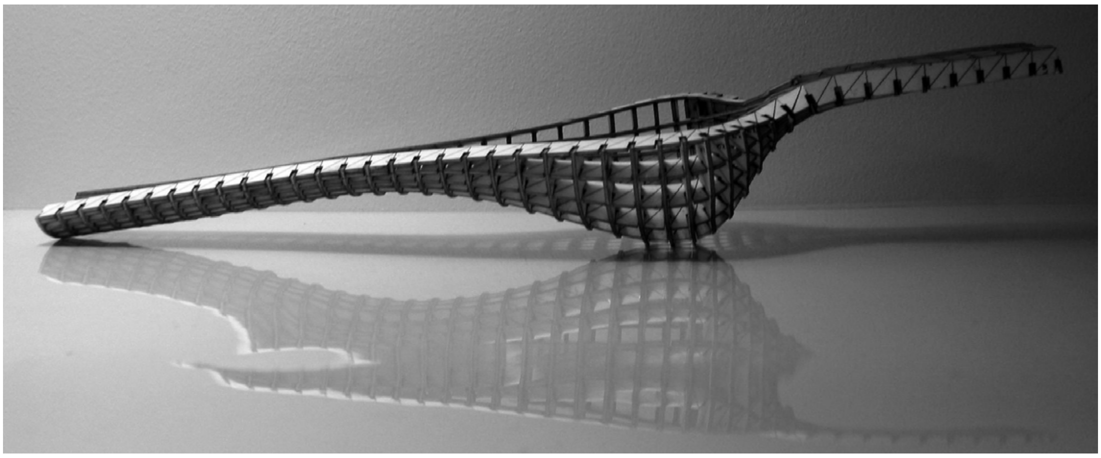

Figure 4.5: Curvature-based tessellation exercise, 2007. A doubly-curved surface is tessellated according to its curvature following the “U” and “V” mesh lines. The surface is then cut into strips, laser-cut and assembled in friction-fit manner. The size of each rectangular cell defined by the mesh corresponds to local curvature degrees.

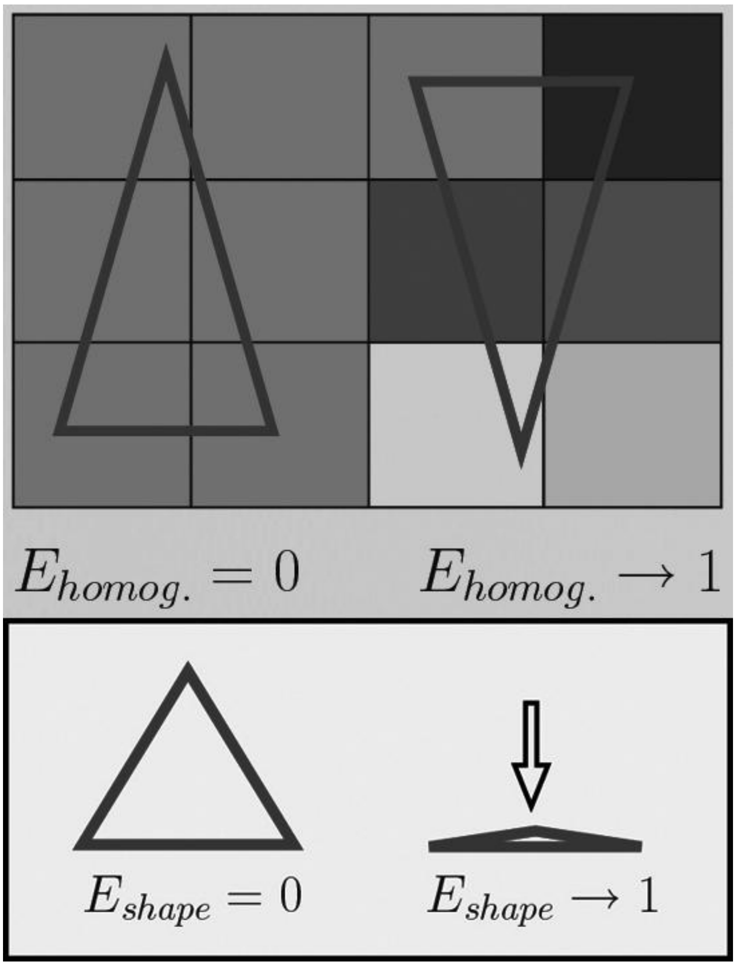

Figure 4.6: OOF2 energy function minimization diagram. Mesh operations work to minimize and “energy” functional *E* of the mesh. Various operations are applied in order to reduce the energy of the mesh relating its distribution to the image pixel distribution of the specimen (Carter, Langer et al. 1998; WC 2001; Carter 2010).

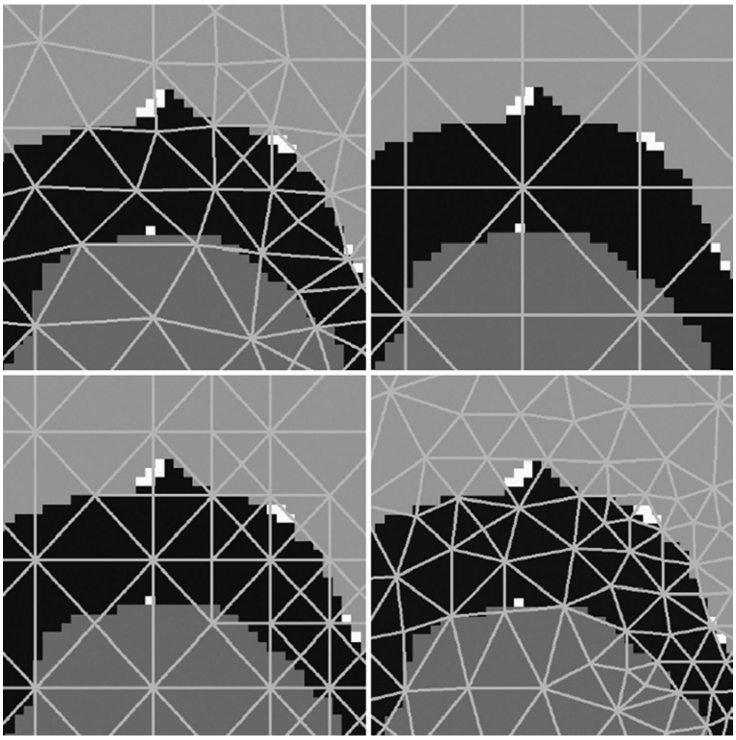

Figure 4.7: OOF2 mesh iteration process based on material constraints defined by the user (Carter, Langer et al. 1998; WC 2001; Carter 2010).

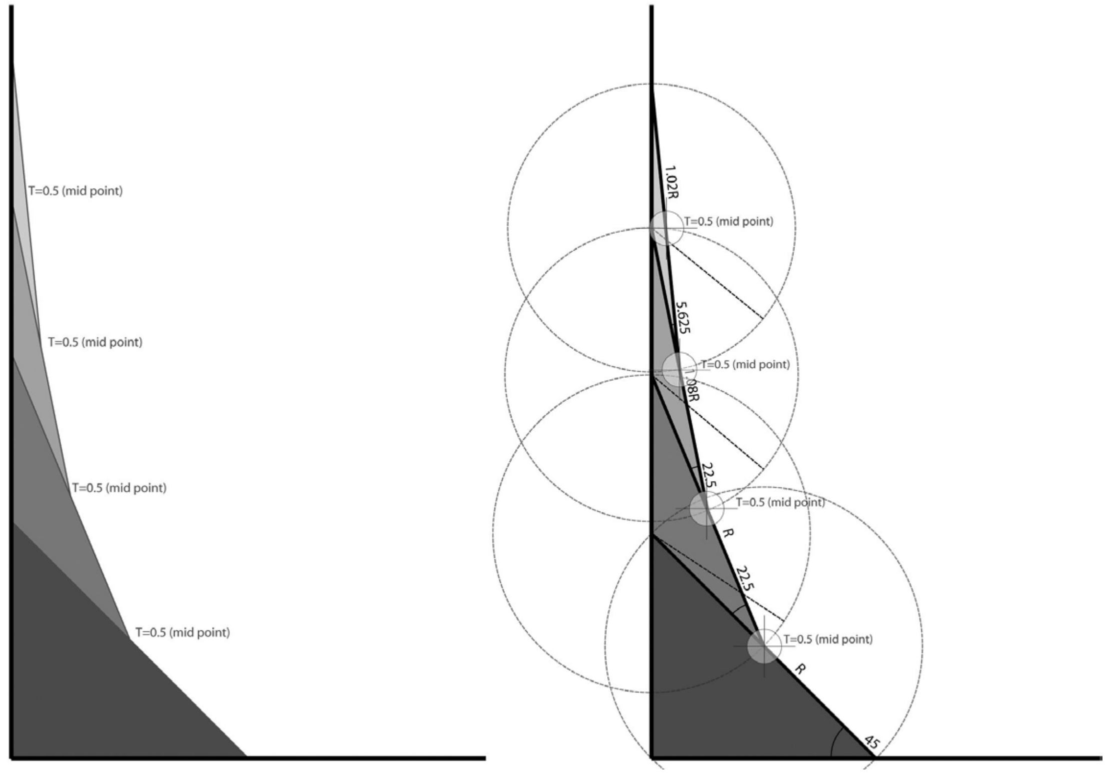

Figure 4.8: Manual desecration of the *soft-kill optimization* (SKO) method developed by Prof. Claus Mattheck, director of the Research Center at Karlsruhe (Mattheck 1998). Left and right images display the rationalization of the method using the *Generative Components* software without and with variable geometrical features respectively.

CHAPTER 5

MATERIAL-BASED DESIGN COMPUTATION

Theoretical and Technical Foundations

> *"Materials are the new software"*
>
> **—AJ Jacobs**
>
> *"A new language requires a new technique"*
>
> **—Philip Glass**

5.1 Nature's Way, Material's Strategy, Computation's New Paradigm and the Formula for Natural Design

If we are to define an ecosystem as *sustainable* a condition in which biodiversity, renewability, and resource productivity are maintained over time then the notion of sustainable design appears enigmatic, if not paradoxical. By its very nature, design is simply *not* sustainable, and the built environment is struggling to reduce its carbon impact upon Nature's weathering. To date, and without a doubt, the most urging problem in the design of the built (and consumed) environment is its massive contribution to the earth's carbon footprint.

5.1.1 Towards Sustainable Products: Multifunctionality and Mass-Customization

The theoretical basis of this thesis is that at the root of the crisis, lays the problem of *functional disintegration*, i.e. the notion that each design constraint whether social, spatial, structural or environmental - must be satisfied by a set of parameters discretely assigned to it. Such design requirements are typically partitioned in terms of both material ("product") and methodological content ("process").

Take, for instance, the design of a building façade. Not unlike the human skin or a plant's tissue, a building's façade acts both as a barrier and as a filter controlling the load and movement of air from the exterior environment into the interior spaces and vice versa. In the artificial world however, barrier and filter-associated requirements are generally treated discretely as opposed to being composed as an integrated tissue. More specifically, the skeletal, load-bearing elements of the façade (designed to provide stability against wind loads) and the environmental elements of the façade (designed to control thermal flow) are assigned separate materials requiring separate processes of design, fabrication, construction and assembly. Steel and glass are typical materials applied for structural and environmental control respectively.

The discrete assignment of materials (e.g. steel and glass) per their discrete respective functions (e.g. structural soundness and environmental/visual comfort) is characteristic of turn of the 20^{th} century architecture, along with the introduction of steel and glass to the design of large scale buildings and skyscrapers. Here, once again, it is the use of innovative materials and their integration within the construction industry that defined the architectural movements that followed (e.g. International Style Architecture, and so forth).

Post-and-beam construction is not in the least sustainable insofar as it aims to combine functions by way of separation rather than integration. In addition to transferring the self-weight of the structure to the ground, the structural components of the building also serve to transfer wind forces as well as to provide support for the cladding and various other functions. The conceptual and operative partitioning between structural and environmental building elements has contributed to various cladding types that followed such as the curtain wall façade and the double skin facade. The curtain wall façade generally is supported by the edge of the building structure such that it is exterior to the skeletal system of the building. In turn, the double skin façade promotes the consolidation of the building's ventilation within the boundaries of two layers of cladding. Thermal insulation is provided between those two skins that meets specific energy demands and user comfort requirements (such as visual, hygienic, tactile, olfactory and acoustic requirements), while the load bearing elements are interior to the skin.

Clearly, there are numerous good reasons for the design world to embrace and promote such strategies of *functional discreteness* in building design and construction; modularity and the ease by which to fabricate and replace building components being one of them. Indeed it may be argued that such age-old construction methods are here to stay precisely for their efficiencies. On the other hand, and considering the state and rate of deterioration of environmental conditions, it is perhaps time to broadly consider alternative approaches to both design and construction, as radical as this proposal may appear.

5.1.2 Towards Sustainable Processes: Integrated Modeling, Analysis and Fabrication Environments

The case of cladding is indicative not only of *functional discreteness*, but it also illustrates the related notion of *methodological discreteness*. That is to say, that the cause (or the effect, both may be equally applied in this case) for functional separation supported by its material counterparts is the outcome of the disintegration between the various processes of design. Not only do we use particular processes to design, fabricate and assemble a specific material, but, more importantly, such disintegration appears to be paramount and inherent in the design process itself: modeling, simulation, analysis and fabrication are all compartmentalized by method and by disciplines, as architects, engineers, scientists and construction experts exercise their own domain knowledge using their own methodological routines. As designers we may ask ourselves: When was the last time you used a CFD[5.1] application in the design of a chair? When have you recently programmed a robotic arm to cut, assemble and construct an arch assembled from bricks? Have you ever used tensor math for the generation of hydrodynamic shapes?

Clearly, much waste is involved in translating a design idea to its physical manifestation, from the drawing board, or the screen, all the way to the building site. Not unlike the products and the buildings that we design, our processes, too, are barely sustainable. Material waste is only one of the byproducts of cutting, milling or molding structural components into their desired shapes and forms. But when considering the design process itself, prior to its physical manifestation in built form, it is clear that processes

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[5.1] CFD stands for Computational Fluid Dynamics. It is considered one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows.

of simulation and analysis executed with state-of-the-art computational software are by their very nature involved with processes of optimization. Regardless of its waste factor, manipulated or not as it is being optimized according to a set of “fitness criteria”, the form of a product or a building is merely a formal statement communicated in the language of geometry. Differences “in degree” - rather than differences “in kind” are generally all that is afforded by the engineering disciplines prior to fabrication. Indeed, structural optimization as I view it is simply a figure of formal diet.

Processes of analysis are indeed not the only routines secondary to formal generation (could there be any other option?). The assignment of material properties to a presubscribed form are generally considered as subsequent to geometrical manifestations. As a result, one may often find cases, especially in recent years, in which the relation between the geometrical form and the material chosen for its construction is completely counter logical insofar as a sustainable design process is desired.

With regards to the incorporation of state-of-the-art design computation and digital fabrication technologies as part of the design process, in recent years we have been witnessing the emergence of two fundamentally different approaches to design. On the one hand there exists a desire to explore an expressive formal repertoire (how curvy can a building become?) while on the other, an aspiration to redefine sustainable design as we know it. Those two approaches are effortlessly detected across the scope of contemporary practice as two opposing worlds, each corresponding to a completely different set of values: formal expression vs. being good to our environment. The former approach celebrates advances in computation and digital fabrication technologies while the latter rejoices in the continuous improvement of building codes as they may become more environmentally friendly. For the green tribe, sustainable design is merely concerned with the evaluation of current building code and practice as it seeks to improve and advance its dissemination amongst designers and architects alike. In this light, any technological advancement devoted to challenges driven by formal content and its transformation into the physical realm is only harming our green regime. When our environment is what we wish to protect, such a disposition holds undeniable legitimacy. Indeed, most of the design processes linked to the generation, analysis and construction of formal challenges are anything but sustainable.

5.1.3 Chapter Organization

Given that both our products and our processes appear to be harming our already injured planet, and given the will to embrace technological advancement, design, it seems, must seek an alternative model for the generation of form. I, for one, turned to Nature in search of a revelation.

The following chapter introduces the assumptions, goals, objectives, issues and questions positioned at the heart of this research thesis. It culminates with a speculation about what the methodological frameworks supporting performative design experimentation might be.

Based on the background research presented in the previous chapters, I present three major *assumptions*: that natural objects are sustainable mainly due to the way in which materials are positioned and distributed to account for structural and environmental pressures such that each object is highly customized and fit for its environment; that form-generation processes in nature are more sustainable as they *integrate* between processes of modeling (growth), analysis (adaptation), and fabrication (material formation and response); and, that in nature the distinction between “material” and “structure” is elusive and irrelevant as they are so well-integrated and formally inter dependent.

The research *goals* focus on achieving a more sustainable design approach which manifests itself in the design of artificial products and processes favoring high levels of customization over mass production; integrating between modeling, analysis and fabrication environments; utilizing a graduated property approach to the design of objects; and favoring material considerations over geometrical expression.

In line with the research goals, research *objectives* aim at: achieving high levels of customization through the integration between multiple desirable functions; achieving an integrated design environment through the integration of form-generation functions and analytical functions; implementing a graduated properties approach in design by developing form-generation environments based on material substance rather than merely on contours of 3-D shape; and, finally, prioritizing matter over shape by developing a design process that takes into consideration substance properties prior to the generation of shape using a *material pixels* approach presented in the following chapter.

Research *issues* range from models that allow incorporating multiple performance criteria, to ways in which to design highly integrated modeling and fabrication interfaces, as well as questions regarding the role of variation and heterogeneity in design and ways in which the prioritization of matter over shape can express itself in form-generation (Figure 5.1).

Research *questions* respectively spring from the issues presented and focus on non-binary computation; universal material units; relationships between material and structure; and the prospect of implementation of the concept of *digital materials*. The research questions presented above form the basis for the program of experimental research.

The chapter ends with a brief review of the methodologies studied and applied to explore the issues and questions raised.

5.2 Research Assumptions: Nature's Products and Processes are Sustainable due to Product and Process Integration

Nature is demonstrably sustainable. Her challenges have been resolved over eons to enduring solutions with maximal performance using minimal resources. Unsurprisingly, Nature's inventions have for all time prompted human achievements and have led to the creation of exceedingly effective materials and structures, as well as methods, tools, mechanisms and systems by which to design them.

5.2.1 Nature's Sustainable *Products*: Structured Difference

Natural structures posses the highest level of seamless integration and precision with which they serve their functions. As previously reviewed in Chapter 2, a key distinguishing trait of nature's designs is its capability in the biological world to generate complex structures of organic or inorganic multifunctional composites such as shells, pearls, corals, bones, teeth, wood, silk, horn, collagen, and muscle fibers (Benyus 2002). Combined with extracellular matrices, these structural biomaterials form microstructures engineered to adapt to prearranged external constraints introduced upon them during growth and/or throughout their life span (Vincent 1982). Such constraints generally include combinations of structural, environmental and corporeal performance. Since all biological materials are made of fibers, their multifunctionality often occurs at nano through macro scales and is typically achieved by mapping performance requirements to strategies of material structuring and allocation. The shape of matter is therefore directly linked to the influences of force acting upon it (Vogel 2003). Material is concentrated in regions of high strength and dispersed in areas where stiffness is not required. It is a well known fact that in nature shape is cheaper than material, yet material is cheap because it is effectively shaped and efficiently structured.

Most importantly, Nature's designs are structured such that they are able to adapt and respond to multiple functions and multiple performance criteria. The form of a tree branch for instance serves its structural requirements, to self-sustain itself under heavy wind loads while at the same time it is designed to allow for the transfer of fluid and heat through its internal and external tissues. In other words, natural tissues are sustainable by way of *functional integration* whereby one material modulates its internal structure in order to correspond to both structural and environmental stimuli.

Multiple-performance negotiation is defined as the capacity to locally vary an object's material properties such that it accurately corresponds to various structural and environmental constraints applied on it as part of the design process. The research assumption is that if products and buildings are designed as systems that *integrate* multiple properties by continuously varying and controlling their internal properties, mechanical effectiveness is enhanced as well as environmental response, and the resulting designed product will, overall, become more sustainable. This assumption requires a new approach for the generation and materialization of form that is not motivated purely by form itself, but rather stimulated and defined by environmental constraints. It is important to note, that such an approach also allows for the *customization* of any given design product or building to fit its particular fitness requirements.

Numerous examples that support this approach in terms of the contribution to sustainable design have been provided in Chapter 3 from the field of product and industrial design. However, as previously identified in Chapters 1 and 3, the main problem with current design approaches embracing multiple-performance negotiation (at least theoretically) is that the assignment of material properties in these cases is consistently *secondary* to their shapes and formal descriptions. I anticipate that the design approach offered by this thesis will extend itself to include the very initial stages of form-generation processes.

5.2.2 Nature's Sustainable *Processes*: Computing Difference

Nature's capacity to generate multi-functional objects is fueled by its sustainable processes. In Nature, processes of modeling, analysis and fabrication are grouped to arrive at an integrated process such that there are literally no differences between such phases. Human bone, as previously discussed in Chapter 2, can remodel itself to fit the type of load it supports. We lose bone tissue in outer space where there is no gravity and we, women, gain bone tissue upon pregnancy to support additional body weight. It is called Wolff's Law, based on the pioneering discoveries of 19^{th} century surgeon, Julias Wolff. Trabeculae (Latin, for "little beams") are the structures in human bone. When bones are stimulated by additional weight, they lay down more calcium structures, more little beams. The bones become denser, harder, and more durable. It would then be natural to assume that Nature engages in processes of modeling while it analyzes, and while it fabricates. Such processes are unified into one integral chain of events whereby the choice of material is directly linked to its functions. Form, as far as Nature is concerned, is beside the point.

The initial design assumption that multi-performance negotiated *products* are more sustainable, and that processes which support it must be developed and applied across the board of design also assumes that there exist *processes* of design generation to support it. Clearly, this is not the case (otherwise we would be growing houses by now, rather than building them!)

If we assume that Nature's Way is, by definition, sustainable, and if we have proven (as previously demonstrated in Chapter 2 of this thesis) that in Nature there exists no separation between processes modeling, analysis and fabrication, then such disintegration must be eliminated and, in turn, replaced by a new approach to design supporting procedural integration.

5.2.3 Heterogeneity and Difference in Nature: Material as Structure and Structure as Material

The study of the classes of shape of organic forms, which may be identified with Goethe's invention of Morphology, is but a fraction of that wider science of form which deals with the forms assumed by matter under all its governing environmental conditions that are theoretically, and mathematically, conceivable. Such sciences, of the forms of living and non-living natural organisms, are characterized by recurring biological themes, and their variations. In Chapter 2, we have reviewed a range of natural objects and processes driven and expressed by material variation. Various examples have been provided that assist in classifying physical heterogeneity and variation as *static* (e.g. the fiber distribution in a tree trunk, or a branch), *quasi-dynamic* (e.g. the continuous arrangement of bone tissues as a function of the loads applied) and *dynamic* (e.g. mutable visco-elasticity in underwater creatures for dynamic mechanical response to control movement) are all compound expressions of the interaction between matter and energy, driven by the mechanisms of growth, fitness and survival. Every physical phenomenon occurring in Nature is in fact composite, and every observable action and effect is a summation of countless subordinate actions (Thompson 1952). Living, as well as non-living organisms, represent, or occupy, force fields of immense complexity. The simplest cases are met with a minimum departure from symmetry as could only subsist under conditions of ideal and general simplicity. However simple Nature's themes may appear to be (rules describing growth, or the distribution of material under load), its physical expressions are far from it. So, Nature, it appears, is defined by heterogeneity.

In Nature, variation and heterogeneity are achieved and assisted in processes that are both internal to the organism itself (i.e. processes associated with growth), and external to it (i.e. processes associated with the interaction between matter and environment). The latter is the subject of our research here, and despite the difficulty that has previously been expressed regarding the need to understand Nature from a materials science and engineering perspective, I have chosen still to attempt to do so.

Imperative to the reading of this thesis is the understanding that variation is inherent to both Nature's "products" and processes. It is achieved by Nature's ability to heterogeneously structure materials, an ability previously referred to as anisotropic structuring. Most biological systems are dominated by fibrous composite structures providing Nature with the means by which to inform structural and material directionalities.

This quality allows natural systems to:

1. Create functional architectures and shapes
2. Introduce and exploit heterogeneity and anisotropy locally (e.g. at the tissue level) and globally (e.g. at the organ level)
3. Modulate physical properties of materials and structures

These mechanisms are applied to deal with:

1. Functional demands
2. External structural and material demands triggered by physical response to environmental conditions
3. Internal structural and material demands triggered by processes of growth

The distinction between "material" and "structure" in Nature is not an obvious one. Take wood for instance; clearly wood can be shaped and formed to fit almost any shape, while at the same time its mechanical performance varies when loaded in different directions. The structural properties of wood for instance, not unlike most biological materials, widely vary when measured with the growth grain or against it such that its hardness and strength may differ for a given sample when measured in different orientations. This property is called *anisotropy* and it is due to *anisotropic structuring* that nature can create sustainable structures efficiently (Vincent 1982).

In Chapter 2, we have defined and reviewed the property of certain materials to be directionally dependent. Such cases are typical of materials that have embedded in them a particular structure defining their physical behavior. In essence, those materials are structures in their own right, their dominating features being dependent on their functional scale. In Nature, unlike the design disciplines, material and structure are strictly consolidated towards their desired function. Thus, a wood sample would be structured quite differently depending on its location in the overall structure of the tree. Such consolidation is consistent with Nature's Way: in Nature, a higher level structure (trunks and branches) is typically composed of multiple copies of lower level structures (wood samples). Also, for every "Natural typology" there is an explicit material organization associated with it (calcium structures for bone, wood structures for trees, and so on).

Finally, biological materials do not distinguish between materials and structures (Rogers 1993). Cost-effective and durable structures are the result of constraint negotiations carried on over millennia. For Nature, the distinction between intelligent material systems and intelligent structures is irrelevant. Hence, such a distinction may only be applied superficially in terms of the scale of a material's micro-structure which governs it behavior, regardless of its size (Rogers 1993).

5.2.4 Summary

The general assumptions central to this research are guided by the motivation to apply Nature's strategies in the design of forms to real world products and processes. The impetus at the heart of such assumptions is fueled by the desire to define a new approach to *Sustainable Design* as we know it. The initial research assumption is articulated on the product level, from which follows the secondary assumption, articulated and geared towards the process level.

In contrast to contemporary practice routines that prioritize the role of geometry relative to materials and their desired performance, this research assumes that an alternative approach to design guided and defined by the use and manipulation of physical matter may yield more sustainable design solutions that do not compromise efficiency. The approach put forth is entitled Material-based Design and is believed to promote the two main ideas governing Nature's Way. Those two ideas are here articulated as the two main research assumptions on the basis of which a new design research field entitled *Material-based Design Computation* is proposed and developed.

5.3 Research Goals: Towards *Natural Design* as a Sustainable Design Approach

Compared to Nature, our own material strategies appear to be much less sustainable and mostly wasteful. Since the industrialized age, the construction industry has been dependent on discrete solutions for distinct functions (Oxman 2008). As previously suggested, building skins are an example of such a claim. Steel and glass possess significantly different structural and environmental properties which relate to significantly different performance requirements. Diversity is achieved by sizing, rather than by substance variation, and it is typically mass produced, not customized. As far as material structuring is considered, in the artificial world, especially in the construction industry, one property fits all. Can nature's ability be emulated in the design of the artificial?

With the assistance of advances in structural and material engineering entering contemporary discourse, architectural culture appears poised for transformation. This aim of this research is to advance Nature's strategies in structuring matter by designing synthetic multifunctional materials competing with evolution's unrestricted time-frame of design process. Fitness, not form, is what actually matters. Welcome the new materiality!

The thesis is motivated by the desire to invent, test and implement a new design approach inspired by Nature with the aim of enhancing Sustainable Design products and processes. Similarly, it is devoted to correspond to the two assumptions raised in this chapter, respectively relating to the design of products and the design of processes. It does so by corresponding to problems raised by contemporary discourse and by questioning the role of computational media in the design process and examining new ways in which such tools, techniques, and technologies could be revisited to redefine processes and products of design generation. Consequently the research questions posed in this section are geared towards design products and processes informed by computational routines and advanced digital technologies. Relevant literature sources related to this knowledge domain have been reviewed in Chapter 4 of this thesis.

The two main research questions raised in this thesis are inextricably linked as interrelated aspects of the same problem. We ask: in order to design in a novel, more sustainable way, a way more tuned to Nature's designs, and assuming that designers are now facilitated with all the computational media required to potentially achieve such a mission, what information can computational units contain (e.g. genetic, property, etc) and how small must such units become in order to contain such information (e.g. pixel as atom, molecule, material substance)?

5.3.1 Environmental Customization

Goal 1: To develop a sustainable design approach to the design of products and buildings that prioritizes mass customization over mass production

The fluttering of leaves in the strong winds affords us yet again with an example of Nature's awe-inspiring abilities for tuning its material properties in just the right amount as she corresponds with conflicting conditions. Designing photosynthetic structures of sufficient rigidity is not a trivial task. Photovoltaic cells (PVC's) embedded within structural cladding systems must confront parallel impediments through the strategic assignment of properties. The surface area of a PV cell, much like other various sophisticated glazing systems, must be designed as both very thin and very rigid. In Chapter 2 we have classified such problems as cases in *performance negotiation*. Such cases are characterized by Nature's necessity to negotiate between seemingly conflicting requirements. Such is the human bone's ability to provide for a highly robust structure while at the same time, to allow for relatively adaptable and dynamic response to changing load forces; or the leaf's ability to provide for structural soundness amid the swaying of branches during times of strong winds while simultaneously satisfying its function to trap solar energy photo-synthetically a function that clearly demands the exposure of maximal surface area skyward. Both the geometrical form of the leaf and its material substance promote significant features here: under strong wind loads, some leaves curl into cones, a response which significantly reduces drag.

All in all, the limits to Nature's mechanical versatility seem immeasurable compared with our own practices. In Nature, a singular material may be programmed to be both stiff and soft (think for example of muscle tissue!). Practical tradeoffs which satisfy and determine what deficiencies must be suffered in one property in order to achieve high values in another are mostly treated by the intrinsic adaptability of dynamic material distribution. And indeed, within the biological world, the properties of a given material change from species to species, from habitat to habitat, and from location to location within a single organism. Similarities of fine tuning material properties appear consistently among very distantly related organisms which are subjected to similar environmental pressures.

In emulating Nature's clandestine methods, Design must lend itself to new ways of considering the negotiation between, and the integration of, seemingly conflicting functions (Figure 5.2). With relatively few materials, Biology produces endless compounds where physical properties are fine-tuned to meet local needs. In design, the tendency to treat every problem discretely often results in the production of waste (material, energy, computation, manpower and so forth). The alternative to design more "naturally" is not a trivial one, namely as it requires that we rethink entirely the established traditions of the design professions; but this, I believe, holds much promise for the future of Sustainable Design. It goes without saying that embracing multi-performance negotiation requires that we also rethink and redefine the design process as a whole.

5.3.2 Form-Generation Process Integration

Goal 2: To develop a sustainable design process integrating design (form-generation) and engineering (form-evaluation and optimization) processes

Sustainable design products cannot possibly emerge without putting into practice approaches promoting sustainable design processes. In ancient times, so-called *vernacular architecture* was characterized by the notion that local materials and structures define the form of habitat. As a result, in old-ages and ancient times, material, geometry and structure were united in the design of local products and environments. Waste of materials and processes was reduced to a minimum as locally available resources and traditions were applied to address local needs. But, more importantly, at times where digital media were absent from processes of design, there seemed to be a fuller, more pronounced integration between processes of design modeling, simulation, analysis and fabrication; Or rather, all such routines were compounded to form an integrated process. Furthermore, processes we currently consider as the final stages of the design process (fabrication, construction and assembly being some of them) were, during ancient times, the very processes that *initiated* any design and indeed, defined its very form.

The segregation between processes of design synthesis often driven by the designer or the architect, and processes of design analysis often driven by the structural or environmental engineer, is typical of contemporary practice. There exists a clear hierarchy in the timing at which each of these routines is applied (else, how can you otherwise analyze that which has not been created?), but also in the discipline or domain knowledge associated with each: the structural engineer will run analytical programs to evaluate the structural soundness of a building component only after it has been designed by the architect. Following, the environmental engineer will run his own analytical routines to confirm its desired performance under wind loads and extreme thermal conditions. Finally, the design is handed to the fabricator and rationalized according to the type and method by which to construct and assemble the component.

In addition, there typically exists some loss of geometrical information in translating design-to-analysis-to-fabrication routines. The conventional design sequence does not necessarily consider in advance which fabrication technology is applied to the production of the part. Consequently, the part is designed, analyzed and fabricated using forms of geometrical rationalization that significantly differ in nature and much information is lost during translation; more about that later.

It comes as no surprise then that the current cycle of design and analysis is anything, but sustainable. Clearly, it is streamlined to fit the logical progress of formal generation from conception to construction; however, the avocation of process integration in lieu of the traditional discrete, streamlined, tradition may lead the way to novel, more sustainable ways of originating form.

Nature, it appears yet again, has it all figured out. As previously demonstrated in Chapter 2 of this thesis, in Nature there exists no separation between processes of design generation ("synthesis") and processes of design evaluation ("analysis"). The human bone re-accommodates its formal organization ("geometry"), through material distribution (material) according to the magnitude and direction of loads applied to it at any given moment (structure). Considering current technological advancement in materials science and engineering, as well as in digital fabrication, it may well be the right time to promote procedural integration.

5.3.3 The Non-Assembly

Goal 3: To develop sustainable design products without assemblies and joints that support smooth transitions between properties

Given that biological materials and structures present nano-, and meso-mechanical heterogeneity that is expected to influence and contribute to their superior performance, we seek to devise a strategy of structural heterogeneity in macro-scale whereby the distribution of macro-mechanical properties is informed by functional constraints. This approach will ultimately result in continuous tissue-like structures, which, unlike the classical assembly approach, promote the distribution of properties and behavior. The assumption is that such forms and structures are more sustainable than conventionally contracted ones due to material efficiency. We aim at predicting that non-uniform material organization over large areas and increased mechanical performance arising from macro-scale heterogeneity lead to significantly different biomechanical properties compared with a uniform material. Such a fundamental concept applicable to a broad class of biological materials, as has been demonstrated throughout chapter 3 of this thesis, serves as a source of inspiration when considering such property enhancements in macro-scale and across multiple media of construction technologies. Speculations regarding the role of heterogeneity in strain concentration (as well as other positive factors) thus point towards its advantages to the mechanical functions of design environments.

This approach, motivated by the desire to consider an alternative approach to form-, and space-making, stands in shear contrast to conventional design methods and compositional construction techniques where parts are manufactured and added together to create an assembly. In contrast to such classical macroscopic architectural designs, we aim at generating design methods supporting highly customized products and environments, more efficient and effective in satisfying their objectives not unlike the way nature has it. Nature ubiquitously utilizes architectural principles at multiple length scales to create efficient, lightweight, high strength load-bearing structures out of relatively weak materials (e.g. 3, proteins, cartilage etc.) Biological materials and structures are thus a source of inspiration, as a starting point for exploring such new design spaces.

5.3.4 Matter over Shape

Goal 4: To develop a sustainable design process that prioritizes material over shape (in contradiction to the traditional design approach where matter is patched onto form).

Conventional design processes rely on the generation of 3-D geometrical form typically using architectural CAD software. The assignment of a design material from which to fabricate the product (or construct the building part), typically follows from the designer's commitment to form. Utilizing state-of-the-art computational modeling environments allows the designer to either generate form by running some form-generation script that typically bears no relation to its physical manifestation, or by subdividing the geometry into constructible components. In both cases, processes of cell generation (and growth) or tessellation (subdivisions) are devised as a means of simplifying the design problem while considering its fabrication and assembly strategies.

We propose that in order to achieve more sustainable design products, processes of form-generation must include tools supporting the integration of analysis software allowing for the parallel iteration between digital form and physical evaluation of its relevant performance. Ultimately, we aim at designing computational environments which may potentially support physical attributes relevant to the architect, such as stiffness and translucency which may contribute to the generation of form itself. Several strategies for achieving this goal will be further developed and presented in the following chapter.

5.4 Research Objectives: Nature's Strategies Recomputed

5.4.1 Stiff and Transparent, Soft and Opaque

Objective 1: To develop a design process that incorporates multiple structural and environmental performance criteria in the design process

An objective function (or the target function) is generally associated with an optimization problem which determines how good a solution is (Atallah, Fox et al. 1999). Structural and environmental optimization, executed through the Finite Element Method (FEM) and Computational Fluid Dynamics (CFD) respectively, allows for the evaluation and local modulation of volume and surface features of an object under a given set of constraints (i.e. loads).

5.4.2 Site to FAB

Objective 2: To develop a design process integrating modeling, analysis, simulation and fabrication in one process.
Integrated design processes save time and computation, and allow considering the design space as one unified environment where modeling, analysis and fabrication can be interrelated. Currently, however, such design platforms are discrete and separated by methods and by tools: the designer typically models a given shape, then sends out this shape to evaluation software for physical simulation and finally, it is assigned a material and a fabrication strategy for its construction. Such protocol discreteness must be removed, if one considers the potential interrelation between geometry, material and structure as part and parcel of the integration between modeling, analysis and fabrication routines. In the scope of this work we seek to invent new ways of working that support those integrations and promote a more sustainable way of making design.

5.4.3 No-Stop-Tissue

Objective 3: To develop a design process that incorporates, computes and generates variable properties in product and building design
This question triggers a set of inquiries into the definition of "material" in design. Beyond its classical definition as a particular substance, one can classify a set of definitions under the rubric of material behavior. The proposal seeks to operate on the latter and claim to control and parametrically modify properties such as elasticity, stiffness, transparency, thermal conductivity etc.
The objective of answering this question lies in the systematic classification of material properties and how they may relate to geometrical manipulation. Here we begin to chart out micro and macro-structural properties along with rigorous descriptions of formal attributes which are potentially parametrically defined.
The proposal also seeks to demonstrate *material differentiation*, defined here as the ability to locally vary material properties corresponding to a given set of conditions and governed by a specific objective function, by selecting a few materials and assigning structural and/or environmental constraints to them. The main goal is to arrive at an algorithm which varies the geometrical and physical properties of a given material according to environmental parametric data informed by the user.

5.4.4 Physical Geometry

Objective 4: To develop a design approach that integrates material properties as part of the design process
Digital representation of physical behavior has been addressed in the fields of computer science, material engineering and mathematics. However, it has never been defined and utilized in design as far as the generation of form is considered. The research aims to examine the validity and usefulness of a multi-dimensional computation which integrates physical behavior (stress, strain, energy etc) as higher dimensional data attached to geometrical representation. Scalar maps as well as vector and higher rank tensor fields may potentially endow the design space with varying properties. Each voxel (pixel based

parametric unit) is per definition non-identical to another and carries added material information in the form of a potential, or a set of directions.

5.5 Research Issues: Design as Second Nature

5.5.1 Multi-Objective Design Fabrication

Issues 1: What design model can support the negotiation and optimization between multiple performance criteria (vs. the traditional single performance negotiation?)
Natural systems are designed to correspond to multiple performance criteria such as structural loads and thermal pressures by means of varying the system's properties in order to accommodate and negotiate between multiple parameters. Contrary to this approach, architectural design traditionally distinguishes material substances by their particular function.

5.5.2 Design without Representation

Issue 2: Can form generation, evaluation and fabrication be computed in one integrated digital and physical environment?
In Nature, form is the outcome of compounding the properties of a material substance with various types of environmental pressures forced upon it by Nature. Collectively, "material" and "environment" are computed to generate and optimize forms of organic substance.
As reviewed in Chapter 2 of this thesis, Nature's ability to integrate processes of (form) generation, analysis and fabrication guarantees that form is consistently optimized against external requirements and internal pressures. Precedents illustrating the shaping mechanisms that govern the form of trees and bones have been reviewed and it is my assumption that when processes of modeling, simulation, analysis and fabrication are unified and consolidated into a coherent form of computation (such as the one governing the formation and structural optimization of cancellous bone), that design reaches its most efficient and effective state; design become "natural".
In light of such theoretical assumptions we are faced with questions regarding the nature of the design *process*. In Chapter 2 we have previously shown that when such processes are made sustainable by integrating shaping and fabrication, the products that such processes produce are in themselves sustainable as they utilize the structuring of material to correspond to multi-performance negotiation.
How, then, does one achieve the consolidation of parameters involved in the generation of form? Paraphrasing on more technical a note: how does one achieve the computational calibration of matter and energy tied to create form without first creating form itself?

5.5.3 Graduated Properties Approach

Issue 3: What is the role of variation and heterogeneity in nature and how does it promote a sustainable approach in the design of the artificial environment?
We seek to define what roles do variation and heterogeneity play in each of the disciplines reviewed in the introductory chapters (biology in chapter 2, and material science and engineering in chapter 3). Here we aim to focus on the mechanisms and methods used to assist and achieve the production of heterogeneous material compositions that correspond to a multiplicity of environmental constraints?

5.5.4 Form via Material

Issue 4: How to prioritize material over shape in processes of design generation and design representation?

The image of the architect as form-giver has for centuries dominated our profession. In most cases, structural strategies are addressed by way of post-rationalization in support of the building's utility captured by spatial properties. In this light, material selection and application are dependent on the structural solutions. Such views emphasize the hierarchical nature of the design process with form being the first article of production upon which both structural and material strategies are tailored. Gehry's monumental architecture provides many such examples (Oxman 2007; Oxman 2008; oxman 2008). Parallel to a "form first" approach, and influenced by the work ethic of leading structural engineers such as ARUP and Buro Happold, an alternative schema prioritizes the function of structure as the main driver of formal expression. "Structure first" is manifested particularly in projects of vast engineering complexity such as bridges and skyscrapers. Conversely, material has traditionally been regarded as a feature of form but not its originator. In nature, it appears, the hierarchical sequence *form-structure-material* is inverted bottom-up as material informs structure which, in turn, informs the shape of naturally designed specimens. It appears that amongst the main contributions of *Nature as a model for Design* is an approach which favors matter (and materials) as a central and significant factor associated with the generation of form in the artificial world. Such is the case, for instance, with bones and other cellular structures the shape of which is directly informed by the materials from which they are made. In nature, in most cases, material comes first. How can a "material first" approach be accommodated by design?

5.6 Research Questions

5.6.1 Non-Binary Computation

Research question 1: Can computational units describing form include attributes additional to shape / geometrical attributes such as stiffness (structural), thermal flow (environmental), transparency (phenomenological) etc?

How would such form-generation tools be developed to consider the incorporation of multiple properties, for each of which are potentially assigned non-binary material properties gauging environmental variance (insofar as various environmental performance criteria are consider per a given heterogeneous material substance)?

The term "binary" is emblematic of the digital world. Take, for instance, any or most typical software applications in the design or the engineering milieu. As previously reviewed in Chapter 4 of this thesis, various such applications exist that support the designer in her mission to generate, simulate and analyze a design. However, most computational media used today to perform such processes assume any geometrical feature to be devoid of any physical property altogether, at least in the very early stages of design. Material is typically assigned to geometrical features only after such features have been generated, and once it is applied, such material is typically homogeneous in its properties; that is it does not vary its physical properties across the surface or volume area of the object being modeled. A given material property is either defined or present or it is not. And, if indeed, material is assigned to a geometrical feature it is generally defined by a set of properties that do not vary in value. Such is for instance the case of assigning "glass", "steel", or "plastic" to an already geometrically described object.

Such binary approaches also provide the basis for analytical functions. As reviewed in Chapter 4, current state-of-the-art Finite Element applications afford the designer with sophisticated form-generation processes based on material properties and some iterative analysis algorithm. The effect, basically, is to gradually erode and omit any redundant material until the minimum amount necessary to perform the structural talks is left (at which point the feature should be fully stressed). The algorithm then terminates. Again, processes such as this one assume homogeneous material. The only possible element conditions, then, are “full of material” or “devoid of material”. But what if, like the form of a leaf or a tree, one could continuously vary any required property (e.g. varied stiffness across the height dimensions) and simultaneously allow for the consideration of various properties per any given location (e.g. varied stiffness coupled with varied translucency). In this case, per any given object, one may assume the variation of a material property coupled with the consideration of multiple properties negotiated for that particular region.

Such processes may potentially become particularly interesting when the designer is able to both generate and optimize a design against multiple performance criteria. Beyond the typical consideration of strength and structural optimization, the designer may also wish to incorporate environmental (e.g. insulation) and visual (e.g. transparency) properties, as well as other architecturally relevant properties of materials. The research questions and assumptions regarding the design and production of objects that are the result of integrating material properties and environmental performance requirements, both in their non-binary manifestations (as is the case in the natural world) are overwhelmingly challenging from both a conceptual, paradigmatic point of view, as well as the technical approaches and tools required for their realization. However, the prospect, and potential implementation of such an approach are incredibly exciting, particularly when the designer is able to integrate physical parameters in the very early processes of form-generation.

Clearly, binary forms of computation are not sufficient for such research assumptions. New forms of “mulnary” design computation supporting the integration of material knowledge, must be further explored, developed and implemented.

5.6.2 Universal Units

Research question 2: Can computational units describing form digitally be calibrated with physical units describing matter such that geometry units = environmental analysis units = fabrication units? How to digitally represent units of matter and units of energy as equivalent units of form in order to integrate between modeling, analysis and fabrication?

How does one integrate between processes of modeling (geometry), analysis (structure) and fabrication (material)? Per a given volume and surface area, how can the physical units of matter be synchronized with units of energy (“performance”) and units of computation (“bits”) in order to achieve such calibration?

We assume that if the units that are being used for geometrical modeling (i.e. “parametric cell” or “associative component”) are equivalent to both units of engineering analysis (i.e. “mesh element”) as well as to units of digital fabrication (i.e. a singular powder molecule extruded by a 3D printer), and, in addition, such units are also equivalent to units of structural measurements (i.e. “load per surface area”) and environmental performance (i.e. “temperature per surface area”), then we arrive at a far-reaching condition in which *units of matter are equal to units of energy, both of which are equal to units of formal representation!*

Such desired calibration between units of modeling (digital matter), analysis (digital matter informed by physical constraints) and fabrication (physical matter) will ultimately result in an integrated design process that bears enormous implications for the state of design its discourse and its practice.

What are the units used to describe and represent physical matter? How are digitally or physically described materials units assembled or disassembled to form the final desired shape (i.e. additive, subtractive and growth-induced strategies?)

What is the hierarchy that is established between modeling, analysis (and/or simulation) and fabrication? What are any interdependencies between the three processes and by which parameters are they characterized?

Current rapid prototyping (RP) and Computer Numerically Controlled (CNC) fabrication technologies offer high precision modeling in physical form. Most of these tools provide for scaled models only. The proposal will touch upon full scale rapid construction technologies which, combined with the Material Computation modeling approach, allow for local modification of material properties within the process of fabrication. State of the art (poly-jet matrix) technologies exist today which support multi-material printing. At this time we are considering the application of a grant to include behavioral parameters within the printing process such that once printed, the physical model can potentially respond to local and global loads and other environmental pressures (see attached research proposal for the Holcim Foundation as an addenda to this research thesis).

5.6.3 Structure minus Material

Research question 3: What is the difference between material and structure in design?

How would such form-generation tools be developed to consider the variation of any given material property, thus affording the designer with internally heterogeneous material substance which corresponds to performance requirements? When dealing with systems that incorporate variation and heterogeneity, how are functional hierarchies achieved, if at all? What is the difference between "material" and "structure" and how are they defined and distinguished within each knowledge domain?"

The distinction between "material" and "structure" is not an easy one when it comes to continuous non-homogeneous substances. Let us attempt to replace the notion of *material assembly* with that of *material distribution*. Such orientation points towards a shift in both method and meaning: rather than achieving functionality by the layering of materials and structures, we devise an integrated system able to modulate the quantities and qualities of its elements in order to achieve a heterogeneous range of material effects. The distribution of properties across a surface or volume element (whether structural or material) establishes differences in behavior that correspond to a range of performance types and degrees. The proposal aims at classifying and defining such differences in building scale and how they may relate to performance analysis and form-generation.

5.6.4 Digital Materials

Research question 4: How can geometrical processes in the generation of form be inculcated with material properties data prior to the generation of form? How to represent material properties in the form generation process?

Current CAD applications, including associative modeling software packages, appear frequently to promote generative approaches to design (Shea 2003). Rather than treating the computational media merely as an "output station" prior to production, the designer is now able to establish parametric relationships between features, methods and/or functions in ways which support design processes of an exploratory nature. However, this liberation which seems to be manifesting itself across the board throughout the continuous phases of the design process is currently mainly driven by geometrical constraints. Generative performative modeling approaches have been introduced which engage principles of engineering with form-finding (Burry 2005). And yet, even when integrating performance factors and tools that are significant in determining architectural form, material organization and behavior are already pre-determined design constraints; predetermined factors. Form-finding, in the digital realm, is thus restricted to the relationship between structure and geometry (and/or fabrication); it does not generally incorporate, and/or support, the expression of material properties, organization and behavior.

This proposal seeks to establish a *synergetic* approach to design whereby material organization and behavior, as they may appear in the physical world, may be integrated into digital tools for design exploration. The approach is based on the premise that *material, structure, and form* can become inseparable entities of the design process which relate to *matter, performance and geometry* respectively. Beyond this theoretical significance, the goal of the experiments presented here is to effectively link the simulation/computational techniques across adjacent scales of physical behavior so that microscopic level physics and mechanisms are incorporated into the description of properties and behavior at the mesoscopic (micro-structural) level, and beyond that, in order to suggest descriptive attributes even at macro scale.

5.7 Methodological set up and preparation for the next chapter: "methodological platforms"

5.7.1 Interdisciplinary Research

By revealing the many aspects of this question, devising knowledge from the disciplines of geometry, material science, and design computation, we seek to demonstrate that such integration is useful and potentially revolutionary in the field of design.

5.7.2 Experimental Research

The research approach is experimental in nature: models are generated and tested in parallel to small scale physical prototypes that will validate and allow for the evaluation of the research aims and goals (Figure 5.3).

5.7.3 Convergent Technologies

We will gather interdisciplinary knowledge that supports the development of a seamless analog computation. In this process we will consider existing models that are currently being used for evaluation and/or optimization processes and attempt to integrate them into bottom up processes of form-generation, as opposed to top-bottom analytical procedures.

5.8 Summary: Methodological Frameworks on the way to Material-based Design Computation

The chapters preceding this one have served as the introductory chapters to the interdisciplinary field of *Material-based Design Computation* as told from the point of view of various knowledge domains I found to be of particular relevance to this research. Chapters 2, 3 and 4 focus on ideas from the fields of biology, material science, and design computation respectively that are instructive to the mapping of theoretical and technical knowledge presented in this thesis.

In the following chapter I provide a brief overview of concepts relevant to the *mapping* of the theoretical foundations of this thesis, classified by their knowledge domain. Combined, the collection of issues provide for the groundwork underlying the field of Material-based Design Computation. Each issue, for which a set of sub-queries has been laid out below, addresses the two significant research questions reviewed in the introductory section of this chapter: the multifunctional *product*, and the integrated design *process*.

As part of the methodological set-up some existing computational applications were used, applied and manipulated that provide for interesting analytical functions. Such functions were identified as carrying potential significance in terms of their capacity to contribute to, and inspire, form-generation processes driven by physical constraints.

When exploring the generative capacity of analysis packages, the aim was to identify procedural modeling issues that may be re-appropriated in processes of form-generation. In addition, natural tissues were investigated in order to better characterize the definition and potential manipulation of material properties and their relation to particular performance criteria.

Optimization processes are usually performed in conjunction with protocols of, and for, evaluation. Once preliminary formal schematics have been laid out, an algorithm is devised which is designed in order to minimize or maximize a given function by systematically choosing variables from within an allowed set. So once the object upon which to optimize, and the objective function defining what and how the optimization should take place, we enter an iterative refinement process controlled by the designer. In this research we propose that the iterative nature of optimization processes, and their ability to integrate evaluative constraints with existing mathematical data, may be applied in design bottom-up on the way towards *Material-based Design Computation*.

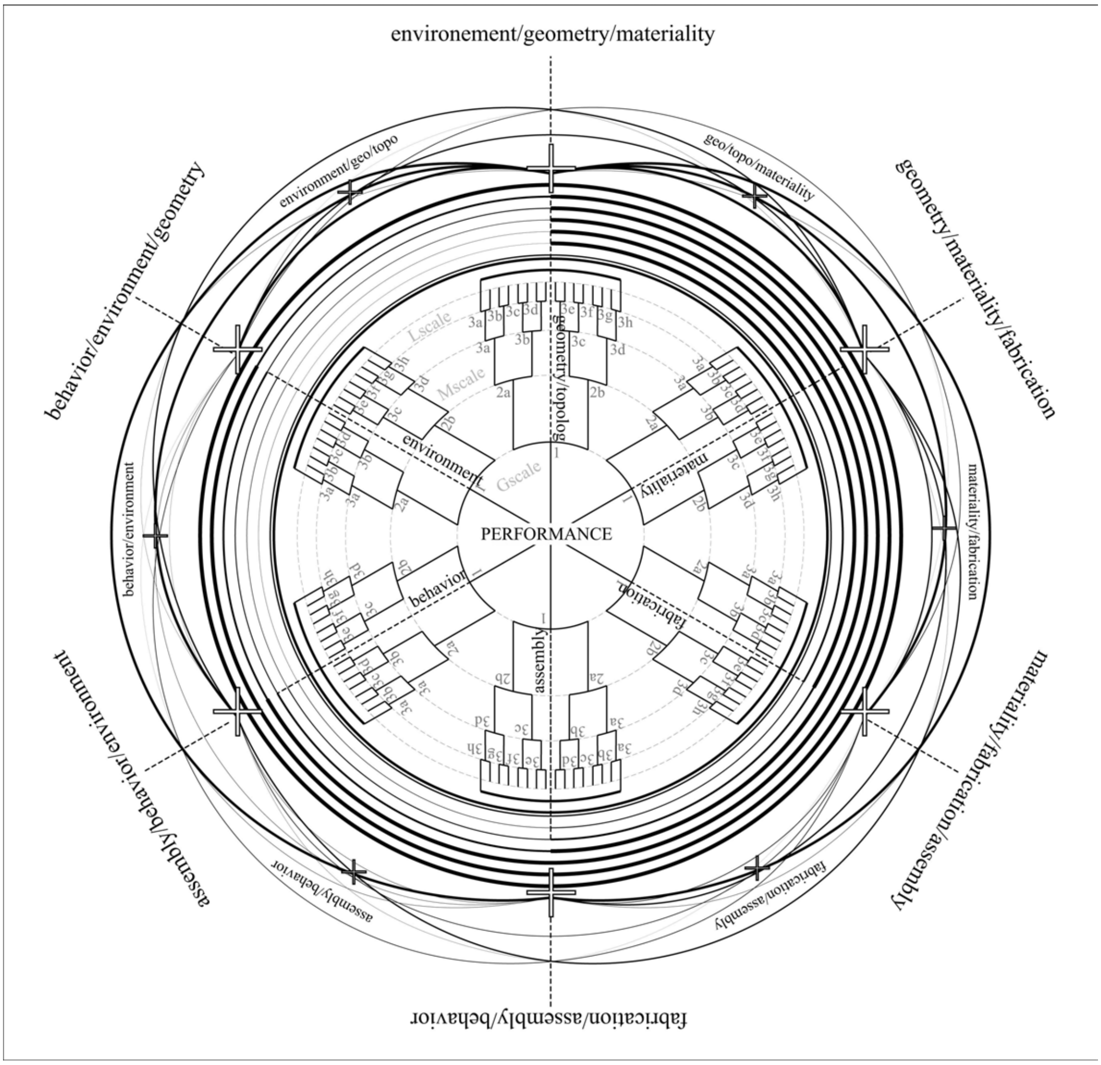

Figure 5.1: The diagram illustrates how various design motivations may be integrated to inform performance-based design. Considerations from the domain of geometry, materiality, fabrication, assembly logic, behavior and environment (with some overlaps) are juxtaposed to direct the form-generation process. The underlying assumption is that the ideal design process integrates between modeling, analysis and fabrication constraints during the form-generation processes, rather than conceiving of such processes as linearly dependent.

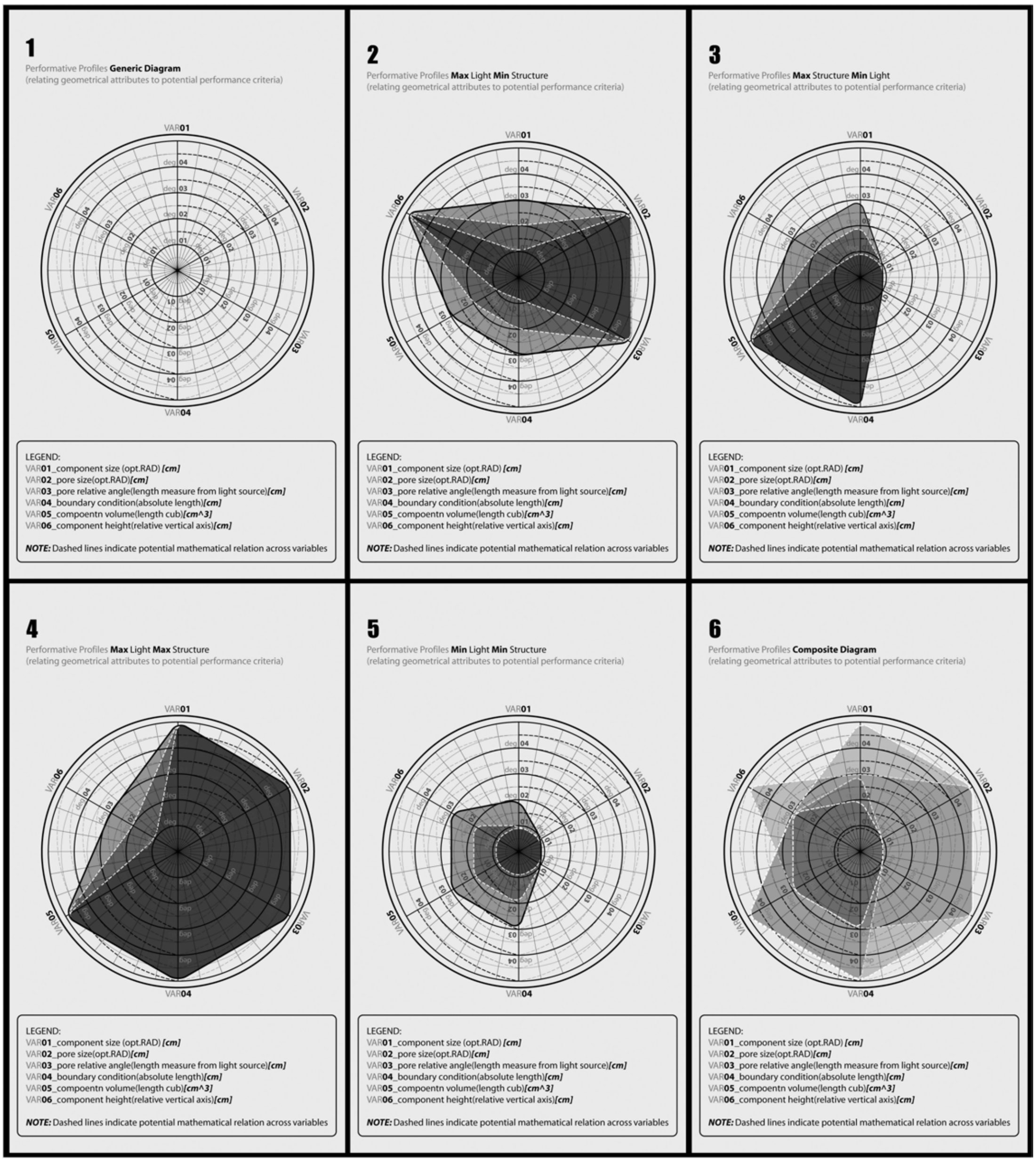

Figure 5.2: Much of the work presented in this thesis follows from the assumption that form is generated through the interaction between material and environment, and that various environmental conditions yield various material manifestations that may fit the designer's goals and constraints. The diagrams above were used to negotiate between 6 performance criteria in 6 distinct conditions requiring different material interventions that may respond and satisfy "environmental customization".

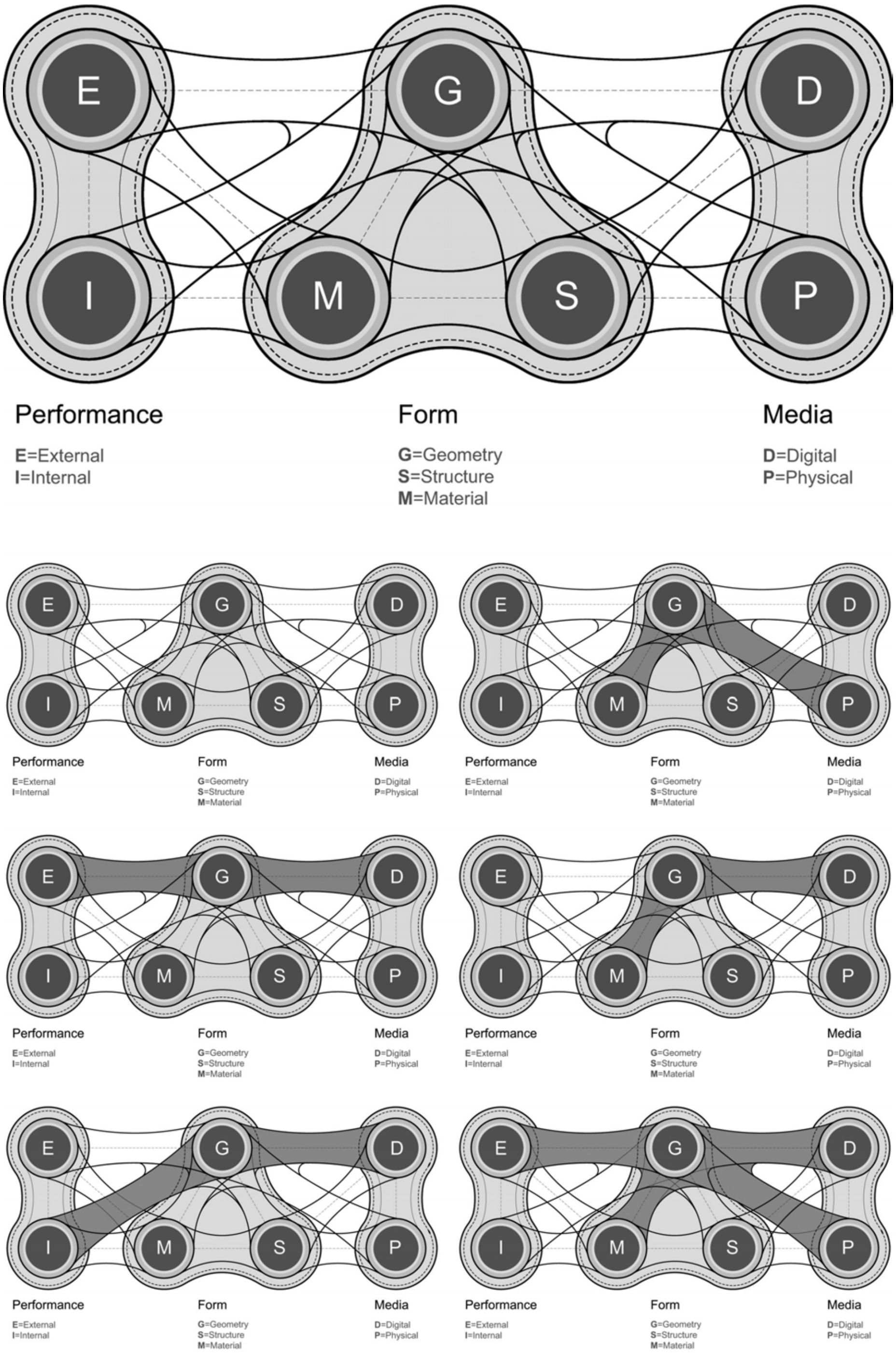

Figure 5.3: Each design experiment presented in this thesis demonstrates some combination between shape, performance and the type of media used to explore this interaction. Under the “performance” rubric are included external and internal performance criteria relating to constraints that are defined as either independent or dependent on the physical material used, respectively. Under the “form” rubric are included parameters in or of relation to geometry, structure and/or material. Under the “media” rubric are included the type of media used to explore and execute the experiment, whether through digital or physical means or whether through some combination of those tools. Each experiment explores the relation between 2 or more elements of this process diagram.

CHAPTER 6

MATERIAL-BASED DESIGN COMPUTATION
Methodological Frameworks

"Up your scale. Each pixel a million megabytes"

— William Gibson (Neuromancer)

6.1 Introduction: Material Form and its Methodological Frameworks

The dominance of the *geometrical* representation of design content has for centuries, prior to the use of computers, contributed to a *geometry-centric* approach in the design of products, buildings and cities. Accordingly, form must first be first conceived in order to be constructed. Naturally, it is unfeasible (theoretically or technically) for processes of conception and construction to occur concurrently. Predictably, design since the time of the pyramids, has been driven by its many forms of expression defined and conveyed in geometrical terms. Material is consistently secondary in this milieu; and it is due to the priority of geometrical representation over physical material considerations, a phenomenon that has led to stream-lining the design process: form first, material later. By methodological extension design conception is to be followed by analysis, simulation, and fabrication. Indeed, how can the fabrication of form be manifest without form's conception?

We have seen that Nature's way is uniquely different. In nature, forms are the result of the matching between material parameters and their corresponding environmental constraints. Shape is then merely a by-product, a derivative of natural behavioral formation. It emerges as an effect exclusive to its particular environmental template. In nature, we have established, form's geometry is predominantly determined by the interaction between material and environment[6.1].

The implications of this interpretation of nature's approach are immense inasmuch as values of sustainability are consequential to the state of habitat. By guiding the emergence of form to be reliant on the

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[6.1] It goes without saying, that the observation of natural structures is time-dependant; growth, and the significance of its contribution to formal transformation and adaptation in nature must not be neglected. In the scope of this thesis, however, I choose to treat my observations into nature as moments frozen in time as it were, where the interaction between material and environmental constraints presented at the time of investigation are considered as relevant.

interaction between material and environment, not without the aid of growth and adaptive mechanisms, nature guarantees and promotes environmental fitness, material efficiency and structural economy all glowingly suitable as relevant candidates for inclusion in the treatise of *Natural Design*. Is nature's way suitable as a model for the design of the artificial?

Given this assumption as a scientific motivation, and, given that we have arrived at the point at which such objectives must now be technically articulated through various disciplinary sources relevant to its validation, how can we then represent the interaction between material and environment such that any resulting form is perfectly attuned to its environmentally prescribed fitness? We must now define a new paradigm of form generation that is capable of achieving such a vaunted objective.

Material-based Design Computation is hereto postulated and demonstrated as a potentially new field in Computer-Aided Architectural Design, with clear orientation towards that which may be defined as sustainable. The *theory of natural design* as first formulated in the introductory chapter is outlined below as a proposal theoretical in its nature; it is supported by a scientific approach which has enabled the experimentation and evaluation that is described in the following chapters.

6.2 Organization

The chapter is organized around a set of methodological frameworks that correspond to issues and problems introduced in the previous chapter. This also provides the presentation of the methods applied to generate and evaluate the design experiments illustrated in the following chapter. These methodological frameworks focus on the two reoccurring themes that were identified as emblematic of natural design: the *multi-functional artifact* and the exploitation of an *integrated conception-construction* process.

6.2.1 Transparent Stone: the Search for the Multi-Functional Artifact

Methods were developed that support the design of multi-functional products and building elements. It is in the multi-functional condition that variations of material properties and composition correspond directly to specific structural and environmental constraints. This approach to design, supporting multi-functionality over discrete utility through the promotion of heterogeneity over homogeneity, seeks to advance and embrace strategies of material distribution over strategies of material assembly.

The methods presented here include strategies for the manipulation of matter in precise directions within the surface area or volume of the design object so as to best adapt it to its mechanical, thermal and optical functions within a given context. As we have observed, in nature fibers and tissues are strategically oriented so as to best cope with the mechanical stresses and strains acting upon them. Similarly, computational modeling units may potentially be assigned physical properties, and strategically distributed to match any such template comprised of environmental constraints.

6.2.2 FAB as you go: The Search for the Multi-Procedural Technology

Any design manipulation of physical matter represented in the digital realm assumes the integration of synthetic (i.e. modeling & fabrication) and analytic (i.e. simulation) functions and processes. In order to achieve design *strategies of material distribution*, and in order that such strategies will indeed carry added value over strategies of material assemblies, new computational processes must be developed and implemented which support the integration of modeling, analysis and fabrication not as sequential hierarchical processes, but rather as an *integrated multi-procedural holistic method* not unlike that occurring in the case of human bone formation.

6.3 Methodological Frameworks

6.3.1 Variable Property Design (VPD)

Variable Property Design is proposed as the set of processes enabling the distribution of materials and their properties in the design of a product or a building. These processes are informed by functional, structural, and environmental constraints. VPD is a therefore a design approach, a methodology, and a technical framework, by which to model, simulate and fabricate functional material organization with varying properties designed to correspond to multiple and continuously varying functional constraints. Such framework includes processes of modeling, analysis and fabrication. Within each process, certain methods have been identified which carry the potential to rethink design not as form-driven, but rather as a behavioral-driven paradigm that may potentially achieve a *natural design*.

Variable Property Design (VPD) includes the sub-processes of Variable Property Modeling; Variable Property Analysis and Variable Property Fabrication. These are defined below.

6.3.2 Digital Anisotropy: Creating Methods for Material Distribution

Nature's artifacts are all anisotropic. Defined as the property of having different values when measured in different directions, anisotropy is central to determining how natural objects are shaped relative to their function and behavior. In design terms, such an ambition appears almost contradictory to nature's way. For example, in architectural CAD, materials assigned to digital data generally lack internal physical directionality due to computational limitations. It is therefore imperative to establish form-generation processes supporting the internal distribution of materials and their properties as a function of any anticipated forces mapped onto the object.

Digital Anisotropy is a term coined by the author to denote the designer's ability to *strategically control the density and directionality of material substance in the generation of form.* In this approach, material precedes shape, and it is the structuring of material properties as a function of environmental performance-requirements that precedes, and furthermore, anticipates their form. Defined below are three classes of *Digital Anisotropy*. Each class is distinguished from the others by the way in which it promotes material directionality changes across various scales whether through organizational variation or through property variation.

6.3.2.1 Distribution-driven Digital Anisotropy

In the case of *Distribution-driven Digital Anisotropy* directionality changes are achieved by generating *organizational* variations in material distribution. Here it is assumed that material properties are *homogeneous* and constant across the surface area or volume of the object (Figure 6.1).

For example, bone tissue is made up of similar material composition (calcium and phosphorus) across various regions of the body. However its mechanical anisotropy is achieved by the arrangement of an irregular lattice work constituting the interior structure of the bone. Those lattices which are made of comparatively homogeneous material are references to the forces acting upon them. One may consider this arrangement of studs and braces as a "structure", but when seen from the point of view of "material distribution", this case is a perfect example of distribution-driven anisotropy. It is comprised of homogeneous material and may or may not be considered a structure depending on its scale and mechanical function[6.2].

[6.2] The reader is encouraged to refer to the technical definitions of anisotropy, further coupled with case studies from the domains of physical sciences and biology. More about the human bone, and the debate introduced regarding the dichotomy between material and structure as scale-driven definitions is provided in chapters 2 and 3.

In computational terms, digital anisotropy may be achieved by considering the units of digital data as *homogeneous* in properties. Their arrangement is conceptually analogous to the arrangement of cellular solids forming a functional structure, say any imaginable type of foam-like structure. However, their "digital assembly" strategy may vary depending on the way in which two or more units are attached and connected (e.g. with or without overlaps, with or without the application of a computational algorithm for their arrangement, etc).

It is important to note that in nature, anisotropy is typically achieved by directionality changes (such is the case of fiber arrangement in wood). However, such changes are essentially made of the same material and are considered homogeneous in computational terms given that the computational units describing matter are symmetrical. As a result, the emergence of *fiber directionality in the digital realm* may be prompted by the serial arrangement of units to form fiber-like longitudinal structures.

6.3.2.2 Property-driven Digital Anisotropy

In the case of *Property-driven Digital Anisotropy* directionality changes are achieved by facilitating *property* variations in material definition. Here it is assumed that material properties are *heterogeneous* and vary across the surface area, or volume, of the object. For example, muscle tissue may be classified as skeletal, smooth, or cardiac depending on the tissue's chemical composition. Local modifications may be observed in different body locations which are characterized by muscle property variation. In this case, mechanical anisotropy is achieved by the specific physical properties of muscle fibers and their (physiological) assembly strategies. Those bundles, which are made of comparatively heterogeneous material, correspond, again, to the forces acting upon them. This case is characteristic of property-driven anisotropy. It is comprised of heterogeneous material and may or may not be considered a structure depending on its scale and mechanical function.

In computational terms, such digital anisotropy may be achieved by considering the units of digital data as heterogeneous in properties. These may include property variations associated with mechanical functionality (i.e. strength and stiffness), visual functionality (i.e. multiple levels of transparency), and acoustical functionality (i.e. multiple levels of insulation capacity) or combinations of such parameters and their assortments (Figure 6.2).

6.3.2.3 Property Distribution-driven Digital Anisotropy

In the case of *Property Distribution-driven Digital Anisotropy* directionality changes are achieved by facilitating combinations of property and distribution variations in material definition. Here it is assumed that material properties are, overall, *heterogeneous* (with local regions that may potentially be comprised of homogeneous material) and vary in location and magnitude (more or less stiff, more or less isolative) across the surface area, or volume, of the object.

Given nature's chemical and physical complexity, it is therefore no surprise that this class is emblematic of *most* natural structures. Combined, fiber directionality, chemical composition and cell arrangement within the tissue and organ level (as a function of their anticipated performance) all contribute to the overall functional and mechanical anisotropy of the structure.

In computational terms, this case represents a composite circumstance in which both directionality and property changes apply. In other words, computational units are both strategically arranged to form micro- or macro-structures as well as vary in properties depending on their location within the structure. Clearly, this class presents computational counterparts for material distribution strategies in Nature that are most challenging to develop in terms of the tools, techniques and technologies currently available to the architect and the designer (Figure 6.3).

6.3.3 Digital Matter 1: Defining a Material Unit

When considering the computational encoding of material data it is important to distinguish between two classes of material units.

6.3.3.1 Symmetrical (Isotropic) Cells: Grains

In this research, in analogy to the physical sciences, grains are defined as, and considered translational symmetrical[6.3]. Not unlike equally sized and formed cells combined in some meaningful way to form a larger lattice system, grains are equivalent to the three-dimensional pixel, or the voxel, scaled down to a pictorial-representation of a digital unit (Figure 6.4).

6.3.3.2 Asymmetrical (Anisotropic) Cells: Fibers

Fibers are considered reflection symmetrical[6.4]. Like natural fibers of various length scales and dimensions, digital fibers are geometrically defined as components containing longitudinal directionality. In this research, due to their geometrical affinity with voxels, we refer to voxels ("digital grains") as the building blocks of digital matter. Similarly, fibers or any form of organizational directionality may be informed by the strategic distribution of grains (Figure 6.5).

6.3.4 Digital Matter 2: Defining a Computational Material Unit

The shape and size of a computational unit may vary depending on the type of representation used to generate it. In the case of an already existing geometrical entity, the computational unit may be used to quantify units of physical matter for purposes of evaluation. One must therefore distinguish between processes that define such material units during form-generation and processes that define them by means of analysis and evaluation. Regardless, in order to understand the theory and methods of Material-based Design Computation it is imperative to first review and presents its foundations and initial assumptions. We provide three definitions of *computational material units* classified by the type of computational process at hand. The unit's shape, size and topology may vary depending on its definition. Later, we will attempt to integrate between these three class representations with the aim of introducing a new design approach enabling the *simultaneous* generation, analysis and fabrication of physical form.

It is important to note that common to all methods described below is the notion of form discretization as a way of *post-rationalizing* an already existing artifact. In order to examine the potential for form-generation processes to emerge by coupling material and environmental constraints from an initial condition that may be defined as "blank slate" (or, blank canvas!), we must first understand how such processes are being addressed within the sub-domains comprising the design process, namely the domains of (a) modeling, (b) analysis and (c) fabrication.

[6.3] Translational symmetry leaves an object invariant under a discrete or continuous group of translations.

[6.4] Reflection symmetry, mirror symmetry, mirror-image symmetry, or bilateral symmetry is symmetry with respect to reflection.

6.3.4.1 Modeling Definition (CAD): Material Tessellation Unit

In Chapter 4 we defined *tessellation* as the process of subdividing a surface into smaller elements geometrically congruent to their neighbors. The size and topology of each geometrical unit may vary depending on the size and topology of the surface or volume being tessellated. For example, doubly curved B-Spline surfaces may be tessellated into doubly-curved tiles, ruled surfaces may be divided into smaller ruled surfaced components, and so on.

From a modeling perspective, tessellations are clearly of major relevance as they provide for methods of post-rationalizing any geometrically-generated objects from digital conception to physical fabrication (Figure 6.6). Three regular tessellations composed of regular polygons are known to symmetrically tile a plane. Tessellations of the plane by two or more convex regular polygons, such that the same polygons in the same order surround each polygon vertex, are called semi-regular tessellations, or sometimes, *Archimedean tessellations*. In the plane, there are eight such tessellations. Simple and relatively known examples of surface tessellation are square and hexagonal tiling. Examples that are more complex include *Penrose tiling*; randomly colored, uniform polygon tiles; or hexagons and pentagons that compose a Buckminster sphere. In Chapter 4 we distinguished between tiling of regular polygons (in 2-D), polyhedrals (in 3-D) and polytopes (for *n* dimensions). A tessellation unit is therefore *geometrically* defined. As such, it may contain information regarding local (a singular unit), regional (multiple units) or global (all units) curvature, but it does *not* typically designate physical properties, or behavior.

In order for a tessellation unit to incorporate physical material properties, a proper relation must be established between the tessellation strategy (size, shape, topology and organization) and the physical requirements such that a correlation between form and behavior might be established. In this case, the result will yield *material tessellation units* that are essentially geometrical entities encoded with physical-behavioral information.

6.3.4.2 Analysis Definition (FEA): Material Mesh Unit

Mesh discretization allows the designer to subdivide a continuous mathematical domain into a set of discrete sub-domains referred to as elements and represented as singular geometrical entities. Lattices and triangulations are common rationalization discretization techniques, where quadrant and triangulated elements may respectively wrap the surface area or volume of the object. Contrary to units defined only via geometrical tessellation, analytical subdivision strategies are typically driven by structural, and other related types of, performance. Such *structural meshes* are used by engineers in order to simulate structural loads, analyze their distribution and predict any potential displacements that may arise as a result, for instance, of vertical, lateral, or torsional loads (Figure 6.7).

More recently, engineers are utilizing mesh-free algorithms in order to post-rationalize a given 3-D form in the process of translating it from the digital domain to its material manifestation via appropriate fabrication routines. Such mesh-free methods, as we have seen in Chapter 4, eliminate some, or all, of the traditional mesh-based view of the computational domain and rely on a particle view of a field problem. Mesh-free methods offer, therefore, an alternative for rationalizing volumes and surfaces by conceiving of them as continuous fields of particles which may potentially carry material data (Figures 6.8-6.12).

In both cases (mesh, or mesh-free oriented methods), one may consider the perfect alignment between form and material behavior by calibrating the size, shape and proximity of the element (whether a quad, triangle, or “particle”) to the size and shape of the material unit from which the form is to be fabricated. Imagine, for example, that the size of a mesh-free particle applied for the purpose of structural analysis precisely matches the size of an imaginable powder molecule, or more realistically speaking a material aggregate providing for the substance of the 3D printing process. As we shall soon discover, the implications of such a methodological/technological alignment seem quite enormous.

6.3.4.3 Fabrication Definition (FGM): Material Maxel Unit

As previously reviewed in Chapter 4, the basic unit for Functionally Gradient Materials (FGM's) representation is the *maxel*. The rendition of the term relates to additive fabrication processes and is used to describe a physical voxel which defines the build resolution[6.5] of either a rapid prototyping, or rapid manufacturing, process, or the resolution of a design produced by such fabrication means.
The *maxel unit* can be thought of as an intermediary representation linking the digital form to its physical manifestation, particularly when rapid fabrication processes are considered. In this respect, the maxel provides for a lower limit material definition establishing the degree of granularity required to manifest three dimensional details of the design. From here, it is relatively easy to imagine the implications of using maxels as the units used for calibrating voxels and printing powder. In this case the designer would be modeling 3-D form using the units used to describe its physical manifestation.

6.3.5 Digital Matter 3: Defining a Material Organization

When considering a unit definition of matter, it is important to also consider any boundary definitions of the unit and the way in which multiple units are connected. For instance, a triangulated unit may be part of some tetrahedral unit such that one unit is shared by two tetrahedral units. Clearly, there exist numerous ways by which to define and inform the cellular organization of units subdividing a given 3-D surface or volume. Not unlike the case in nature, such cellular tissues are typically made of an ensemble of cells. Cells are not necessarily identical, but from the same origin and together carry out a specific function.

6.3.5.1 Modeling Definition (CAD): Tessellation Tissue

When considered from a geometric modeling perspective, the subdivision of a geometrical entity typically serves to rationalize the surface for fabrication purposes. In this case, each "unit" or "cell" serves as a material component the size and curvature of which is dependent on the material and fabrication method applied. The unit's edges are used to define geometrical continuity such that for highly curved surfaces, smaller cells are assigned and for areas of relatively smooth curvature larger cells are assigned. It is important to re-emphasize that aside from surface rationalization for fabrication purposes, such subdivision units contain no material, or behavioral, parameters.

6.3.5.2 Analysis Definition (FEA): Mesh Tissue

Tied to an analytical framework, meshes constructed for structural or environmental analyses are, by their very nature, subsidiary to formal generation. In Chapter 4 we reviewed a variety of techniques to consider the design object as one which is made out of multiple smaller units, the size, color and shape of which are determined as a function of the type of performance being evaluated. In this case, the subdivision is inherent in both the geometry and the objective functions driving the design.

[6.5] The "build resolution" is a term used to denote the granularity of a rapid prototyped part using additive fabrication technologies. The desired build resolution is typically determined by the thinnest section in the X-Y directions throughout the part (generally wall thickness or surface features); the thinnest section in the Z direction. This includes the depth of engraved or raised lettering; the overall size of the part; and the final appearance required for the part. The factors determining the resolution typically include the thickness of each layer or slice through the CAD model, and the diameter of the laser spot used to draw each layer. Combined, these two factors will determine the smallest feature, or thinnest wall, a given resolution will create.

The goal here is to subdivide the design object such that its analysis might satisfy certain performance constraints. Unlike the previous example, where units are defined purely by their geometrical nature, in the case of structural analysis each unit, or element, carries with it specific performance data associated with internal material properties (e.g. stiffness) and external environmental conditions (e.g. strain due to load).

6.3.5.3 Fabrication Definition (FGM): Maxel Tissue

Over-scaled, the aggregation of powder grains produced for purposes of rapid fabrication, might appear to the observer as a large pile of oversized molecules randomly arranged, arbitrarily ordered and bonded with adhesive resin. In real life, these homogeneous material molecules are used as the "build material" for the rapid prototyped model.

As previously reviewed in Chapter 4, the basic unit used for the representation of functionally gradient materials is the *maxel* typically defined by the location and volume fraction of individual material components. In fabrication terms, the maxel is used to describe a physical voxel the size of which defines the build resolution of a design produced by means of rapid prototyping. For example, in the case of functionally gradient materials, a finite element analysis (FEA) application may be applied which uses a triangulated or quadrilateral mesh within which each element is defined by its own structural properties and the size of the element is defined by the fabrication plotter resolution. In this case, all units representing the different stages of modeling, analysis and fabrication are aligned and calibrated. Assuming that units of modeling (tessellation) may indeed be calibrated with units of analysis (mesh) and units of fabrication (material atoms), the generation of form might become synonymous with growth.

6.3.6 Digital Assembly: Approaches for Digital Anisotropy of Digital Matter

Amid the representation of material and structure across various scales and media (e.g. modeling, analysis and fabrication), it is relatively easy to imagine how design information may be "lost in translation". Once the object has been geometrically defined and expressed, through its post-rationalization and towards its materialization, the designer moves freely between units of geometrical form, units of analytical computation and units of physical matter. What if we were to assume that all design units are calibrated across media? And, what if following such an assumption, a design object could be described in fabricating terms simultaneous to its being analyzed? (Figure 6.17) Can designs be "grown" to accommodate environmental conditions? As how material is defined and expressed within each of these media becomes radically reformulated, could such an attempt for the universal calibration of matter yield a new way of thinking and making design?

The following methodological frameworks were created for the purpose of experimenting with the idea of *universal material calibration* in search for a natural way in, and for, design. Entitled *Tiling Behavior* (TB), *Finite Synthesis Method* (FSM), and *Variable Property Fabrication* (VPF), each such methodological framework refers to a distinct representational media respectively including modeling (material-based tessellation), analysis (material-based simulation) and fabrication (material-based prototyping) computational platforms associated with material-based design computation processes.

6.3.6.1 Generative Modeling: Tiling Behavior

Patterns in nature often inspire textures and patterns in architectural and design domains. However, in the synthetic world geometrical considerations preceded material choice. *Tiling Behavior* proposes a material-based approach to tiling, whereby each tile, or group of tiles, represent various material properties as an integral part of the form-generation process. *Tiling Behavior* (Oxman 2009) questions the role of tiling as a rationalizing method and offers an alternative theoretical framework and technical grounding for processes of *material-based tessellation*.

The technical objective is to introduce a quantitative characterization of *property mapping*, as it may potentially be applied to a tiling algorithm using some tessellation routine, for example *voronoi tessellation*[6.6] . In this research framework, the network of tessellated Voronoi cells is used as an element in the *Voronoi Finite Element Method* (V-FEM) developed by the author and presented in the following chapter. Various characterization functions and geometric parameters are generated, and V-FEM is executed for plane-strain analysis of doubly curved surfaces, from which global and local responses are evaluated (Oxman 2009).

The aim is to establish processes of surface tessellation as rudimentary to form generation by postulating that tessellation algorithms could and should include physical data that is expressed geometrically. By considering parameters such as variable stiffness as functions informing the design of complex form, the work offers a theoretical and technical approach to *tiling behavior* (Oxman 2009).

The work proposed and developed here introduces the concept of tiling behavior as a theoretical framework, a methodological setup, and a technical approach that extends its role as rationalizing technique beyond geometrical representation. This work demonstrates *tiling behavior* through the development of computational tools that include material properties and their assignment to corresponding structural and environmental performance data (Figure 6.13).

6.3.6.2 Generative Analysis: Finite Synthesis Method (FSM)

The basic iterative algorithm for finite element optimization is based on reducing material concentration where it is not required for purposes of structural or mechanical performance (such purposes are, of course, defined by the objective function). In other words, if we begin the design process with a solid block of material and specified load conditions, then following this procedure, stress distribution is recalculated and elements with minimum stress values are removed. This process is applied to a specific objective function (i.e. structural optimization) while assuming a relatively homogeneous material distribution. The optimization algorithm, which may be combined with certain Genetic Algorithm (GA) functions to assist with fitness evaluation, considers binary functions ("retain, or remove, material") at the scale of the element.

Simplified, the basic iterative algorithm for finite element structural optimization operates as follows:

1. Begin with solid block of material and specified load conditions;
2. Run finite element analysis to calculate stress distribution;
3. Check for any elements at less than maximum allowable stress;
4. If no, then terminate, otherwise;
5. Remove some of the lowest-stressed elements;
6. Go to 2.

The effect, basically, is to eat away redundant material until the minimum amount necessary to perform the structural task is left (at which point, all material left should be fully stressed). The algorithm then

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[6.6] Voronoi tessellation is a geometric dual of Delaunay triangulation and one can be derived from the other. Given a set of N points in a plane, Voronoi tessellation divides the domain into a set of polygonal regions, the boundaries of which are the perpendicular bisectors of the lines joining the points.

terminates. Such typical algorithm assumes homogeneous material (Figure 6.14). The only possible element conditions, then, are "full of material" or "empty". However, the designer may potentially decide to *vary material properties* of an element (e.g. variable-density metal foam), such that the element properties can continuously vary from 0 (empty, no material) to 1 (full of the strongest available material), thus generating heterogeneous material organizations. Accordingly, the final steps in the algorithm would gradually reduce the strength of some of the least load-bearing elements.

Given this highly innovative ability to synthesize and control material distribution, the experimental research based on this methodological platform develops and investigates architectural forms that become possible when we can continuously vary material properties. This becomes particularly significant in considering not only strength and structural optimization, but also insulating properties, transparency, and other architecturally relevant properties of materials which can be optimized against multiple performance criteria.

In this methodological framework, we propose a general approach to the problem of computational form-generation of shapes with continuously varied material properties satisfying prescribed material conditions on a finite collection of material features and global constraints. The fundamental approach is guided by the conversion of the analytical process into a synthetic one. In other words, the aim is to apply the logic and computation of finite element approaches to the problem of design synthesis, rather than design analysis.

Such a process requires that the designer redefines the analytical unit and mesh components as *synthetic* cellular entities which are further connected, combined, "grown" or woven to form a surface, or volume, based on the integration of internal material properties and external environmental constraints. It is challenging to imagine how this may be achieved without an initial state (i.e. a boundary solution). Such a state might simply be assumed to be the initial volume of material assumed prior to the application of site forces considered, e.g. an initial state defined by a homogeneous cube of given size and properties. From here it follows that the parameterization of shape may be guided by both the subsistence of material (per given material unit, material is either present or eliminated) and its various potential qualities with their proposed ranges (e.g. from hard to soft, from opaque to translucent, and so on).

This proposed framework is inspired by problems of heterogeneous material modeling in the fields of material science and computer-aided geometric modeling as it may potentially be applied to larger scales in design and architecture. It is theoretically complete in the sense that it supports the representation of all potential material property functions while considering only the most generic parameters regarding mechanical behavior, environmental impact, and spatial or visual effect. More specifically, the aim is to generate 3D forms that correspond to a given set of performance requirements which are then mapped and computed as material properties. For example, a pattern representing wind-load conditions may potentially be mapped to a given material with specific physical properties. This will generate the initial solid volume element (Figures 6.15, 6.16).

The experiments under this rubric are considered synthetic insofar that analytic data is used to further develop and generate the 3D form. Granted, the designer does not begin with a "blank slate" situation, but rather, natural structural specimens are, in certain of the experiments, used as the initiating "material". In other words, rather than generating 3D form from an initial homogeneous chunk of material, structural and organizational models are derived from scanned micrographs of natural structures and are further reconstructed by computing their hypothetical physical response. In each case, a computational experiment is performed that accounts for physical responses to structural components in the original image.

We use the Object Oriented Finite Element Analysis (OOF) environment as the methodological foundations for these experiments. As reviewed in Chapter 4 of this thesis, the OOF environment was developed at MIT's Department of Material Science and Engineering in collaboration with NIST (National Institute of Standards and Technology), for analyzing the effects of microstructure on material properties. It is unique in that it combines a finite element method together with material properties. It serves to predict material behavior under a range of objective functions defined by the user such that given a 2-D image of the specimen, one can analyze its physical behavior based on a hypothetical assignment of physical properties to geometrical attributes (Carter, Langer et al. 1998; Carter 2010).

The computation is performed using an image-based finite element application. Physical properties are imposed onto the image after which a computational mesh is created which includes the image-property information. The computation produced various data sets including stress and strain data, heat flow, stored energy, and deformation due to applied loads and temperature differences. The results are spatially analyzed and converted to a constructible data structure using *Mathematica*.

The input files include micrographs and simulations using all available micro-structural data with no mean-field approximations. Constitutive relations which translate stresses into strains using Young's modulus are defined by the user. OOF converts an image, or a micrograph, of a heterogeneous, multi-component material into a finite element mesh with constitutive properties specified by the user. It is a tool to test physical properties and to investigate the influence of microstructure on macroscopic behavior, via finite element analysis.

6.3.6.3 Generative Fabrication: Variable Property Fabrication (VPF)

We propose to integrate the material-computation design environment which has been described with a direct fabrication capability. Currently, there exists no rapid prototyping technology which allows for a continuous modification of material properties such as strength, stiffness, density and elasticity as continuous gradients across the surface and volume area of a functional component. Such variations are usually achieved as discrete changes in physical behavior by printing multiple components with different properties and definite delineations between materials, and assembling them only after the fabrication process has been completed. Such processes result in material waste and lack of functional precision.

Variable Property Fabrication (VPF) aims at proposing a novel material deposition 3-D printing technology which offers gradation control of multiple materials within one print to save weight and material quantity while reducing energy input. The result is a continuous gradient material structure, highly optimized to fit its structural performance with an efficient use of materials, reduction of waste and the production of highly customized features with added functionalities.

From a fabrication point of view two methodological frameworks are considered that aim at the following:

1. *Product* framework: Fabrication with variable density and elasticity properties as opposed to the fabrication of discrete components, each with homogeneous materials and properties.
2. *Process* framework: Integration of environmental performance data as part of the fabrication process. For instance: structural load mapping simulated in an FM environment is mapped on top of the fabrication software which, in turn, informs property distribution in the printing process.

The first methodological framework (1) is product-oriented and as such, it may be applied in a traditional design context in which there is a separation between modeling, analysis and fabrication processes. If well achieved, it is considered as a novel fabrication technology which can potentially 3D print any given design (within a certain scale limit) with variable properties as defined by the user.

The second methodological framework (2) is process-oriented and as such, it promotes a novel approach to the design of objects informed by their environment. Assuming that a full calibration may indeed be achieved between modeling, analysis and fabrication units describing and depicting the distribution of matter, then each "tile" or "element" carrying geometrical and physical data may be mapped on to a fabrication unit manifesting such specific material properties and behavioral attributes.

Both methodological frameworks are mutually exclusive and may be experimented with independently of each other. In Chapter 7 we review a set of experiments each promoting one or both frameworks in different stages of the design process. These experiments culminate with the introduction of a new technology developed by the author and coined *Variable Property Rapid Prototyping* (Oxman 2009).

Variable Property Rapid Prototyping (VPRP) is a novel technology which enables the controlled variation of material properties during the process of material deposition in a 3D printing application. This technology combines a novel software environment coined Variable Property Modeling (VPM) with a mechanical output tool designed as a 3D printer. VPRP allows for physical prototyping of graduated properties in product design scale, based on the design and fabrication logic of Functionally Gradient Materials (FGMs). Currently, there exists no rapid prototyping technology which allows for modifying material properties such as strength, stiffness, density and elasticity as continuous gradients across the surface and volume area of a functional component. Such variations are usually achieved as discrete changes in physical behavior by printing multiple components with different properties and definite delineations between materials, and assembling them only after the fabrication process has been completed. Such processes result in material waste and lack of functional precision. VPRP introduces the ability to dynamically mix, grade, and vary the ratios of different materials in order to produce a continuous gradient, highly optimized to fit its structural performance with an efficient use of materials, reduction of waste and the production of a highly customizable features with added functionalities.

6.3.7 The Variable Property Design Environment: Coupling Material Properties and Environmental Performance Requirements

What if instead of designing with shapes, one would design with material properties? What if voxels alone could incorporate both material and environmental data and generate any 3D form as a function of its interaction with the environment and the parameters mapped between, and on top, of those two domains. What if material would spatially distribute itself as a function of anticipated load coupled with required light and thermal conditions? The field of Material-based Design Computation as a design paradigm requires that we rethink from the bottom-up both our design products and our processes as informed by the environment.

Can functional grading, informed by the coupling of internal material properties and external environmental constraints, be designed, not purely as a post-rationalization technique, but rather become an integral part of the form-generation process? This is the basic question at the heart of the Variable Property Design (VPD) Environment that was invented as one of the methodological platforms for the development of this new design approach/technology, its models, its tools and its applications.

6.3.7.1 Issues and Objectives

The main problem addressed by the VPD environment is how to generate unit-based information in a CAD setting that promotes the generation of form? Imagine, for instance, the use of functionally gradient materials, the functional distribution of which are directly informed by the environment and simultaneously fabricated via rapid prototyping technologies. Given their variation of properties across volume and surface area, FGM's could potentially be 3D printed by sending the machine a layer-by-layer pixel sheet such that when they are stacked they are represented as voxel clouds (Hopkinson, Hague et al. 2006). Functional grading, though, is something to be designed, and voxels, are merely representative of physical data scanning. However, given their representation as discrete elements defining a continuous whole, able to carry 3D information (scalars, vectors) as well as physical information (tensors), voxels are ideal entities to design and edit graded functionalities.

Volumetric property design is new to CAD and CAM systems and offers an alternative to NURB and STL representations. The diagram below exemplifies the need for a Variable Property Modeling (VPM) paradigm (Hopkinson, Hague et al. 2006).

The structure of a nerve's dendrite, schematically represented in Figure 6.18, nicely illustrates the notion of variable properties in multiple domains: the outer layer of the dendrite is stiffer then its inner substance. Its inner substance displays variation in conductivity depending on the location of the electrical signal. In other words, the nerve displays variation both across its longitudinal section (in the length dimension) and its transversal section (perpendicular to the length dimension). Such variation is incredibly difficult and challenging to account for in any traditional 3D modeling software.

6.3.7.2 VPD Domains

Within the VPM modeling environment, the program must translate desired model properties to material properties. The VPM environment gives the value of any property at any point (high or low conductivity / stiff or soft) in order to structure the correct material composition and emulate both its structural and electrical performance. Currently, transition functions that compute gradient property distribution across one or multiple dimensions do not exist in CAD.

The VPM environment is developed in order to cater for such requirements and present physical data and material composition by treating voxels as tensors (geometrical entities containing multiple physical parameters), or by computing transitions between multiple compositional phases as extrapolation functions. Clearly, the distribution of materials must be limited by the boundary of the solid, or, its domain.

Freeform design has seen an abundance of software packages supporting complex modeling environments in terms of surface and solid descriptions through NURBS and/or mesh architectures. Predominantly, the challenge in design has been focused around the geometrical description of form as propertyless features to which material is assigned homogeneously in the process of fabrication. The VPM modeling environment supports the representation of solids as geometrical features described by their material composition. The distribution functions of properties across the domain are valid, but not exclusive, to that domain.

6.3.7.3 VPD Material Properties

The VPM environment distinguishes between two classes of properties: discrete properties and variable properties. Discrete properties (DISC-props) are constant, and are assigned to areas of constant properties across the surface, or volume, area of the domain. Being independent of each other, discrete properties cannot intersect. For instance, when relating to the extreme cases of strength, a voxel cannot be defined as soft and stiff at the same time. Variable (VAR-props) Properties are assigned for advanced property distribution such as the one discussed in the example above. Variable properties describe areas with gradient material composition across the surface, or volume, area of a domain.

6.3.7.4 VPD Distribution Functions

A distribution function will typically describe the value of a given property (i.e. strength, conductivity) as a function of location. The VPM environment distinguishes between absolute and relative distribution functions. An absolute distribution function is defined by a function and the distance to, or from, a given property. The function computes the relation between the relative distance, given by the user, and the property fracture. For example, the material is X times softer in Y times the distance from the boundary of the model across its length. The relative distribution function is defined by two properties and a function. From any given point, the shortest distance is calculated to the maximum magnitude of both properties.

In the example shown above, the domain contains the geometrical representation of the solid itself, its properties include stiffness and conductivity, and its distribution functions compute the transition from stiff to soft regions and from highly-conductive to low-conductive regions within the domain.

Like the example above, many other products and building components require a rethinking of their modeling environment in order to achieve the ability to design and edit graded material compositions as the ones offered by *Functionally Graded Materials* (FGMs). The limited functionality with current CAD systems is due to conventional fabrication technologies which do not take graded properties into account.

6.3.8 Eco Voxels: Definitions

The technical approach facilitating Variable Property Design considers the digital voxel as a material proxy mediating between its pre-defined material properties and the environmental constraints included within one unique, or multiply negotiated, objective functions.

6.3.8.1 Voxel-Space

A voxel, defined as occupying material space, can be extended to represent physical and tensor properties in a computational space. These local material properties physically and spatially interconnect component parts into a connected whole. The 3D space occupied by the proxy-voxels (with equal footing in both digital and physical domains) is defined as the Voxel-Space. In addition to each voxel incorporating material and environmental data, it may also potentially contain data indicating its relative location within a “voxel cloud”. For example, suppose we are discussing the curvature-stress-color aspects of an object, a voxel could occupy a position in curvature-stress-color space, but transmit information about its relative position in the object.

The motivating assumption here is that if a finite computational representation unit (e.g. pixel, voxel, maxel) can potentially contain a *multiplicity of physical data* relating to various conditions (e.g. density, transparency), than a design can be computationally generated that matches precisely its particular constraints for every given such representational unit. It then follows that, if this finite unit correlates in size and in space with the units applied to describe any performance data (e.g. structural, environmental), then differences required in material behavior are perfectly matched to difference portrayed in material properties. In other words, given that we can computationally represent constant and dynamic states of energy (e.g. force, heat) confined to specific boundary conditions, and given that we can theoretically negotiate and assign multiple physical properties to the materials and their micro-structures defining the design, then the distribution in properties can potentially and precisely match the distribution in performance constraints defined by the environment in the form-generation process. In this sense, form becomes the by-product of integrating material performance, environmental performance and fabrication data.

As a result, the size and property measure of a computational unit must correlate with:

- The size and properties of the *energy* unit (e.g. Joules/other units of work)
- The size and properties of the *material* unit (e.g. grain, cells, fibers)
- The size and properties of the *geometry* unit (e.g. triangulated mesh)

- The size and properties of the *fabrication* unit (e.g. powder molecule)

6.3.8.2 Objective Functions Informing the Voxel Properties

As recalled, an objective function is a mathematical function associated with an *optimization problem* which determines how good, or fitting, a solution is. In the simplest cases, this requires solving problems in which one seeks to minimize, or maximize, a real function by systematically choosing the values of real, or integer, variables from within a given set. This formulation, using a scalar, real-valued objective function, is probably the simplest example; the generalization of optimization theory and techniques to other formulations comprises a large area of applied mathematics. More generally, it means finding "best available" values of some objective function given a defined domain, including a variety of different types of objective functions and different types of domains (Atallah, Fox et al. 1999).

The process of adding more than one objective to an optimization problem adds complexity and also requires strategies for negotiation. For example, in order to optimize a structural design, the designer would seek a design that is both light and rigid. Given that these two objectives may conflict, a negotiation strategy must apply. Within the scope of possible designs to satisfy the solution space there will be one lightest design, one stiffest design, and an infinite number of designs that are some compromise of weight and stiffness. This set of trade-off designs is known as a Pareto set, and the curve created plotting weight against stiffness of the best designs is known as the *Pareto Frontier* (Das and Dennis 1997). A design is judged to be Pareto optimal, if it is not dominated by other designs: a Pareto optimal design must be better than another design in at least one aspect. If it is worse than another design in all respects, then it is considered dominated and is not Pareto optimal.

6.3.8.3 Pareto Optimal Voxels (POV)

Pareto Optimal Voxels (POV's) as formulated by the author are three-dimensional computational units that incorporate more than one performance constraint, and do so in a continuous non-discrete, non-binary manner. In other words, we seek to define a POV as (1) a unit which can contain data of various kinds, such as structural load requirements and acoustical requirements, both incorporated into the computational description of the unit, and, (2) a unit the description of which per any given performance criteria (e.g. structural and/or environmental) can be expressed in non-binary, non-discrete, but continuous terms. For example, when considering transparency characteristics, the designer would be able to assign such visual parameters from an entire set of options ranging from opaque state to transparent state with various translucency states in between.

6.3.8.4 Property Definitions of Material Voxels

Material-voxel properties are defined as the intermediary media between environmental impetus and material response. (i.e., force is an environmental impetus, extension is a material response, and stiffness is the material property that mediates the two). Granted, we are considering wider sets of couplings between environment and response, and these are reflected in the complexity of the material.

For example, the representational unit would contain material properties. Given an environment, the material response would be computed through the material properties, the representational unit's connectivity, and its geometry. It is important to note that the consideration of material property distribution as it is informed by the environment is generic in the sense that environmental constraints are collected over time and responded to within a static object that is, at least for now, devoid of any dynamic capabilities. Clearly, the environment is dynamic and not predictable. In other words, the design, which is based on the negotiation between environment and the optimal response, could be considered dynamic—but the construction of the artifact is static: it happens only once.

6.3.8.5 Hierarchies of Material Voxels

It is important to note the potential of considering such computational units as hierarchical, instead of merely correlating the size and property measures. In this research, such hierarchies are considered mainly during the process of modeling, where groups of voxels are hierarchically organized as a function of their performance and material attributes. However, one could imagine that the designer can have control over the design by distinguishing between larger voxels that keep track of environmental responses that are "roughly homogeneous" on a larger scale. These responses could potentially be composed of sub-voxels that do the same job at a smaller scale. The sub-voxels then would communicate with their voxels which would communicate with the other voxels within the domain. This hierarchy could be extended to as small a unit as is defined by the type and magnitude of performances addressed in the environment.

6.3.8.6 Unit Definitions of Material Voxels

We distinguish between three types of units:

1. Energy unit: This unit is derived and defined by the environmental field or impetus (e.g. temperature, electric field, illumination, and so on). These elements should also scale with the gradient of these variables (i.e., if illumination is changing rapidly, then the computational unit must be small enough to capture the gradient).
2. Material Unit: The material units are defined by both the material properties (i.e. stiffness, density, transparency and so on), and by the micro-structural organization of multiple units (i.e. grains, fibers etc).
3. Geometry Unit: this unit is defined by its shape (i.e. triangle, tetrahedron, etc) and by the connectivity established between two or more units (i.e. triangles that are part of some tetrahedron, tetrahedral that share the same triangle, etc).

6.3.9 Eco Maxels: Types

The desired integration between processes of modeling, analysis and fabrication and their related representational platform assumes that units of energy may be equivalent in form and dimension to the units of physical matter as they are discharged from a fabrication machine for rapid manufacturing. This condition carries implications that are profound for products and processes of design alike as it promotes the unification between constraints, properties and emergent form. In other words, the integration and parametric homogenization between units of work (energy) and unit of matter (form) has the potential to yield new forms of design space where design "units" can denote a combination of factors relating to the interaction between matter and energy in the production of form.

Below I have identified several such couplings between energy and *Material Voxels (Maxels)* that have served this thesis in the experimentation with classes of emergent material organization. It goes without saying that the parametric negotiation and calibration *between* these types has proved to be a significant, and possibly unresolved, challenge to be experimented with as part of the design process depicted in the following chapter.

Note that each voxel/maxel type is, in fact, a tensor including geometrical parameters indicating it size and location in space, material parameters indicating physical properties relevant to its behavior, and environmental parameters indicative of the type of environmental forces, and any of their combinations, governing the design.

6.3.9.1 Pressure Maxels (Load) - Designing with Structural Parameters

Load induced growth, as one of the relevant factors that shape trees, bones and other natural specimens, both in the process of growth as well as during maturity, is a process informed by the interaction of the material on the one hand (wood, bone, etc), and the environmental pressure (load) on the other. Rather than distinguishing between the two, pressure maxels are conceptualized here as material units shaped and informed by various degrees of pressure (not unlike processes of pressure treatment for wood, or load induced growth in a broken leg) given some initial shape.

Pressure maxels[6.7] are therefore directly related to any anticipated loading data (Figure 6.19). For each design object, whether *pre*, or *post*, its generation, a structural analysis package is typically used to establish the distribution of load and potential displacements under vertical, lateral, or any combination of loads. The distribution of anticipated load as a function of specific and relatively constant loading conditions is then mapped to material properties which are, in turn, assigned to the shape (in the case of material-based tessellation) or combined together to *form* the shape (in the case of material-based form-generation).

A series of fabrication materials ranging in properties from rigid to flexible were used to counteract anticipated local loading conditions previously defined as part of the design context. The parameters that were considered in the description of the fabrication materials included tensile strength, elongation to break, tensile tear resistance, and shore hardness of various types. The exact data for each parameter is given in relation to each experiment and defined per its context.

The main aim is to implement a range of properties to account for anticipated structural load, as opposed to the more typical case of distinguishing between hard and soft materials implemented as separate structural components, as is the case in the application of steel and glass as the respective structural and environmental components of building.

6.3.9.2 Thermal Maxels (Heat) - Designing with Environmental Parameters

Heat flux or thermal flux, also referred to as heat flux density or heat flow rate intensity, is defined as the flow of energy per unit of area per unit of time. In SI units, it is measured in $\frac{W}{m^2}$. Given that this dimension occupies both a direction and a magnitude, it is considered a vectorial quantity. In order to determine the magnitude and direction of a thermal voxel in the digital domain which occupies the design space, we assume the limiting case where the size of the surface or volume element making up the design object is infinitesimally small.

Heat flux is often denoted ϕ_q, the subscript q specifying heat flux, as opposed to mass or momentum flux (Figure 6.20).

Heat flux measurement is often achieved by measuring a temperature gradient over a stock of material with known thermal conductivity. This method is analogous to a standard way to measure an electric current, where one measures the voltage drop over a known resistor.

The implications of design processes informed by the energy balance of which heat flux plays a crucial role are enormous. Rather than adding ACAV systems to a façade, building materials have now the capacity to sustain, and potentially control, internal heat distribution relative to environmental needs. In

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[6.7] Also conceptually understood as "stress maxels" this respect, the concept of heat-maxels material units the properties of which are informed by temperature parameters may indeed promote an integrated approach to form generation driven by environmental analysis and simulation.

6.3.9.3 Light Maxels (Light) - Designing with Phenomenological/Visual Parameters

Beyond the practical architectural requirements for the quantity of daylight relative to the size and location of a space, the qualities of natural light and its distribution within the space have great visual and even sensorial implications on the inhabitant (Figure 6.21). Unlike the family of engineering parameters, architectural parameters are at times associated with phenomenological criteria which are not always quantifiable.

Light can be measured and used in many different ways. Amongst the many quantities of light, one may include luminous energy (whose units are Q_v and SI units are lumen seconds), luminous flux (whose units are F and SI units are lumen), luminous intensity (whose units are I_v and SI units are candela), luminance (whose units are L_v and SI units are candela per square meter), illuminance (whose units are E_v and SI units are lux), luminance emittance (whose units are M_v and SI units are lux), and luminous efficacy (whose units are M_v and SI units are lumens per watt).

Motivated by the ambition to explore multiple qualities of light and their effect on the environment both from an energy and a comfort perspective light maxels are defined as material units the properties of which are directly informed and associated with qualities of visual value. The dominant material properties explored and implemented are related to the opacity or transparency of the material unit, and the various levels of translucency in between.

6.3.9.4 Comfort Maxels (Physiological Pain) - Designing with Physiological Parameters

Similarly to the mapping of load, heat and light, the designer might also engage the mapping of other parameters such as physical comfort (when occupying a furniture piece, or leaning against a soft wall), or, alternatively, physical pain, when attempting to treat a medical condition. However, unlike the parameterization of load, heat and light, pain-mapping appears to be significantly more challenging with regards to its evaluation, analysis and prediction (Figure 6.22).

Defined as “an unpleasant sensory and emotional experience associated with actual or potential tissue damage, or described in terms of such damage”[6.8] , numerous theories are associated with the quantification of the sensory and affective sensations of pain; and it is this process of quantification that is required for the establishment of material shape and distribution in the design of a product or a building part.

Comfort maxels could be thought of as mechanical stress associated with physical pain or relief. Material units are applied to counteract any physical sensation of discomfort or pressure. “Pain”, in this context, provides for the environmental constraints coupled with the material properties associated with the maxel. Indeed, one of the main challenges still remains as in the other cases the sizing and shaping of each of these components relative to the mapping of mechanical discomfort. More regarding this is presented in the description of the experiments in the following chapter.

[6.8] This often quoted definition was first formulated by an IASP Subcommittee on Taxonomy: Bonica, JJ (1979). *Pain* 6 (3): 247252. ISSN 0304-3959.PMID 460931. It is derived from Harold Merskey’s 1964 definition: “An unpleasant experience that we primarily associate with tissue damage or describe in terms of tissue damage or both.” Merskey, H (1964). *An Investigation of pain in psychological illness, DM Thesis.* Oxford University.

6.4 Summary: From Experimental Material-based Methods to Experimental Design Computation

This chapter has introduced the methodological frameworks for Material-based Design Computation. Its main objective has been to act as an intermediary link between the issues and questions raised in the previous chapter, and the design experiments testing the research assumptions, in the following chapter. The method frameworks were presented as the various methods applied (and frequently, invented) in the research; furthermore, they have offered an experimental and organizational structure according to which to interpret and to further extrapolate the experimental results within a larger design context.

Set with the theoretical task of introducing the methodological foundations of natural design and the technical foundations for Material-based Design Computation, this chapter has focused on the two major issues that the author has found to be central to establishing these foundations. The main goal was to define a set of design methods that would support the generation of multi-functional objects, including buildings, as well as to enable the integration of analytical routines with synthetic ones in the overall production of form.

Organized by order of complexity and specificity, the method-frameworks include both conceptual and technical depictions of tools and technologies employed to both generate and analyze the design experiments introduced in the following chapter.

Conceptual frameworks are driven by theory, whereas technical frameworks are driven by technological appropriations. The main ideas focus on the notion of *Variable Property Design* a process which promotes the distribution of material properties as it is directly informed by the environment. *Digital anisotropy*, in its various classes, has been presented as a mechanism by which to achieve physical distribution in the digital realm. In order to implement such force-driven shaping or distribution of material, a material unit must be defined that incorporates both physical properties and environmental constraints. Fibers and grains were introduced as classes of material organization. Following this, several processes have been presented, each characterized by its scale and contribution to the *structuring* of form, that promote Material-based Design Computation from a modeling perspective (*Tiling Behavior*), an analysis perspective (*Finite Synthesis Method*) and a fabrication technology perspective (*Variable Property Fabrication*). Finally, an inclusive computational environment has been developed which supports the integration of these three platforms into one in which a modeling, analysis and fabrication milieu has been invented that operates in processes not unlike nature's way. This computational environment points towards the calibration of material and environment units as homologous in terms of their formal representation. In this way (and, assuming that we are currently investigating only additive fabrication methods) physical material fabrication units are identical to analysis mesh elements which are, in turn, indistinguishable from cellular, or tessellated modeling units. These units are termed *Eco-Pixels* and they are unique in that they combine geometrical, performative (structural or environmental) and manufacturing data within one singular unit. Units are assembled into a tissue-like form and further into solids via the same mechanisms, further discussed and experimentally developed in the following chapter. We have focused on mainly four classes of *eco- material-pixels* (maxels) as we address different types of data and combinations of such data. They include Pressure Maxels (relating or of relation to structural parameters), *Thermal Maxels* (relating or of relation to environmental parameters), *Light Maxels* (relating or of relation to visual parameters) and *Comfort Maxels* (relating or of relation to physiological parameters). The following chapter in which the experiments are described is structured according to the organization of theoretical and technical concepts offered by the methodological frameworks.

Variable Property Design of materials with heterogeneous properties across a wide array of scales and applications holds a profound place in the future of design and engineering. The ability to synthetically engineer and fabricate such materials using VPD strategies appears to be incredibly promising as it increases the product's structural and environmental performance, enhances material efficiency, promotes material economy and optimizes material distribution. Among other contributions, *Material-based Design Computation* promotes a design approach through digital fabrication of heterogeneous materials customized to fit their structural and environmental functions.

To offer a more theoretical, perhaps futuristic, summary, assuming that the environment of an artifact can be perfectly mapped and defined with sufficient material information, then the environmental response of the artifact could be computed with arbitrary accuracy. If a metric for the quality of a particular response is defined, and the set of all possible designs and material choices could be enumerated, then it is possible to select, or better yet, *generate* an optimal design. If this is the case, then the environment and the response metric would uniquely determine the optimal design; because the design is computed, so would be the means to create the artifact. The practice of architecture is at last reawakening to its new role as (a) *second nature*.

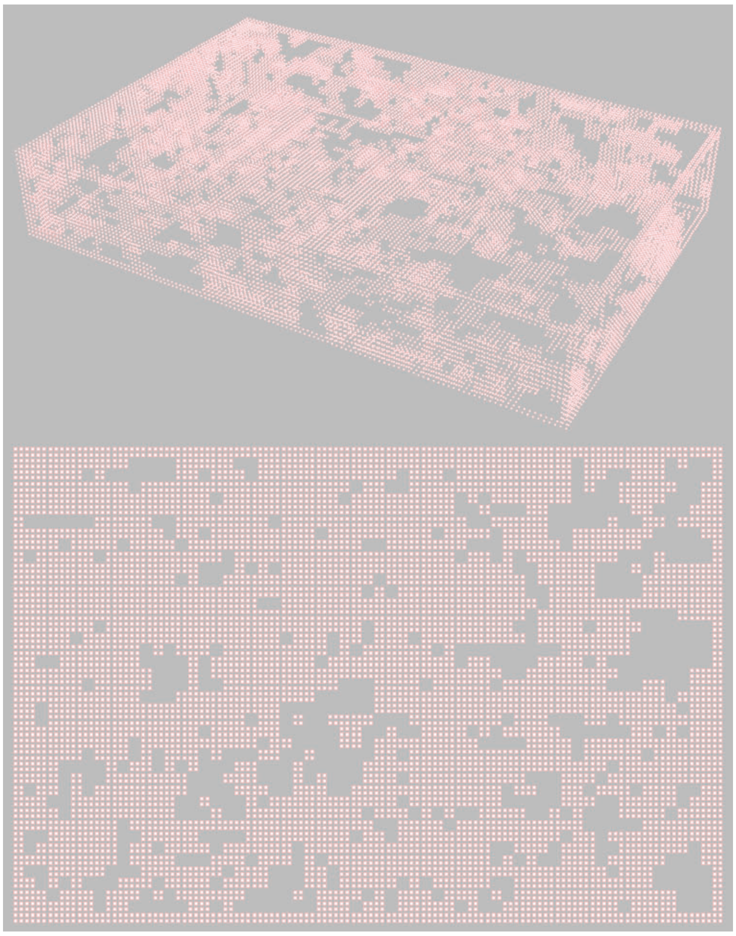

Figure 6.1: Distribution-driven digital anisotropy considers the allocation of pixels as analogous to that of homogeneous physical matter. In this case, every pixel contains equal properties (represented by the color red), however, the heterogeneous organization of pixel-groups on a larger scale, defines its overall performance, depending on the property at hand. In this case, the cube is heterogeneously structured due to the non-homogeneous distribution of “pixel units”.

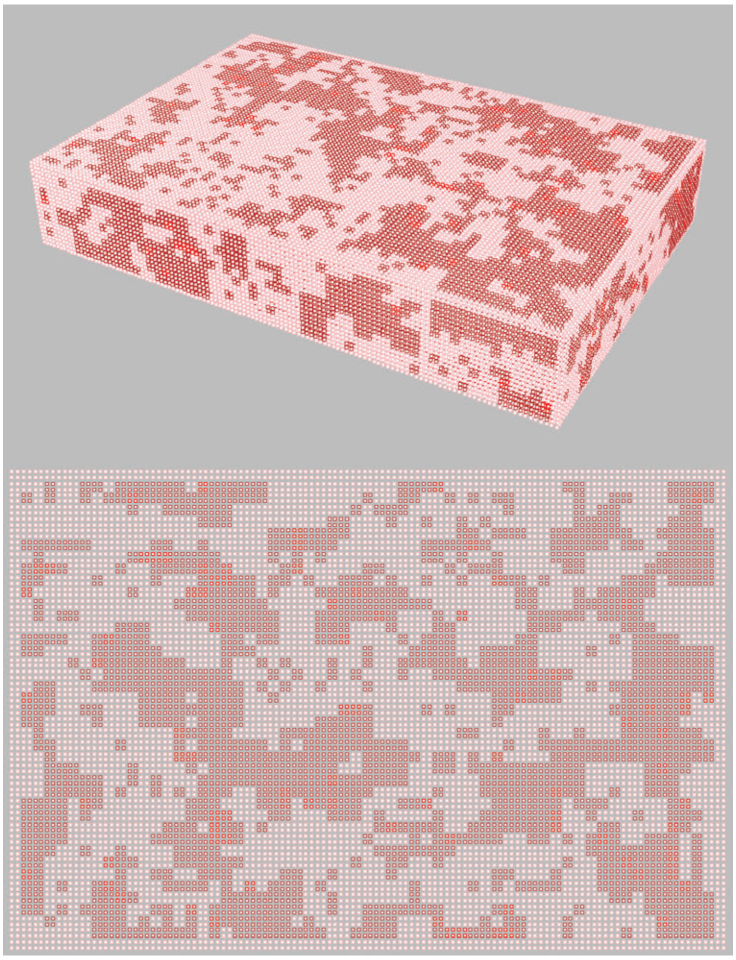

Figure 6.2: Property-driven digital anisotropy considers the allocation of pixels as analogous to that of heterogeneous physical matter. In this case, every pixel contains specific properties represented by different colors. For example, darker colors may represent stiff opaque units, while lighter colors may represent transparent soft units, corresponding to a particular loading scenario coupled with a desired visual spatial performance.

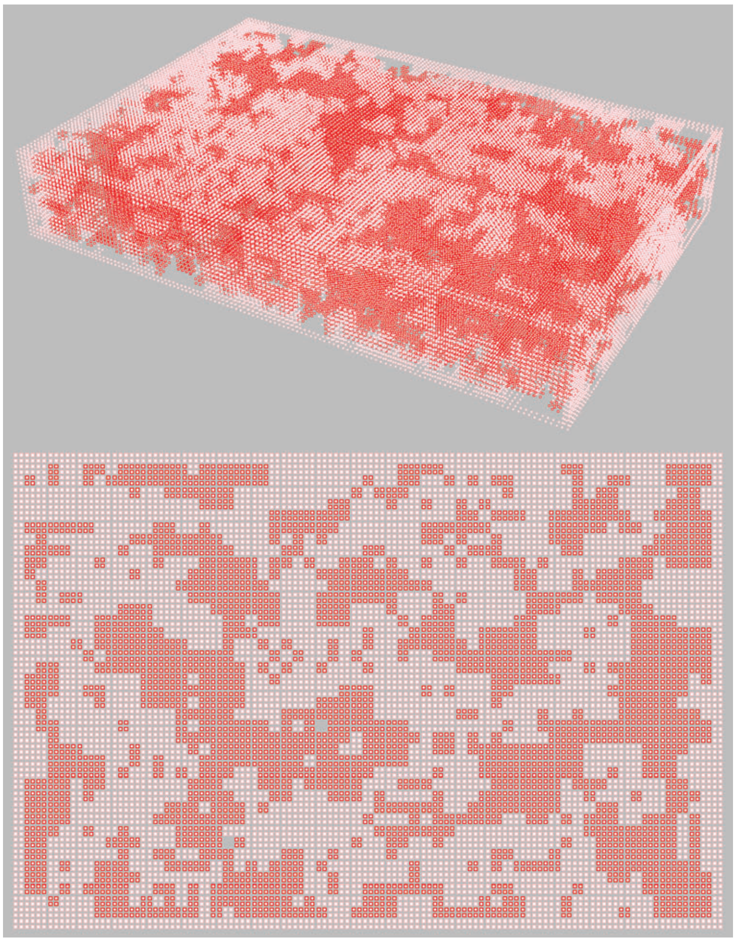

Figure 6.3: Property-distribution driven digital anisotropy illustrates a composite scenario made up of the two previous examples. In this case, empty spaces within the cube may be defined by distribution anisotropy, while property-variation represented by color may be defined by property distribution.

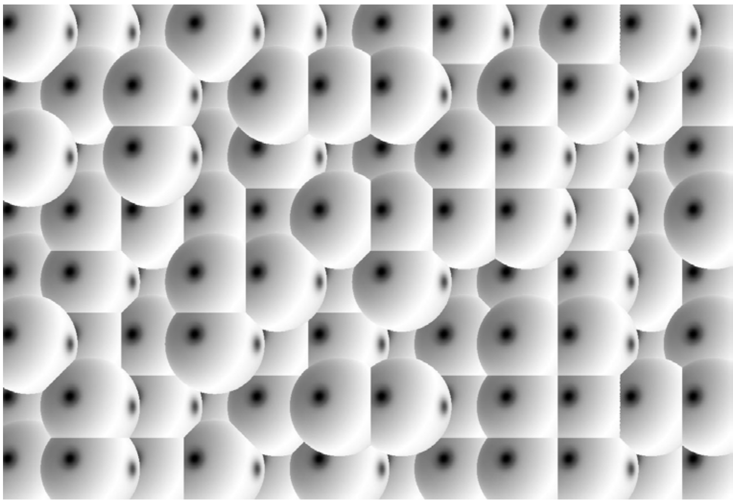

Figure 6.4: “Grains” are defined as symmetrical isotropic cells. In this image, all “material units” are defined as spheres of equal volume contributing to the overall isotropic nature of each unit. Anisotropic behavior is defined by the heterogeneous distribution of spherical units.

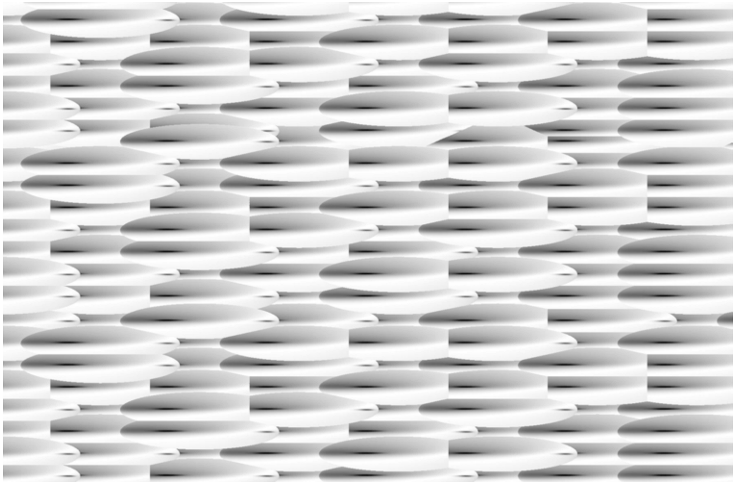

Figure 6.5: “Fibers” are defined as anisotropic cells. In this image, all “material units” are defined as ellipses defining the overall trajectory and orientation of the global tissue-like structure. Anisotropic behavior in this case is defined by both the orientation of an individual “material unit” as well as the overall organization of all units.

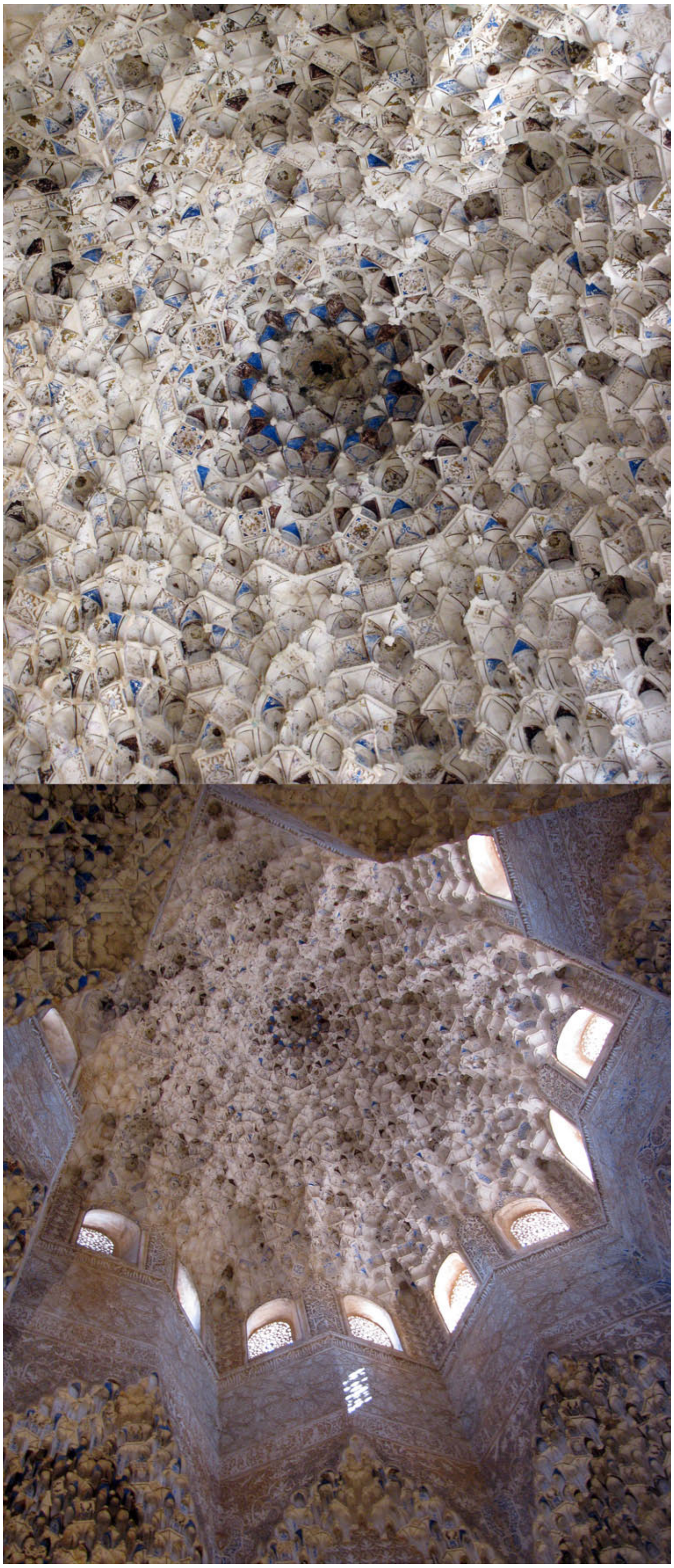

Figure 6.6: Tilings with translational symmetry in the Alhambra palace in Granada, Spain. Photographs by author

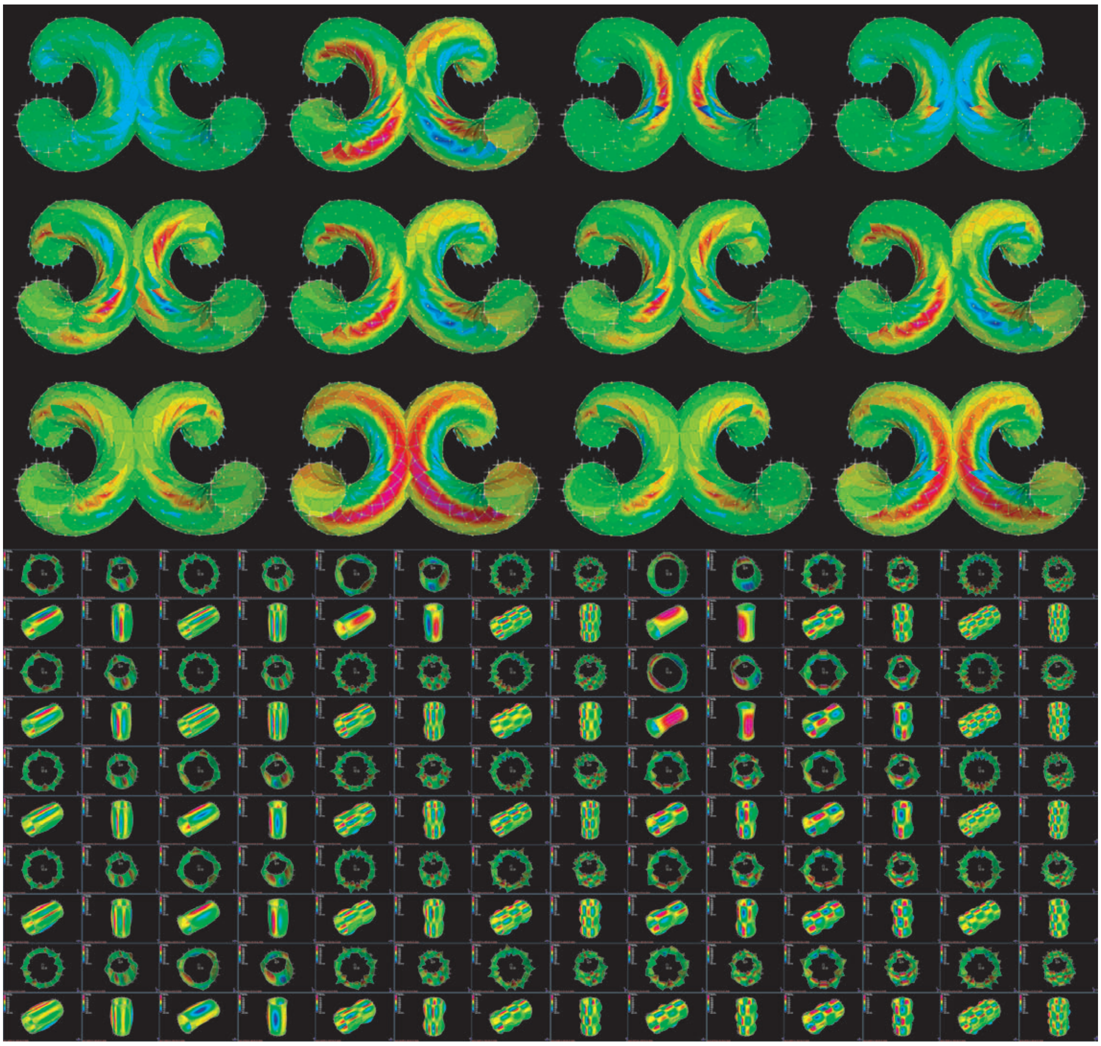

Figure 6.7: Finite-element analysis performed on a helicoids (top) and cylindrical surfaces (bottom) resulting in surface tessellation patterns as a function of load magnitude and direction. A triangulated mesh is assumed throughout the model whereby each individual mesh element is discretely loaded. The top section illustrates the application of torsional load on two helical structures; the bottom section illustrates the application of vertical load on a cylindrical surface. Image produced by the author using the Strand-7 software. From *Perofrmative Morphologies* by the author, Architectural Association, 2005.

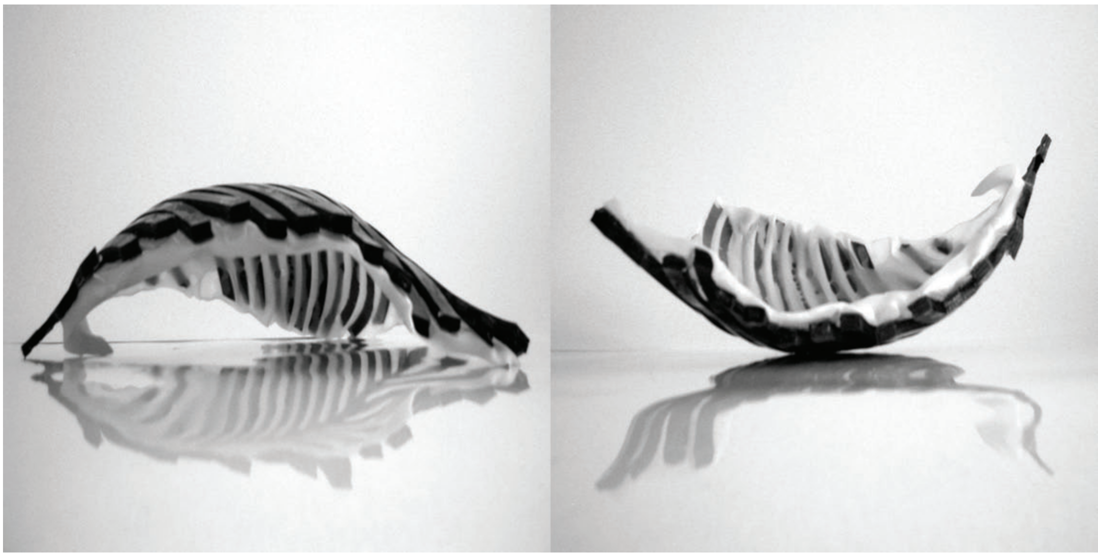

Figure 6.8: *Shrink-warp*, 2007 (Oxman and Rosenberg 2007). Experimentation into digital from-finding computation supported by FEM and particle analysis. The 3-D curvature of the surface presented is induced by the application of resin in 2-D followed by stress release. The initial form is 2-dimentiional (elastic membrane + resin impregnation) and curves in 3 dimensions upon the relase of the stretch. Residual energy is released to generate the 3-D form. This process is then computed for various types of 2-D resin impregnations resulting in various 3-D curvature types.

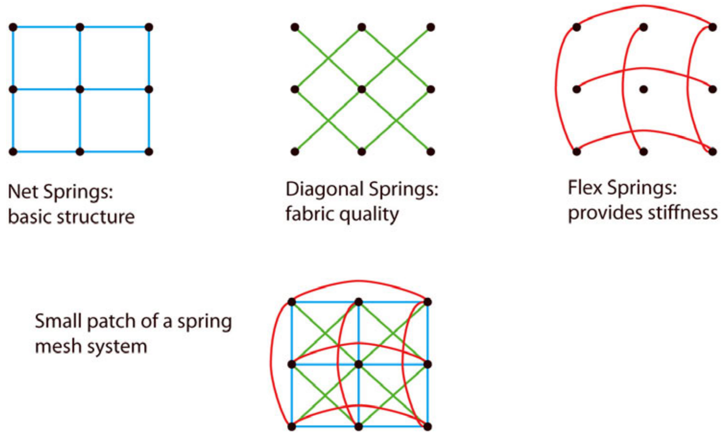

Figure 6.9: *Shrink-warp*, 2007, *Material-data fields* (Oxman and Rosenberg 2007). Composite image illustrating the stretch fabric simulation logic. Three underlying computational structures were modeled as the initial mesh: (a) net springs provide for the basic structure (stretch); (b) diagonal springs mimic fabric behavior (shear); (c) flex springs provide for additional stiffness (bend).

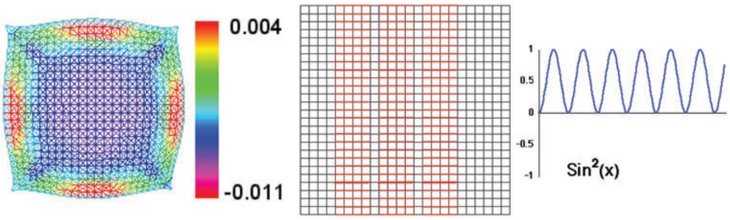

Figure 6.10: *Shrink-warp*, 2007, Material-data fields (Oxman and Rosenberg 2007). Left: Gaussian curvature representation indicating areas of positive and negative curvature in the mesh. Right: Increasing the length of red regions driven by a $\sin^2 x$ curve introduces intrinsic deformation to the mesh.

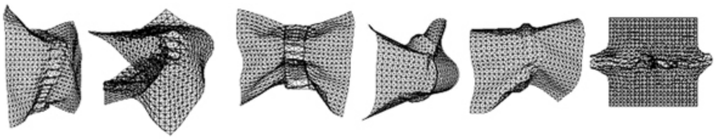

Figure 6.11: *Shrink-warp*, 2007, Material-data fields (Oxman and Rosenberg 2007). Digital simulation of resin impregnation which is applied perpendicular (left) and parallel (right) to stretch. Further reading (Oxman and Rosenberg 2007)

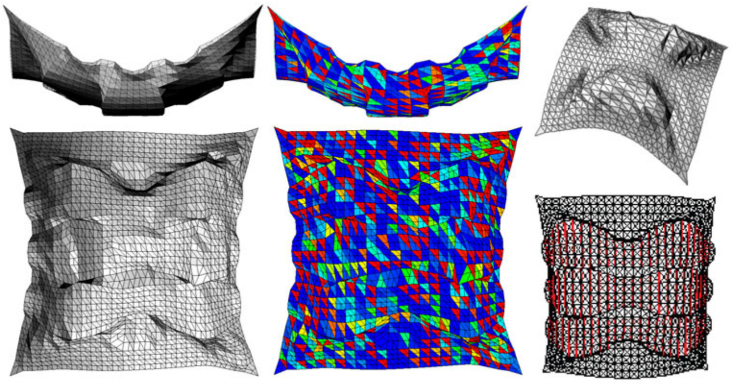

Figure 6.12: *Shrink-warp*, 2007, Material-data fields (Oxman and Rosenberg 2007). Digital simulation of intrinsic forces in mesh. Further reading (Oxman and Rosenberg 2007)

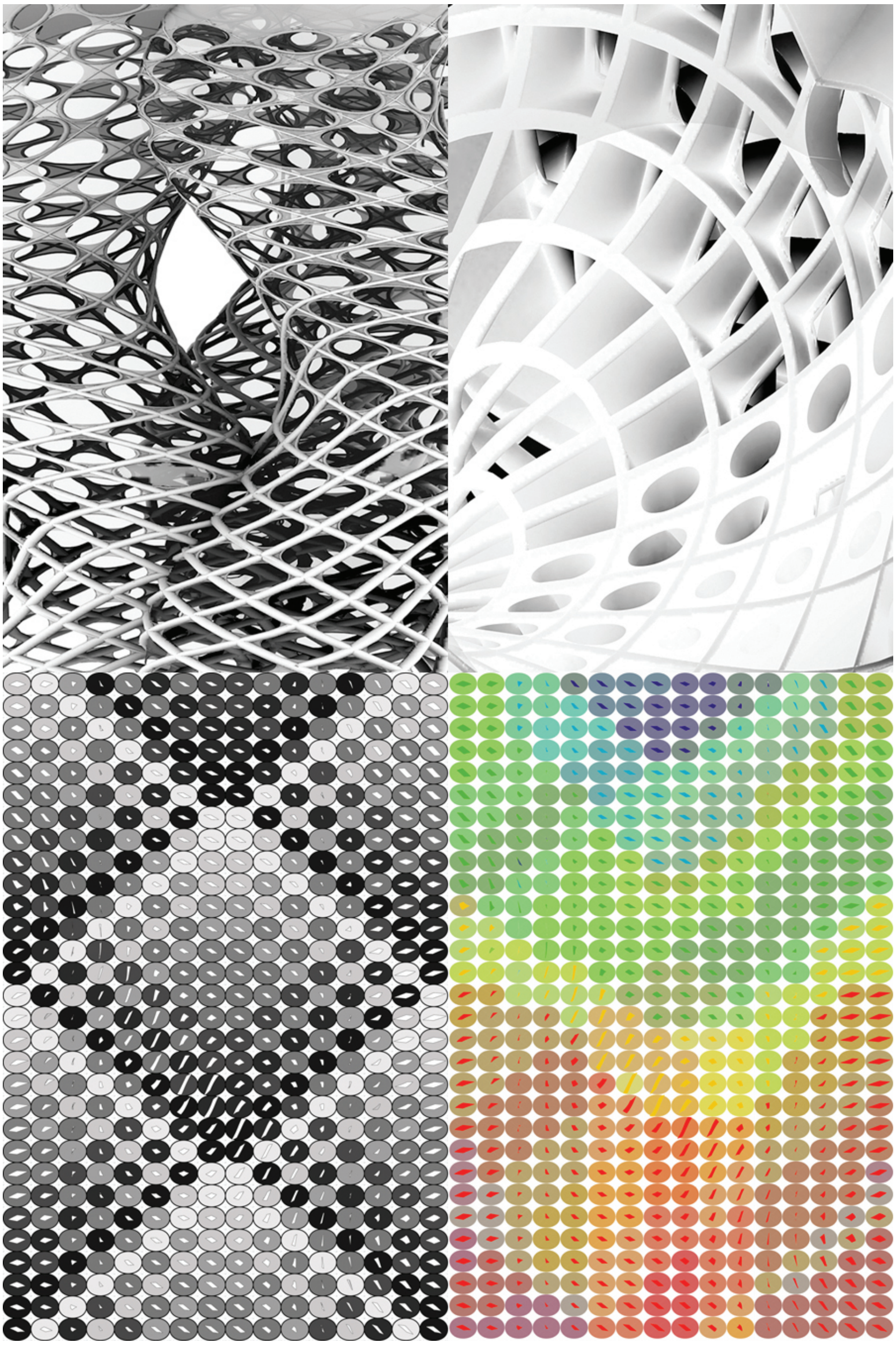

Figure 6.13: *Tiling behavior* promotes the integration between geometrical tessellation processes and material assignment. Rather than treating surface tessellation merely as a post-rationalization algorithm for the generation of developable surfaces (i.e. tiles that are constructible), *tiling behavior* calls for the inclusion of material properties in the tessellation process. The top images illustrate a tower design, the tiling of which is informed by self-loading and wind-loading profile. The bottom images include information regarding the size, and desired property values (thick/thin or opaque/transparent) as informed by site-specific performance. From *Performative Morphologies* by author Architectural Association, 2005.

Figure 6.14: The Mercedes-Benz bionic car was developed as a *concept car* designed as a super lightweight structure, aerodynamic, safe, spacious and environmentally compatible. A soft-kill optimization algorithm was used that approximates the minimum material needed for structural performance at any given region. This process is very similar to the one depicted in the 6 step FEA method above. Source: *http://blog.bcarc.com/tag/biomimicry/*

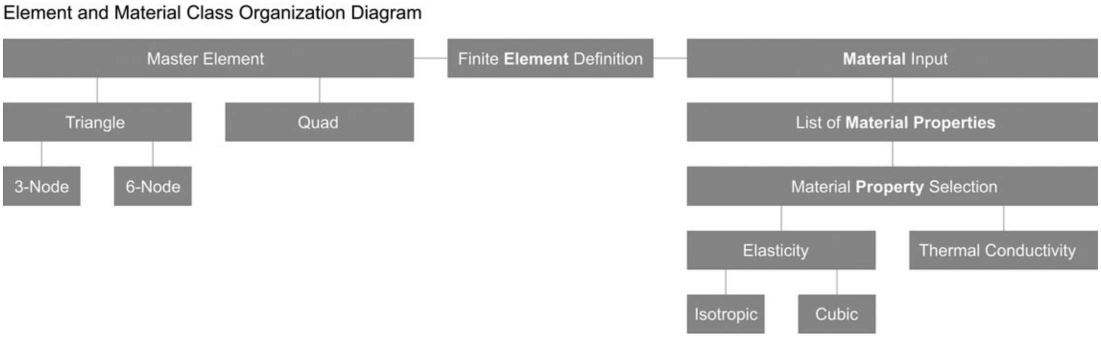

Figure 6.15: Element and material class organization diagram for OOF2. The diagram demonstrates the interrelation between analytic and synthetic computations as the program converts a micrograph into a finite element mesh with constitutive properties specified by the user.

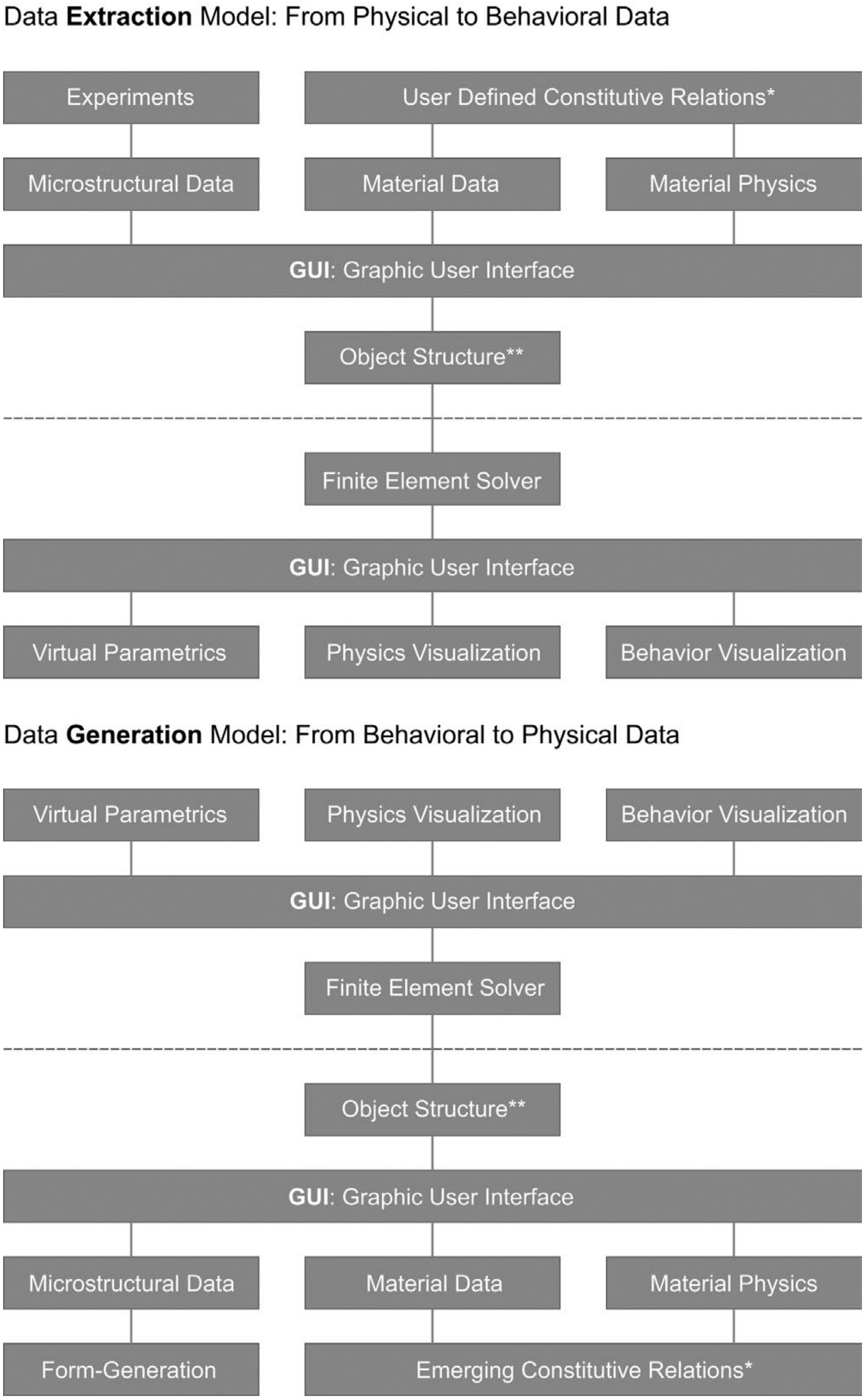

Figure 6.16: The concept of finite-element synthesis was developed to allow for the integration of analysis and synthesis in processes of form-generation. The OOF model is conceptually inverted bottom-up to generate the form of a synthetic tissue based on physical (material) and behavioral (environmental) data.

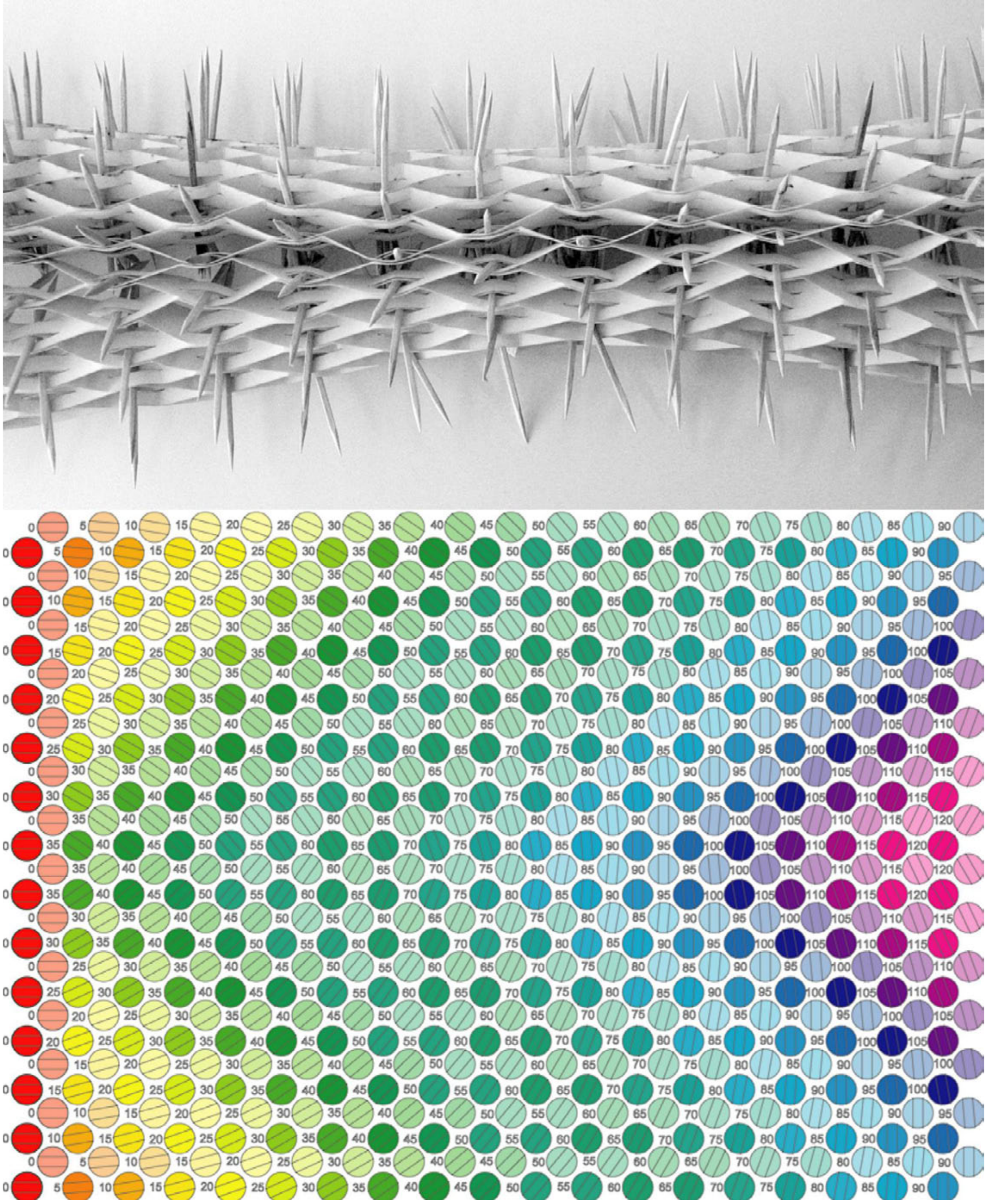

Figure 6.17: The concept of variable-property fabrication (VPF) entails that each fabrication “unit” as small as material grain or as large as a structural component, has its own set of properties that define its local behavior. This image, from the *Rapid Craft* series (Schnitzer Exhibition, MIT, 2007) demonstrates the notion of VPF in a relatively large scale compared to units of functional-gradient materials. A 2-D paper model is assembled from strips with internal slots. The slot orientation is described in the bottom diagram and informs the 3-D surface orientation. The steeper the slot angle that connects between two neighboring stripes, the curvier the surface becomes.

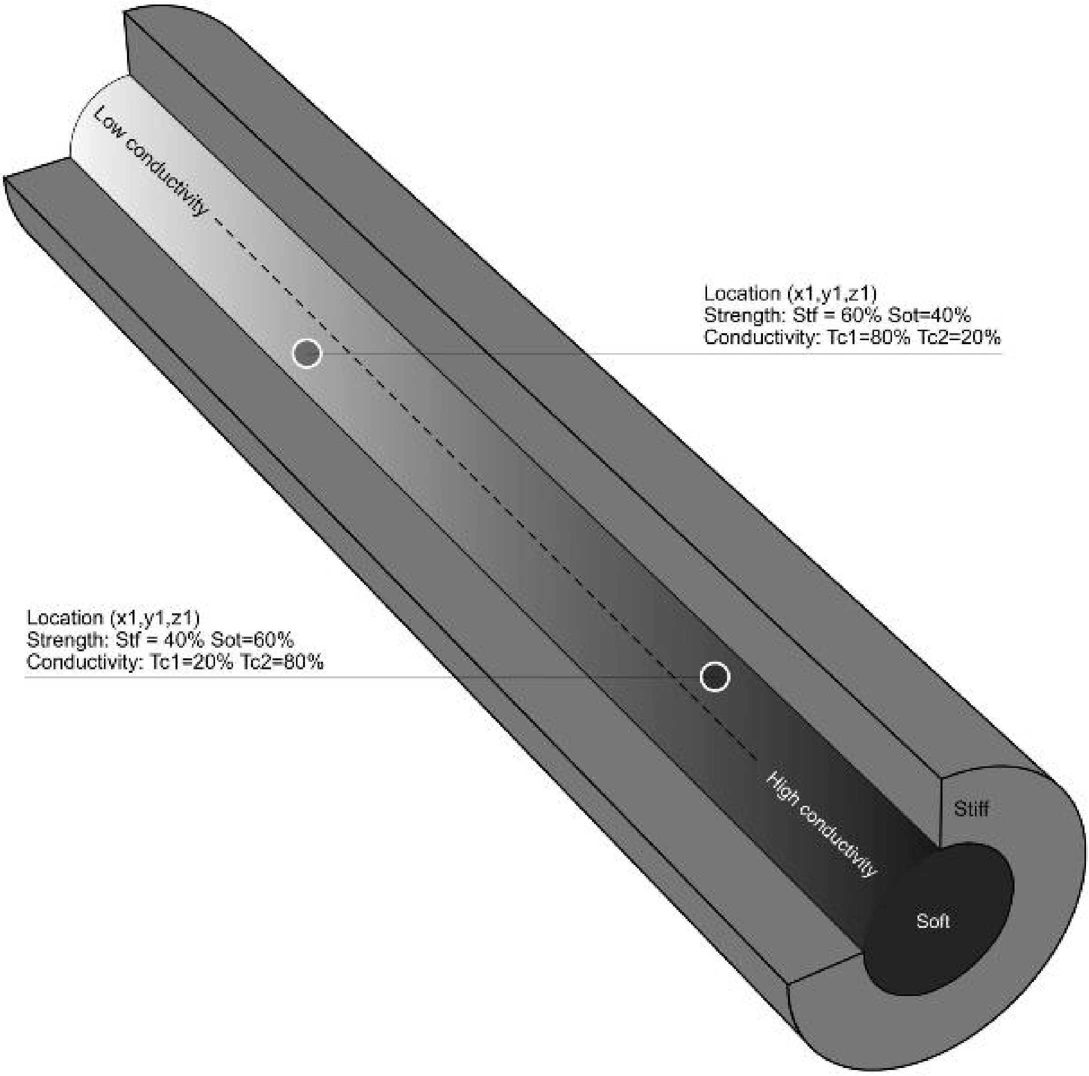

Figure 6.18: Schematic 3D model illustrating multiple variable property representation, based on (Hopkinson, Hague et al. 2006)

Figure 6.19: The concept of “pressure maxels” suggests that pressure and load levels could be accommodated for by distributing materials and modifying material properties respectively. Material is eliminated in regions where it is not loaded, and may be softer or transparent in regions where it is not required to fulfill structural support. The variation of material properties is represented by pixel color.

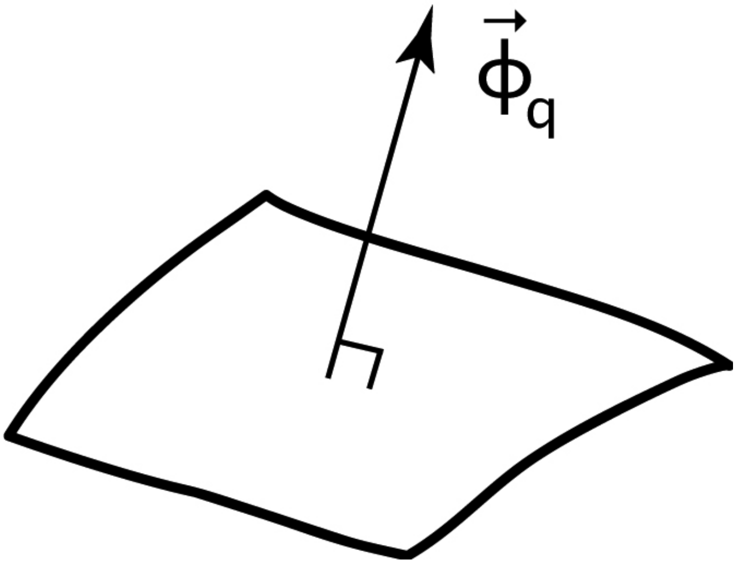

Figure 6.20: Heat flux ϕ_q through a surface.

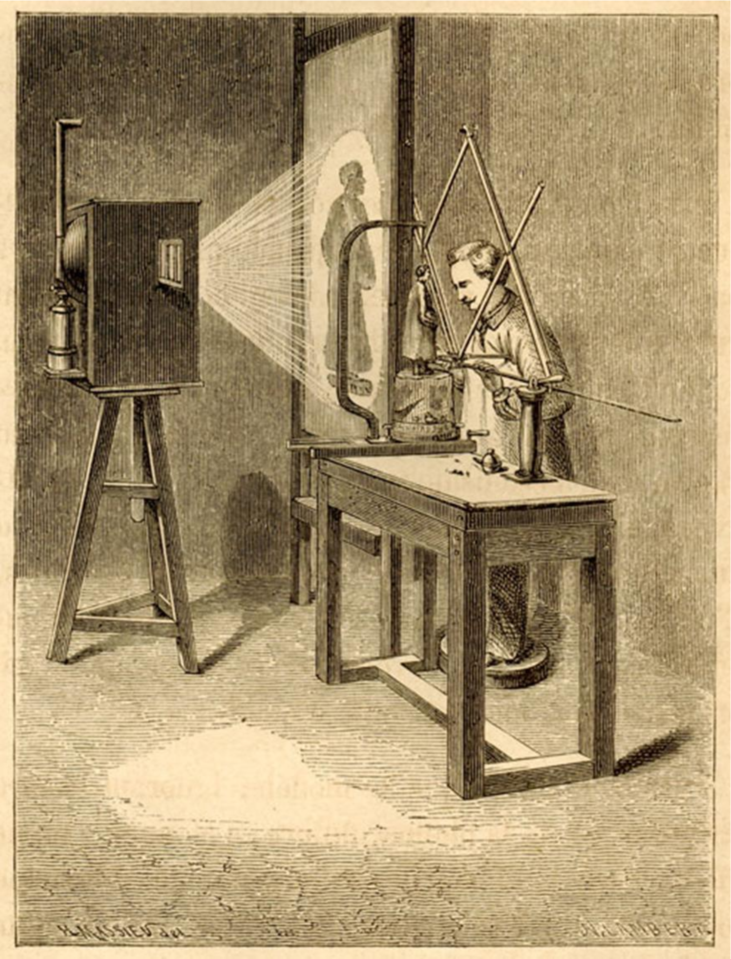

Figure 6.21: The concept of "light pixels" suggests that translucency ranges could be accommodated for in the design process by way of controlling material distribution. This idea is inspired by one of the first rapid prototyping technologies from the 1860's known as photo sculpting. The method was developed with the aim of regenerating accurate 3-D replicas of a given object by projecting multiple prints of different angles and carving them relative to the reference artifact. Photo sculpting employs 2-D projections to regenerate 3-D objects; "Material pixels" may potentially employ 2-D planes as they are informed by light to generate 3-D form.

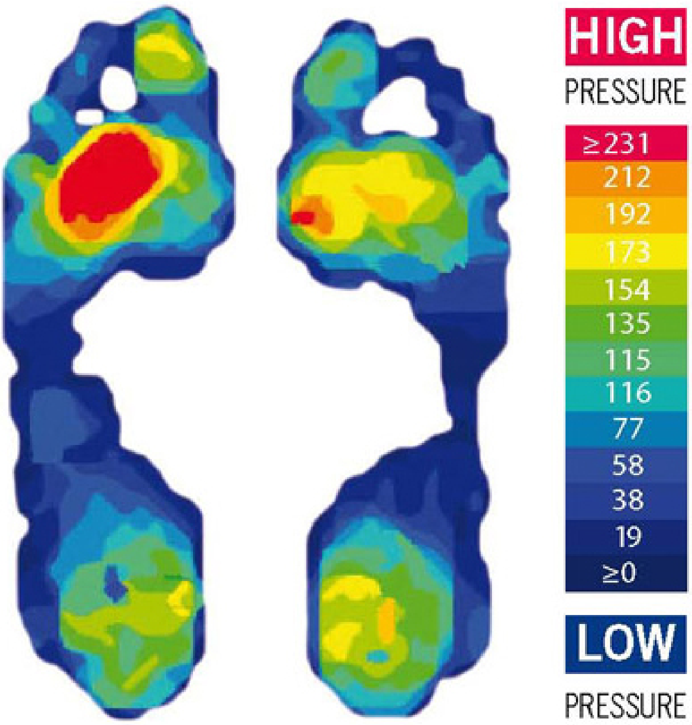

Figure 6.22: Pain is challenging to define and to quantify. Moreover, universal solutions are typically insufficient as each patient's profile is different. Pain can be individually mapped using ultrasound devices that may potentially inform the design of a restorative device such as an orthopedic shoe or a splint. The concept of "comfort maxels" suggests that material properties can be organized and distributed as a function of individual analysis. Source: $http://www.trelleborg.com/en/Applied-Technology/Energy-Control/Comfort-and-Impact/$

CHAPTER 7

NATURAL ARTIFICE

Experiments in Material-based Design Computation

> *"...I think I have found out (here's presumption!)*
> *the simple way by which species become*
> *exquisitely adapted to various ends."*
>
> **— Charles Darwin**[7.1]

7.1 Introduction: A Journey into Natural Design

7.1.1 *Carpal Skin*: A Pilot Project as a Design Scenario

Imagine this: a medical patient suffering from *carpal tunnel syndrome* requests aid to help maintain her life routines while minimizing muscular wrist pain during various activities. Typing, piano-playing and rock-climbing are but a few of the patient's desired activities which she is ardent to pursue. Her physiological demands are quite challenging to sustain under conditions of repetitive stress trauma.

A preliminary online search turns up the optimal solution: a medical *carpal tunnel* splint designed for various types of hand *orthosis*. The splint is known to effectively limit wrist flexion and extension during repetitive hand motion as it assists in helping heal the effects of *carpal tunnel syndrome*. It is typically made up of two hard and soft components, combined such that the removable aluminum splint can easily be inserted into a soft fabric glove. Available in three sizes, it is comprised of a dual layer of cotton stretch Lycra to increase comfort and improve circulation.

However, problems reported online generally relate to the glove's generic form and, as a result, its inability to match the patient's particular "pain profile". In addition, a different kind of glove, made of different types of materials, is required for the various activities. The ordinary glove therefore lacks multi-functionality as well as any potential for customization.

[7.1] Letter to Sir Joseph Hooker (11 Jan 1844). In Charles Darwin and Francis Darwin (ed.), *Charles Darwin: His Life Told in an Autobiographical Chapter, and in a Selected Series of His Published Letters* (1892), 173-174.

Carpal Skin (Oxman, 2010, *Boston Museum of Science*) was designed to resolve and better assist the patient in *customizing* the glove to her wrist so as to fit the patient's anatomical and physiological needs across various types of activities (Figure 7.1).

Here is how *Carpal Skin* is made: bending sensors are attached to the patient's hands and wrists. Movement control is measured and evaluated according to the relative magnitude and duration of pain, qualified by the patient as an aching sensation measured in intervals between 1 and 10. Each interval is mapped to a material stiffness parameter ranging between very stiff and very soft. A software package averages the data such that stiff and soft materials are distributed in order to restrain particular movements executed during particular activities. Various degrees of stiffness are mapped to their respective various degrees of qualified pain levels. This information is then mapped on top of a 3D surface representation of the patient's hand and wrist previously 3D scanned into the computer.

The glove is finally 3D printed as one continuous object using a Variable Property 3D Printer (Oxman 2009) which modifies the glove's material properties as well as its thickness on the fly as it emits photopolymer material of varying elastic modulus.

Attached to the outer shell of the glove is a "breathable" foam liner wicking away moisture from the skin. The lightweight material offers the patient's wrist support while maintaining a high level of comfort. A thermoplastic outer shell can be heat-molded to fit the user's individual needs.

7.1.2 Why is *Carpal Skin* Unique?

Carpal Skin, which will later be described in further technical detail, is but a single case demonstrating a design process that is intrinsically coupled with the set of constraints and performances established as the drivers for its design. One may claim that this is true of any engineering problem. However, this process differs in several ways:

7.1.2.1 Form-finding

The texture and material distribution (both of which are informed by the required distribution of stiffness) of the glove are *not* determined a-priori, as they would have been, given a typical design process. It is rather the outcome of matching performance constraints to corresponding material properties.

7.1.2.2 Customizability

Given such a form-finding process, a highly customized product one unlike any other - is formed. In other words, Carpal Skin allows for the generation of a singular holistic process which can potentially be applied to different cases. For each patient, with his own special anatomical and physiological requirements, the process (and, as a result, the product itself) is customized.

7.1.2.3 Multi-functionality

The glove morphology is determined by negotiating several requirements such as the need for assigning stiff and soft regions in high proximity to correspond with movement control and comfort respectively[7.2].

[7.2] It is important to note that the mapping between pain and stiffness levels was qualified and reduced to several levels defined by the designer. This mapping process requires further mathematical reformulation.

7.1.2.4 Material Property Continuity (Continuity versus Componentizations)

Traditionally, design products are fabricated by assembling multiple parts with their discrete mechanical properties. In this case, an integrated continuous tissue-like morphology is developed and its properties differentiated. Material properties and behavior are directly associated with specific pathological and physiological conditions.

7.1.2.5 Process Integration

Contrary to the typical design process, where design representation from conception to fabrication is guided by stream-lining generative and analytical routines, we have proposed and demonstrated an integrated process where analysis procedures define a "material space" in which to generate the form and by which to map environmental requirements to physical properties. We begin by mapping performance criteria to material properties, which, in turn, directly inform the rate and volume of mixtures of materials as they are deposited to form the glove object surface.

7.2 Basic Assumptions of the Experiments

Carpal Skin is representative of the type of design objectives sought after in the context of Natural Design. Each experiment represents a different kind of investigation into both the theoretical and technical foundations of the thesis. A few significant issues must however be clarified, before describing the experiments and related findings.

7.2.1 Generation vs. Mutation

One of the most significant inquiries central to this thesis relates to the definitions and related processes for the origin of (artificial) form. What is the *origin of form*? How do we invent form? How do we generate it? On what basis do we begin?

In the research we have attempted to define a set of issues and questions developed in the fifth chapter, which were then coupled with methodologies and technologies devised to address those issues and research questions as developed in the previous chapter. Each of these issues, however (i.e. multi-functionality, process-integration, etc.), could be explored and tested in *different stages of the design process*. In other words, one can explore the extent to which the theoretical and technical foundations of Natural Design and Material-based Design Computation are applied to a form generation process beginning with no form and ending with full construction of the generated design. Conversely, one might also apply these ideas within an *intermediate* phase of an on-going design, after certain initial formal assumptions have been made. For example, the form of a chair might be "designed from scratch" including both overall shape and material both the result of mapping and negotiating between different criteria at different stages as directed by the designer. However, the overall form of that same chair may have well been pre-conceived applying other values, assumptions and processes, while other aspects such as *material* and *texture* may be designed subsequently by a completely different process[7.3].

In the context of this chapter, experiments are presented demonstrating both of these basic design processes. The first is total integrated design without prior ideation, the second, a form of design in which there is *a prior* condition related to overall form, or typology. In the experiments we have explored the potential of material guided form-generation processes in both of these conditions. At times, the experiments are set as complete cohesive explorations with no a priori formal ideation decisions such as that of

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[7.3] This is particularly true of design projects that begin with certain conditions given or requested by the client or the curator.

overall form in the design of a chair. In the first case, such experiments include only an initial mapping of relevant environmental conditions as well as functional requirements to be satisfied are defined as inputs of the design process. In certain of the experiments, these contextual/functional parameters are expanded by various options for the type of material properties and organization are experimented with due to their potential implications for the application of material-based design computation to performance conditions of sustainable design. In the second case, there already exists some high-level a priori design decision such as overall form. We may refer to the first case as *form generation* (morphogenesis); while the second case may be termed *form mutation*, or form refinement.[7.4]

In order to clarify such a distinction between processes that explore the generation of form and processes exploring the *mutation* of form, we have indicated for each experiment what assumptions were made. The overall objectives have been to test the theoretical assumptions and methodological/technological inventions of Material-based Design Computation in a range of these two generic conditions of design. In all experiments we have also given priority to the testing of Material-based Design Computation to function as a medium of Natural Design, that is, to produce design solutions with implicit ecological potential, e.g. multi-functional performance, gradated materiality, etc.

7.2.2 Static vs. Dynamic Objects

The experiments focus of processes of design and fabrication which are informed by structural and environmental performance parameters. Of great significance in considering the following experiments as validating the thesis' research questions and theoretical, methodological and technological inventions is the distinction between static and dynamic objects and processes. The research described in this thesis focuses on *performance-driven form-generation of static objects*. Real-time performance mappings (i.e. charting the solar trajectory, etc.) as might be applied to dynamic and responsive objects are not here considered (more about this later as we contemplate future directions).

Dynamics (material response in real time) is, in a sense, the natural relaxation of the boundaries of the scope that this research attempts cover. However, I consider the methods and technologies invented as having important relevance and implications for the development dynamic responsive design. It is certainly a technical step, but not at all a conceptual one, to imagine the dynamic local control which optimizes the designs demonstrated here being implemented as actuators in a physical artifact that is also dynamic. I will address this in my conclusions regarding the general implications and fields of influence of Material-based Design Computation.

7.2.3 Process vs. Product Experimentation

The experiments presented here may be classified into product and process-oriented experiments exploring issues, topics and questions from shared perspectives of design and production, and, indeed, from the perspective of potentially identifying them as mutually inclusive. Ultimately, as in nature, processes of design fabrication and manufacturing may potentially take place simultaneously with processes of form-generation. To again employ the case of the human bone: the bone's form is the result of dynamic analysis paralleled with integrated fabrication (or rather, formation) processes.

Despite this vision of *integrated form generation and formation/fabrication* and its significant potential implications for the future of design, most of the experiments relate to the research issues of Material-based Design Computation as a form generation medium. Further experiments relate to Material-based Design Computation as a medium that is integral with, and influential upon, enhanced attributes of

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[7.4] It is at times challenging to decipher between the two, as various manipulations of any existing form may result in its topological reformulation fabrication such as muti-functional performance. The focus within which each experiment has been undertaken (form-generation versus fabrication) made clear to the reader.

7.2.4 Engineering vs. Architectural Performance

The dichotomy between engineering and architectural performance is particularly relevant when considering the drivers of form. The two disciplines represent value systems which are at times conflicting; hence, some clarification regarding selection and definition of performance factors is required. From an engineering perspective, it is fundamental that a building remains stable. From an architectural perspective achieving optimal visual and thermal comfort may be equally important. Clearly, a hierarchy naturally emerges that defines the importance of loading requirements over, for instance, effects created when light hits the building's skin. It is to be noted, that for most experiments performance criteria including physical performance attributes, such as structural, thermal, and acoustic requirements have been the main bases of the research.

7.2.5 Computational Form-Finding vs. Computational Form-Making

Processes of *form-making* are diametrically opposed to processes of *form-finding*. As previously discussed and demonstrated in Chapter 4, the almost ubiquitous presence of computational tools in the design disciplines has cultivated and promoted a certain culture of making whereby all that is modeled, is buildable. That may be the case, but not without paying a serious price in material redundancy and waste.

Form-finding protocols seek instead to instigate design processes in a way as natural as can be relative to the design problem and the materials at hand. We have previously discussed to physical form-finding techniques promoted during the 1970's in Europe by Frei Otto and his research institute, the ILS. In the following experiments we present a similar approach in the the digital domain that may be considered, *computational form-finding*. This approach values material behavior and performance over geometric form generation. In those experiments in form-generation, form is generated in direct response to force. The main idea behind each of the experiments demonstrated below is to consider the integration between environmental performance requirements, material choice and the propagation of form as a by-product of this unification.

7.3 The Form of the Immaterial: Introduction to the Experiments

When contemplating the form of the environment, one's rationale rarely contemplates the immaterial. We tend to note what is physically laid before our eyes as we ponder its origin. Look around you and you will find that any natural or man-made object occupying your visual landscape is actually an uncanny amalgamation of forces, materials, and processes that culminate in the form of things soap bubbles, chairs, trees, shells, huts, cones, skyscrapers, lampshades and so on. No problem of form is as consequential to architecture and design as the one posed by translation from conception to production. In the course of finding form, many factors are at work negotiating the space of formation, as complex and compound as it may be. Granted, nature has for millennia devised her own computations for the generation of form, not the least of which is the marvel of the genetic code and its contribution to growth. What is the physical process by which form is generated? To examine this, we have by now understood nature's way and the many implications of design as the science of the artificial. How then can we achieve the science of the artificial computationally and in consideration of materiality? In such a universe of synthetic creation, under persistent threats of environmental implications, "finding form" merely for form's sake is simply not enough. In the experiments, computational form-finding methods have been developed that support the integration of material properties under environmental constraints. This potentially achieves a synthesis between the theory, methods and technologies of Material Computing and the inherent ecological values of natural design.

Each project is, in effect, an exploration into the nature of finding form within a given context process or product driven, as it corresponds to a plethora of conditions and restraints defined by the designer and her vision. These explorations are consistent with the ambition to computationally form-find the shape of a product, a building element, or a more abstract object through the various methods by which it has come into the world is of relevance to our contemporary discourse.

As we examine the form of load, heat, light, comfort, and pain to name those parametric pixilated environments which I have classified in the previous chapter we discover the richness and complexity of conditions achievable by our tools; we arrive, once again to a novel kind of practice where process-formation is as equally, or more, significant than the formation of products or buildings (Figure 7.2).

The designer frequently exists in conditions guided by processes of conflicting nature: a surface must be composed of a structurally robust, yet transparent, material, or a chair that requires the negotiation between softness and rigidity, etc. The Modernist tradition, as we have seen, has handled such functional negotiations by discretely assigning materials and building systems to pre-determined functions. Structural components and functional partitioning remain to this day as symptomatic of modern design. The following experiments aim at introducing a shift in discourse and method from mono-functional design promoting homogeneous material distributions, to multi-functional and highly customizable products supported by integrated procedural routines.

The experiments are classified according to the system of classification offered in the previous chapter. Each experiment is a specifically designed study of the effects of form-generation as the result of a cluster of diverse environmental factors as the design drivers in Material-based Design Computational form-finding.

7.4 Experiments in Material-based Design Computation

The following section provides an overview of the experiments that were conducted in the development and testing of the models, methods and technologies of Material-based Design Computation. The purpose was to test, evaluate and further refine these developments. The experiments are organized according to the physical condition factors which were employed as input in order to generate material form as a function of physical input. In the following section further detailed descriptions of selected experiments is provided.

The majority of these experiments may be considered process oriented. Process-oriented experiments are aimed at testing the models, methods and techniques that have been developed for supporting computational form generation routines. The process by which the design has emerged is the most significant aspect of this group of experiments. Each such process holds some implications for the family of particular parametric constraints and their association with material properties in the derivation of form.

7.4.1 The Form of Load: Load Generated Material Systems

7.4.1.1 Vision: Artificial Bone

Imagine an aquarium-like container filled with calcified matter. Imagine that this sand-like material can simply remain or fade away from its container depending on the stress level introduced to it. Loads, in the form of local weights, or, more precisely, the boundary conditions defining the *perimeter* of this sand-tank as it rests on a flat plane, are set up in various locations and in a range of magnitudes and directions. The sandy grains then reorganize themselves as the matter precisely maps its distribution to the orientation and magnitude of the load. Unloaded regions wither away as a cellular structure emerges as an accurate representation of the loads that have brought it about.

There is much structural redundancy in the construction industry. This is frequently attributed to local building codes. However, in many cases such redundancy is merely the result of an architectural expression dominating the logic of the engineer. The structural engineer is generally guided by the spirit of material minimalism to guarantee that material waste is avoided and efficiency is maximized. Can such force-driven form-generation processes become computationally supported not as post-rationalization mechanisms implemented via analysis and simulation, but rather, can they contribute directly to the emergence of form, not unlike our vision for the formation of artificial bone?

7.4.1.2 Load Generating Material Systems: Monocoque

Museum of Modern Art, Permanent Collection, 2008

The experiment was designed as a process supporting structural shell generation via computational form-finding. It is important to note that in this case, unlike other experiments presented here, the process of formal generation was applied atop an existing shell structure as an a priori input in the design process such that the form-generation process was limited to the texture generation and any geometrical and topological manipulations that followed. This condition is very similar in nature to the tessellation algorithms discussed in the previous chapter.

Monocoque (*French* for “single shell”) stands for a construction technique that supports structural load using an object’s external skin; it represents an alternative approach to the fabrication of a skin-like membrane. Traditionally, building skins are comprised of internal structural frameworks and non-bearing external elements. In this class of structures, the internal and external skins are *integrated* into one continuous surface. The density of this “structural skin” corresponds to a given set of hypothetical multi-scalar loading conditions. The entire weight of *Monocoque* is supported by its skin, with thicker areas reminiscent of natural vascular structures bearing most of the load, while no internal supports are required.

As a result, this process promotes the heterogeneity and strategic distribution of material properties. The process of such *material-based tessellation* is governed here by the computation of a Voronoi pattern, the density of which can potentially correspond to multiple loading conditions of various directions and magnitudes. The distribution of shear-stress lines and surface pressure is embodied in the allocation and relative thickness of the vein-like elements built into the skin.

The physical prototype represents a strategy for the design and fabrication of single shell structures. The component was 3-D printed using the *Polyjet Matrix Technology* that simultaneously assigns a range of structural properties to multiple parts of an object and “prints” it out of multiple materials within a single build. This technology creates composite materials that physically represent preset combinations of mechanical properties (Figures 7.3-7.7).

7.4.1.3 Load Generating Material Systems: Cartesian Wax

Museum of Modern Art, Permanent Collection, 2008

In this exploration, made of hard and soft, opaque and translucent, wax composites, I have attempted to experiment with material distribution within a material skin. Imagine for a moment, that instead of assigning hard-opaque and brittle-transparent materials for their respective functions (i.e. concrete and steel to support the structural elements of a building-skin, and glass to provide for the environmental elements of the building-skin allowing visual and thermal flow), it might be possible to vary their properties smoothly, and depending on the exact function required for a precise location within the building. In this way, the designer could assume maximal control over the distribution of properties relative to their anticipated functions. One can only contemplate the extent to which material waste due to structural redundancy and modularity and componentizing could be minimized.

Cartesian Wax experimented with the possibility of applying such method. Here, a continuous tiling system was differentiated across its entire surface area to accommodate for a range of potential physical conditions such as light transmission, heat flux, and structural support. The surface is thickened locally where it is structurally required to support itself, and modulates its transparency according to the light conditions required, or desired. 20 tiles were assembled as a continuum comprised of multiple resin types from rigid to flexible, from opaque, through translucent to transparent. Each tile is designed as a structural composite representing the local performance criteria as manifested in the mixtures of liquid resin (Figures 7.8-7.10).

7.4.1.4 Load Generating Material Systems: Stalasso

Boston Museum of Science, *At the Frontier of Ecological Design* Exhibition, 2010

Many natural structures are formed by processes of mineralization (i.e. bones and shells). Such processes result in the introduction of metals such as gold into a rock. The resulting new composition modifies the rock's structural traits by making it stiffer and stronger. Can we mimic these mineralization processes in design?

Structural composites are mixtures of materials strategically deposited to account for the structure's required performance. Here this process has been redefined by forming a forest of columns the structure of which is defined by the ratio of stiff to soft materials. Each stalactite-like column is locally stiffened by an array of structural channels across its length.

Think of the flutes of the Classical Greek column; these channels celebrated the classical style by providing ornamentation. In this experiment we explored the gain in structural behavior by assigning different material properties to them (Figures 7.11, 7.12).

7.4.2 The Form of Heat: Heat Generated Material Systems

7.4.2.1 Vision: Construction Melanin

If buildings were to their sites what our skin color is to our environment, we could legitimately attempt making many claims regarding the state and progress of adaptable architecture. Skin color is an accepted typical indication of the geographical region where one's ancestors had originated (Figure 7.13). This is due to a class of chemical compounds found in plants, animals and some micro-organisms, in which melanin serves predominantly as a pigment. Skin pigmentation is directly determined by the amount of melanin present in the skin. Melanin's photochemical properties make it incredibly efficient in absorbing harmful UV-radiation and transforming it into harmless amounts of heat through a process termed internal conversion. Regional solar conditions have therefore a direct effect on skin pigmentation. In areas in which inhabitants have been exposed to high levels of direct sunlight, skin pigmentation becomes increasingly darker to effectively protect itself from the sun. In areas where less sunlight is experienced, the skin embodies the ability to adapt rapidly when exposed to the sun.

Melanin, as an indicator of the environmental conditions governing the inhabitant's "site", and can be considered in this context a factor, or variable, indicative of environmental customization, in this case, of the human skin color. When extended to design, a design's feature, as expressed not by skin color, but rather by material properties and organization, may be locally informed by its environment. In other words, the form, texture and material composition of a building skin can share the same topological features when designed for a hot climate site and a cold climate site, but their geometrical features may be considerably different. This condition has generally been referred to as "difference in degree" vs. "difference in kind".

In the following set of experiments we speculate regarding the possibility of generating a material architecture informed by local conditions. Mostly, we refer to various hypothesized thermal circumstances, and at times explore them as we negotiate between other constraints such as structural stability.

The experiments demonstrated in this section are unique in that they share common methods implemented for computational form-finding based on existing analytical platforms. In the previous chapter I have referred to such routines as belonging to the class of *Finite Synthesis Methods*, based on FE software. The general aim was to generate new forms based on forms found in nature coupled with hypothetical speculations regarding their anticipated "mutations" under different sets of conditions. Consider the melanin case, and think of each such hypothetical condition as theoretical environments in which a product or building type evolves. Based on the compound relation between a given, constant material organization (in our case we refer to tissues found in nature) and a variable environment, we generate alternative forms. These generation processes are based on the analysis and simulation of material properties and the predictions of how such properties may behave under given conditions (e.g. thermal flux).

7.4.2.2 Heat Generated Material Systems: Subterrain(s) & [X,Y,Z,S,S,T]

Museum of Modern Art, Permanent Collection, 2008 Museum of Science Boston, 2009

The physical features of tissues found in nature express the distribution and magnitude of the forces that have influenced their expression. These environmentally driven forces embody the complex relations between physical matter and its environment contributing to what may be perceived of as a multi-dimensional force field: the *immaterial* environment within, and by which, form emerges.

Subterrains are a series of experiments exploring the notion of material organization as it is informed by combinations of temperature and load conditions. The purpose of this experiment was to test the capabilities of analytical software to act as a potential synthetic environment for form-generation. Natural *micro*-structural 2-D tissues were visualized, analyzed and reconstructed as 3-D *macro*-scale prototypes by computing their hypothetical physical responses. However, rather than replicating the expressions of such responses in micro-scale, we examined their expressions in building scale, considering building materials and their properties. In other words, we consider artificial materials as input which corresponds to existing behavioral constraints.

An object-oriented finite element application was used[7.5] to predict and determine material behavior according to assigned properties and performances. Such criteria include stress, strain, heat flow, stored energy and deformation due to applied loads and temperature differences. Physical properties were imposed onto the image; a computational mesh is then created that includes image-property information; the computation then produces various data sets (i.e. heat flow, stored energy, and so on). The interaction between the directional morphology of the specimen and the tensor direction produces physical effects that emphasize the tissue's spatial texture in different ways. The resulting model is six dimensional and includes 2-D information (X, Y), out of plane deformation (Y), elastic stress (S), strain (S) and temperature flux (T). The tissue was then reconstructed using a CNC mill and metal/steel and wood composites. Anisotropic in nature, grain directionality and layering are informed by the analysis resulting

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[7.5] The OOF software was developed at MIT's Department of Material Science and Engineering in collaboration with NIST (National Institute of Standards and Technology), for analyzing the effects of microstructure on material properties.

in laminated structural composites the structure of which is informed by the hypothetical computational environment which has been set up (Figures 7.14-7.18).

Three natural tissues were examined, each defined by its properties, its environment and its scale.

7.4.2.3 Load Generating Material Systems: Monocoque

Boston Museum of Science, *At the Frontier of Ecological Design* Exhibition, 2010 Art and Design Biennale, Seville Granada, 2009

One of the unique articles resulting from this exploration was a graphic method representing exclusively physical material data. In this "intermediate abstraction", the original image is a two dimensional object reflected in the density and morphology of the computed mesh, the out-of-image deformation produces the relief represented by the density of the mesh, elastic stresses produce the line-thickness, flux is encoded with color data, and stored energy is represented by superimposed numbers (Figures 7.3-7.7).

This process was reapplied for three different meshes representing three different cases uniquely defined by their environmental templates and their scale. The images were assigned material properties according to their gray values: bright tones were associated with stiff elastic properties (by analogy, a stiff spring), high thermal conductivity (like a metal: cool to the touch on cold days, hot to the touch on hot days), and intermediate value of thermal expansion (the increase in volume of a material as its temperature rises, and the reason expandable joints are used in bridge structures). Dark tones were associated with compliant elastic materials (by analogy, spongy foam), low thermal conductivity with no thermal expansion. Middle tones received intermediate elasticity and thermal conductivity, but larger thermal expansion. The combined image and its properties are subjected to stretching and heat flow in the vertical and horizontal directions. The interaction between the directional morphology of the image and the stretch direction produce physical effects that emphasize image features in different ways.

The results were spatially analyzed and converted to a constructible data structure and graphical images using *Mathematica* software.

7.4.3 The Form of Light

7.4.3.1 Vision: Photon Fabrication

As creators of form, we may often discount the function of light as an equivalent contributor to the promotion of environmental performance as are other such immaterial factors such as load and heat. This condition has understandably emerged mostly due to the dichotomy that lies between engineering performance criteria on the one hand, and design, or architectural, performance on the other. However, when it comes to light, there are numerous cases where dark or un-shaded spaces are acceptable. Granted, there are few design parameters without which we cannot realize a design. However and as generally accepted, light carries immense environmental implications as well as serves as a means for the manipulation of spatial and visual perception.

With regards to its perceptual qualities: For Luis Kahn, as well as for many other prominent architects and designers, it was due to the presence of natural light that architecture could be brought to life. Light, for Kahn, was not only an instrument of our perception of things, but the very source of matter itself. It represented nature with all her laws by which all matter is bound. Kahn was especially fascinated with the cyclic nature of light and attributed both significant environmental and psychological significance to its daily and seasonal fluctuations.

But can light really *generate* form? There are several ways in which we may approach such inquiry. Firstly, one may simply distinguish between the integration of light within the process of form-generation or rather consider its effect post the production of some artifact. In this thesis, I am primarily concerned with the former, the generative form potential of light.

From a generation perspective, the attributes of light (i.e. illumination, refraction as well as intensity, duration and direction, etc.) may be included and hierarchically assigned by order of significance to the design. In the case of *Natural Computation*, as reviewed in Chapter 4, design attempts have been made to treat light as an attractor-like parameter controlling the distribution and organization of building components (in the design of a building skin for instance) in, or against, the direction of predominant light. Such is the case known as Computational *Phototropism*[7.6] , where the design product, or building, “grows” (or is kinetically designed to “move”) in response to light.

In this section we consider two works experimenting with these ideas in the development of tools supporting light-guided material architectures from different perspectives. The first, considers the potential for digital photo-tropisms to inform the “growth” process of a design, as expressed in the design for an inflatable furniture piece that expands its volume once pressure is applied; here the aim is to develop a packing algorithm. The second explores the potential for light-related surface analysis tools to serve as synthetic media in the generation of a doubly-curved surface, the curvature of which is guided by light with the aim of optimizing against shading criteria.

7.4.3.2 Light Generated Material Systems: *Tropisms*

Plants often grow in fashion to maximize the surface area of their branching geometries while maintaining structural support. Indeed, much of natural morphology may be simulated by tubular forms that do not simply expand or elongate but, rather, bifurcate, trifurcate and so on. *Tropisms* examined the potential of digital branching growth systems to be applied in the design of products and building elements made of smaller components. Each such geometrical component, defined here as a *Generative Component* was defined by its volume and direction relative to its neighboring components such that when combined these components form a recursive system. The use of branching growth systems in this case thus serves to explore certain organizational principles in natural systems and their potential implementation in a generative design environment.

This work assumes an inherent, and potentially instrumental relation between geometry and performance in devising advanced analytical functions (some of which already exist today as built-in user features) to support generative design explorations. In historic design conventions geometry has traditionally promoted *descriptive* manifestations of form. Beyond the realm of geometry, the concept of performance which may inform such manifestations also carries the important potential for design generation. This work explores the relation between geometry and performance from a computational-geometry perspective. It does so by revisiting certain analytical tools which are offered in most of today’s 3-D modelers and support the evaluation of the geometrical nature of any generated surface object, specifically curvature and draft angle analysis. It is demonstrated that these tools can be reconstructed with added functionality assigning 3-D geometrical features informed by structural and environmental performance respectively. In the examples illustrated surface thickness (as a function of structural performance) is assigned to curvature values, and transparency (as a function of light penetration performance) is assigned to light analysis values. In a broader scope this work promotes a methodology of performance-informed material form generation by means of computational geometry. In this case vector and tensor math was exploited to reconstruct existing analytical tools in order that they might be adapted to function as design generators.

[7.6] In Nature, Phototropism is defined as the plant’s movement in response to light. Growth hormones are produced which cause the stem cells on the side away from the light to multiply causing the stem to tilt. The leaves are then closer to the light source and aligned to intercept the most light.

Demonstrated below is an L-system, developed as a cellular automaton algorithm. The design takes as input variables describing the initial rules for 'growth' and 'decay' coupled with a set of local 'attractor' points orienting the organization by defining its direction of "growth" (Figure 7.19).

Most importantly, this exploration represents the generative potential of associative modeling environments. As multiple constraints are incorporated in the definition of a "component" (i.e. the component's variables), it is more than a geometrical static feature unconcerned with its neighboring components (as is defined by the laws of"growth") and its global environment (as is defined by "global variables"). However, in this specific case the definition of a component, and in the context of its potential to serve as a "material unit", this element includes only features that are geometrical in nature while lacking any physical material qualities in either the processes associated with its modeling or its fabrication.

7.4.3.3 Light Generated Material Systems: Raycounting

Museum of Modern Art, Permanent Collection, 2008

In 1860, the method of *photo-sculpting* developed with the aim of regenerating accurate 3-D replicas of any given object by projecting multiple prints of different angles, and carving them relative to the reference artifact. The method employs 2-D projections to regenerate 3-D objects.

Fascinated by photo-sculpting, which might well be considered the earliest rapid prototyping technology known, I began to imagine a conceptual space in which one could in fact sculpt and alter the form of matter by means of light. In practicality, this would mean surveying the shifts of the sun for a given site, and letting form emerge as a function of these conditions combined with the physical attributes of the predominant type of material involved, for example, in building.

Raycounting is a method for originating form by registering the intensity and orientation of light rays. 3-D surfaces of double curvature are the result of assigning light parameters to flat planes. The algorithm calculates the intensity, position and direction of one, or multiple, light sources placed in a given environment and assigns local curvature values to each point in space corresponding to the reference plane and the light dimension. The models explore the relation between geometry and light performance from a computational-geometry perspective. Light performance analysis tools are reconstructed programmatically to allow for morphological synthesis based on intensity, frequency and polarization of light parameters as defined by the user (Figures 7.20-7.23).

7.5 Experiments in Material-based Design Computation: Case Studies in Experimental Design

How to define the form of something that is not merely objectively defined? What might be considered comfortable for one user, or patient, may result in discomfort or pain for another. This is true for most of the design products and buildings that we design. It is precisely this ability to consider and negotiate between as many constraints with as many variations as possible that make a design customizable to the user. As we have previously determined, the two significant characteristics of natural design include customizability and multi-functionality.

Two additional experiments are presented below as *case studies in experimental design*. That is, they are generally more complex than the previous experiments in, for example, dealing with multiple performance factors. The first is a material informed process for the design of a chaise lounge, and the second is a wrist splint designed to treat carpal tunnel syndrome. These product-oriented case-study experiments acted as design test-bed environments in which to test some of the methods and tools developed in the previous section of this chapter. In each case, we begin with a particular function in mind that may potentially direct the types of performance investigated.

Given the product focus of the works below, the methods presented are more tightly linked to the fabrication process. Processes were created that incorporate the material properties data (from which the models were printed), in the form-generation process.

Unlike the previous experiments, the case studies demonstrated here present the designer with actual data and parameters, both material (desired physical behavior) and environmental, with which to design. Unique to these works is the requirement to support parametric negotiation between multiple constraints that do not typically line up. Such a multivariate performative condition is, of course, emblematic of design, in general.

7.5.1 The Form of Comfort

7.5.1.1 Vision: Chairs that Grow, Buildings that Breathe

Here we seek to explore the ideas of customizability and multi-functionality in the design of a furniture product. Of relevance to the consideration of these experiments as innovative, is the traditional modern method of furniture design in which the functional components of the furniture piece are discretely treated in terms of material choice and fabrication. As a result, assembly processes are required that join such functional components together. Contrary to this approach, and not without the aid of digital fabrication tools, we aimed to synthesize and unite between these functional components. In this way, a *singular system* of material is locally modified to accommodate for the multiple functions of the furniture piece: its structural stability and its comfort, as defined by the user. Here, once again, customization and multi-functionality play an important role in allowing the user to inform the process by which the furniture piece is generated and produced according to a highly-specific set of parameters. Furthermore, the mixtures between materials and their expression may be modified to accommodate for such needs. Mass production processes are here transformed into *mass-customization routines* that are also characterized by their capacity to *incorporate and negotiate between various parameters*.

7.5.1.2 Case Study in Environmentally Generated Material Systems: *Beast*

Art and Design Biennale, Seville Granada, 2009

Like the mythical creature of Mary Shelley, Beast is an organic entity created synthetically by the incorporation of physical parameters into digital form generation protocols. It has been referred to as a *Performative Chaise* (Oxman 2009).

A single continuous surface acting both as “structure” and as “skin” is locally modulated to satisfy load-bearing functions and comfort functions respectively. The chaise combines structural, environmental, and corporeal performance by adapting its thickness, pattern density, stiffness, and translucency to load, curvature, and skin-pressured areas in that order. Multiple algorithms were generated that correspond to these potentially conflicting variables, such that stability is mediated with a sense of comfort upon surface contact, and structural integrity - with visual and sensual experience. In this light, the chaise exemplifies the negotiation between engineering and experiential performance. It is a method as much as an object of pleasure; and the method promotes material and structural integrity mediated by the physical attributes of the act of sitting and lying down against a hard-soft surface (Figures 7.24, 7.25).

The traditional chaise is transformed here to promote lounging of a different kind. The cellular pattern applied to its entirety is designed to increase the ratio of surface area to volume in occupied areas where the body potentially rests. A *pressure map analysis* was conducted that matched the softness and hardness of the cells to cushion and support the sensitive and highly-pressured areas. *By analyzing anatomical structures that cause concentrated pressures, Beast became softer and flexible where pressure needs to be relieved.* The relative volume of each cellular cushion is locally informed by pressure data averaged with values representing structural support and flexibility. Its density is informed by global and local mean curvature values such that denser, smaller cells are organized in areas of steeper curvature whereas larger cells are found in areas of shallow curvature.

Beast is printed from 5 different materials varying in strength and elasticity. The surface patches are 3-D printed using a new multi-jet matrix technology which *simultaneously deposits materials of different properties corresponding to structural and skin-pressure mappings*. Stiffer materials are positioned in surface areas under compression and softer, more flexible materials are placed in surface areas under tension.

The chaise's continuous surface adapts to the person using it by matching body load to stiffness in the computational design processes applied before its actual fabrication. Its thickness, pattern density, stiffness, flexibility and translucency are modified according to load, curvature, and skin-pressured areas respectively. *Beast* can gauge the body shape and pressure areas of someone sitting or lying down on it by being softer and flexible where the body's pressure needs to be relieved. In its full size, *Beast* would be strong enough to support a person's weight yet be flexible enough to nestle a human body with comfort. The traditional chaise is transformed to promote lounging of a different kind (Figures 7.24-7.25).

7.5.2 The Form of Pain

Nature's engineering expertise is in matching material properties to environmental pressures, be it the formation of stiff materials for load bearing functions, or insulating materials as protection from extreme temperature gradients. The human skin is designed in the same fashion and acts simultaneously as a structural and an environmental filter and barrier.

In the very same way that load or temperature parameters can be mapped in order to design structures that are highly optimized for their function, physical pain can also be mapped in the design and production of medical assistive devices such as pain reducing splints. The experience of physical pain is, in particular, very personal; it is uniquely experienced and relatively differently treated for each individual. Pain is especially difficult to define or to map when compared with other quantifiable data, and it is one of those conditions that are poorly understood by conventional medical science.

The *form of pain* was an experimental case study, an attempt to consolidate structural support for the wrist with a feeling of comfort in a way uniquely defined by the patient.

7.5.2.1 Case Study in Environmentally Generated Material Systems: *Carpal Skin*

Boston Museum of Science, *At the Frontier of Ecological Design* Exhibition, 2010

Carpal Skin is a prototype for a protective glove treating carpal tunnel syndrome. The syndrome is a medical condition in which the median nerve is compressed at the wrist, leading to numbness, muscle atrophy, and weakness in the hand. Night time wrist splinting is the recommended treatment for most patients before going into carpal tunnel release surgery.

However, the main problem inherent in immobilized braces is that since they are mass-produced they often are too big, too small, or too constricting in terms of mobilization. In this case, as is the case with most muscular and nerve-related syndromes, mass customization (contrary to mass-production) is much preferred.

Carpal skin promotes a process by which to map the pain-profile of a particular patient its intensity and duration - and distribute hard and soft materials to fit the patient's anatomical and physiological requirements limiting movement in a customized fashion. The design generation process involves case-by-case pain registration and material property assignment. The 3-D scan of the patient's hand, including its pain registration, was mapped to a 2-D representation on which the distribution of stiff and soft materials was applied. This pain-map was then folded back to its 3-D form and 3-D printed using photopolymer composites.

In this particular prototype, stiff materials constrain the lateral bending motion at the wrist, and can be identified by the oblique trajectory of dark and stiff materials. Soft materials allow for ergonomic wrist support and comfort through movement. The local thickness changes correspond to strategic areas across the surface area of the wrist in cushioning and protecting the wrist from hard surfaces as well as allowing for a comfortable grip. These thickened bumps also increase flexibility and enhance circulation and relief pressure on the Median Nerve as it acts as a soft tissue reshaping mechanism. The custom-fit property distribution built into the glove allows for passive, but consistent, pulling and stretching simultaneously.

The form-generation process was inspired by animal coating patterns, with the exception that in place of colors we are controlling stiffness variation (Figures 7.26-7.28).

7.6 In-Depth Descriptions of the Experimental Research: the Case for Digital Matter

The following sections present in-depth descriptions of several of the experiments demonstrated above. The objective is to elucidate the scientific innovations that were applied in the sequence of experiments and experimental case studies. We focus on three cases of design generation informed by material properties in three distinct phases of the design process as described in the previous chapter: modeling, analysis and fabrication; the integration between those three processes will be later considered and demonstrated.

More specifically, *Beast* is presented as a case for *tiling behavior* (*variable property modeling*); *Ray-counting* and *Subterrain* are presented as cases for *finite element synthesis* (*variable property analysis*); The third framework, promoting *variable property fabrication* is considered in the following chapter as I introduce a novel technology supporting processes for variable-property 3-D printing.

7.6.1 Tiling Behavior: *Beast* as a Case Study of Variable Property Modeling

7.6.1.1 Overview

The research developed in the *Beast* case study demonstrates the method termed by the author *Tiling Behavior*. We present the design, analysis, and fabrication of the chaise lounge created by the incorporation of physical parameters into digital form-generation protocols. As previously described, the cellular pattern applied to its entirety is designed to increase the ratio of surface area to volume in areas optimized for a sense of comfort.

By analyzing anatomical structures that cause concentrated pressures, the chaise becomes softer and flexible where pressure needs to be relieved (Figure 7.29). The relative volume of each cellular cushion is locally informed by pressure data averaged with values that represent structural support and flexibility. Global and local mean curvature values inform its density, such that denser, smaller cells are organized in areas of steep curvature, whereas larger cells are found in areas of shallow curvature.

The chaise's natural relation of structural and sense datum is propagated in variable polymer composites, offering a wide range of physical properties. Through these algorithms, force conditions naturally propagate functionality. Stiffer materials are positioned in surface areas under compression, and softer, more flexible materials are placed in surface areas under tension (deflection zones). State-of-the-art technologies are applied here for the first time to cater for a large range of physical properties and behaviors. The surface patches are printed in 3-D, using a new multi-jet matrix technology which simultaneously deposits materials of different properties in correspondence to structural and skin-pressure mappings.

7.6.1.2 Voronoi Tessellation: Introduction

Tiling has been the subject of many innovative design projects in both academic and practical frameworks as it tightly relates to issues of fabrication and assembly of components. This work represents an attempt to rethink the role of tiling not only as formal maneuver for the rationalization of form-materialization but rather as a means to incorporate physical behavioral constraints early on in design. It does so by introducing a theoretical and technical approach termed *Tiling Behavior* which explores the integration of tessellation-generation along with a finite-element method approach to mechanical optimization termed *V-FEM*.

Voronoi tiling appears in disparate fields (Turk 1992). In this method, each tile is defined by the set of points that lie closest to each generated point (i.e., a hexagonal tiling derives from a hexagonal lattice of generating points). Many algorithms exist that produce simple versions of Voronoi tessellations from point clouds. Fast Voronoi algorithms have been developed with computational geometry techniques, but the computations are generally time-consuming.

A Voronoi tessellation is an example of a tiling generated by a random point process, in which the tiling develops algorithmically from points that appear on a surface by some random or informed process. In most cases, a homogeneous, uniform, random distribution (also called a Poisson process) generates the points. In such a uniform process, no position is favored over another: the Voronoi tiling segments the object at the length scale of the average distance between points. As a result, the tiling is homogeneous when averaged over larger distances. However, the Voronoi tessellation need not derive from such a uniform, random process.

Figures 7.30-7.37 demonstrate this idea in digital and physical media. The individual texture components (i.e., the SP line loops) derive from a Voronoi tessellation, but the point cloud density is a function of the object's local geometric curvature, demonstrating the concept of *curvature-based tessellation*. In this case, because local stiffness and tactility depend on local tile size, the object's geometry is intrinsically coupled to its material behavior, and as we shall explain, the converse is also true.

7.6.1.3 Voronoi Tessellation in Curved Surfaces

Because the Voronoi definition includes a distance function (i.e., "closeness" is a comparison of distances), the Voronoi construction depends on what is meant by distance. In the simple case of a Voronoi construction on a two-dimensional plane, the common choice is the Euclidean distance $\sqrt{(d = x^2 + y^2)}$, also called the L2-norm), but there are an infinite number of ways to define a distance. For the Euclidean distance, the Voronoi tiles are all polygons, for which each shared polygon edge is (a segment of) the perpendicular bisector of the ray that joins the generating point centers of the two tiles. The set of all rays connecting neighboring Voronoi centers is a skeletal structure that is "dual" to the Voronoi construction, and is called a Delaunay triangulation. However, the resulting polygonal structure is particular to the definition of distance.

On curved surfaces, such as the uniformly curved sphere, the definition of distance is generally complicated as the tile edges have out-of-surface curvature. For non-uniformly curved objects, the distance definition, and the algorithms to find their corresponding tessellations are complex and typically undeveloped. In these cases, the tile edges have non-uniform in-plane and out-of-plane curvatures.

There are methods to use a simpli?ed distance metric to produce a Voronoi tessellation on a curved surface. An example follows. A point cloud can be generated on the vertical projection of a surface, or a point cloud on a curved surface can be projected vertically to a plane. In the first case, a uniform cloud distribution on the plane produces a non-uniform point cloud on the surface; in the second case, a uniform point cloud on the surface produces a non-uniform cloud on the plane. In either case, the Euclidean algorithm can be used to produce a Voronoi tessellation on the projected plane, and that tessellation can be projected back onto the surface. Such methods are possible on limited surface types (i.e., graphs of the form $z = f(x, y)$. The surface's angle of inclination from the vertical produces the non-uniformity of the point cloud: points become arbitrarily close in regions where the surface approaches verticality.

The choice of algorithm may potentially have property-related consequences. Figure 7.37 illustrates the effects of this algorithm. A full implementation of an L2-norm on a U and V coordinate system embedded in a surface of the form $x(u, v), y(u, v), z(u, v)$ would be computationally prohibitive. An algorithm that approximates this norm produced the final object.

In Figure 7.37, note the density increase at regions of large squeezing. The illustrated solution: a uniform point cloud on the 3-D surface is a non-uniform cloud on the UV plane. The Voronoi construction in the UV plane produces odd-looking cells on the UV-plane, but uniform Voronoi on the 3-D surface.

7.6.1.4 V-FEM: Weighted Material Selection

During the initial stages of the design, the texture inherits the geometrical features of the design as defined by the user. Such geometrical features, in the case of the chaise, are customized to fit body curvature criteria. The initial distribution of cells corresponds to the type and degree of curvature: smaller, denser cells are located in regions of high curvature, and larger, sparser cells are located in regions of low curvature. Material properties correspond to both structural requirements (self-stability with no additional enforcement members) and environmental requirements (assigned to the body pressure mappings). For the structural performance, a stochastic computational process was developed, in which stiffer materials are assigned to vertical regions, which work for buckling, and softer materials are assigned to horizontal regions, which work for bending (Figure 7.32). The probability of a material being stiffer or smoother depends on the angle defining the level of horizontality in the chaise.

Regarding the environmental requirements, the degree of pressure mapped onto the chaise defines the relative height of each cell, such that softer and bigger silicon bumps are located in regions of higher pressure.

The chaise was fabricated using a multi-material 3-D printing technology. Thirty-two sections were assembled, each comprised of five material combinations ranging in stiffness from hard to soft.

Fabricated as a scaled prototype, this project is potentially under way to mass manufacturing. In considering assembly in full scale, some rigorous evaluation processes must be accommodated. In the case of the current scaled build, the model was fabricated from photopolymers, which mimic the properties of polypropylene. It simulates toughness (Izod notched impact of 44.22 J/M), flexibility (elongation at break of 44.2 percent) and strength (elastic modulus of 1,135 MPa) of polypropylene. Such materials appear to be incredibly robust for the generation of small-scale models and some implementations in product, and industrial design. However, since most of these technologies are developed for prototyping purposes, material fatigue may prohibit full-scale development. In which case, there appears to be significant need for the development of robust materials that can pass for structural loading cases that match FEA simulations and functional testing.

7.6.1.5 Design Method: Voronoi Finite Element Tessellation Method (V-FEM)

The Voronoi cells applied in this work were obtained by Dirichlet tessellation of complex 3-D surface representations. This process involves the discretization of a heterogeneous curvature domain based on the location of a finite set of behavioral heterogeneities defined by mechanical behavior. The application and generation of tessellations based on fitness criteria and material properties has been demonstrated. This approach, termed V-FEM, promotes an alternative to traditional optimization algorithms that are applied on top of an already existing model. In other words, the V-FEM methods promotes and integral approach to generation-through-optimization whereby a finite-element like method is inherently linked to behavioral data and geometrical organization.

7.6.1.6 Design Technique: UV Recompression Algorithm

The UV re-compression algorithm implemented in this work demonstrated how to apply a voronoi mapping on highly-complex doubly curved 3-D NURBS surface. The need for such an algorithm was introduced by the difficulties presented in using projections and resulted in extreme UV-squeezing conditions where point cloud density increases at regions of large squeezing. The solution involved the transformation of a uniform voronoi point cloud mapped on the 3-D surface into a non-uniform point cloud on the UV plane. Illustration solution: uniform point cloud on 3-D surface is a non uniform cloud on the UV plane. As noted above, the voronoi construction in the UV plane produces odd looking cells on the UV-plane, but a uniform voronoi pattern on the 3-D surface. Such recompression algorithm may potentially be generalized to include other types of tiling patterns based on complex point cloud registrations.

7.6.1.7 Experiment Summary

Complex models that correspond to a multitude of fitness functions require sophisticated tools for their evaluation. The work presented in this paper focused on the generation and implementation of V-FEM as an approach to *behavior tiling*. However, the structural and environmental evaluation of this tool has yet to be developed. A shape annealing approach to tile-typology that considers the dynamic growth of tiles as a function of vector mapping appears to offer one such promising direction.

7.6.2 Finite Synthesis Method (FSM) 1: *Raycounting* as a case for Variable Property Analysis

Computational geometry has customarily been used as a means for the description and analysis of form. To a lesser extent it has been made instrumental for purposes of design generation. Central to this condition is the partitioning between analysis and generation. Given the significance of analytic tools to the explorations and potential generation of form, it is the integration of such tools and techniques as propositional rather than merely descriptive that may provide the user with the capability to exploit computational analysis as a driver for design generation incorporating built-in performative considerations. The *Raycounting* experiment, previously described as an attempt to generate light-induced curvature, was developed in the *Rhinoceros* software package using the *Visual Basic* scripting environment. It assumes a constructed 3-D surface with zero thickness and evaluates the geometrical features of such a surface (i.e. curvature, rate of curvature, directionality, etc). On the basis of these evaluations, certain functions are then applied to the existing geometry in order to further enhance its performance-oriented features based on desired structural and light performance criteria (i.e higher curvature regions are developed for shading purposes where such areas are required). The tool created to generate the project employ a doubly curved NURBS[7.7] surface as an input and generate a 3-D solid geometry as output.

7.6.2.1 Light as Geometry

The main objective of this work is to promote a novel methodology which supports the seamless integration of geometry and performance. It does so by identifying certain analytical representation methods

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[7.7] NURBS are mathematical representations of 3-D geometry that can accurately describe any shape from the simplest to the most complex 3-D free-form surface or solid. Because of their flexibility and interactivity as well as their accuracy, NURBS models can be used in various processes from illustration and animation to manufacturing.

and incorporating them into the generation process. It is this ability to quantify and describe performance criteria in the language of geometrical representation that can anticipate such integration (Figure 7.39).
Multi-objective representations supporting the designer with various interpretations regarding the potential performance of a design object endorse and promote a design process that is *generative* in nature. Illustrated below is an example of multi-objective representation. The color map to the left includes an array of colors ranging from red to blue; red - indicating synclastic curvature (bowl-like surface features, also known as *positive* curvature) and blue indicating anticlastic curvature (saddle-like surface features, also known as *negative* curvature). Other NURBS-based analysis tools include geometric continuity, deviation, curvature graph on curves and surfaces, naked edges, and working surface analysis view-port modes (i.e. draft angle, zebra stripe, environment map with surface color blend, Gaussian curvature, mean curvature, and minimum or maximum radius of curvature respectively).

7.6.2.2 Reconstruction Analysis Tools as Generative Algorithms

The aim is to evolve a 3-D geometry based upon, and corresponding to, the geometrical features, as have been analyzed by the software; the geometry being of any given zero-thickness surface geometry such that this surface may potentially become a 3-D design artifact. In order to simplify this aim, two of the most common analysis tools were reconstructed and recomputed with additional functions supporting the generation of 3-D objects. Each tool was computed to include a set of potential geometrical attributes which would be modified according to pre-defined performance constraints. Such attributes include surface thickness and transparency, both of which are computed for every sampled surface point across its area. In this particular project, the thickness of the surface is attributed to two types of analyses including *curvature analysis* and *draft angle analysis*.
Moreover, the thickness of the surface is a function of its local curvature and location (relative to a given light source) as measured at any given point. This thickness parameter adds spatial, structural and shading data as part of the surface's geometrical description. From this follows that the "thickness" attribute, corresponding to the curvature-analysis routine, may suggest structural stability or spatial enclosure, whereas the "thickness" attribute which is applied relatively to the position of a light source may indicate, for instance, degrees of translucency which display a range of light effects from opaque to transparent depending on the surface thickness. So depending on the material which would later be assigned for the design, and assuming such material may change its transparency as a function of its thickness (such as foam or plastic for example), thick profiles will be opaque and thin profiles will give the effect of being almost transparent.
Such processes, by the very nature of informing geometrical attributes with performance data, demonstrate the very many forms of "translation" which typically remain hidden from the user. The so-called "translation" in this case is comprised of operations ranging from curvature analysis to the assignment of *informed geometrical features* based on such analyses. This process is iterative by nature as it may correspond to an array of geometrical parameters (representing various physical performance attributes) and may be applied and re-adjusted iteratively in the generation of the final form. However, the process of assigning performative interpreters to geometrical data requires the build-up of some translational functions to parse the math and turn it into representable performance data, usable for the designer.

7.6.2.3 Mathematical Foundations for Tool Reconstruction

When considering how tools of analysis may be modeled in order to incorporate 'propositional interpreters' of performance criteria (i.e. the relation between the degrees of curvature to structural performance, or the relation between thickness and degrees of transparency) we assume that geometric quantities and descriptions may incorporate and represent the physical properties of matter. Thus we seek to incorporate physical data within the three-dimensional (thickness) representation of geometric form. Geometric form thus becomes "materialized" from the point of view of performance analysis. This potentially renders analysis and generation of computational geometry: iterative in both directions; interactive; and inherently performative.

The fields of physics, structural engineering and material science contain numerous cases in which formulas are specified to include and solve relations between physical properties of matter through geometry. Such for example are Maxwell's "method of drawing lines of force and equi-potential surfaces" from the late 70's (Maxwell and Garnett 1881).

Given the descriptive capacity of such media, the aim now becomes to rewrite such notational correspondence between various representations *in terms of* geometry (Figure 7.40-7.42).

In these notations, and as previously reviewed in Chapter 4, *scalar* quantities are those that can be represented by a single number (i.e. mass and temperature). There are also *vector*-like quantities, such as force, that require a list of numbers for their description (so that direction can be accounted for). Finally, quantities such as *quadratic forms* naturally require a multiply-indexed array for their representation. These latter quantities can only be conceived of as *tensors*. Actually, tensors can be generalized to include other simpler objects: scalars and vectors are special kinds of tensors. The feature that distinguishes a scalar from a vector, and distinguishes both of those from a more general tensor quantity is the number of indices in the representing array. This number is called the *rank* (or the *order*) of a tensor. Thus, scalars are rank zero tensors (with no indices at all) and vectors are rank-one tensors.

When relating two types of vectors (such as displacement and gravity), we are in essence generating a tensor object in mathematical terms. Tensors which relate two vectors of the same type are known as *polar tensors*, whereas tensors which relate two vectors of different types are known as *axial tensors*. The different vector types may include for instance velocity, displacement, acceleration, gravity or torque.

Combined, vectors and tensors make up a space of an arbitrary dimension, n. In most cases this description implicitly denotes some space (no need for an explicit space of position). In order to break away from the primacy of numbers over matter (or performance), and to allow the user to compute the math on spatial entities (and not only numbers), we may begin to look at vectors as spatial and mathematical things, rather than purely numerical entities.

We may now take advantage of usual vector algebra operations available in 3D space ("R3") to study the curvature (departing from linearity) and torsion (departing from planarity) of curves in space[7.8].

Let us now smoothly move from curves to surfaces through the description of the manifold. Manifolds are important objects in mathematics and physics because they allow more complicated structures to be expressed and understood in terms of the relatively well-understood properties of simpler spaces.

A *manifold* is a representation of a mathematical space in which every point has a neighborhood which resembles Euclidean space, but in which the overall geometry may be more complicated. Manifolds may be classified according to dimension. For example, lines are one-dimensional manifolds, and planes two-dimensional manifolds. In a one-dimensional manifold (or one-manifold), every point has a neighborhood that looks like a segment of a line. Examples of one-manifolds include a line, a circle, and two separate circles. In a two-manifold every point has a neighborhood that looks like a disk. Examples include a plane, the surface of a sphere, and the surface of a torus.

A *Riemannian manifold* is a manifold possessing a metric tensor. Simply put, the metric tensor is a function which tells us how to compute the distance between any two points on a given space. The metric tensor is defined abstractly as an inner product of every tangent space of a manifold such that the inner product is a symmetric, non-degenerate, bilinear form on a vector space. This means that

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[7.8] Since we are interested in curves with non-zero speed everywhere, we can always re-parameterize to achieve unit speed.

it takes two vectors as arguments and produces a real number. It should be noted that the array-of-numbers representation of a tensor *is not the same thing as* the tensor insomuch as an image and the object represented by the image are not the same thing. For instance, the mass of a stone is not a number. Rather, the mass can be described by a number relative to some specified unit mass. Similarly a given numerical representation of a tensor only makes sense in a particular coordinate system. Some well known examples of tensors in geometry are quadratic forms, and the curvature tensor.

In the framework of this work, fundamental vector math was used to regenerate the analysis tools along with their added functionality. Two scripts were developed corresponding to the two surface-based analytical tools including curvature analysis and draft angle analysis. The following sections describe the sequence of operations that were executed to reconstruct and reconfigure these tools for the purpose of performance-based design generation.

7.6.2.4 Curvature Analysis Tool

The "curvature analysis" command in modeling software packages such as *Rhinoceros* and *Digital Project* is one of a series of visual surface analysis tools. These commands use NURBS surface evaluation and rendering techniques to visually analyze and display surface smoothness, curvature, and other geometrical properties. Such commands may potentially inform or guide the design process in that geometrical attributes may be translated or interpreted as performance manifestations. This section describes the regeneration of the Surface Curvature Analysis command and the process in which spatial and structural information are the outcome of manipulating a free-form surface to give it structural integrity using computational geometry. The aim is to employ an existing geometry-based tool of analysis in order to foresee the structural properties of the input geometry.

Firstly, let us describe the surface analysis command as it exists in the software[7.9]. Following the basic definitions, a detailed description of the script which was used to regenerate the command in a design context will be given.

Some basic definitions:

1. Gaussian and Mean Curvature: At any point on a given curve in the plane, the tangent line is the line best approximating the curve passing through this point. In addition, it is possible to represent the best approximating circle that passes through this point and is tangent to the curve. The reciprocal of the radius of such a circle is the curvature of the curve at this point.

2. Principal curvatures: The principal curvatures of a surface at any given point are the minimum and maximum of the normal curvatures at that point. Normal curvatures are the curvatures of curves on the surface lying in planes including the tangent vector at that given point. The principal curvatures are used to compute the Gaussian and Mean curvatures of the surface.

3. Gaussian curvature: The Gaussian curvature of a surface at a point is the product of the principal curvatures at that point. The tangent plane of any point with positive Gaussian curvature touches the surface at a single point, whereas the tangent plane of any point with negative Gaussian curvature cuts the surface. Any point with zero mean curvature has negative or zero Gaussian curvature.

4. Mean curvature: The Mean curvature of a surface at a point is one half the sum of the principal curvatures at that point. Any point with zero mean curvature has negative or zero Gaussian curvature. Surfaces with zero mean curvature everywhere are minimal surfaces. Surfaces with constant mean curvature everywhere are often referred to as CMC (Constant Mean Curvature) surfaces. CMC

[7.9] The software referred to in this work is the Rhinoceros and *Digital Project* platforms in particular.

> surfaces have the same mean curvature everywhere on the surface. Physical processes which can be modeled by CMC surfaces include the formation of soap bubbles, both free and attached to objects. A soap bubble, unlike a simple soap film, encloses a volume and exists in equilibrium where slightly greater pressure inside the bubble is balanced by the area-minimizing forces of the bubble itself. Minimal surfaces are the subset of CMC surfaces where the curvature is zero everywhere. Physical processes which can be modeled by minimal surfaces include the formation of soap films spanning fixed objects, such as wire loops. A soap film is not distorted by air pressure (which is equal on both sides) and is free to minimize its area. This contrasts with a soap bubble, which encloses a fixed quantity of air and has unequal pressures on its inside and outside.

To summarize, a smooth surface has two principal curvatures. The Gaussian curvature is the product of the principal curvatures. The Mean curvature is the average of the two principal curvatures. By convention, most of the software packages which incorporate such analysis tools do so by assigning a color-coded pattern on top of the surface which assists the user to determine the type and degree of curvature for any given surface. In the framework of surface curvature analysis, the color red is usually assigned to a positive value of the Gaussian curvature, green is assigned to zero Gaussian curvature, and blue to negative value of Gaussian curvature. Any points on the surface with curvature values between the values which have been specified by the user will be displayed using the corresponding color. For example, points with a curvature value half way between the specified values will be green. Points on the surface that have curvature values beyond the red end of the range will be red and points with curvature values beyond the blue end of the range will be blue. A positive Gaussian curvature value means the surface is bowl-like and is also called: *synclastic* curvature. A negative value means the surface is saddle-like and is also called: *anticlastic* curvature. A zero value means the surface is flat in at least one direction (i.e. planes, cylinders, and cones). The Mean curvature displays the absolute value of the mean curvature and is useful for finding areas of abrupt change in the surface curvature. The Max radius option is useful for flat spot detection. By default, red areas in the model indicate flat spots where the curvature is practically zero. The Min radius option determines whether the surface includes areas where it may bend tightly (so as to generate an intersection) when it is offset beyond a certain threshold limit determined by the user. In this case, the Red color will be set as the radius of offset distance, and the blue will indicate this dimension, multiplied by a factor of 1.5. The red areas indicate regions in the surface which will self-intersect upon offset. Blue areas are geometrically sound in this respect. Areas from green towards red should be viewed with suspicion.

7.6.2.5 Curvature Analysis Tool Reconstruction

The aim of reconstructing the curvature analysis tool was to use the analysis as a 3-D form-generator driven by structural performance considerations. In this case surface thickness is created by offsetting the original surface in a non-homogeneous manner, corresponding to surface curvature. By convention, highly curved areas across the surface have been assigned minimal thickness; while smooth regions have been assigned maximum thickness. This method allows for the application of thickness that is curvature-dependant on the original zero-thickness surface and acts as a “smoothing” function across its entire surface. This method also has structural implications: the smoothness function allows treating surface thickness in the context of stability and orientation. In this project specifically, the aim was to design a wall-mounted element which would be structurally sound and self-supportive while still remaining light-weight and economic to fabricate.

The script was generated based on an existing NURBS surface model. This surface has zero-thickness prior to the application of the script. Initially, the script runs an automatic surface re-parameterization method. The parameter values of the surface object are recalculated so that the parameter space of the surface object is roughly the same size as the 3-D geometry of the object (surface generated by user). This function may be executed automatically (by default) to allow for a quick calibration of the parameter space. Proceeding re-parameterization, the script asks the user to enter the number of rows and columns across the surface to establish its underlying geometry and define a grid of registration nodes. Every surface is roughly rectangular. Surfaces have three directions: u ("rows"), v ("columns"), and normal. The u and v directions are like the weave of cloth or screen. The u-direction is indicated by the red arrow and the v-direction is indicated by the green arrow. The normal direction is indicated by the white arrow. The u, v, and normal directions may be thought of as corresponding to the x, y and z axes of the surface. The "rows" and "columns" entered by the user establish the granularity of u and v intersection points: the higher the values, the more points distributed across the surface for the purpose of sampling or attribute assignment which will take place at a later stage. In the next step the script computes surface normals and plots them in the modeling environment. This function returns two 3-D points that define the normal to a surface at a parameter. It takes two parameters as input: the object's identifier (the user generated surface) and an array containing the UV parameter to evaluate. The array elements which are returned include a point on the surface at the specified parameter (given at each u and v intersection) and a point normal to the surface at the specified parameter. The normal registration allows computing the curvature registered in each U and V point as defined by the user and assign a color to those points. Finally, based on the sampled curvature an offsetting function assigns surface thickness matching the curvature analysis mapping. Maximum and minimum thicknesses are defined by the user and scaled automatically to generate thickness range according to sampled surface curvature values.

7.6.2.6 Draft Angle Analysis Tool

The draft angle analysis tool maps out the projection pattern on a given surface from the point of view of a predefined construction plane. The projection is the transformation of a surface defined by points in one plane (the "construction plane", which is by default the active view port) onto another plane (the original generated surface) by connecting corresponding points on the two planes with parallel lines. The draft angle depends on the construction plane orientation. When the surface is vertical/perpendicular to the construction plane, the draft angle is zero. When the surface is parallel to the construction plane, the draft angle is 90 degrees. These angles are assigned a color map to allow for a gradient color representation of the draft angle. The Draft Angle dialog box allows the user to set the angle for the color display. The density of the mesh can also be adjusted, if the level of detail is not fine enough. The "pull direction" (the direction from which the surface is being viewed, defined by the location of the construction plane) for the Draft Angle Analysis is the z-axis of the construction plane in the active view port when the command starts. The normal direction of the surface points toward the "pull direction" of the model. Changing the construction plane before using the Draft Angle Analysis command allows the user to define any direction as the pull direction. Recent CAD packages include the function for a dynamic draft angle analysis which allows moving and rotating the model in real time while analyzing the dynamic draft angle of the model (Figure 7.44, 7.45).

7.6.2.7 Draft Angle Analysis Tool Reconstruction

Similarly to the surface-curvature analysis tool reconstruction, the draft-angle analysis tool is applied to a zero-thickness surface generated by the user. The surface re-parameterization method is applied automatically by the script, followed by U and V registration grid definition and surface vector computation. In addition to the normalized surface vectors, plotted as well are the vectors which extend from the light source (or alternatively the view-port orientation point) to the U and V surface registration points. These two sets of vectors (surface vectors and vectors connecting between the surface and the light source) are used to calculate the draft angle, which is the angle between the surface and the light source as sampled in points across the surface. This set of angles may be conceptually regarded as a tensor field linking the geometrical properties of the surface to a localized agent outside it, which determines its light effects. A threshold value is entered by the user which determines the smallest angle from which the light source does not “see” the surface, an angle in which an opening is applied to the surface to allow for more light in. Finally, the range of angles is normalized to fit a range of thickness (minimum and maximum thickness is defined by the user) which allows for varied surface sections to be generated. The result of this script is a set of planar sections which modify their thickness according to their relative distance from the any user defined “light source” location (Figure 7.45).

7.6.2.8 Surface Curvature Analysis Script Reconstruction Results

The aim was to link surface curvature data as sampled by the program, to structural performance considerations. Varied thickness was applied to each point across the surface which matched its curvature in direct relation: the smoother the curvature the thinner the surface. This added functionality allows the user to directly associate the mapped curvature to surface thickness and to generate 3D geometries out of zero-thickness NURBS surfaces (Figures 7.41, 7.43, 7.46-7.49, 7.51-7.52).

7.6.2.9 Draft Angle Analysis Script Reconstruction Results

The results, as illustrated in Figure 7.50 demonstrate the variations of behavior with regards to light performance. The user defines the location of a “light source” relative to the existing surface and a threshold value which defines the minimum angle at which a hole is formed in the surface. In this example, the holes are formed where minimum light rays hits the surface (below an angle of 20 degrees). As a result, the hole-pattern formation is informed by the light source location and the threshold value under (or over) which the surface is fenestrated.

7.6.2.10 Summary

This work emphasized the generative potential that exists within analytical tools for geometrical evaluation. The assumption at the core of this work remains that such tools may inform the designer in the search for formal expression and that they contain opportunities to transcend the geometric-centered description of form by linking it to performance criteria (spatial, structural, environmental, etc).

To conclude, analytical tools are computed as geometrical statements. These statements may serve as “multi-objective” representations bridging between geometry and performance, geometry and construction, and geometry and manufacturing. The work sought to demonstrate such an approach by reconstructing two analysis tools for structural and environmental performance thus providing additional functionality.

In presenting the prospects for an emerging professional profile of informed tool-making this approach seeks to promote a new model for contemplating form and practicing design. If such a prospect is legitimate, then it is the knowledge of computational geometry that is becoming one of the significant forms of disciplinary knowledge of the new computational design professional.

Design incorporates multiple manifestations of form from the point of view of geometry, material selection, performance, and construction. Each manifestation promotes its very own method of process and media of representation. However, some representations may be generated which support multiple manifestations simultaneously while reciprocally informing each other.

This experiment attempted to define certain analytical forms of representation based in computational geometry as the enabling representation which correlates geometry to performance by means of generative computational processes. Such enabling representations are in most cases analytical in nature and offer multiple translations to occur based on a unifying code of interpretation. Such tools are also intermediate in nature, a property which renders them generative.

Beyond the notion of performance-driven interpretations based on computational geometry methods, this work has also engaged with the notion of computational analysis as a source for strategizing material distribution. Rather than breaking down the design into a series of componentized elements aiming at straightforward and simplified assemblies, this exploration demonstrates an alternative approach favoring material distribution over strategies of composition. This method promotes design manifestations which are not concerned with the notion of "buildability" to begin with, but rather let formal statements be informed by behavior and performance which result in the gradient distribution of material qualities and effects.

7.6.3 Finite Synthesis Method (FSM) 2: Subterrain as a case for Variable Property Analysis

Derived from micrographs of a butterfly wing, a scorpion paw, and a leaf section, the models were produced by computing hypothetical physical responses of the structure derived from each micrograph. In each case, computational experiments were performed that account for physical responses to structural components in the original sample.

The computation was performed using a public domain image-based finite element application: OOF2 ($http://ctcms.nist.gov/oof/oof2$). Physical properties were imposed onto the image and a computational mesh was created with the image-property information (Figures 7.53 – 7.55). The computation produces data for equilibrium stresses and strains, steady-state heat flow, stored energy, and deformation due to applied loads and temperature differences (Figure 7.56, 7.57).

The final models are six-dimensional: the original image is a two-dimensional object reflected in the density and morphology of the computed mesh, the out-of-image deformation produces the relief (i.e. spatial texture), elastic stresses produce the line-thickness, flux is encoded with color data, and stored energy is represented by superimposed numbers.

The images were assigned material properties according to their gray values: bright tones were associated with a material characterized by having stiff elastic properties (by analogy, a stiff spring), high thermal conductivity (like a metal: cool to the touch on cold days, hot to the touch on hot days), and intermediate value of thermal expansion (the increase in volume of a material as its temperature rises, and the reason expandable joints are used in structures such as bridges). Dark tones were associated with a material characterized by having compliant elastic materials (by analogy, spongy foam), low thermal conductivity with no thermal expansion. Middle tones received intermediate elasticity and thermal conductivity, but larger thermal expansion. The combined image and its properties are subjected to stretching and heat flow in the vertical and horizontal directions; the interaction between the directional morphology of the image and the stretch direction produce physical effects that emphasize image features in different ways.

7.6.3.1 Subterrain 1

Subterrain 1 is based on a micrograph of a leaf structure. The image has bright and dark stripes that evolve into isolated dark patches in a matrix of brighter material.

Stretching the tissue and causing heat to flow in the vertical direction shows how vertical stripes provide avenues for heat flow (blue to red tones) and decomposes into a more disorganized heat flow pattern, but continues to reflect the underlying morphology of the image. Most of the force (as indicative by the mesh line thickness) is transmitted by the brighter material, but accentuated where the material alters its morphology over a short distance. Vertical stretching causes the material to store energy (text-numbers) in the bright parts of the vertical bands in the lower regions and in the bright matrix in the upper material. Rumpling is produced by stress transfer between the softer material and the stiffer material; there little stress transfer in the bands and significant rumpling appears around the isolated patches.

When the image is subjected to horizontal stretching and heat flow, the laminar structure at the bottom of the image restricts heat flow because of the insulating effect of the darker phase—gaps in the darker layers produce short-cuts that produce the heterogeneous pattern of high heat-flux density (blue patches). In the upper region, the heat-flux pattern is similar to that in the vertical loading because there is no preferential direction in the underlying image structure, but the texture is rotated due to the direction of heat flow. The stress in the laminar region is more uniformly distributed, and comparison of the vertical and horizontal cases illustrates the interplay of loading direction and material texture. The homogeneous stress state reduces the rumpling, which in this case is produced mostly by thermal expansion contrast.

7.6.3.2 Subterrain 2

Subterrain 2 is based on a micrograph of a scorpion paw. The image has a skeletal structure of gray struts which are interlinked by a brighter cellular network. This composite structure is embedded within darker tones that will be associated with a very compliant, low thermal conductivity material, like air.

The image's mid-gray and dark tones have contrast that tends to run in the horizontal direction. By comparison, directional texture in the brighter, cellular, matrix is less evident. Properties from this cellular structure will tend to dominate the resulting patterns from the physical properties, because it is assumed to be a stiffer load bearing material and more thermally conductive.

For both vertical and horizontal loading cases, thermal flow seeks out optimal paths for heat conduction along similarly aligned portions of the cellular matrix. Only the fractions of cellular struts that are connected and align with the thermal gradient significantly participate in heat flow. Gaps in the cellular matrix shed heat flow to the skeletal structure. Again, because the cellular portions are stiffer, only the aligned structural components contributed to load bearing and energy storage. Texture in the pattern is produced by the loading direction.

7.6.3.3 Subterrain 3

Subterrain 3 is based on a micrograph of butterfly wing's scale (Figure 7.55). The mesh brings out the foliated structure at the largest scale where the central leaf-like structure pinned to a light gray backbone. Each leaf has a vertical texture of bright and continuous laminar materials that are cross-linked by lighter gray and darker elements. The cross-links have a horizontal texture.

In the horizontal loading condition, the lower-left leaf does not participate in load or conductivity because it is isolated by a dark band on its right. While the heat flow is left-right, the nearly vertical high-conductivity materials contribute to significantly, but non-uniformly, to heat flow, because heat flux is limited by the small gap between the central and lower-left leaf-structure. Dark gaps within the leaf structure present obstacles to heat flow. The load is born uniformly across the leaf structures and is only slightly influenced by the underlying image. Energy storage patterns reflect the leaf micro-structure. Rumpling reflects the macroscopic differences in the leaf-branch structure.

For the vertical loading of this mesh, all of the vertical elements of the leaf-structure are exposed in the heat-flow pattern because they are the principle conduits for heat conduction. Within each leaf, most of the load is transmitted by the stiff vertical elements; between the leaves the load is concentrated within the horizontal gaps. Rumpling occurs between the leaf structures and within the leaf structure where the horizontal texture produces stiffness mismatch in the load-bearing direction.

7.7 Classification of Experiments According to Units of Matter

7.7.1 Classification Methods

When considering each of the experiments previously demonstrated as an individual work it is generally challenging to assess its contribution to the theoretical framework presented in this treatise. Combined, however, the body of experiments illustrates various aspects of Natural Design and Material-based Design Computation that together form a consistent whole (Figure 7.58).

In this section I attempt to classify all experiments by several parameters, each referring to one aspect of the theoretical and technical foundations presented. Within each experiment we consider the following questions as forms of classification:

1. Within which media is the smallest material unit defined? A material unit may be initially defined in either the digital or the physical domains.
2. What is the method used to describe a material unit? A material unit may be defined using geometrical descriptions (tiling behavior), analytical descriptions (finite element synthesis), or fabrication descriptions (variable property fabrication).
3. Within which process is the smallest material unit defined? A material unit may be defined within the modeling process, the analysis process or the fabrication process.
4. By which performance criteria are material units defined? A material unit may be defined by a singular performance criteria or a combination of various structural and environmental criteria. Such may include the various performance constraints previously described: load, heat, light, comfort and pain.

As our design challenge calls for a novel way of generating form, promoting the integration between tools and the negotiation between performance constraints, I have sought to break down the problem into discrete experiments. As classified in the chart presented below, each experiment is primarily defined by its unique definition of “matter” and the way in which “matter” and “performance” are negotiated to generate a design.

As a result, various techniques emerge that are unified by a material-based design rationale but approach this rationale differently. Some projects examine a material-based approach only in a later stage in the design process: the texture design applied onto *Beast* for instance, was implemented only after the overall form of the chaise was determined. With *Carpal Skin*, the form of the glove is dependent on the patient’s anatomy, and so the actual texture-generation process takes place only after scanning, In *Subterrain*, the design is directly determined by the natural tissues that served as a specimen for the prediction of physical behavior; in this case the initial form with which we begin is determined by the specimen; and so on.

7.7.2 Eco Maxels

As previously discussed in Chapter 6, we have determined that in order to promote the integration between form and physical behavior we must consider methods promoting the integration of the three main phases in the design process: modeling, analysis and fabrication. We have also determined that in order that such integration may be achieved, we must make the assumption that the units describing form must directly relate to performance input and fabrication output.

For this purpose, we have identified several such pairings between performance input types and material (or, fabrication) output types. The design itself is, in essence, a mediator between those input and output units (i.e. light and wax, load and fiber-composite etc). We have termed such pairings “eco-maxels” to indicate that material pixels defined in the digital and physical domains are organized and oriented in ways that correspond to environmental performance requirements. Amongst them are included pressure maxels, thermal maxels, light maxes, and comfort maxels. We proceed with a brief classification of the experiments according to these types.

7.7.2.1 Pressure Maxels (STRUCPIX) computational unit is defined by structural performance

Whether prompted by dead, or live-load, and whether applied on a building element or on a furniture piece, load is typically a major contributor to the shaping of form. Pressure maxels are defined as units of matter that potentially incorporate the relationship between stress, derived from the load applied on the sample, and strain, derived from measuring the deformation of the sample (i.e. elongation, compression, or distortion). The nature of these maxels varies from material to material. All of the experiments demonstrated in this chapter have dealt with properties of load in one way or another.

We have explored three strategies for the inclusion of load criteria within the form-generation process:

1. *Tiling behavior*: in these cases, the initial form had already been modeled whereas the pattern or texture applied to its surface is developed by considering both the existing curvature and the type of loading cases anticipated. Variable surface thickness as a function of curvature and load is one such option.

2. *Finite element synthesis*: here, the form too has already been introduced. However, it is through its analysis and the braking-down of its surface area to smaller finite-element material units that allows the designer to treat the form locally against any anticipated loads. In this case material properties may be assigned to an analysis element comprising its mesh.

3. *Variable property fabrication* methods may be implemented that support the partitioning of the form such that each of the components comprising it is fabricated from materials with various properties respectively.

7.7.2.2 Thermal Maxels (TEMPIX) computational unit is defined by environmental performance

Relative to the type of material assigned to a “material unit”, such unit may carry properties relevant to the thermal performance of the object including, for instance, steady-state heat flow and stored energy. In the series of experimented presented we mainly focused on exploring such properties as part of the *finite element synthesis* approach. These experiments were informed by physical specimens the properties of which were modified according to some hypothetical environmental condition. For instance, we explored how a structure, organized as a butterfly wing scale, would behave like when scaled up and when performing under certain environmental (thermal) conditions.

7.7.2.3 Light Maxels (LUXPIX) computational unit is defined by environmental performance

The consideration of light as a design parameter is challenging particularly due to its properties typically being considered as perceptive and affective. In the experiments I was motivated by the possibility of combining and negotiating between parameters such as structural load and other visual qualities, due to effects created by light. The finite element synthesis approach considers situations in which we are optimizing against multiple objective functions as opposed to a singular one. For example: how does one accommodate a region (within the design product) that is both "robust and transparent" as opposed to the typical combination of "robust and opaque". Moreover, how does one control the variation of ranges of properties such that their expressions as data structures generate heterogeneity of material properties as a function of performance?

The consideration of light as a driving parameter for the design was expressed particularly in *Raycounting*. In this experiment each "material unit" may indeed be considered as a material atom ejected from the 3-D printing machine. The accumulation of such units to form larger objects defines its unique light effects through geometrical manipulations.

7.7.2.4 Comfort Maxels (CLINPIX) computational unit is defined by physiological performance

Beast and Carpal Skin were explored as cases examining the complex relationship between engineering parameters, architectural (perceptual) effects, and physiological requirements. In this sense, these two experiments are the most sophisticated in terms of the tools and the methods they represent. All three methodological frameworks were experimented with in this context:

1. *Tiling behavior* was implemented as a strategy for surface tessellation where each cellular component incorporates material data satisfying local structural and comfort (soft/stiff) performance

2. *A Finite element synthesis* approach was implemented specifically in the analysis of physiological requirements both in the case of the chaise and the glove design. Based on the wrist 3-D scanning results, for instance, we generate the distribution of material properties required and so on.

3. *Variable property fabrication* was specifically experimented with for the wrist band considering the need for a new technology which directly links performance mappings to a fabrication machine which allows for continuous variation of properties on the fly by controlling material mixtures.

7.8 Proto-Fabrication: The Missing Link

Motivated by a desire to consider a novel alternative approach to digital design that supports the integration of physical matter (and behavior) *prior* to the generation of form, the experiments illustrated in this chapter explore principles of Material-based Design Computation. Based on a family of frameworks introduced in the previous chapter, each work attempts to develop the tools and design methods associated with these methods.

We have demonstrated that in order to achieve computational form-finding processes which assimilate the functions of form, material and structure; we must *design*, rather than *select* our materials and methods as architects and designers. The experiments have introduced the idea of *eco-maxels*: printable 3-D physical pixels that are informed by environmental performance requirements. Various families of *eco-maxels* have been identified, amongst others that host a set of functions and performance unique to a particular design objective. Typically, such functions may introduce conflicting conditions which must be negotiated in the process (stiff and transparent, light and robust, etc.).

Serving as proxies for material data informed by environmental constraints, Eco-Maxels contain various relevant expressions to the design product. These expressions, communicated through locally defined physical properties and behavior, are distributed as one continuous tissue, to satisfy the design's conditions and requirements. Such an approach celebrates the conditions of material distribution and heterogeneity over the assembly of homogeneous components. For architecture and design in general this field of the (computational) design of material structures with the potential of heterogeneous condition-responsive material opens a totally new world of design, a world of extraordinary promise and potential. Granted, we have explored a multitude of techniques to distribute matter as a function of performance negotiation in the digital domain. However, we have not yet discussed the intrinsic interfacing potential of the conceptual and technological innovations of material-based design computation to integrate the virtual world of computing with the real world of materialization. How can such theoretical contributions come to be expressed directly and spontaneously in the realm of physical fabrication.

The mechanical response of materials designed and engineered with spatial gradients in composition and structure appears to be of considerable significance in all sub disciplines of design from product design, to medical devices, to buildings as well as to the technologies which fabricate and construct them.

Currently, there exists no rapid prototyping technology which allows for the smooth modification of material properties such as strength, stiffness, density and elasticity as continuous gradients across the surface and volume area of a functional component that is assigned to one singular nozzle. Such variations are usually achieved as discrete changes in physical behavior by printing/manufacturing multiple components with different properties and distinct delineations between materials, and assembling them only after the fabrication process has been completed. Such processes result in material waste and lack of functional precision. Variable Property Rapid Fabrication aims at introducing a novel material deposition 3-D printing technology which offers gradation control of multiple materials within one print to save weight and material quantity while reducing energy inputs. The result is a continuous gradient material structure, highly optimized to fit its structural performance with an efficient use of materials, reduction of waste and the production of highly customized features with added functionality.

In this chapter we have illustrated an array of experiments and case study experimental implementations to apply and evaluate theories, models, methods and technologies of material-based design computation. What we have imagined and generated in the digital domain, in the series of material experiments, in the design of a furniture product and a medical device have ultimately supported and scientifically and intellectually promoted a fabrication technology that is their realization in a new technology. The following chapter introduces the technology by which to achieve variable property fabrication and opens the lens to a new world of architecture and design potential of which up to now we have only dreamt. Now to the materialization of our dreams...

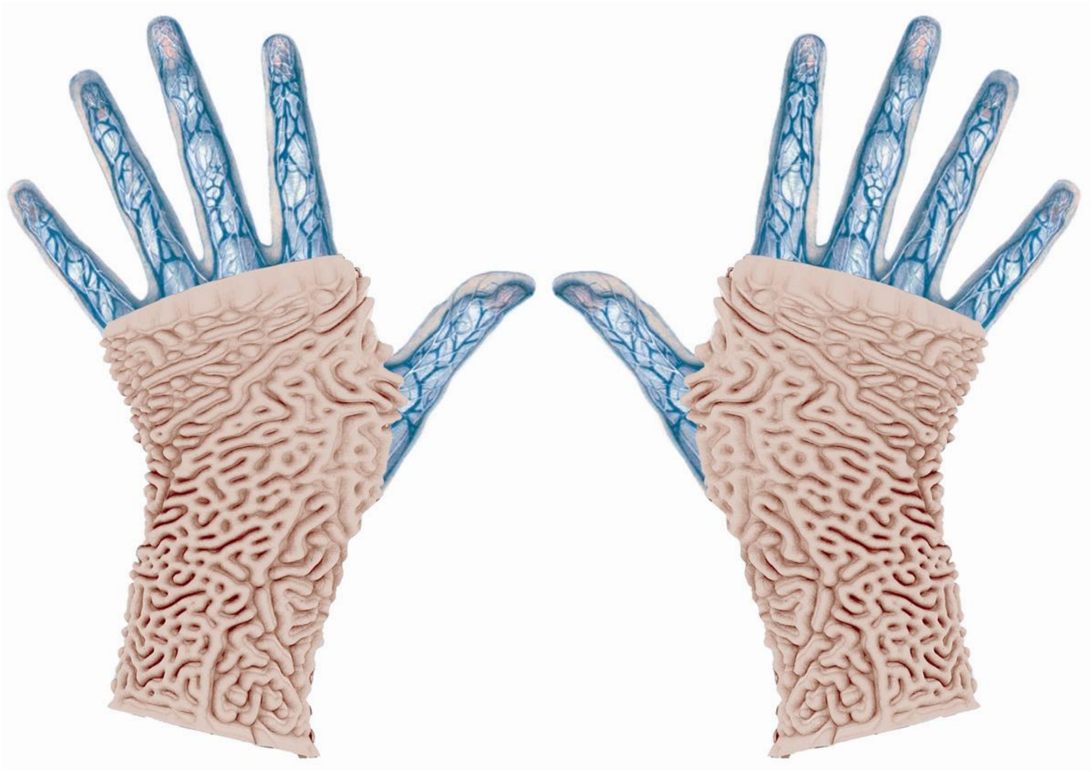


Figure 7.1: *Carpal Skin*, prototype for a Carpel Tunnel Syndrome splint, 2008, Boston Museum of Science. Digital model of prototype. Local thickness changes correspond to strategic areas across the surface area of the wrist in cushioning and protecting it from hard surfaces as well as allowing for a comfortable grip. These thickened bumps also increase flexibility, enhance circulation and relieve pressure on the Median Nerve as it acts as a soft tissue reshaping mechanism.

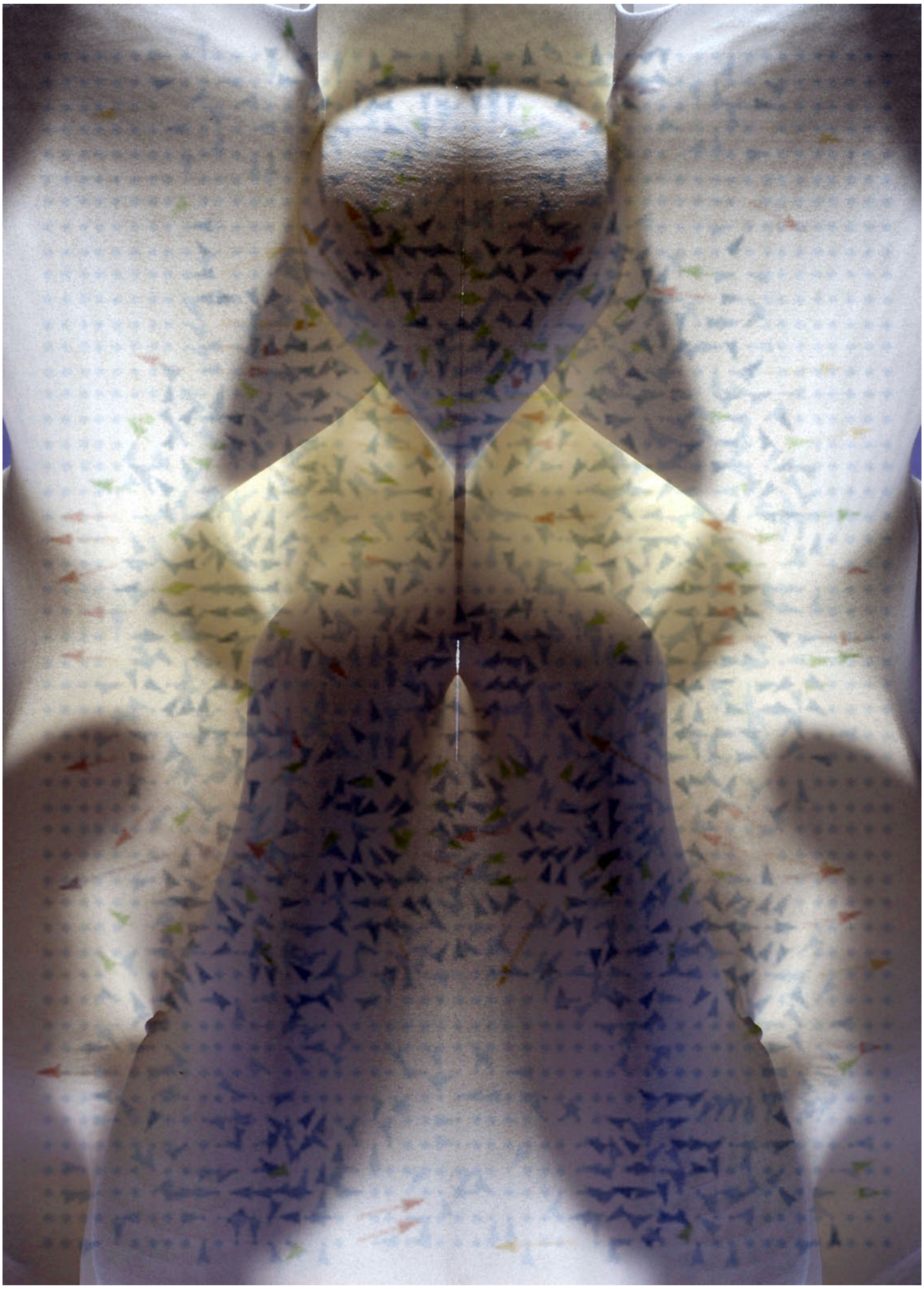


Figure 7.2: *Raycounting*, 2007, Museum of Modern Art, NY (Permanent Collection). Raycounting is a method for originating form by registering the intensity and orientation of light rays. 3-D surfaces of double curvature are the result of assigning light parameters to flat planes. The algorithm calculates the intensity, position and direction of one, or multiple, light sources placed in a given environment and assigns local curvature and material stiffness values to each point in space corresponding to the reference plane, the light dimension and structural stability requirements.

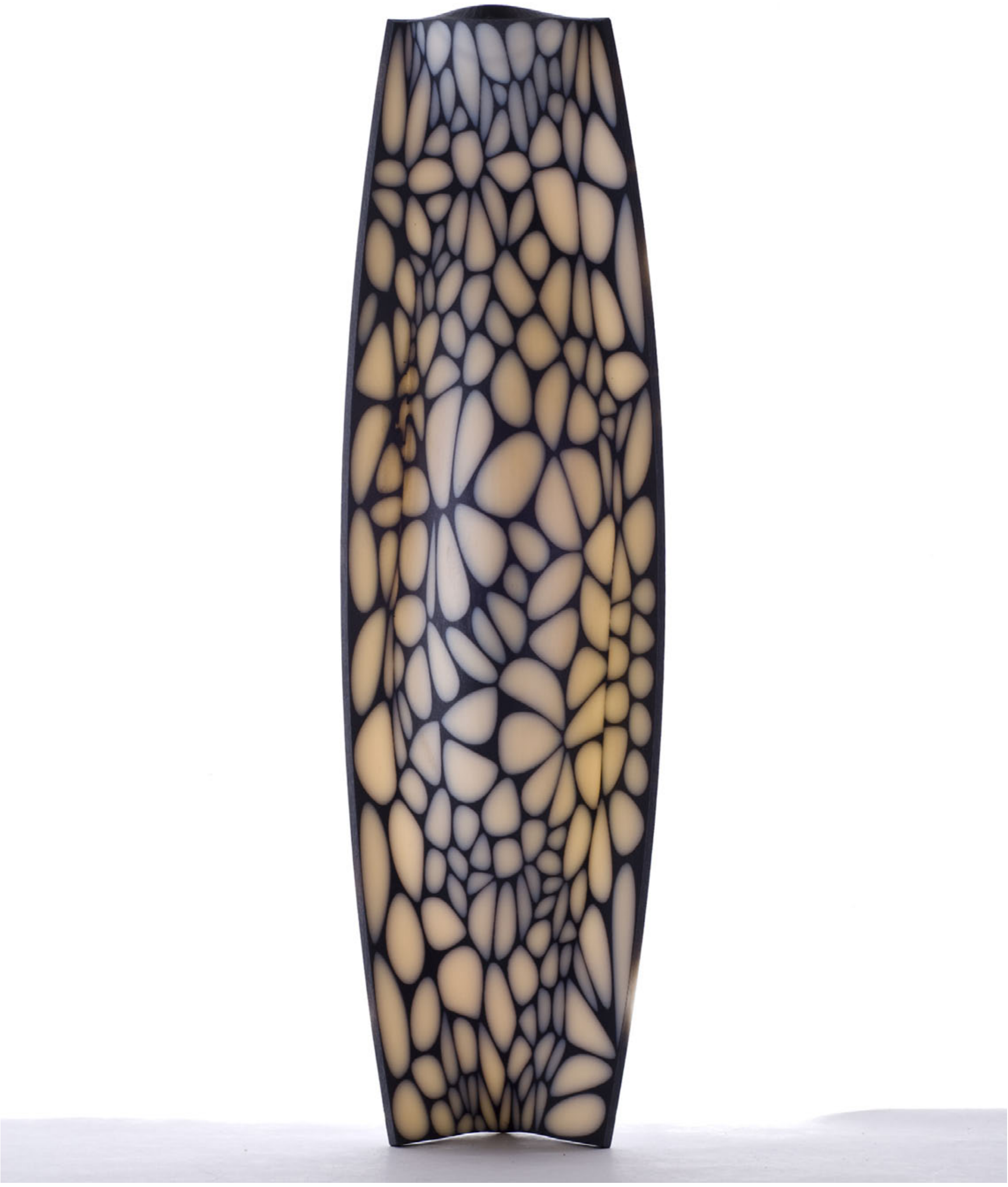


Figure 7.3: *Monocoque*. Prototype for a Structural Skin, 2007, Museum of Modern Art, NY (permanent collection). Monocoque illustrates a process for stiffness distribution informed by structural load based on a voronoi algorithm.

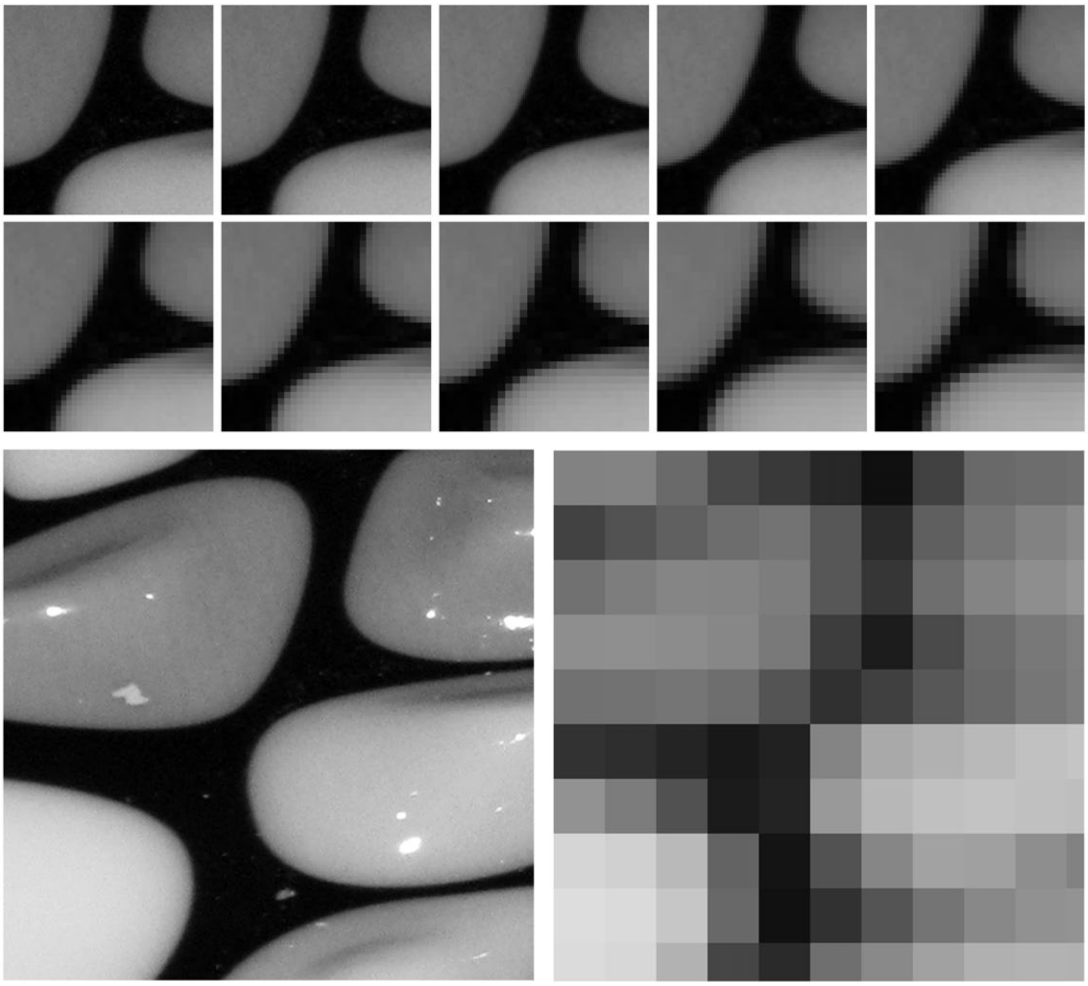


Figure 7.4: *Monocoque*. How small is small? How big is big? This composite image demonstrates various definitions of a "material unit" from a geometrical cellular entity to a physical volumetric pixel element.

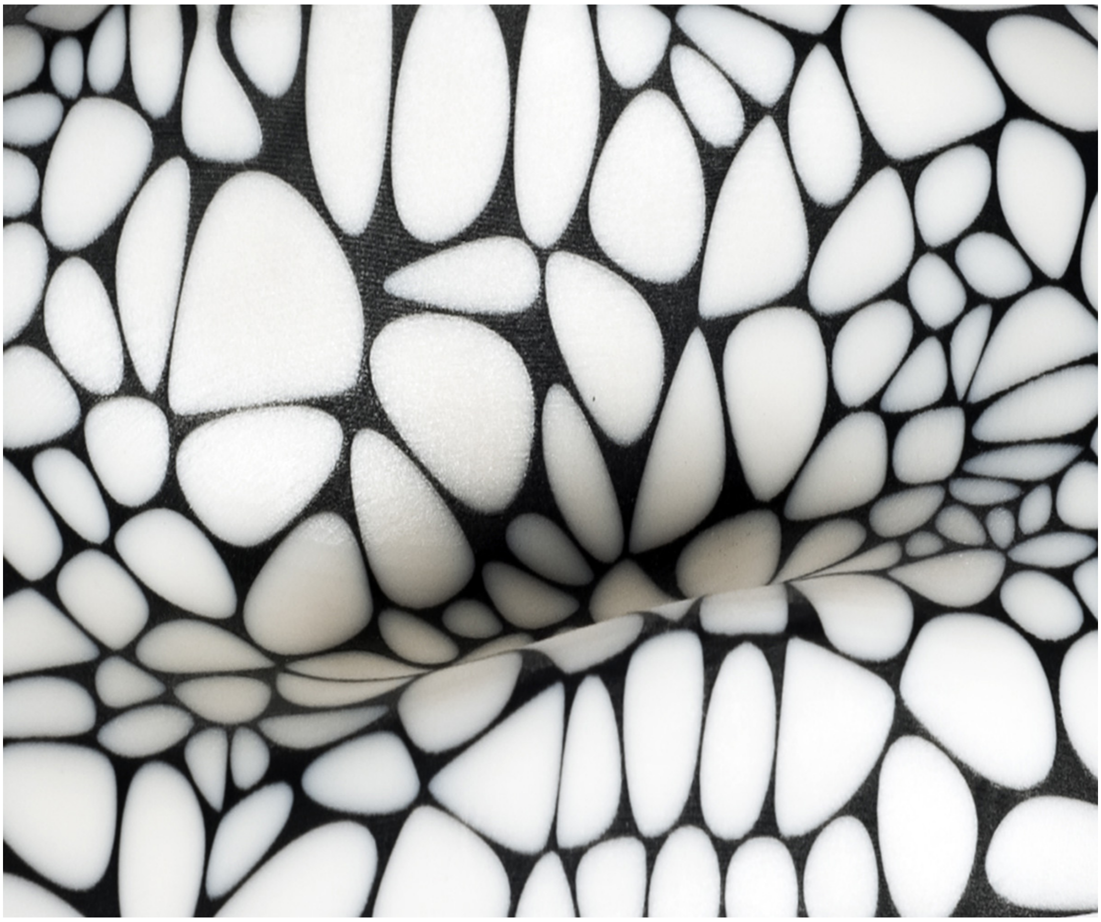


Figure 7.5: *Monocoque*. The distribution of shear-stress lines and surface pressure is embodied in the allocation and relative thickness of the stiff vein-like elements built into the skin (black) and the soft (white) cellular components between them.

Figure 7.6: *Monocoque*. Images of early study models 3-D printed using one material (top) and final model 3-D printed using multiple materials (bottom). The image illustrates the ratio between global surface curvature and local cell size and density: larger cells are positioned in regions of positive (sinclastic) curvature and smaller cells are positioned in regions of negative (anticlastic) curvature.

Figure 7.7: *Monocoque*. Images of an early study model demonstrating the notion of the “structural skin”: one material is locally thickened to account for structural support on the one hand, and light transmittance on the other. This continuous material system stands against the notion of assigning discrete materials for discrete functions.

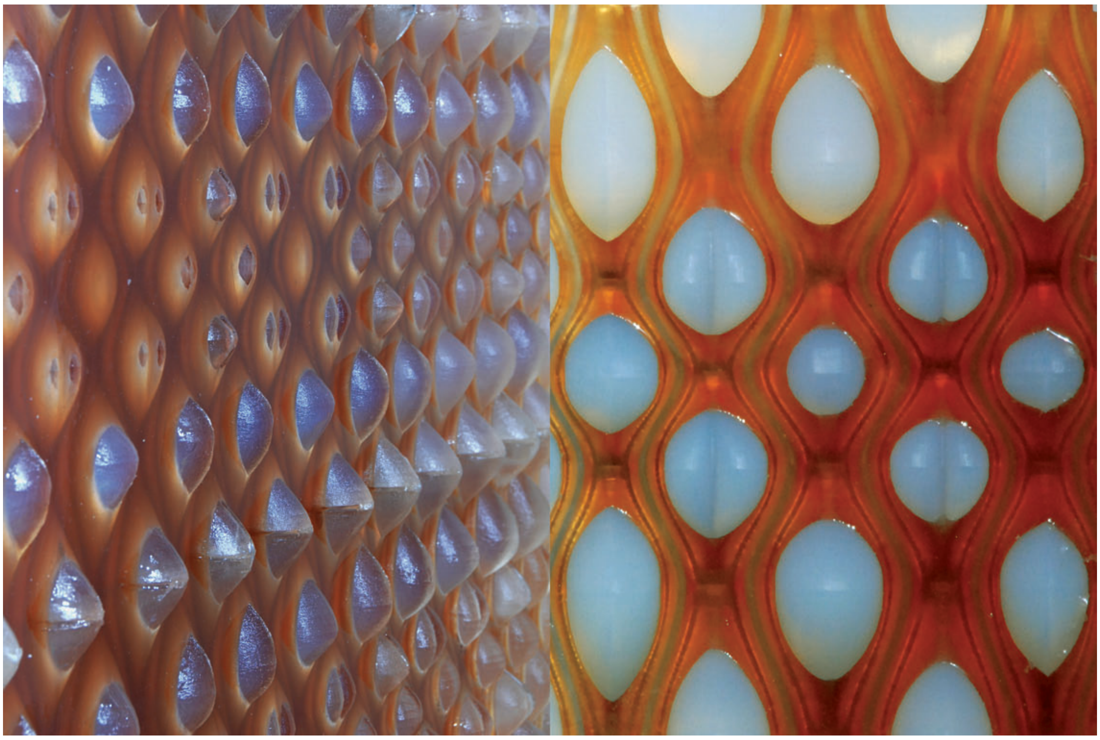


Figure 7.8: *Cartesian Wax* (Resin composites, 2008, Museum of Modern Art, Permanent Collection). Right: Museum installation dimensions: 4'x5'. Left: Detail view of an individual tile.

Figure 7.9: *Cartesian Wax*. Images demonstrating the fabrication process: an individual mold (in blue) was modeled, fabricated and used to model the 20 tiles comprising the structural skin.

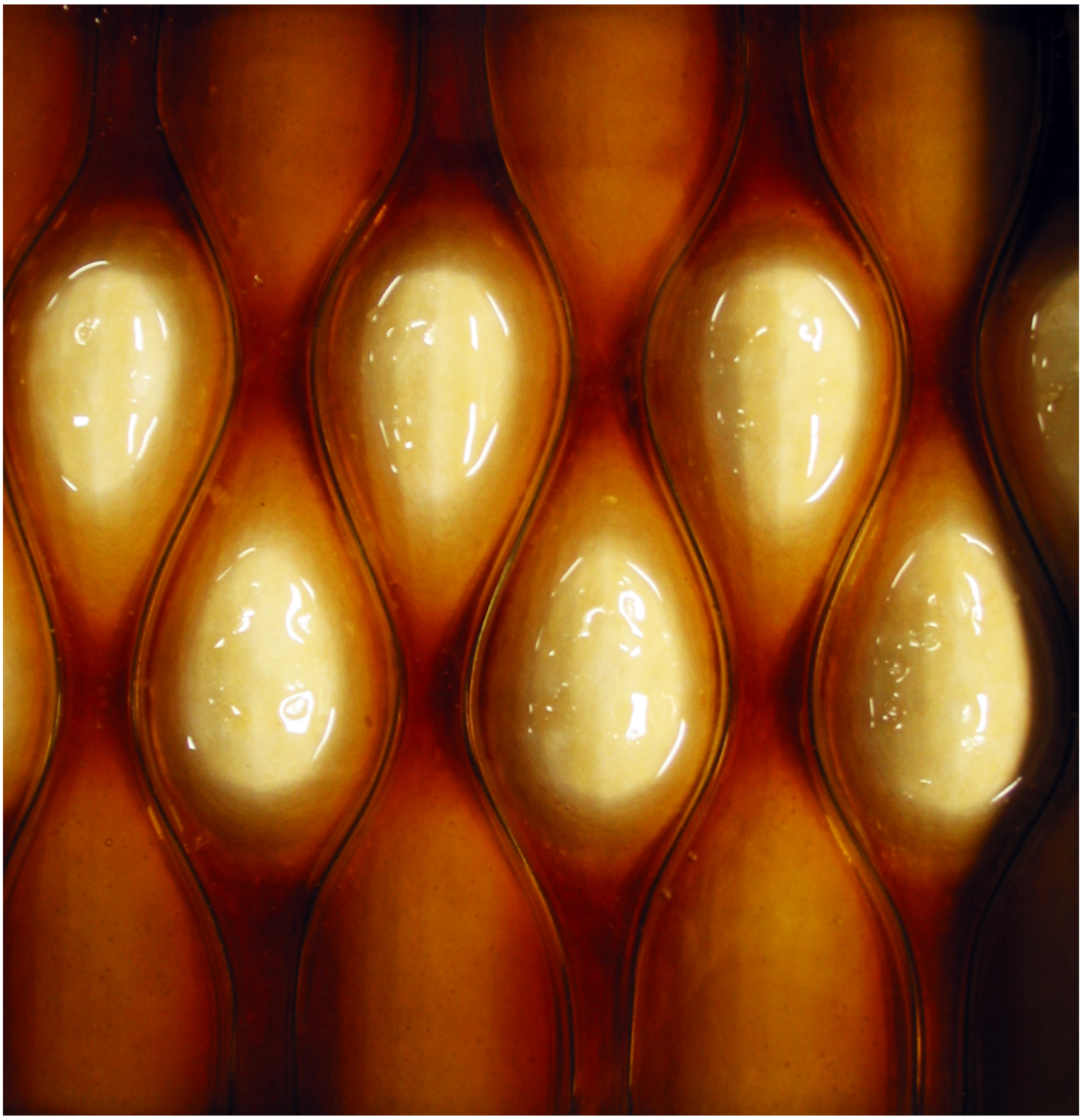


Figure 7.10: *Cartesian Wax*, early study model. In this model, metal wires are inserted into the skin to create a composite giving structural support to the soft skin. Resin is distributed based on geometrical features: regions of positive curvature are covered with thinner layers and regions of negative curvature are covered with thicker layers to explore the interaction between light transmittance properties of the surface and its structural integrity within one continuous material system.

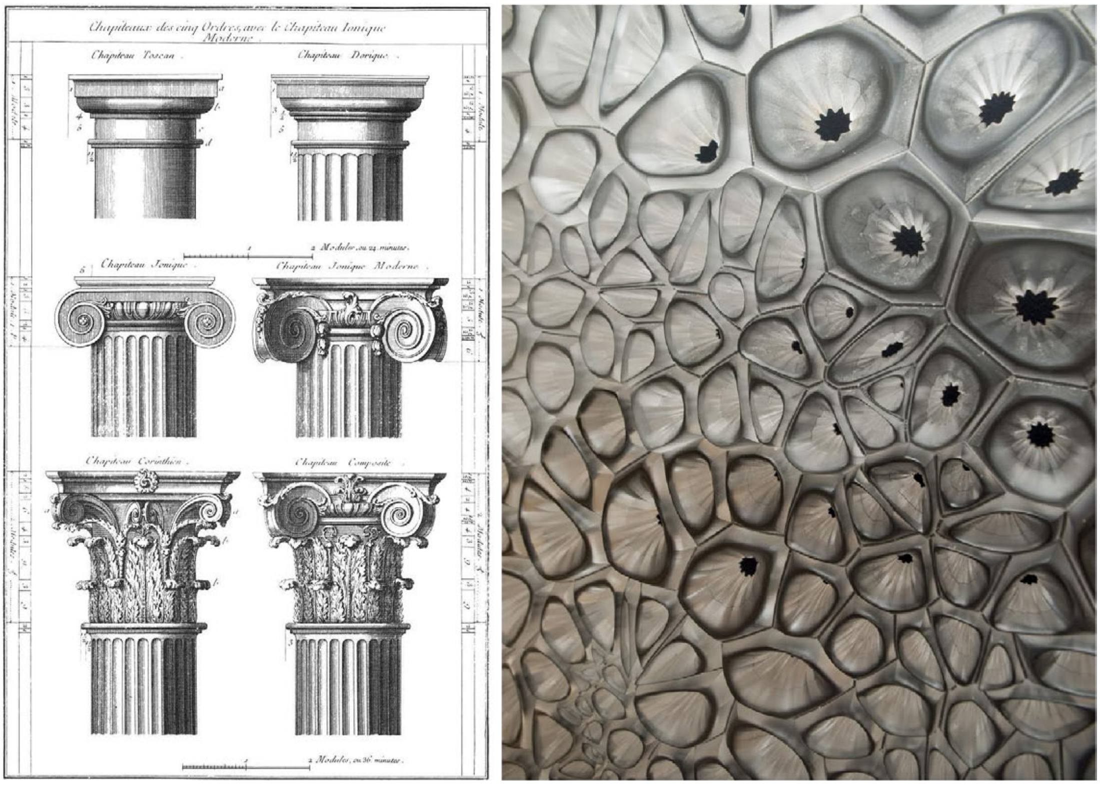


Figure 7.11: *Stalasso* (Plexiglas mold Resin composites, 2010, Boston Museum of Science) juxtaposed with an illustration of the three Greek column types representing the classical orders (Source: Encyclopedia Britannica). The typical shaft of a Doric column was fluted mainly for ornamentation purposes. “Fluting” refers to the shallow grooves running vertically along the cylindrical surface. Stalasso questions the role of “flutes” as structural elements, providing for local stiffeners to the vertical column in areas which tend to buckle. Right photograph: ©Emily Roose, courtesy Museum of Science Boston

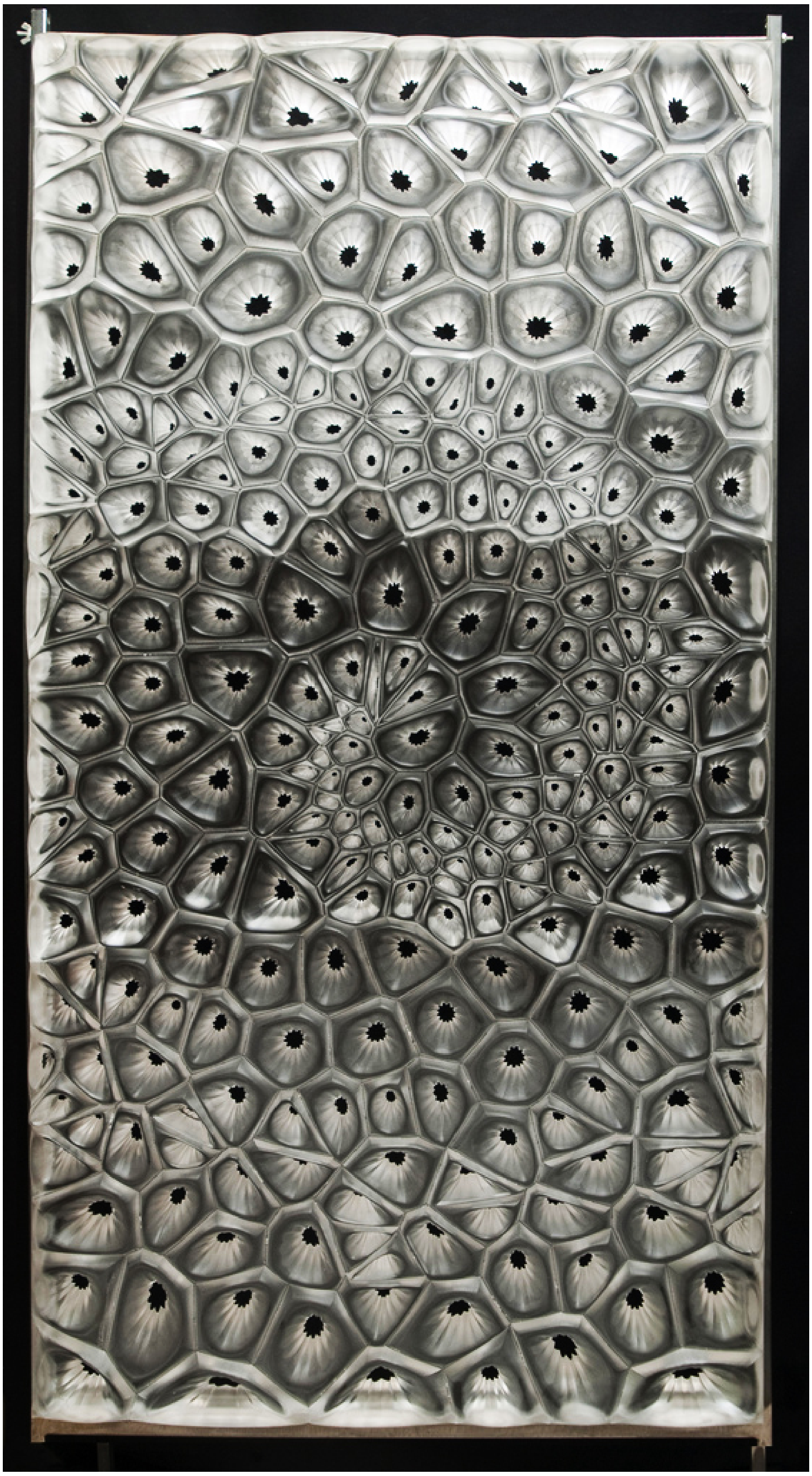


Figure 7.12: Stalasso (Plexiglas mold Resin composites, 2010, Boston Museum of Science, Collection). Image of the Plexiglas mold, designed as a “forrest” of fluted columns arranged in a Fibonacci sequence. Work in progress, currently at the Museum of Science. Photograph: © Emily Roose, courtesy Museum of Science Boston

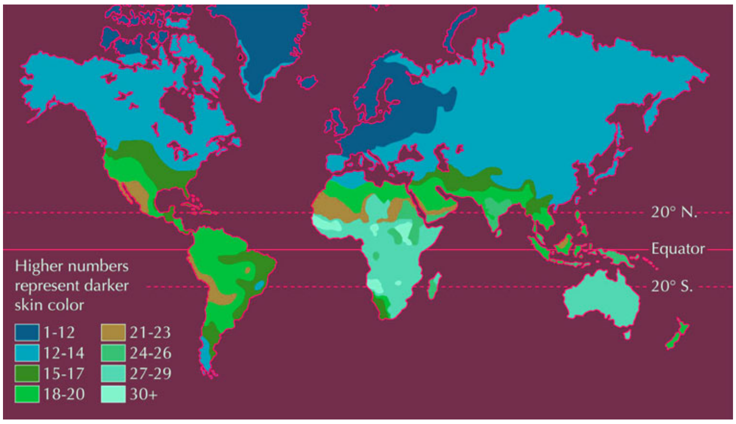


Figure 7.13: Variation in human skin color is associated with levels of UV irradiation, which are higher near the equator. Modified from Barsh, G. S., PLosS Biol. 1:019, 2003 Public Library of Science. Human skin variation is regarded as a fitness function, optimized and customized to the human's environment. Highly-customized form-generation processes operate in a similar fashion. In the cases below we explore variation in material property as a function of site-specific climatic conditions.

Figure 7.14: *Subterrain*. Images of 3 the physical models reconstructed in composite wood based on the OOF analysis. Each physical tissue (from left to right: leaf, scorpion paw, and a butterfly wing scale) was analyzed and reconstructed in 3 dimensions corresponding to pre-defined hypothetical environmental conditions. Fiber orientation and density are defined by the simulation.

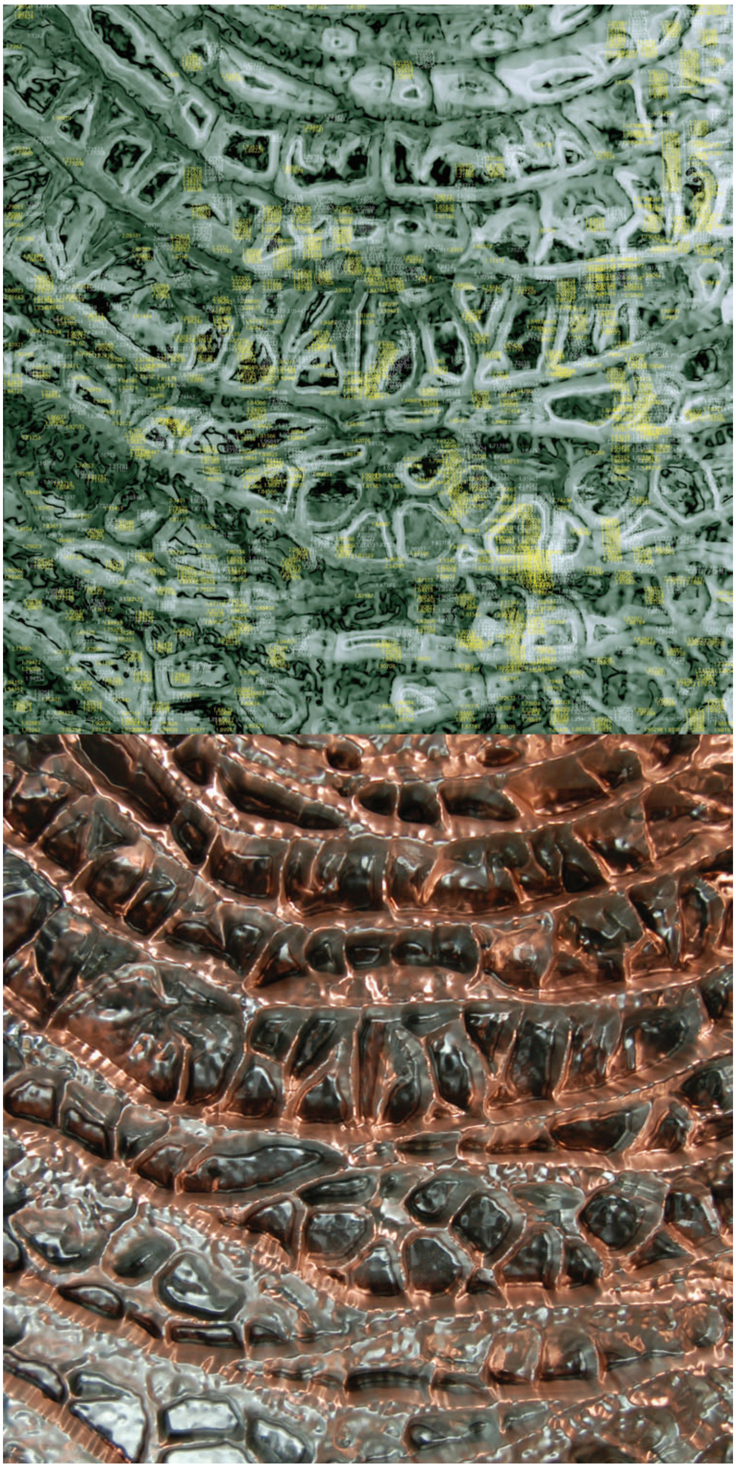


Figure 7.15: $|X, Y, Z, S, S, T|$ (Pronounced "exist", aluminum and low carbon steel composites, 2008, Museum of Science Boston). Variable property analysis and fabrication of natural specimens. The model incorporates 6 dimensions including 2-D information (X, Y), out of plane deformation (Y), elastic stress (S), strain (S) and temperature flux (T). The tissue is reconstructed using a CNC mill and metal/steel composites. In this case material layering strategies are employed for areas requiring structural stiffness as defined by the designer. Top: computational analysis performed on physical tissue. Bottom: physical model. CNC milling by *Airborne* technologies, CA, USA

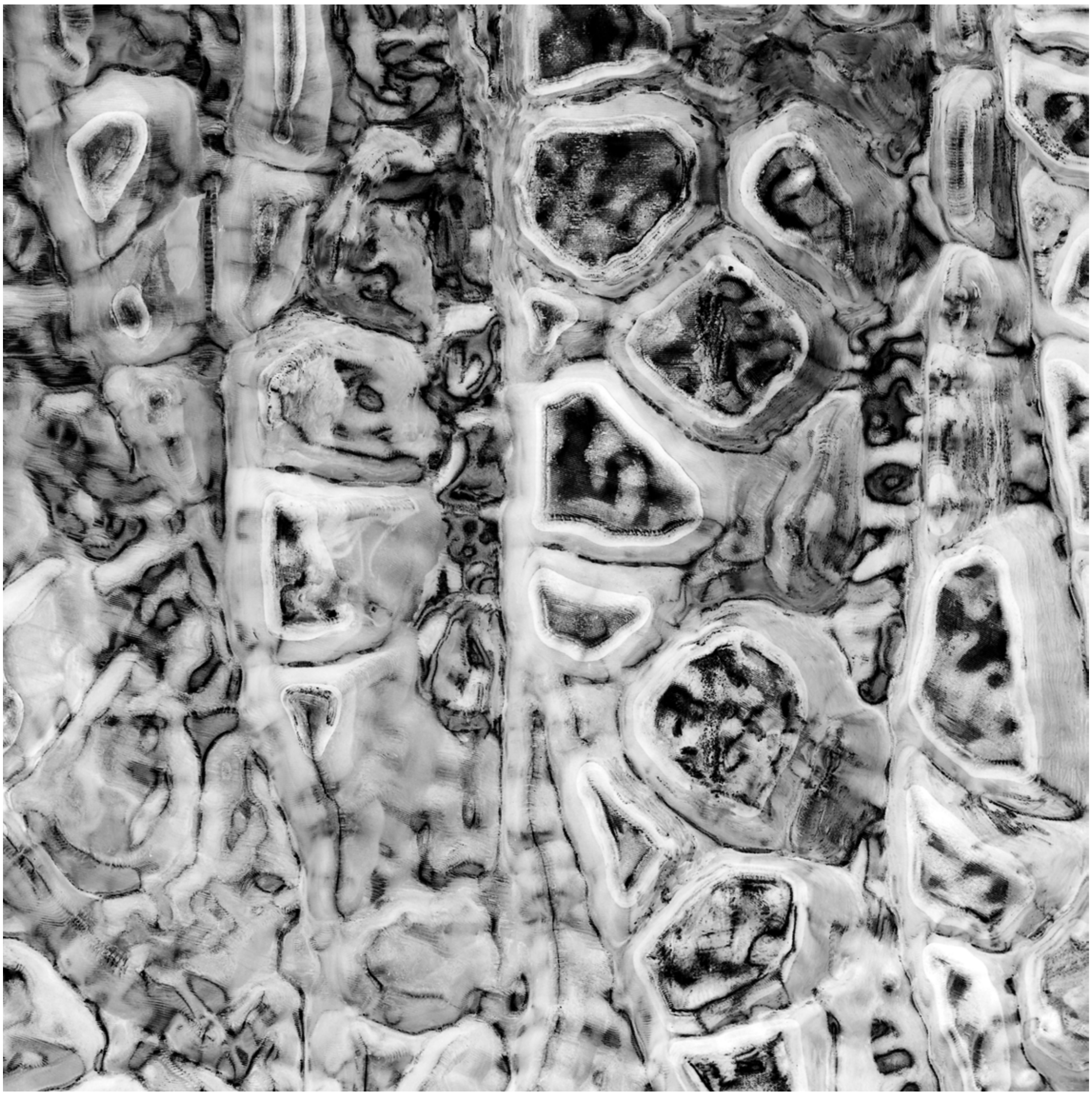


Figure 7.16: $|X, Y, Z, S, S, T|$. Detail of physical model.

Figure 7.17: *Fatemaps*. Multi-colored 3-D printed composite resin models: overall (top), detailed (middle), and elevation (bottom) views. Colors represent variations in material property corresponding to hypothetical environmental conditions.

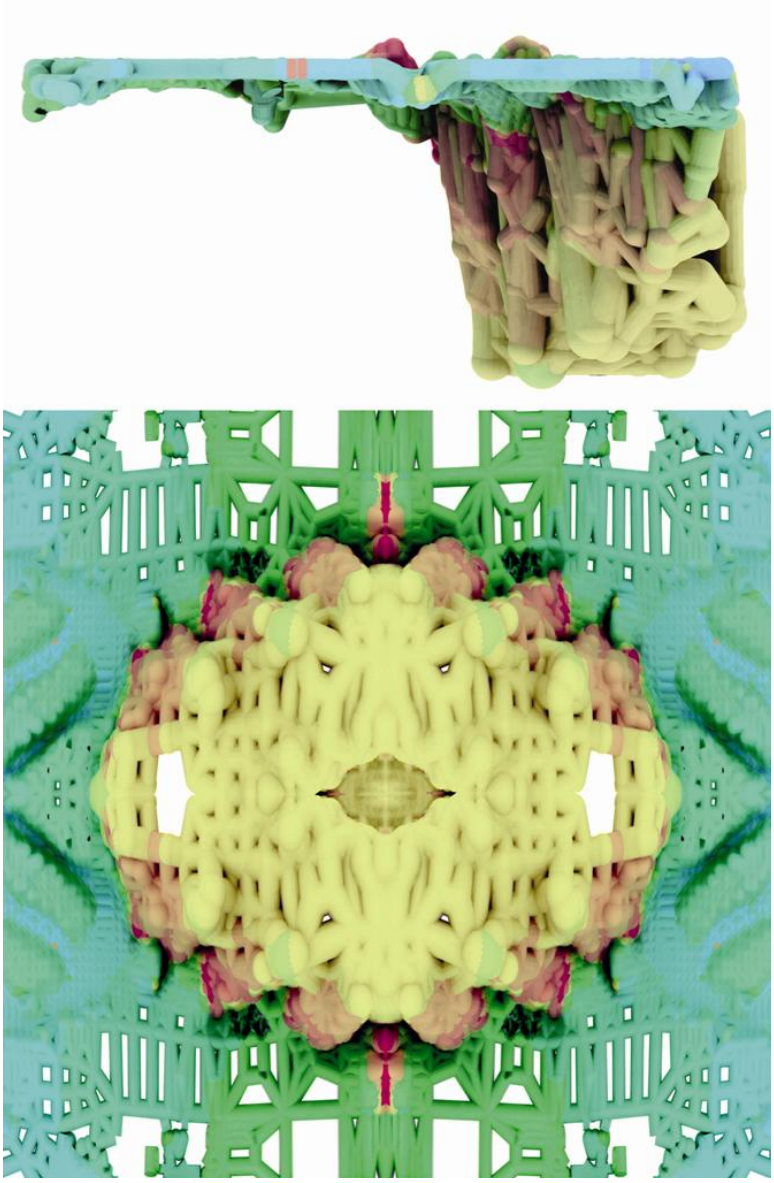


Figure 7.18: *Fatemaps*. digital models of elevation (top), and top (bottom) views. Colors represent variations in material property corresponding to hypothetical environmental conditions.

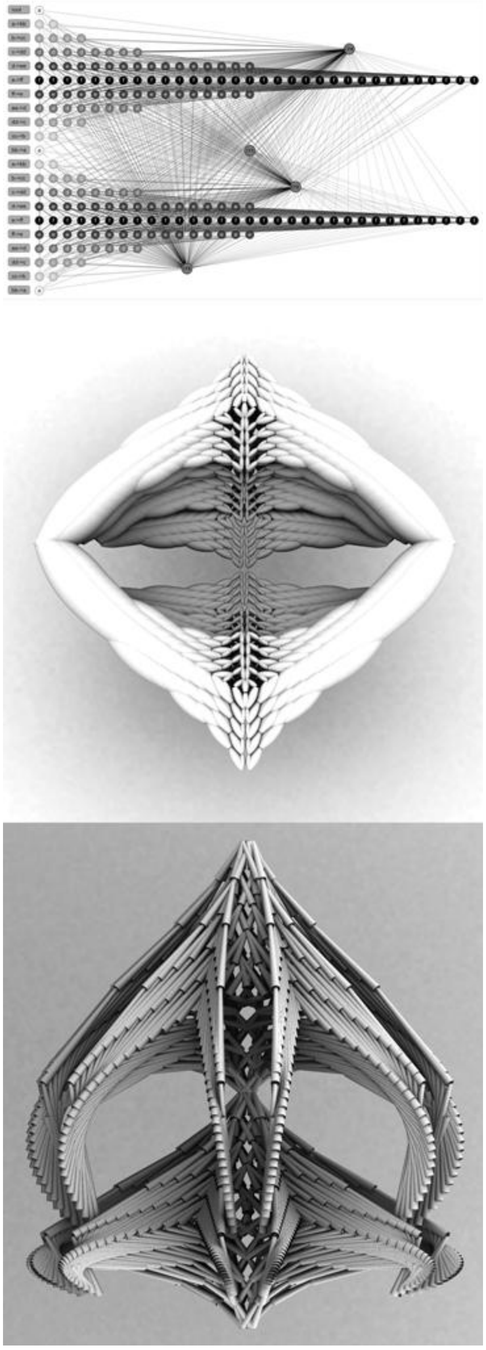


Figure 7.19: *Tropisms*: light-responsive structural systems and logic dependency graph illustrating parametric association between physical features and environmental conditions. The model was generated using the *Generative Components* software.

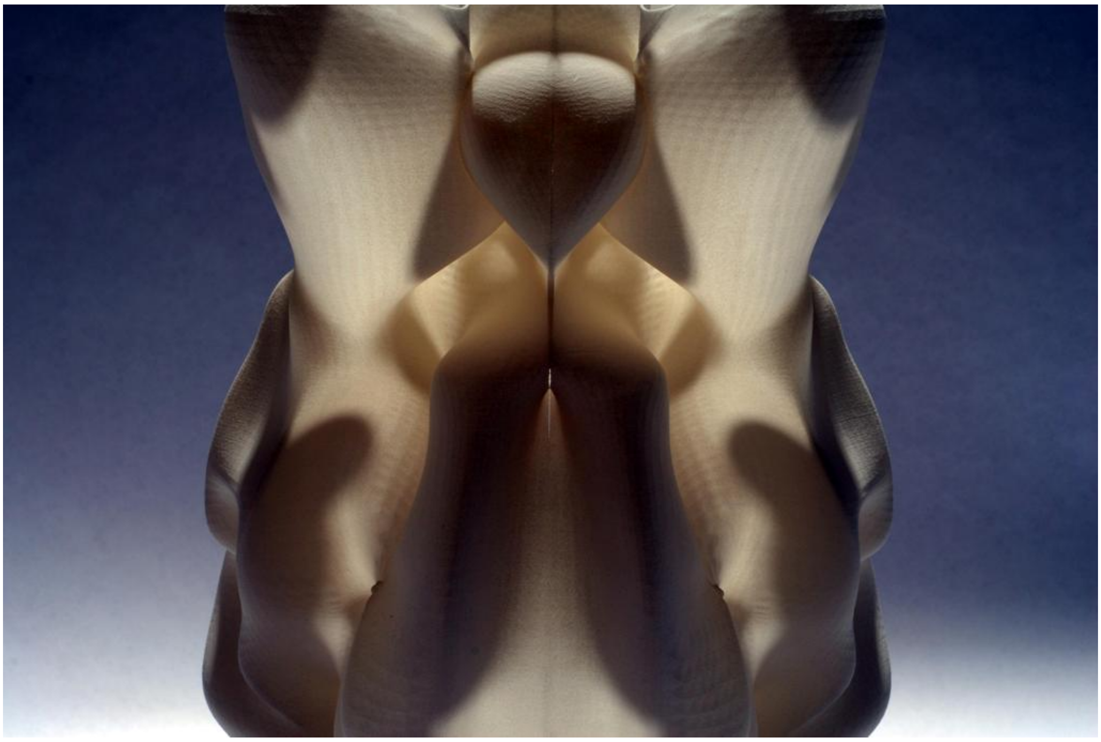


Figure 7.20: *Raycounting*, 2007, Museum of Modern Art, NY (permanent collection). Raycounting is a method for originating form by registering the intensity and orientation of light rays. 3-D surfaces of double curvature are the result of assigning light parameters to flat planes. The algorithm calculates the intensity, position and direction of one, or multiple, light sources placed in a given environment and assigns local curvature and material stiffness values to each point in space corresponding to the reference plane, the light dimension and structural stability requirements. Material thickness and properties assignments are informed relative to the light conditions and graduation of translucency as required and defined by the designer.

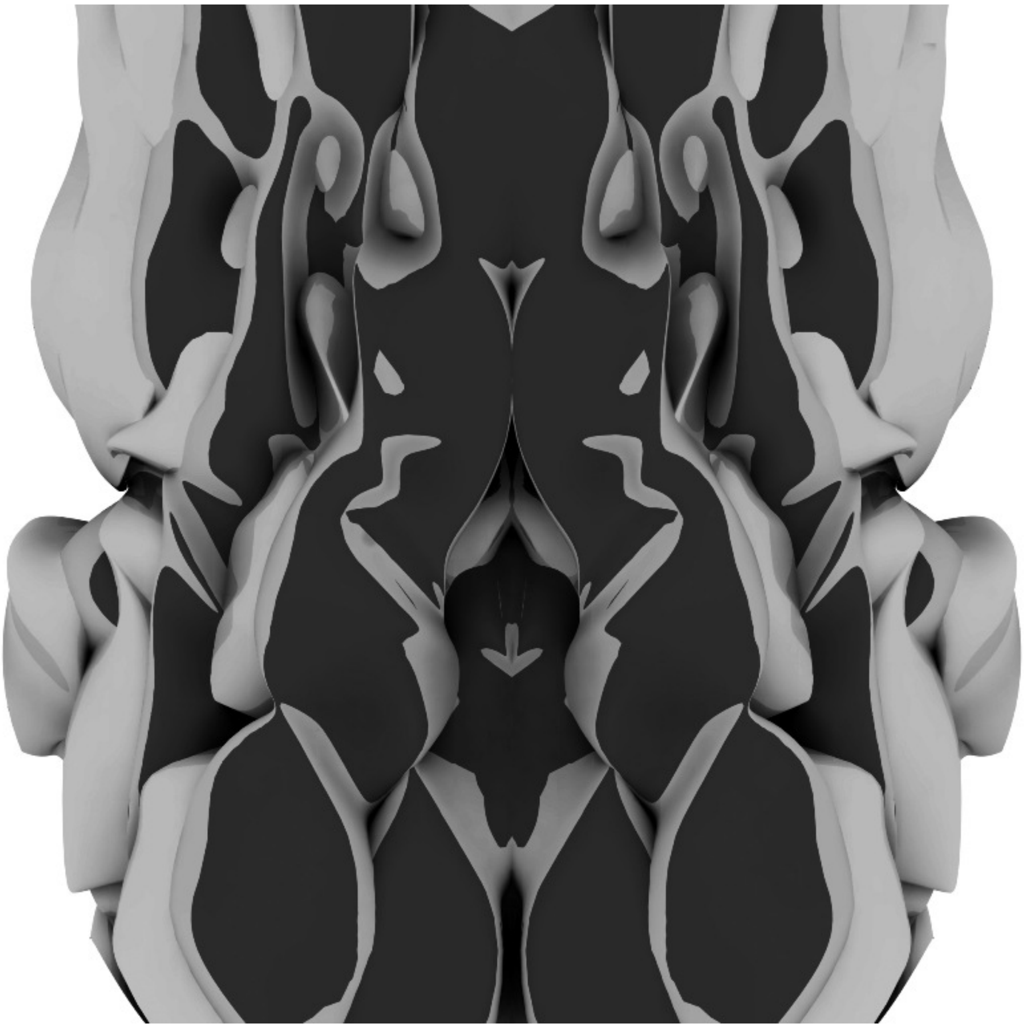


Figure 7.21: *Raycounting*, 2007, Museum of Modern Art, NY (permanent collection). Digital model demonstrating translucency as a function of light distance and direction represented by color range.

Figure 7.22: Raycounting, 2007, Museum of Modern Art, NY (permanent collection). The physical model demonstrates the interaction between structural parameters and light parameters. Two surfaces form structural “pockets” to provide for support where required, and unite to one continuous surface, to allow for light absorption where required.

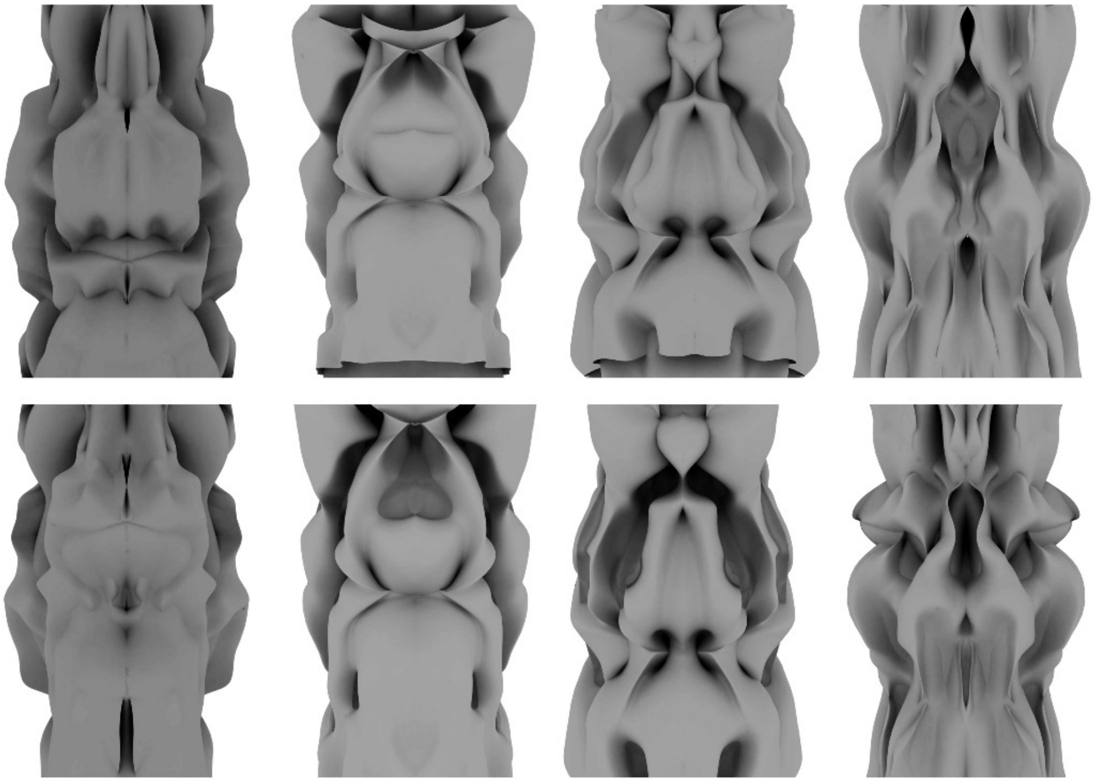
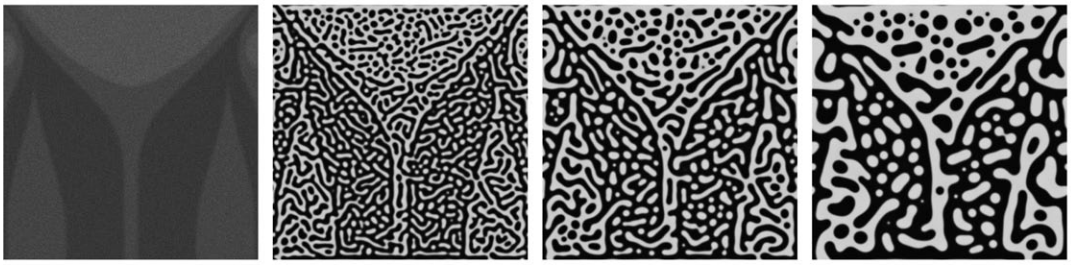


Figure 7.23: Raycounting, 2007, Museum of Modern Art, NY (permanent collection). Raycounting demonstrates that design based on performance parameters results in the generation of processes rather than the direct generation of design products. Here, the main idea was to reconsider local environmental conditions as the site for a particular design intervention. The form of the objects is defined by parameters such as light intensity, magnitude, direction, and illumination. Various types are generated.

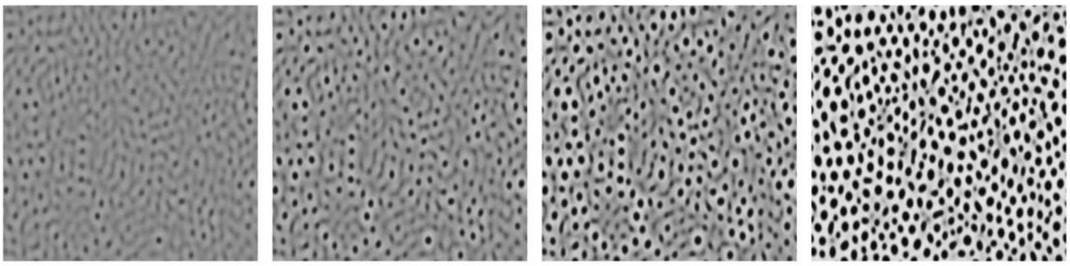
Figure 7.24: *Beast*. Prototype for a Chaise Lounge, 2008, Boston Museum of Science. The chaise combines structural, environmental and corporeal performance by adapting its thickness, pattern density, stiffness, flexibility and translucency to load, curvature, and skin-pressured areas respectively. It is patterned with 5 different materials color-coded by elastic moduli. Stiff (darker colored) and soft (lighter colored) materials are distributed according to the user's structural load distribution; Soft silicon "bumps" are located in regions of higher pressure.

Figure 7.25: *Beast*. Prototype for a Chaise Lounge, 2008, Boston Museum of Science. When placed right side up, property patterns appear as stiffer materials, characterized by darker colors, are placed in vertical regions (susceptive to buckling) and softer materials, characterized by lighter colors, are placed in horizontal regions (susceptive to bending).

Figure 7.26: Prototype for a Carpel Tunnel Syndrome Splint, 2008, Boston Museum of Science. Physical model of prototype. In this particular prototype, stiff materials constrain the lateral bending motion at the wrist, and can be identified by the oblique trajectory of dark and stiff materials. Soft materials allow for ergonomic wrist support and comfort through movement.



Full 2 Material Set: Evolutionary Stage **01** **Full** 2 Material Set: Evolutionary Stage **02** **Full** 2 Material Set | Evolutionary Stage **03** **Full |** 2 Material Set | Evolutionary Stage **04**



Partial 3 Material Set: Evolutionary Stage **01** **Partial** 3 Material Set: Evolutionary Stage **02** **Partial** 3 Material Set: Evolutionary Stage **03** **Partial |** 3 Material Set | Evolutionary Stage **04**

Figure 7.27: Carpal Skin. Prototype for a Carpel Tunnel Syndrome Splint, 2008, Boston Museum of Science. Physical model of prototype. Material distribution charts illustrating a range of potential solutions informed by size, scale, direction and ratio between soft and stiff materials. The charts are computed on top of an optimized unfolded representation of the frontal and dorsal planes of the patient's hand and refolded following material assignment to construct the 3-D glove.

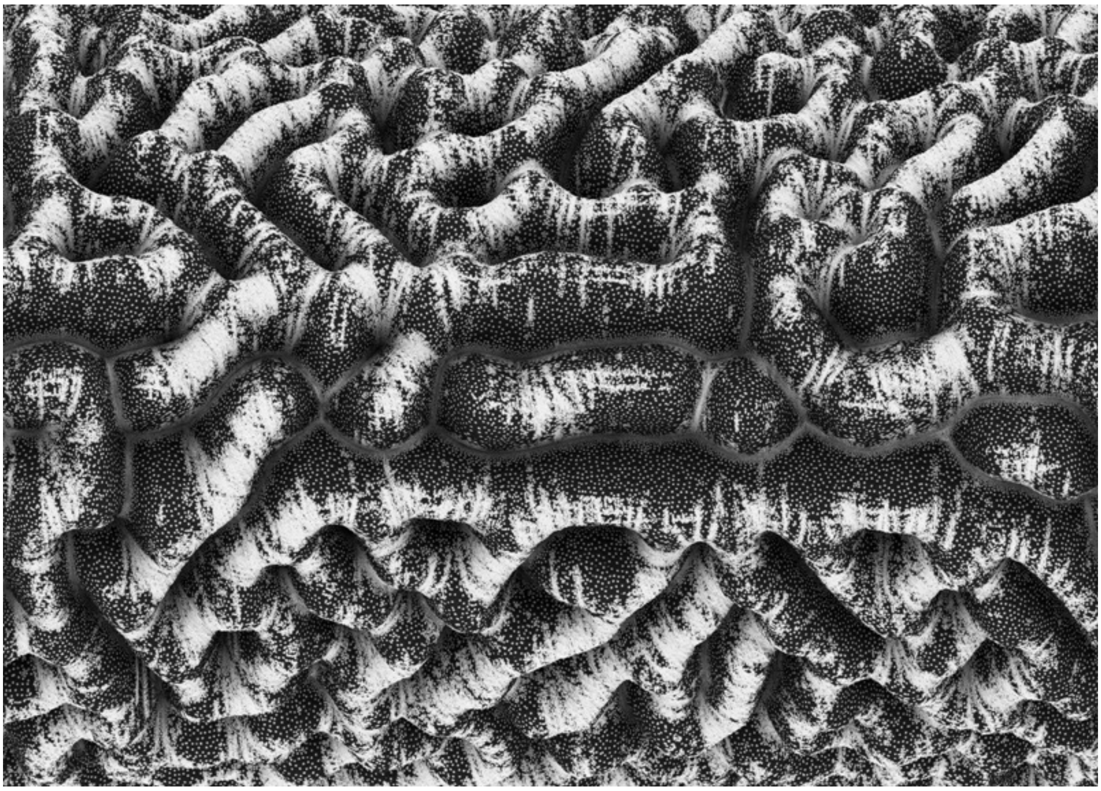


Figure 7.28: Carpal Skin. Prototype for a Carpel Tunnel Syndrome Splint, 2008, Boston Museum of Science. Detail illustrating the distribution of material properties as a function of movement constraint and control. The custom-fit property-distribution functions built into the glove allows for passive but consistent pulling and stretching simultaneously.

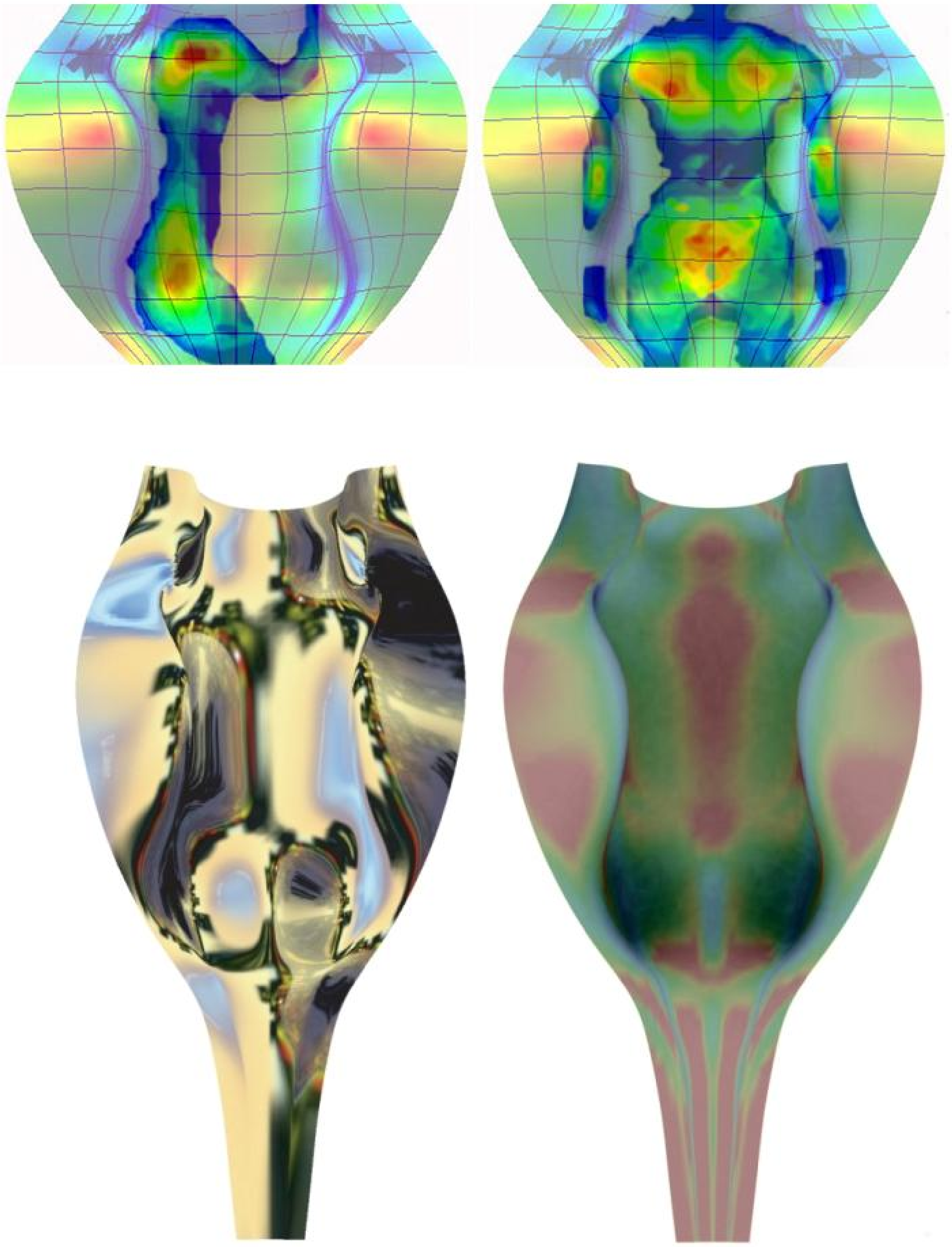


Figure 7.29: Beast. Prototype for a Chaise Lounge, 2008, Boston Museum of Science. The design of the Chaise Lounge is informed by material properties assigned to body pressure map registration, body form and body weight distribution. Color ranges mapped on the body and the surface area of the Chaise represent the distribution of material properties (from stiff to soft) negotiated to fit both structural and physical comfort requirements. The top images represent pressure maps; the bottom images represent degree of curvature mappings.

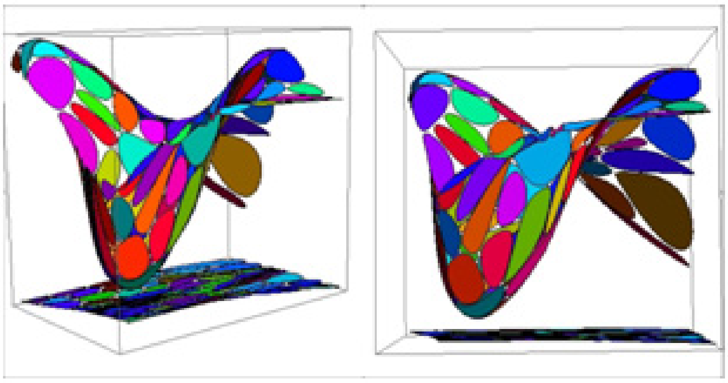


Figure 7.30: Example of Voronoi construction with a vertical projection. The tile-squeezing correlates to angle between the surface normal and the projection vector.

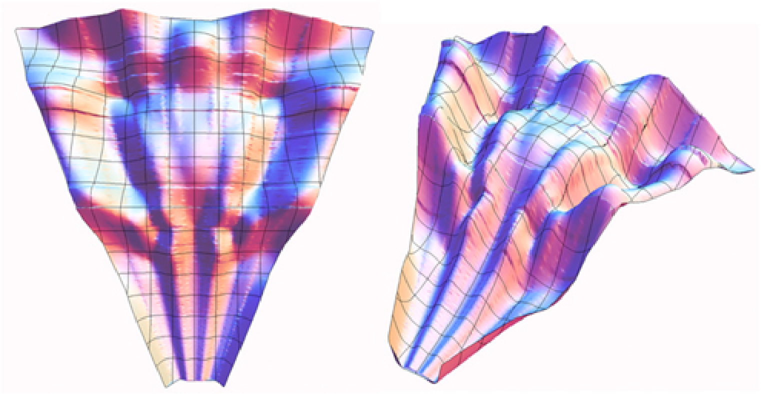


Figure 7.31: Beast. Prototype for a Chaise Lounge, 2008, Boston Museum of Science. Point cloud density representation indicating load distribution as mapped from the curvature analysis. The height value for each point on the surface represents curvature values in UV space for which a voronoi discretization algorithm is applied and material properties assigned.

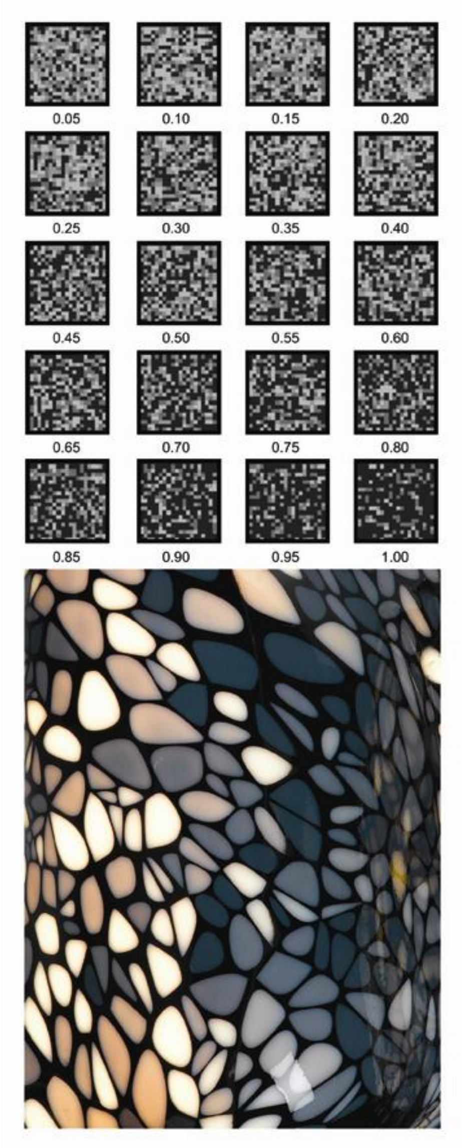


Figure 7.32: Beast. Prototype for a Chaise Lounge, 2008, Boston Museum of Science. Bottom: Detail of 3-D physical construction and material weighing charts. Stiffer materials (distributed in vertical regions under compression) are dark while softer materials (distributed in horizontal regions under tension) are translucent. Top: Material weighing chart. The elastic-modulus of each component is defined relative to the comfort level defined by the user and the average amount of force exerted per unit area. An algorithm then assigns one out of five materials for physical construction.

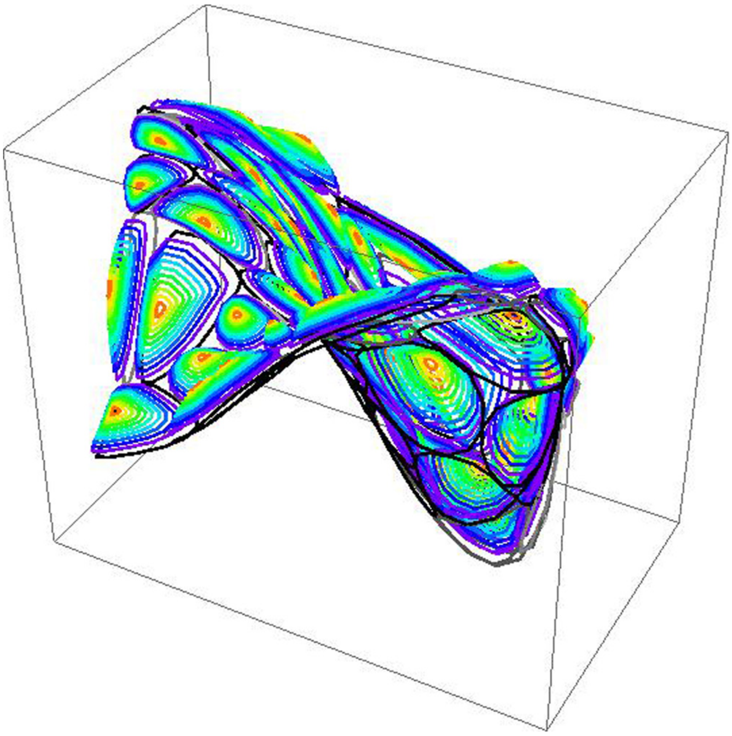


Figure 7.33: Weighted material selection: a stochastic computational process assigns a stiffness ratio corresponding to environmental performance. The relative height of the soft silicon bumps corresponds to the body pressure mappings.

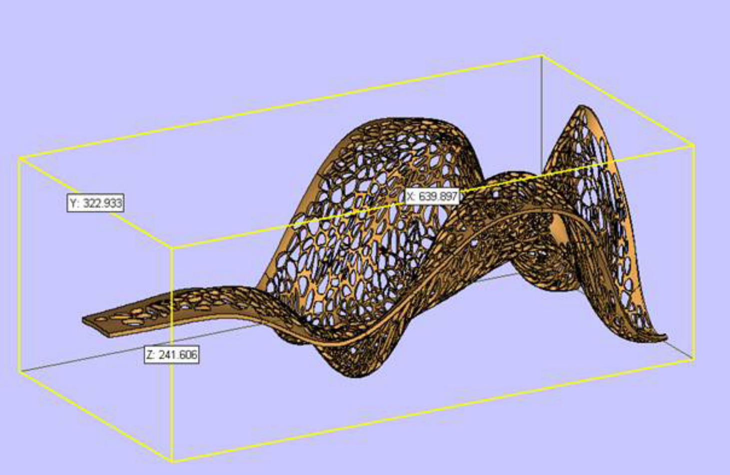


Figure 7.34: 3-D assembly model comprised of 32 sections for multi-material printing.

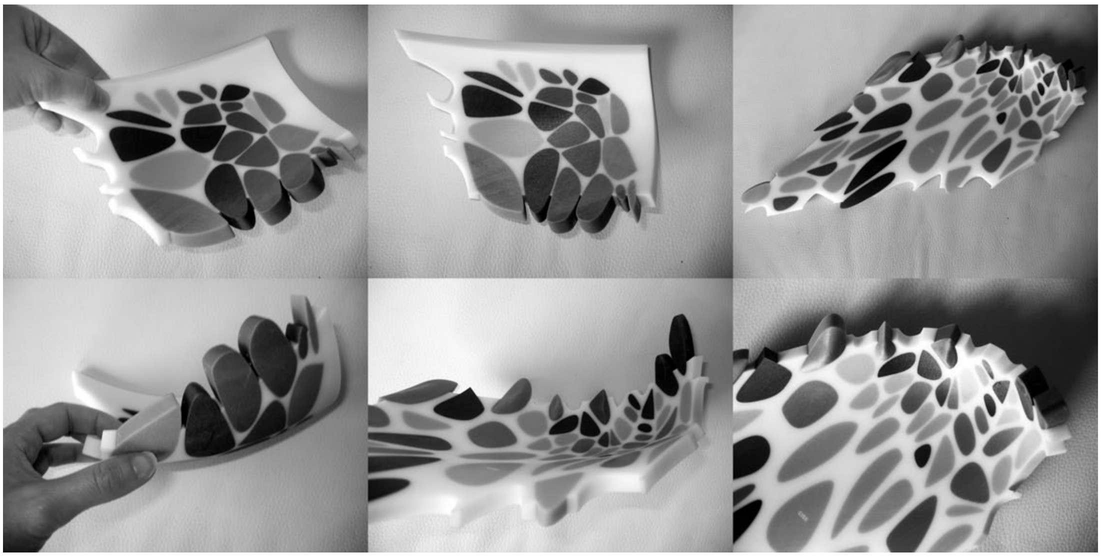


Figure 7.35: 3-D printed parts illustrating assembly logic

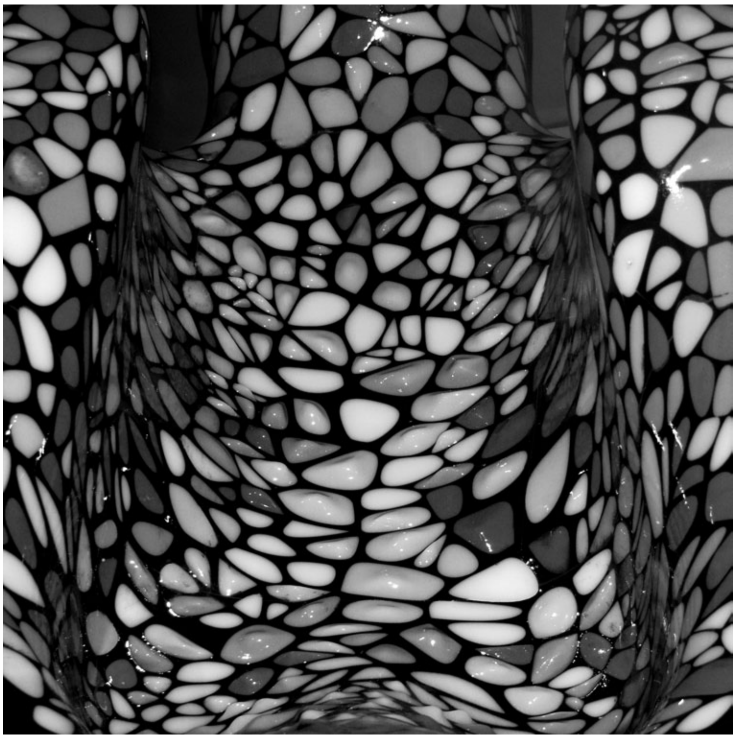


Figure 7.36: *Beast*, final assembly.

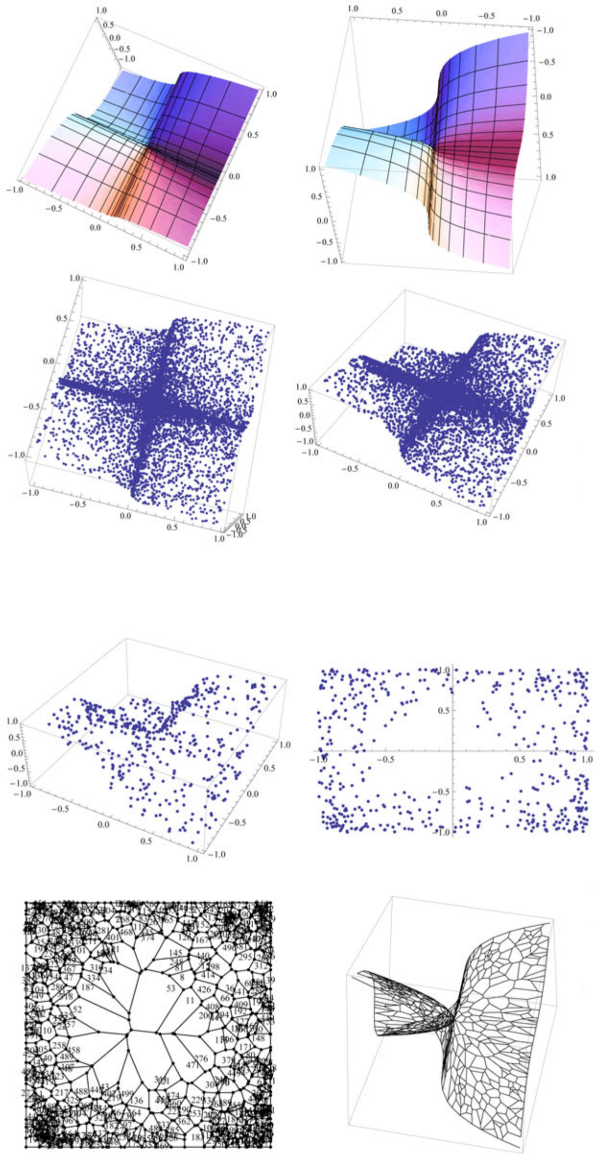


Figure 7.37: From top to bottom: Example surface to test UV squeezing; Example point cloud producing UV-squeezing. Note that point density increases in regions of high “squeezing” levels; Bottom images illustrate the solution to the “squeezing” problem: uniform point cloud on 3-D surface is a non-uniform cloud on the UV plane. The voronoi construction on the UV plane produced odd-looking call on UV-plane but a uniform voronoi on the 3-D surface

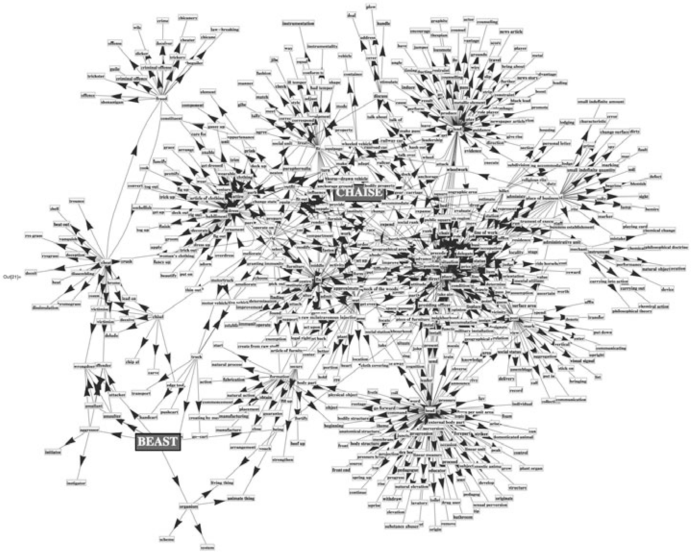
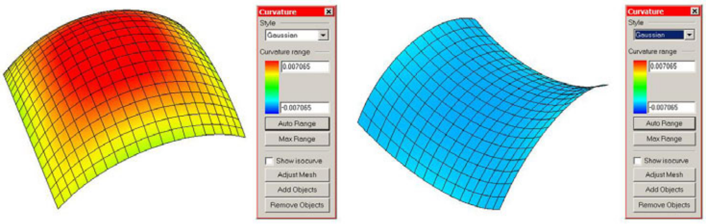


Figure 7.38: Beast, mapping of experimental design process.

Figure 7.39: *Raycounting*, 2007, Museum of Modern Art, NY (permanent collection). The project negotiates between structural performance criteria (self-stabilization of doubly curved surface) and light performance criteria.



Curvature

Style: Gaussian

Curvature range: 0.007065 / -0.007065

Figure 7.40: Left: Surface with positive Gaussian curvature (synclastic). The surface is bowl-like. Right: Surface with negative Gaussian curvature (anticlastic). The surface is saddle-like.

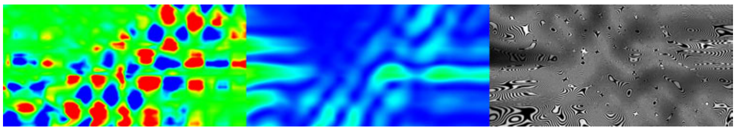


Figure 7.41: Multi-objective representation: Visual NURBS surface analysis tools. Left: Curvature analysis (used to evaluate curvature). Middle: Draft-Angle analysis (used to evaluate curvature in relation to viewing point). Right: Zebra analysis (used to evaluate surface smoothness).

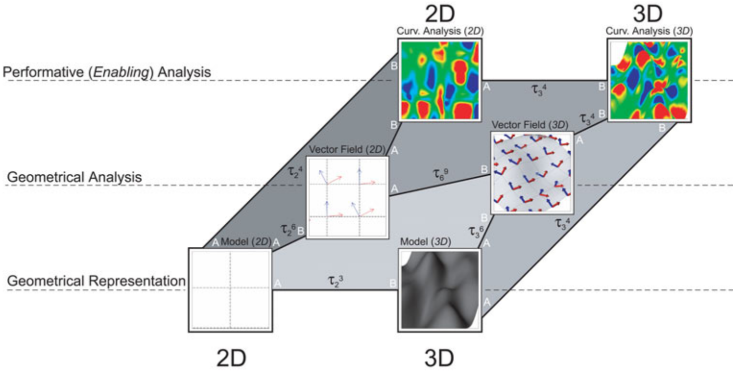


Figure 7.42: Computational geometry reciprocal transformations diagram: the diagram illustrates 2D (left) and 3D (right) representations from bottom to top and increasing in complexity, from the basic descriptive geometrical representations (bottom), to forms of analysis (middle) and performative-enabling analysis representations (top).

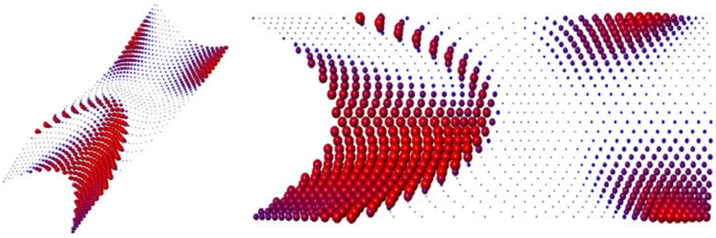


Figure 7.43: Curvature analysis reconstruction and thickness generation: the modeled surface is reconstructed as an array of spheres the size and color of which correspond to the degree of curvature mapped by the command.

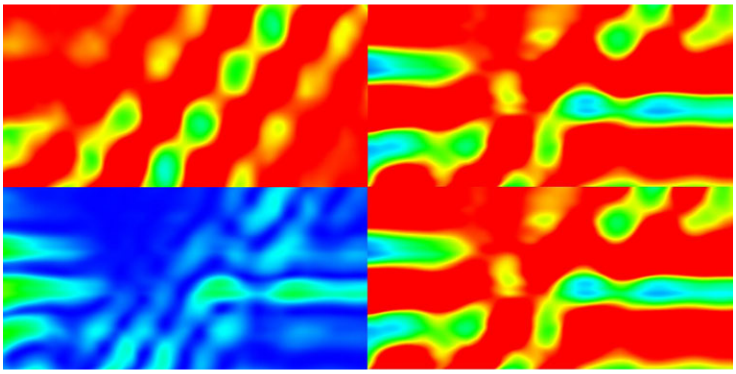


Figure 7.44: The Draft-Angle analysis command allows the user to evaluate surface curvature relative to angle of viewing point. The image is comprised of four analyses taken from four different views (top view, isometric view, and front and back elevations).

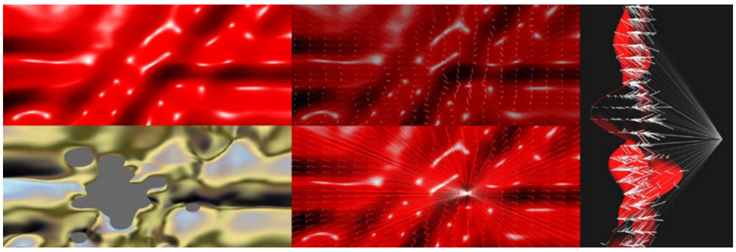


Figure 7.45: Composite image illustrating the phases of the draft angle analysis tool reconstruction and application: Left-top: Initial surface generated by user. Left-bottom: final result of tool application. Right images illustrate the process of vector re-parameterization and computation of light-source angle relative to the surface.

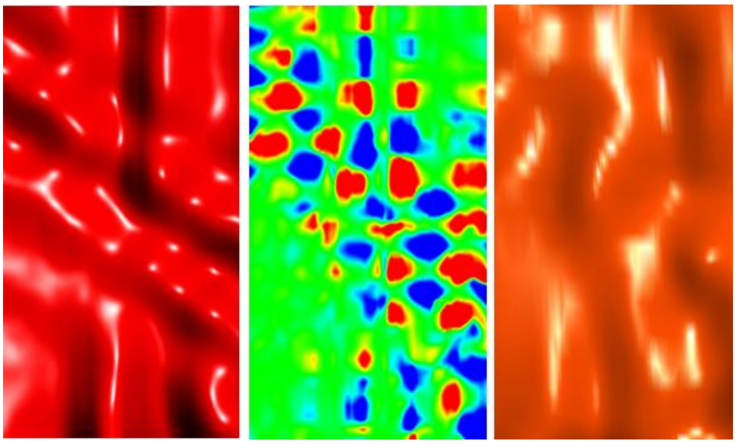


Figure 7.46: Curvature analysis tool reconstruction: Left: initial surface. Middle: Curvature analysis. Right: additional surface corresponding to distributed thickness function for structural support.

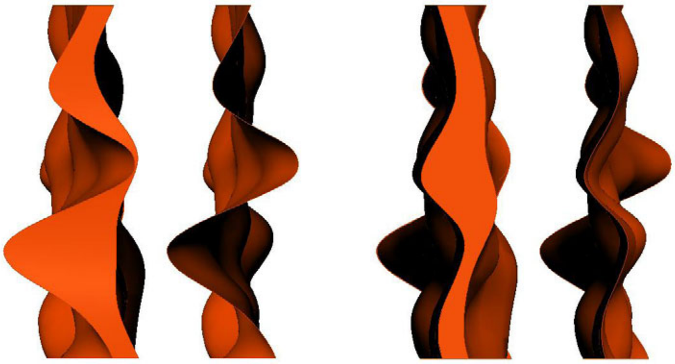


Figure 7.47: Initial and final elevation views of the surface with and without thickness. Left and right images illustrate the two elevations before and after the application of varied thickness corresponding to curvature mapping.

Figure 7.48: Elevation views of final *Raycounting* models demonstrating the two interacting surfaces. The interstitial space between the surfaces allows for the generation of “structural pockets” for support and for the modulation of light.

Figure 7.49: Elevation views of final *Raycoounting model*

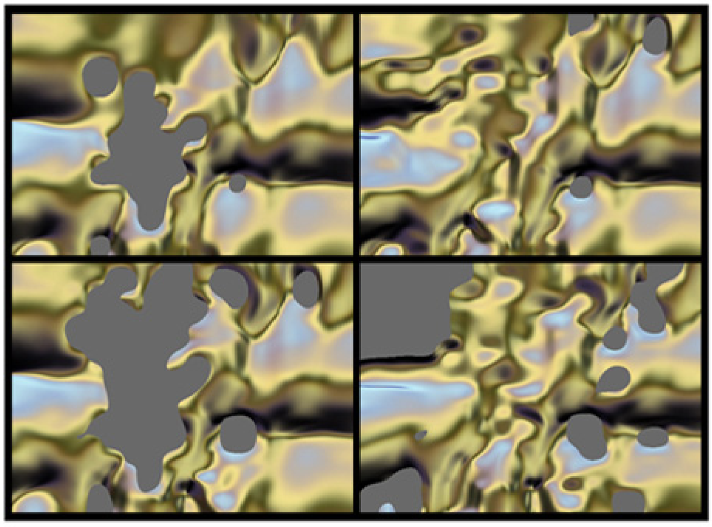


Figure 7.50: Composite image showing four results of four corresponding iterations of the draft-angle script. The holes in the surface are generated when the angle between the light source and the surface approaches a minimal threshold value defined by the user. Following this, the surface is thickened locally corresponding to curvature values to allow for the differentiated thickness of the surface in its entirety to correspond to both intensity and directionality of light source.

Figure 7.51: Composite image showing four results of four corresponding iterations of the draft-angle script. The holes in the surface are generated when the angle between the light source and the surface approaches a minimal threshold value defined by the user. Following this, the surface is thickened locally corresponding to curvature values to allow for the differentiated thickness of the surface in its entirety to correspond to both intensity and directionality of light source.

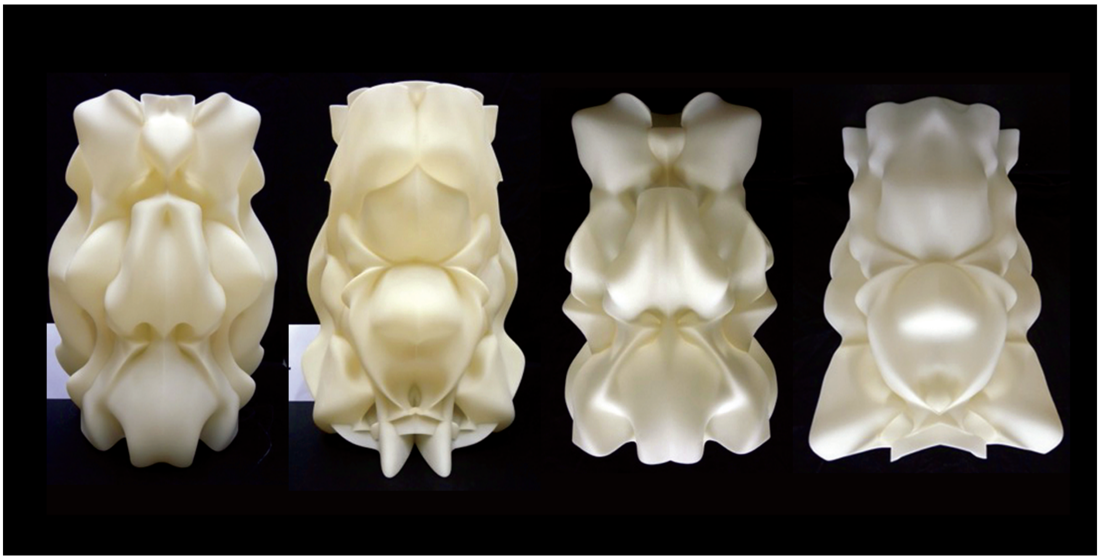


Figure 7.52: Composite image digital (top) and physical (bottom) results of four corresponding iterations of the draft-angle script. The holes in the surface are generated when the angle between the light source and the surface approaches a minimal threshold value defined by the user. Following this, the surface is thickened locally corresponding to curvature values to allow for the differentiated thickness of the surface in its entirety to correspond to both intensity and directionality of light source.

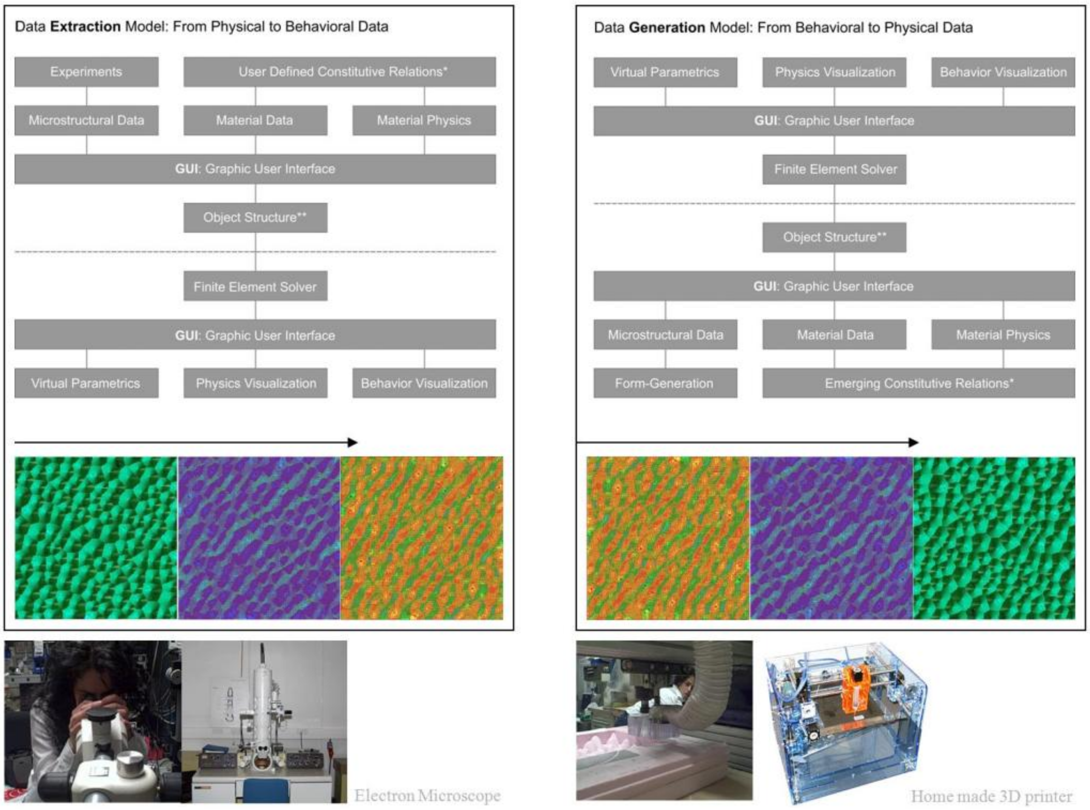


Figure 7.53: Subterrain, process chart.

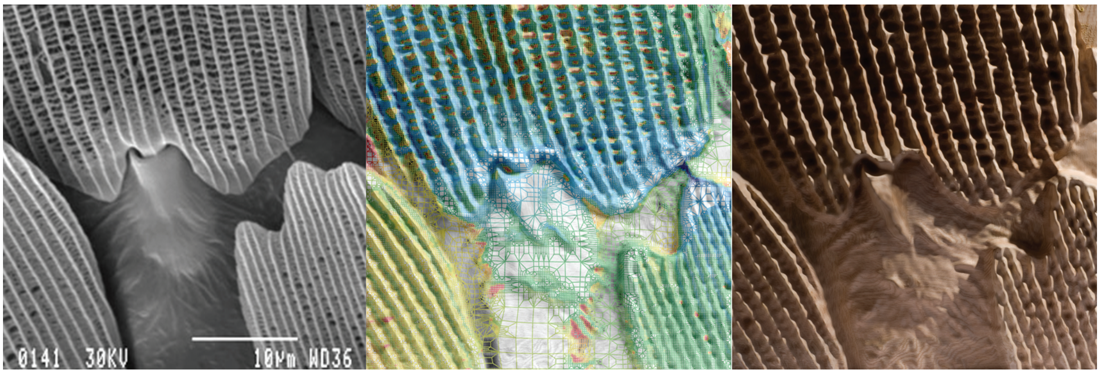


Figure 7.54: *Subterrain*, 2007, Museum of Modern Art, NY (Permanent Collection). Variable property analysis and fabrication of a butterfly wing. An object-oriented application (OOF2) determines the material's behavior according to stress, strain, heat flow, stored energy and deformation due to applied loads and temperature differences. The tissue is reconstructed using a CNC mill and wood composites. In this case fiber directionality assignment and layering strategies are employed for areas requiring structural stiffness as defined by the designer.

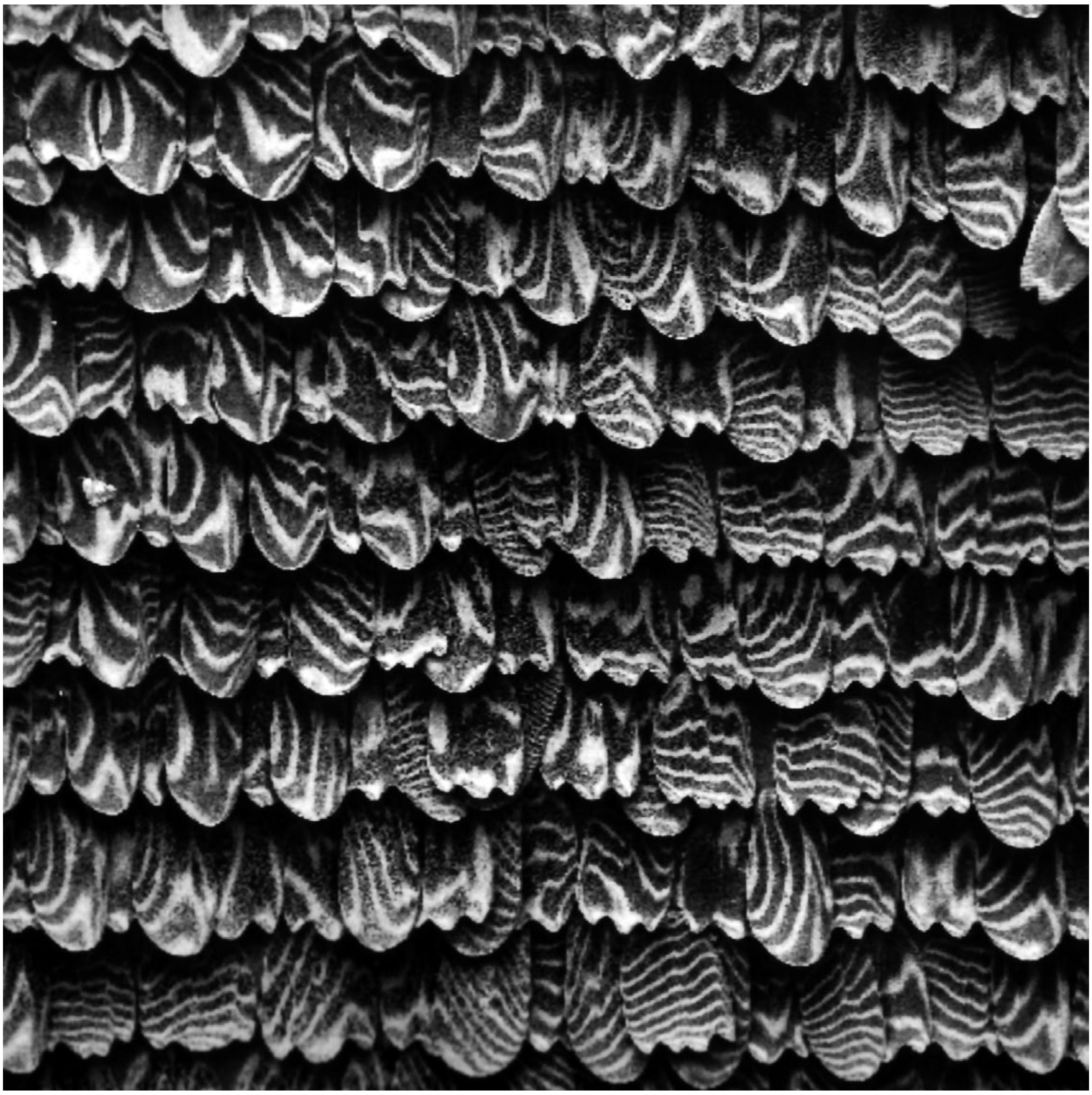


Figure 7.55: *Subterrain*, 2007, Museum of Modern Art, NY (permanent collection). Butterfly wing specimen.

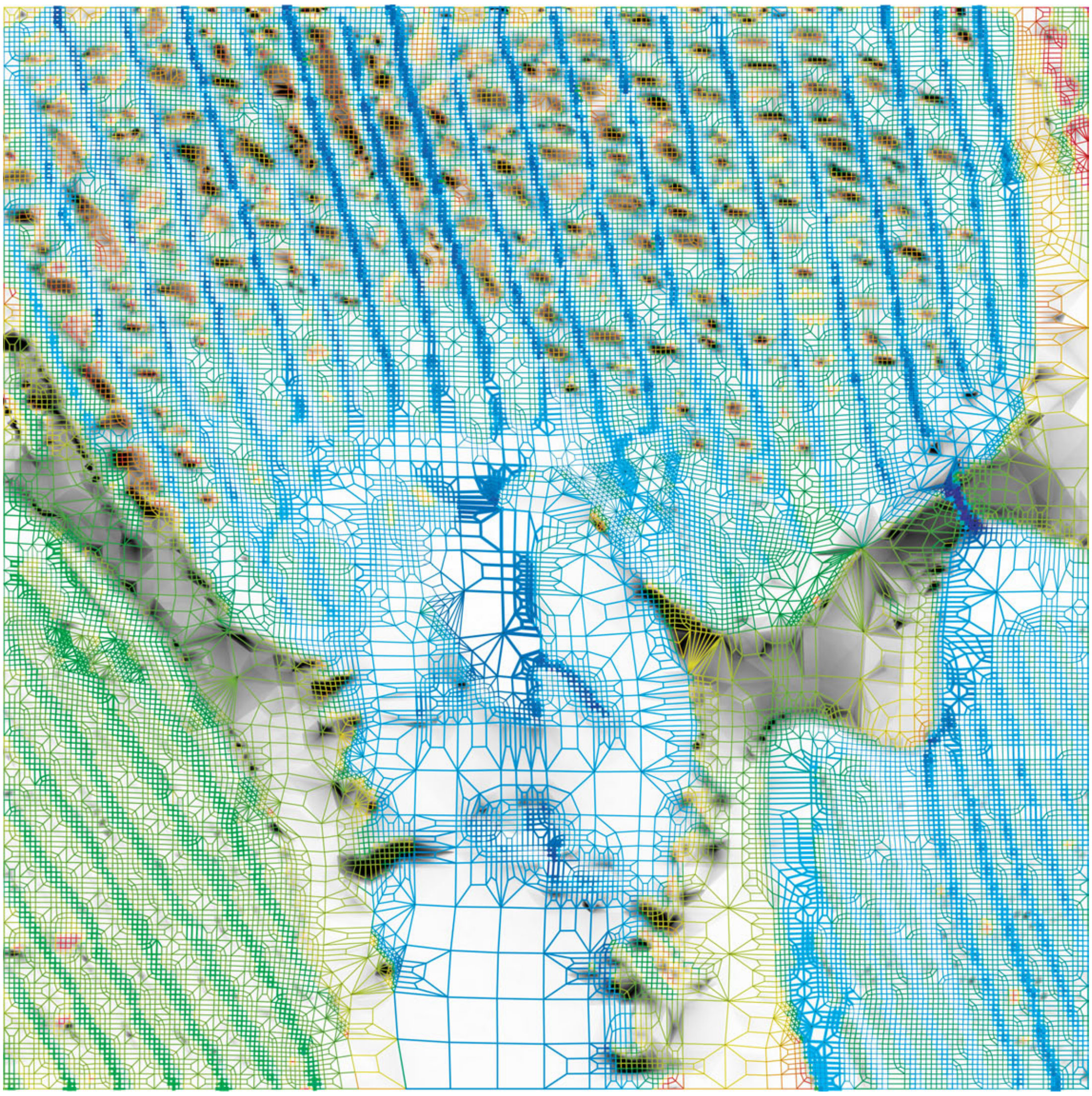


Figure 7.56: *Subterrain*, 2007, Museum of Modern Art, NY (permanent collection). The final models are six dimensional: the original image is a two dimensional object reflected in the density and morphology of the computed mesh, the out-of-image deformation produces the relief, elastic stresses produce the line-thickness, flux is encoded with color data, and stored energy is represented by superimposed numbers. Diagram detail.

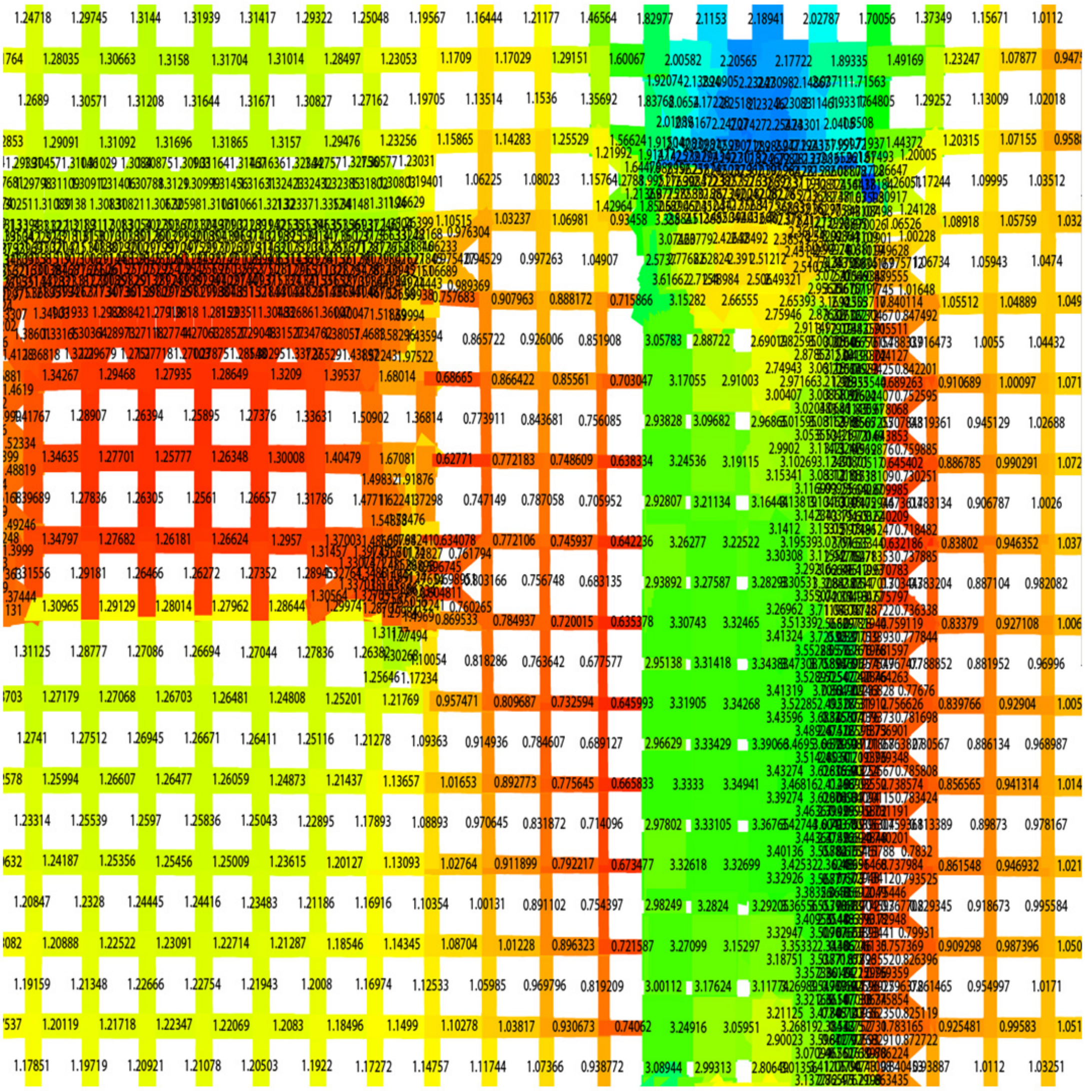
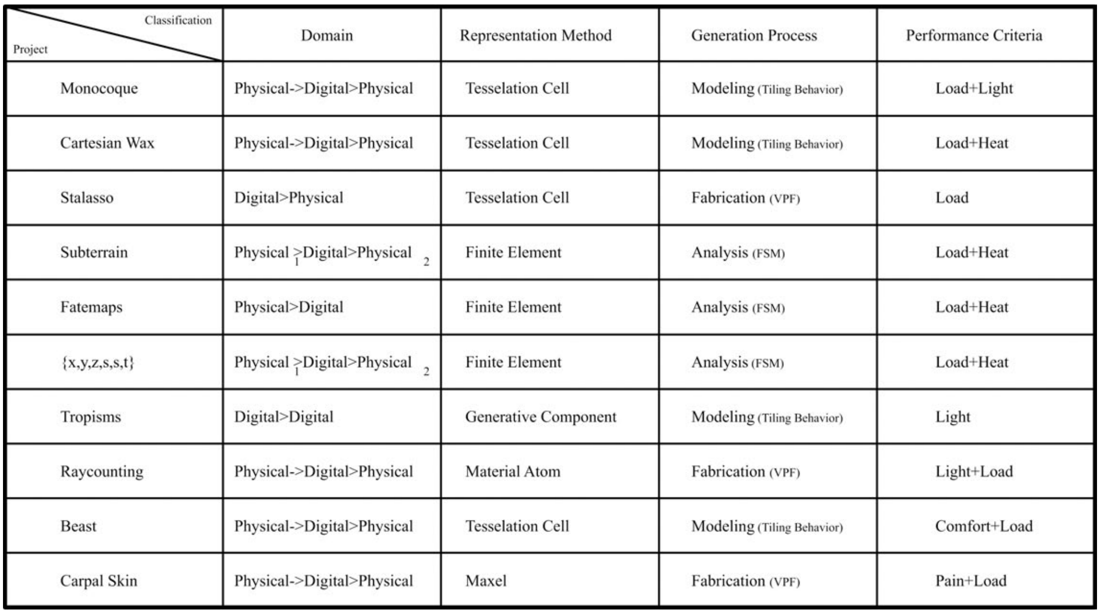


Figure 7.57: *Subterrain*, 2007, Museum of Modern Art, NY (permanent collection). The final models are six dimensional: the original image is a two dimensional object reflected in the density and morphology of the computed mesh, the out-of-image deformation produces the relief, elastic stresses produce the line-thickness, flux is encoded with color data, and stored energy is represented by superimposed numbers. Diagram detail.



Classification Project	Domain	Representation Method	Generation Process	Performance Criteria
Monocoque	Physical->Digital>Physical	Tesselation Cell	Modeling (Tiling Behavior)	Load+Light
Cartesian Wax	Physical->Digital>Physical	Tesselation Cell	Modeling (Tiling Behavior)	Load+Heat
Stalasso	Digital>Physical	Tesselation Cell	Fabrication (VPF)	Load
Subterrain	Physical$_1$>Digital>Physical$_2$	Finite Element	Analysis (FSM)	Load+Heat
Fatemaps	Physical>Digital	Finite Element	Analysis (FSM)	Load+Heat
{x,y,z,s,s,t}	Physical$_1$>Digital>Physical$_2$	Finite Element	Analysis (FSM)	Load+Heat
Tropisms	Digital>Digital	Generative Component	Modeling (Tiling Behavior)	Light
Raycounting	Physical->Digital>Physical	Material Atom	Fabrication (VPF)	Light+Load
Beast	Physical->Digital>Physical	Tesselation Cell	Modeling (Tiling Behavior)	Comfort+Load
Carpal Skin	Physical->Digital>Physical	Maxel	Fabrication (VPF)	Pain+Load

Figure 7.58: Design experiments classification chart

CHAPTER 8

NATURAL FABRICATION
Variable Property Rapid Prototyping Technology

> *"Every block of stone has a statue inside it and it is the task of the sculptor to discover it"*
>
> **— Michelangelo**

8.1 Introduction

8.1.1 Nature's Way

In his "On Growth and Form", D'Arcy Thompson postulates the general principles according to which the form of an organism is informed by complex phenomenon referred to as "growth". This process includes the direct actions of certain molecular forces and other complex slower processes, indirectly resulting from chemical, osmotic and other forces, by which material is introduced into the organism and transferred from one part of it to another (Thompson 1952). If we might speculate that growth is to Nature what fabrication is to Design, then the notion of shaping and making come to include more than the straightforward manifestation of shape. In Nature, form is informed by the interaction of matter and energy; and it is due to the distribution of matter and its properties that such interaction is made possible in the physical realm. Moreover, it is impossible to find cases in Nature were an object is made out of one consistent and homogeneous material. Even when considering the inner fabric of wood for instance, one finds an articulated microstructure governing the orientation of fibers, determined according to the trunk's mechanical behavior.

Granted, such processes have vast implications for their *potential* contribution to form as a factor in sustainability, i.e. as a function of material efficiency and energy consumption. Therefore, what we can learn from Nature as we redefine the field of fabrication in the age of global warming is of greater significance than simply the advancement of fabrication technology. Can fabrication devices be invented to exploit certain of the attributes of material-based design computation that we have defined in the previous chapters and thus be made intrinsically, or "naturally", sustainable? How can we introduce similar processes to those characterized by Thompson as “natural” in the design of the artificial? Can emerging fabrication technology, in its potential linkage to material-based design computation and in its intrinsic technological ability to produce heterogeneous materiality, produce a ”second nature”?

8.1.2 Michelangelo’s Way

Form-making in the physical domain operates quite differently from Nature’s way. Since ancient times, the shaping of matter has consisted mainly of processes of component assemblies. Such material components are typically homogeneous in properties and assembly with other components of different properties is required in order to achieve variation in physical behavior.

Evidence dating back nearly two million years ago suggests that man’s very first fabrication tools were made for two purposes: cutting and pounding, as in early shaping processes (Napier 1965). This definition is consistent with the two distinct paths by which contemporary fabrication technologies have been defined since then, by and large, throughout the industrial revolution. Indeed, one typically finds that the term “fabrication” in its industrial context may be applied to either *additive* or *subtractive* processes of form-making (Figure 8.1). More specifically, it is relatively easy to distinguish between processes operating by the (1) additive logic of building blocks: accumulating matter in layers, in units, or using any other type of additive component; and (2) processes operating by subtractive logic, not unlike Michelangelo’s method of sculpting form in marble, as if to reveal the shape concealed by it (Figure 8.2).

In carrying forth material-based design computation into fabrication processes, I have elected to focus on *additive fabrication processes*, specifically *layered manufacturing technologies*, and potential ways in which such processes could inform the distribution of matter as a function of external environmental constraints in the shaping of buildings and products (Figure 8.4).

8.1.3 Digital Fabrication and its Ecological Discontents

Spatial gradients are clearly a predominant feature in the way that Nature goes about making things. To an extent, there have been various attempts to mimic such processes in industrial scales within a range of applications.

Indeed, the mechanical response of materials designed and engineered with spatial gradients in both composition and structure is of considerable significance in disciplines as diverse as biomechanics, fracture mechanics, optoelectronics, geology, nanotechnology, product engineering and even architectural design. Damage and failure resistance of surfaces to normal and sliding contact or impact can be substantially controlled and modified through such gradients. Moreover, the attainment of spatial gradients in building scale may have momentous impact on the state of sustainable design: building parts can in this way be customized to fit their various specific functions. Consider the potential material economy implications, for instance, of the fabrication of a concrete beam which varies its physical properties across its internal surface area. In a more complex example of the potential of spatial gradient production by printing, consider the potential for a “bone-printer”.

Gradient materials clearly hold a profound place in the future of material engineering and the ability to synthetically engineer and fabricate them using additive fabrication is incredibly promising as it increases the product’s structural and environmental performance, enhances material efficiency, promotes material economy and optimizes material distribution. Beyond this, such a technology further offers new possibilities for the integration of engineering performance criteria with architectural criteria.

Currently, varied mechanical properties are mostly achieved in small scales, and mostly by injection molding a highly costly process which presents the designer with serious time and size constraints.

In this chapter I introduce a novel material deposition technology entitled *VPRP*. VPRP stands for *Variable Property Rapid Prototyping* (Oxman 2009). The technology offers gradation control of multiple materials within one print to save weight and material quantity thus reducing the energy input and promoting new possibilities for a non-componentized architecture.

8.2 Rapid Prototyping: State of the Art

8.2.1 3-D Printing: the Discrete and the Discontinuous

3D printing machines speed product design by facilitating visualization, physical production and the testing of prototypes. However, such machines are typically limited to using only one material at a time; very few high-end 3D printers which accommodate the deposition of multiple materials operate discretely (one material is assigned to a singular nozzle); or if they are able to deposit mixtures, they are pre-mixed.

We introduce *variable property printing* as a novel method and technique introducing the ability to dynamically mix and vary the ratios of different materials in order to produce a continuous gradient. This ability would expand the potential of prototyping, since the varying properties could allow for optimization of material properties relative to their structural performance and for more accurate evaluations of the intended final product, such as stress testing. Dynamic gradients could also contribute to efficient conservation of material usage. This project establishes a novel technology that can produce a continuous gradient, using colors as a substitute for material properties. This technology has been termed Variable Property Rapid Prototyping (VPRP) by the author (Oxman 2009).

8.2.2 Comparison to Existing RP Technologies and Prior Arts

VPRP differs profoundly from other similar RP/RM technologies. There are many other emerging Rapid Fabrication (RF) and Rapid Manufacturing (RM) technologies. Generally all related technologies could be classified by the material phase used in the extrusion whether these are liquid-based (such as stereolithography), powder-based (such as selective-laser sintering), or solid-based processes (such as fused deposition modeling). I review two technologies that are of relevance to the comparison with VPRP: The PolyJet Matrix technology, extruding multiple photopolymers simultaneously, and the FDM technology, an alternative solid-based fabrication process.

8.2.2.1 How does VPRP differ from OBJET's PolyJet Matrix technology?

OBJET $Geometries^{TM}$ PolyJet Matrix technology, currently applied to their $Connex500^{TM}$ 3D printer, operates by using ink jet heads with two or more photopolymer model materials; the OBJET process is a dual-jet process which can combine materials in several ways, enabling the simultaneous use of two different rigid materials, two flexible materials, one of each type, or any combination with transparent material. Each material is funneled to a dedicated liquid system connected to the PolyJet Matrix block, which usually contains 8 printing heads. Each material is designated two synchronized printing heads, including the support material. Every printer head includes 96 nozzles. Preset composites of model materials are ink-jetted from designated nozzles according to location and model type, providing full control of the structure of the jetted material and hence of its mechanical properties. This enables each composite material, called a "Digital Material", to provide specific values for tensile strength, elongation to break, HDT and even Shore values. The materials are extruded in 16 micron thick layers onto a build tray, layer by layer, until the part is completed. Each photopolymer layer is cured by UV light immediately after it is extruded. The gel-like support material designed to support complicated geometries, is easily removed by hand and water jetting. However, OBJET's materials are deposited by preset combinations; they are distinct and cannot be mixed to generate gradient transitions.

8.2.2.2 How does VPRP differ from Stratasys' FDM technology and Contour Crafting?

Stratasys Fused Deposition Technology (FDM) operates by laying down a soluble thermoplastic polymer for support in parallel to the extrusion of the build material. Parts are created by extruding material through a nozzle that traverses in X and Y to create each 2D layer. In each layer, separate nozzles extrude and deposit material that forms the parts and material that form supports where support is required. Another interesting and relevant FDM technology, is Contour Crafting (CC), invented at the University of Southern California by Behrokh Khoshnevis (Khoshnevis 2004). This technology exploits the surface-forming capability of trowelting to create free-form planar surfaces out of construction ceramics and concrete. The extrusion nozzle has a side trowel, the traversal side of which creates smooth outer and top surfaces on the layer, as material is being extruded. This side trowel can be deflected to create non-orthogonal surfaces (Khoshnevis 2004). However, the FDM technologies presented above clearly use only one material at a time such that variation in properties can only be achieved by fabricating multiple parts and assembling them post the printing process.

8.3 Variable Property Fabrication Software

Beyond its contribution as a novel additive fabrication technology, the implications of VPRP on the CAD industry are most significant and require that we revisit current applications used for the geometrical description of 3D form and structural analysis of prototypes.

8.3.1 Representing Variable Properties

Current CAD applications do not support the descriptions of internal material composition. However, some options exist which employ digital entities capable to describe micro-scale physical properties of materials and internal composition. Such entities include features such as voxels, finite-elements, particle system elements, and vague-discrete modeling elements, all of which have been introduced in Chapter 5. We have concluded that the common denominator for these four methods is the representation of physical behavior and/or material properties by assigning properties to discrete features comprising the model, weather by using voxels, elements, particles or point-sets. One major disadvantage of all entities mentioned above is their consumption of computational power in calculations. Also, the editing of such formats is made difficult by the lack of a robust method to relate between them in order to combine and integrate modeling and analysis routines.

As we moved away from CAD and entered the discipline of Material Science, however, we found what had inspired the conception of the *Variable Property Modeling* environment. Functionally Graded Materials (FGMs) are characterized by the gradual variation in composition and structure over their volume, resulting in corresponding changes of the material's properties. Such materials can be designed and engineered for a specific set of functions and applications. Various approaches based on particulate processing, perform processing, layer processing and melt processing are used to fabricate FGMs.

Given their variation of properties across volume and surface area, FGM's could also be 3D printed by sending the machine a layer-by-layer pixel sheet such that when they are stacked they are represented as voxel clouds.

Inspired by the convergence of ideas from the field of computational geometry and material science and engineering, in Chapter 6, I introduced the concept of Eco-Voxels as potential material units which may contain performance data (in addition to geometrical data) in various stages of the form-generation process. Such elements are potentially representative of variable properties in the generation of the final design form.

The VPRP technology is supported by a novel method for form-generation entitled Variable Property Modeling (VPM) able to design, manipulate and fabricate graded materials. We have reviewed the elements comprising the variable property computational environment in Chapter 5.

Within the VPM modeling environment, the program must translate desired model properties to material properties. The VPM environment gives the value of any property at any point (high or low conductivity / stiff or soft) in order to structure the correct material composition and emulate both its structural and electrical performance. Currently, transition functions that compute gradient property distribution across one or multiple dimensions do not exist in CAD.

The VPM environment is developed in order to cater for such requirements and present physical data and material composition by treating voxels as tensors (geometrical entities containing multiple physical parameters), or by computing transitions between multiple compositional phases as extrapolation functions. Clearly, the distribution of materials must be limited by the boundary of the solid, or, its domain.

8.3.2 Variable Properties Control Module

The software control module is written in *Processing*, an open source environment that facilitates data visualization. Material mixture ratios may be controlled through sliders (Figure 8.5), but absolute quantities are controlled so that only the ratio, not the total output amount, changes.

Color selection (analogous to material selection in the suggested software) operates according to the following schematics:

User drags the slider to change the color
$\Downarrow$
Software outputs relative motor speed to change based on input
$\Downarrow$
Color change

8.4 Variable Property Fabrication Hardware

8.4.1 General Technical Descriptions

8.4.1.1 Materials

Different colored glues are used to represent different materials (Figure 8.5, 8.7). We melt and remold glue into thirds of a stick so that three may be fed into a heating chamber which accommodates one normal stick. Three modified glue dispensers are arranged radially in a surrogate housing such that they feed these thirds into one heating chamber, acting also as a mixing chamber. The glue dispensers are controlled by 9V motors. Since we use the same pushing mechanism as commercial handheld glue guns, the mechanism must be reloaded after every push, so deposition is non-continuous, which is compensated for in software. The resins used in this demonstration are resin glues. It is important to note that such materials could easily be replaced by thermo-plastic polymers, silicon rubbers, or other resins[8.1].

8.4.1.2 Support Materials

In solid-based processes, support materials are necessary to ensure the stability of the part in the process of printing. Support materials removal can be manual, or when water soluble supports are employed,

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[8.1] Different materials require different nozzles. Structural materials should be considered for further implementations.

they are removed by simply being dissolved, an advantage when fabricating highly complex 3D forms. The VPRP technology demonstrates the ability to control material mixing in order to achieve different properties using the same nozzle. The technology currently works without extruding support materials, which are materials deposited in negative regions of the 3D prototype in order to support it in the process of building. It is important to note that for more accurate and complex builds of 3D forms, it is possible to incorporate support materials, such as soluble resins, that would be extruded in parallel to the *build* materials. Much like Stratasys' machines, one could also implement extruded polymer support.

Following the logic presented by the VPRP technology, support materials may also be implemented as variable property mixtures using the exact same method. In this way, support materials can vary in stiffness and/or density depending on the complexity of the region being printed. Such an implementation increases speed and efficiency of printing. In the case of density variation, such a method would decrease material use in cases where minimum support is needed due to local geometrical simplicity.

8.4.2 Body and Mechanism

8.4.2.1 Overview

In order to dispense the trifurcated glue sticks into the same heating chamber, aluminum plates have been machined that function in the same way as the sliding trigger guides in the original housing, but the trigger assemblies are angled so that the glue sticks will all be pushed into the same chamber (they are flexible). These are fastened to a round baseplate with screws. On the bottom side of the baseplate, we have attached a heating chamber. Figure 8.6 illustrates the various components of the entire assembly.

8.4.2.2 Trifurcation Bushing

Each plastic trigger (Figures 8.8, 8.9) is designed to push a whole glue stick via a frictional force angled downward. We insert a bushing which is a solid cylinder with a third of its arc cut away as shown in Figure 8.6, so that the plastic ring guiding the glue stick is reduced to the size of the third.

8.4.2.2.1 Guide Plate

The aluminum guide plate is water-jetted from $\frac{1}{4}''$ thick aluminum. Its primary purpose is to replicate the slot that would guide the trigger in the original housing. It also supports the motor in order to ensure proper shaft alignment.

8.4.2.2.2 Motor Interface

1. Mechanical Interface: Each motor is mounted to a guide plate for alignment. Its D-shaft is coupled to the trigger via a set screw in a hub that is bolted to the trigger.
2. Electrical Interface: The servo motors are connected to a microcontroller board controlled by the software module (see further descriptions in section 3). On the reuptake (after exceeding the motion range of the trigger), a motor's direction must be reversed in order to reload. The speeds of each motor are independently controllable by varying the voltage feed. For this demonstration we have used V9 motors. These motors could be replaced by steeper motors allowing more accurate control of material extrusion and the mixture's speed and power.

8.4.2.2.3 Nozzle

A truncated glue gun heating chamber/nozzle receives the glue sticks. An aluminum plate is screwed to its side so that it may be attached to the rest of the assembly.

8.4.2.2.4 Base-plate

All of the guide plates are screwed onto a round water-jetted base-plate, and the nozzle is mounted to the underside. A tapered plastic bushing (3D printed) in the center of the plate guides the angled glue sticks so that they are all forced into the nozzle opening (See Figures 8.10 and 8.11 for final assembly).

8.5 Limitations and Future Work

Some complex individual components, such as the heating chamber / nozzle and the plastic trigger that advances the glue sticks, are taken from commercial glue guns in order to streamline the construction of the nozzle, although this does not result in the most efficient deposition since, as previously mentioned, the mechanism reloads after every push. The rest of the components are designed to avoid complex manufacture and can be easily screwed together; most pieces are either lathed or require minimal machining beyond a 2-D profile. This experimental setup has certain limitations which should be reconsidered and addressed in any future development of this technology.

8.5.1 Material Experimentation

We use colors as the simplest way to demonstrate gradient printing. However for example, if epoxy is used as the deposition material, one would vary the ratios of resin and hardener, but the functional range of the resulting mixture would be limited and must be determined. Other possibilities include fiber composites, which may be varied in hardness by changing fiber orientation, and selective laser sintering, which allows porosity and consequently material strength to be controlled.

In addition, mechanics calculations are currently limited to the linear elastic response of materials, as with the design experiments presented in Chapter 7 (and, specifically, projects that have been 3-D printed using the Connex 500 technology). There are also size limitations on components made using the VPRP machine (5mm thick material strips as defined by nozzle diameter).

8.5.2 Software Development

Most of today's Rapid prototyping technologies create products in a point-by-point fashion. Selective-laser-sintering (SLS) and stereolithography (SLA), for instance, initiate prototype solidification at areas of contact between the stock material and the laser as the laser traverses the X, Y and Z planes. Other layer manufacturing technologies, such as 3D Systems' *In Vision* machine and Objet Geometries machine, deposit the material point by point. In these systems, the prototype is constructed drop by drop using a modified inkjet system. When supplied with one or more extra jets, both systems could build graded material parts, also known as *functionally graded materials* (FGM's)[8.2]. This type of graded internal structures is only possible when taking an additive approach to manufacturing. However, it is still impossible to represent FGM's in a CAD environment. Most commercial CAD systems are in the category of 'B-rep' modelers. This means that the inside of the 'solids' using these modeling techniques are as empty as the volumes surrounding the solid. Therefore, for most CAD systems, even though they are

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[8.2] Such capability is currently limited to the micro scale only known as ‘solid’ modelers, they are, in fact just surface representation protocols of the geometry defining the 3D form. All RP production formats, STL predominantly, are thus numerical representations of those geometries.

The Variable Printing Method (VPM) offers a novel approach to modeling and fabrication of 3D solids as it offers a way to represent the internal structure/composition of the form at individual points within the volume of the part. Currently, this method is explored by using colors as a representation of material properties. In the future, we anticipate that 3D printers will be designed as “FGM machines” which are provided with information to ‘print’ the desired graded material distribution.

8.5.3 Software-Hardware Calibration

Furthermore, the voxel model as presented by the *Variable Property Design* environment allows the designer to evaluate the mass properties of the modeled object. In other words, the total material volume can be obtained as a simple sum of all the non-zero voxels of the volume buffer. However, a significant issue to consider is the calibration between software and hardware “material units” such that both are suitably scaled by the parameters given by the fabrication technology (i.e. layer thickness, horizontal resolutions, and so forth). This measure is a reasonably accurate estimate of the actual volume of the object, since each voxel translates to a precisely quantifiable unit of material deposited during fabrication. It can also be applied independent of the object’s topology.

Combined with the VPD environment, a voxel based modeler can ultimately provide the capability to design a composite object with materials selectively placed at individual voxels. There is no need to compute the complex geometries of the interleaved materials because each slice of the voxel buffer can be directly read out during fabrication and several masks per-layer can be created to deposit the different materials. A voxel will then be of molecular dimensions: we have yet to define the dimensional range of material voxels relative to the type of performance being mapped as part of the form-generation process.

8.6 Summary: Towards a Natural Fabrication

For earlier civilizations, approaches derived from fabricating form have been guided by what was possible in terms of material resources. In fact, prehistoric time periods are defined by the materials most widely employed for tool-making. (Addis).Fabrication methods by which to shape objects and to construct buildings and cities were equally affected by the tools of an era. Every age, with its materials and methods, made its preceding age obsolete. Whether stone, bronze, iron, plastic, or silicon, materials were in many ways the very defining constituents of culture.

Common to the ages was a compositional approach to fabrication whereby elements of different properties were assembled to form a larger, functional prototype. Such a compositional approach is consistent with the fact that materials were typically defined by consistent and homogeneous properties. The attainment of heterogeneity was mostly pursued through assembly and composition (i.e. the assemblage of concrete and glass, or steel and rubber).

Beyond the notion of homogeneity, the fabrication of form was typically concerned mainly with bringing into physical manifestation the desired object. Whether through chiseling or sculpting, both subtractive and additive approaches to fabrication were involved with the shaping of bulk material with consistent properties across its volume. In this way, fabrication was limited in its *a priori* informing of any design.

The digital age is now affording the designer with almost limitless possibilities when it comes to the making of form as rapid prototyping processes are allowing the designer to directly translate any modeled form into a physically fabricated one. However, such technologies only support the fabrication of an object made out of materials with homogeneous properties. However, in a period so charged with environmental threats, material waste and retrofitting by assembly are high prices to pay for the formal freedom. It appears that not much has changed since the Stone Age.

Nature knows better. In Nature, fabrication is synonymous with growth, and the form of an artifact is directly informed by its function and fitted to its environmental conditions. Such "natural fabrication" strategies are by their very definition, sustainable.

Variable-property modeling, coupled with a variable property fabrication approach, as presented in this chapter are suggestive of a new direction in design fabrication, and, indeed, a new direction in architecture. Not unlike the ways of nature, we aim to facilitate the variation of material properties through a "heterogeneous materiality" as a function of environmental performance which thus becomes an integral part of the form-generation process.

Figure 8.1: Additive and subtractive fabrication methods as illustrated in natural processes and artificial form-making processes respectively: Left: *Carlsbad Caverns*, New Mexico. Right: *Pieta* by Michelangelo.

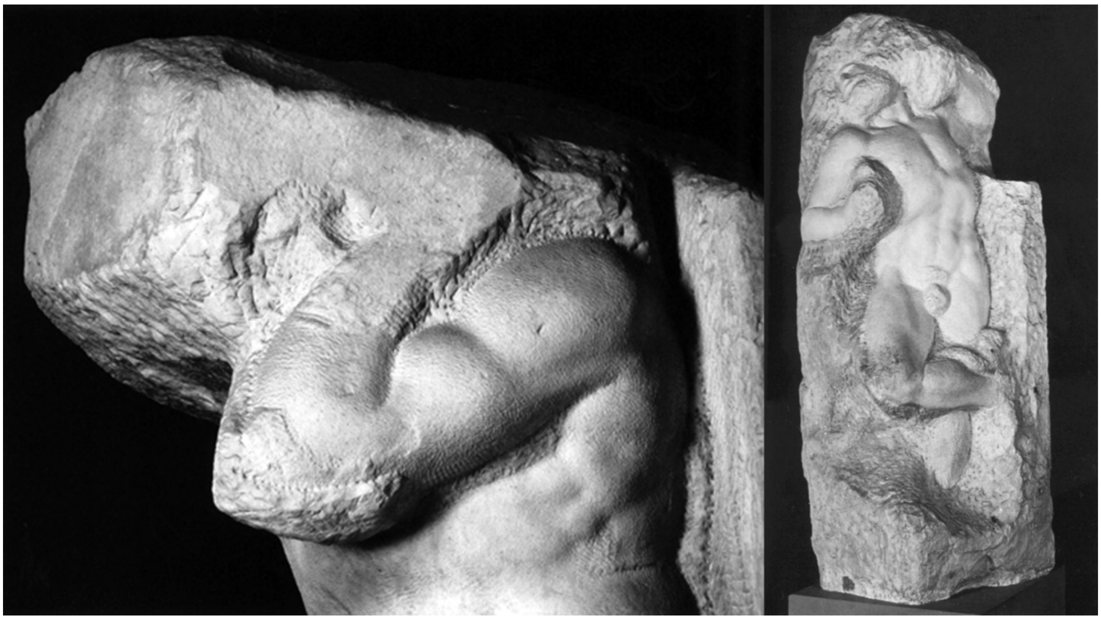


Figure 8.2: Two images of Michelangelo's "Dying Slave" (1513-16, marble, Louvre Museum, Paris) are used to illustrate the concept of subtractive fabrication.

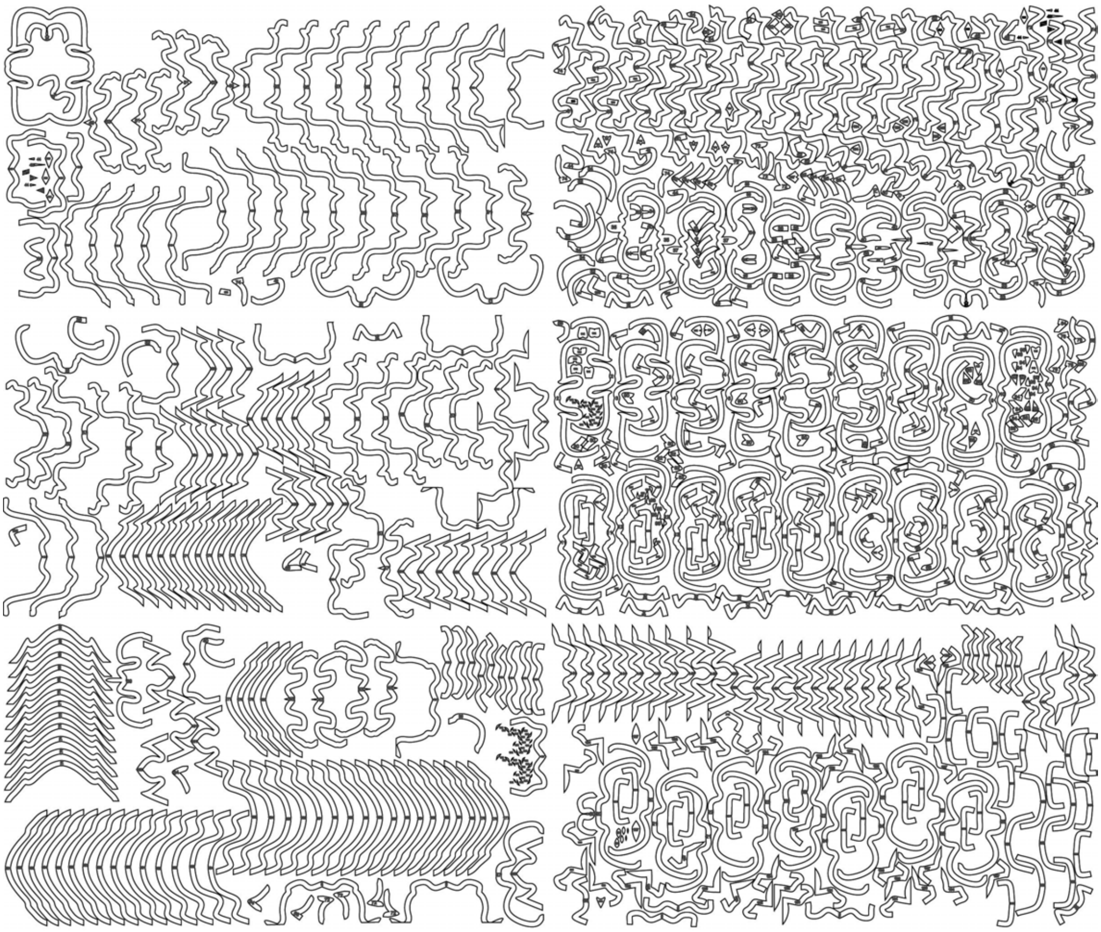


Figure 8.3: Laser cut components nested for cutting (*Raycounting*, 2007). Belonging to the family of CNC technologies, laser cutters allow for the assembly of 3-D pieces from 2-D components. Such process is considered subtractive and is associated with relatively large amounts of material waste. In addition, the physical properties from which the object is made are dependent on the physical properties of the 2-D strips which are typically homogeneous in nature.

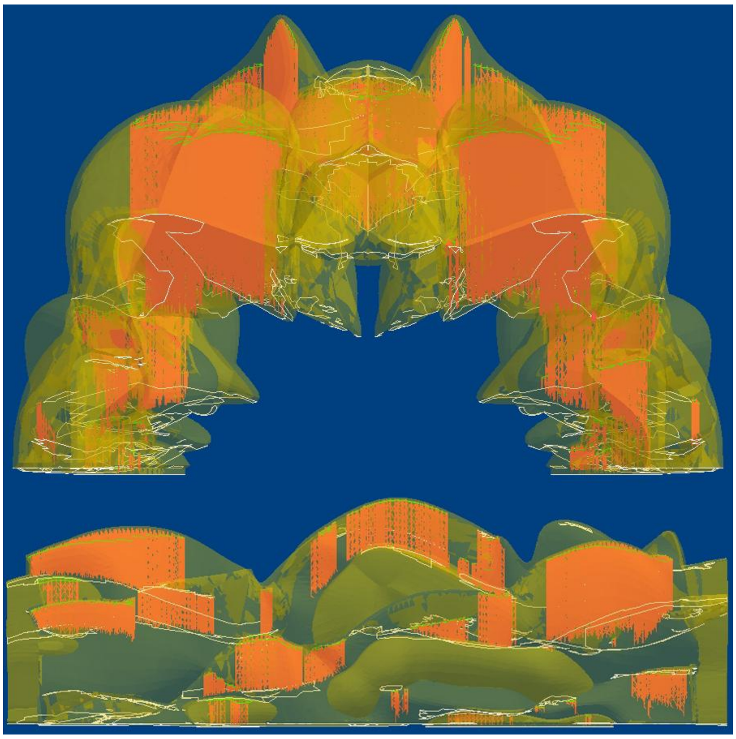


Figure 8.4: Image of the laser sintering process applied to generate a 3-D model negotiating between structural and environmental constraints through the specification of material thickness and translucency level (*Raycounting*, 2007). Dark orange segments in the image represent regions within the model that are filled with material for purposes of self-stabilization. Left-over regions are transparent. Additive manufacturing technologies allow the designer to control precise locations of material deposition, and, depending on the material property, to relate to more than one discrete performance criteria (i.e. structure and light performance).

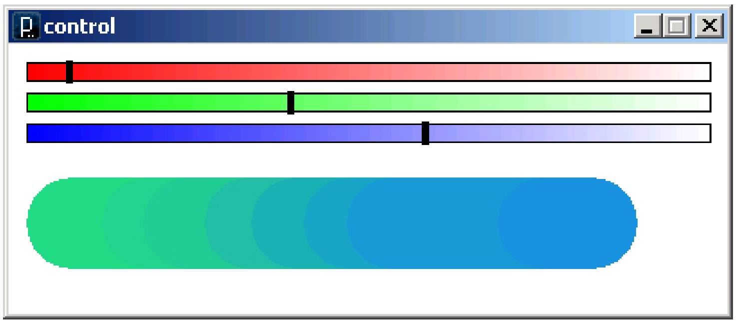
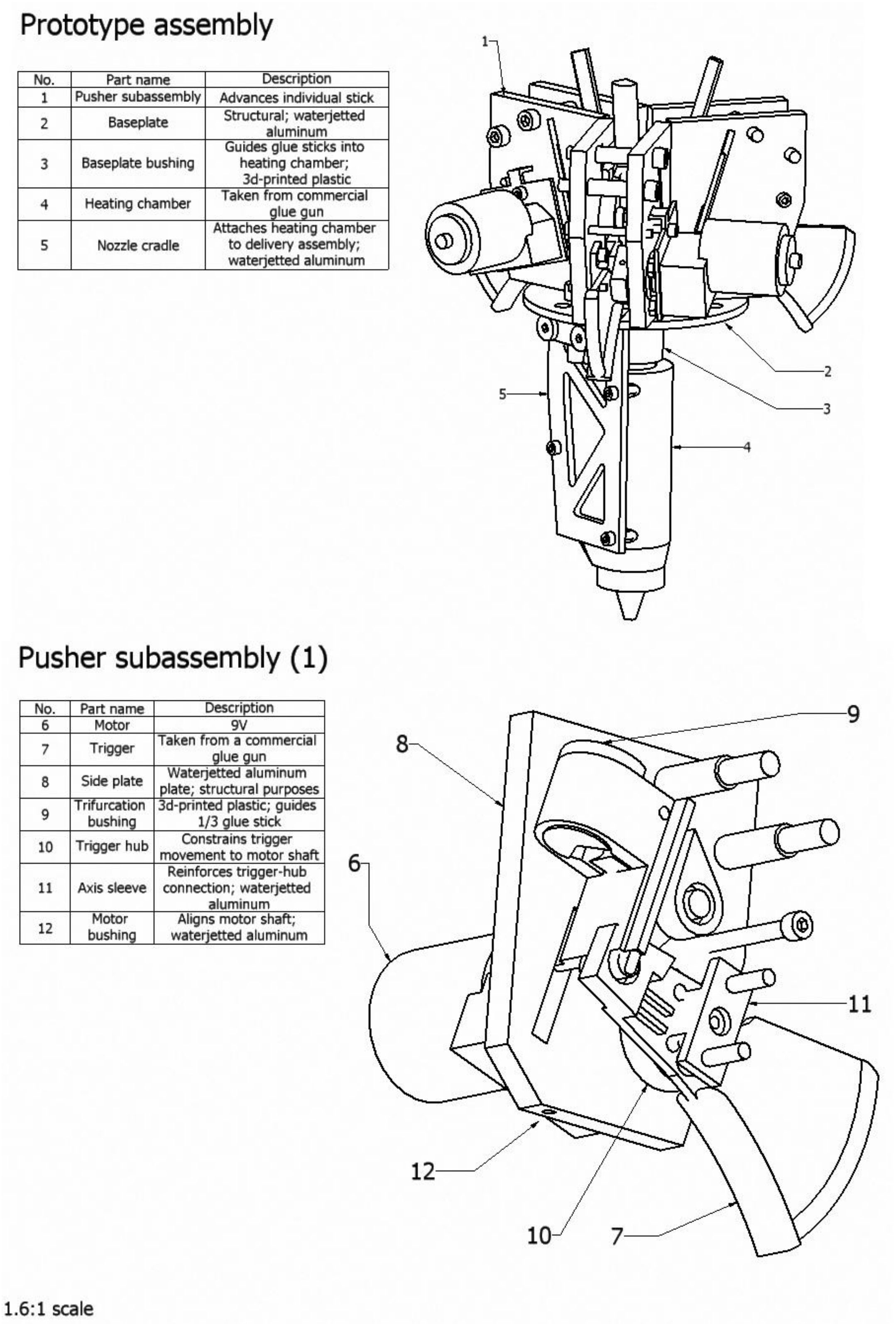


Figure 8.5: Screen shot of control module developed in the *Processing* environment. Color variation represents changes in material properties as assigned by the designer (i.e. density, elasticity, etc). This software control module is directly linked to the hardware (3-D printing) module controlling the physical deposition and variation of material properties as a function of its anticipated performance.



Prototype assembly

No.	Part name	Description
1	Pusher subassembly	Advances individual stick
2	Baseplate	Structural; waterjetted aluminum
3	Baseplate bushing	Guides glue sticks into heating chamber; 3d-printed plastic
4	Heating chamber	Taken from commercial glue gun
5	Nozzle cradle	Attaches heating chamber to delivery assembly; waterjetted aluminum

Pusher subassembly (1)

No.	Part name	Description
6	Motor	9V
7	Trigger	Taken from a commercial glue gun
8	Side plate	Waterjetted aluminum plate; structural purposes
9	Trifurcation bushing	3d-printed plastic; guides 1/3 glue stick
10	Trigger hub	Constrains trigger movement to motor shaft
11	Axis sleeve	Reinforces trigger-hub connection; waterjetted aluminum
12	Motor bushing	Aligns motor shaft; waterjetted aluminum

1.6:1 scale

Figure 8.6: llustration showing prototype and pusher assembly and their respective components. Based on the commercial glue-gun assembly, the prototype is designed as a multi-material deposition mechanism allowing for property variation defined by continuously gradient property mixtures.

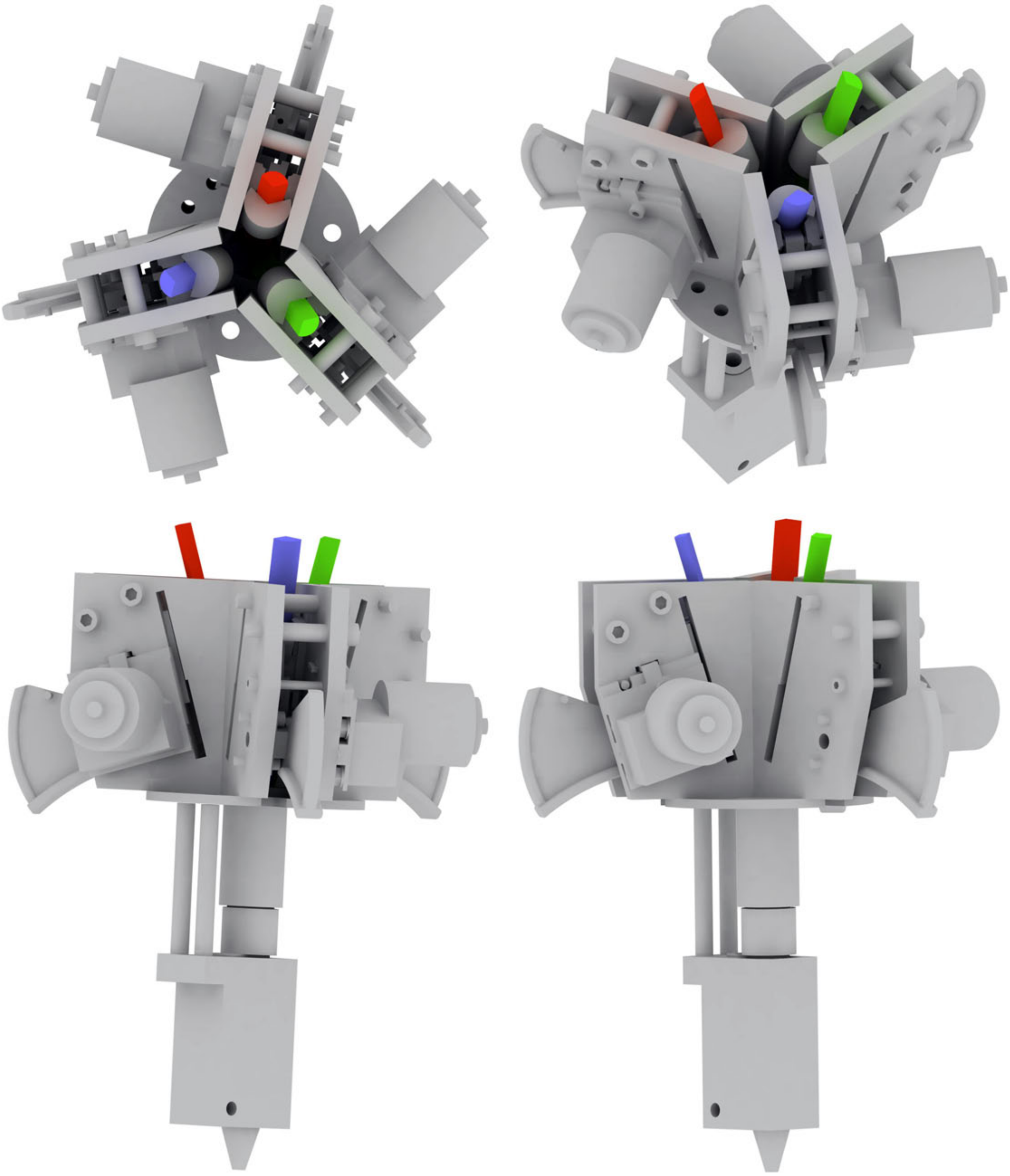


Figure 8.7: Top, isometric and lateral views of the VPRP prototype. Based on the commercial glue-gun assembly, the prototype is designed as a multi-material deposition mechanism allowing for property variation defined by continuously gradient property mixtures.

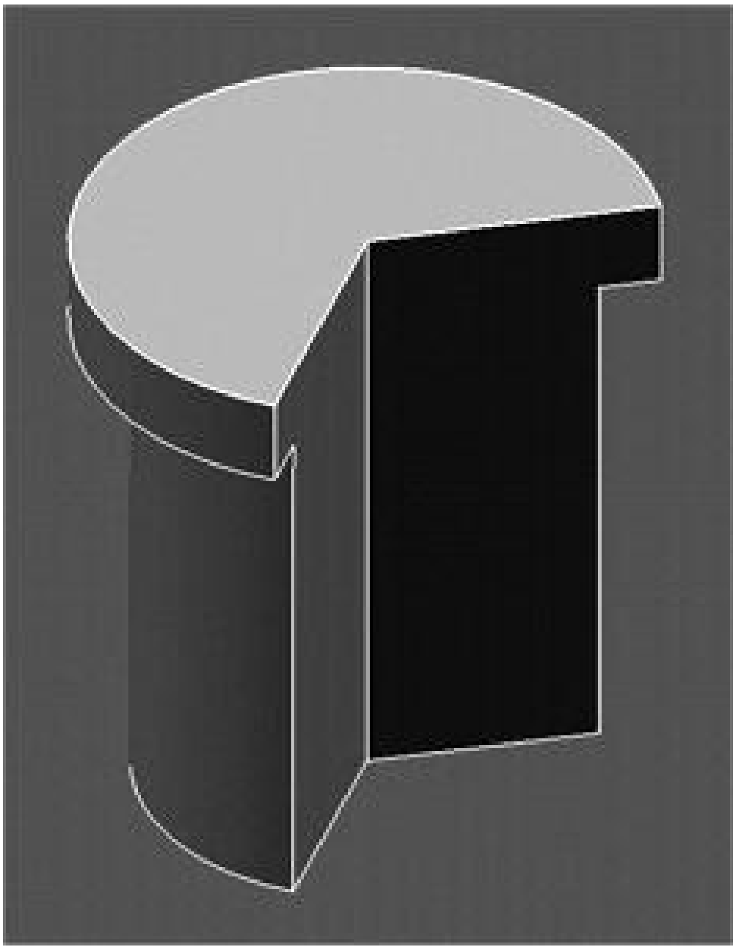


Figure 8.8: Close up of tri-bushing.

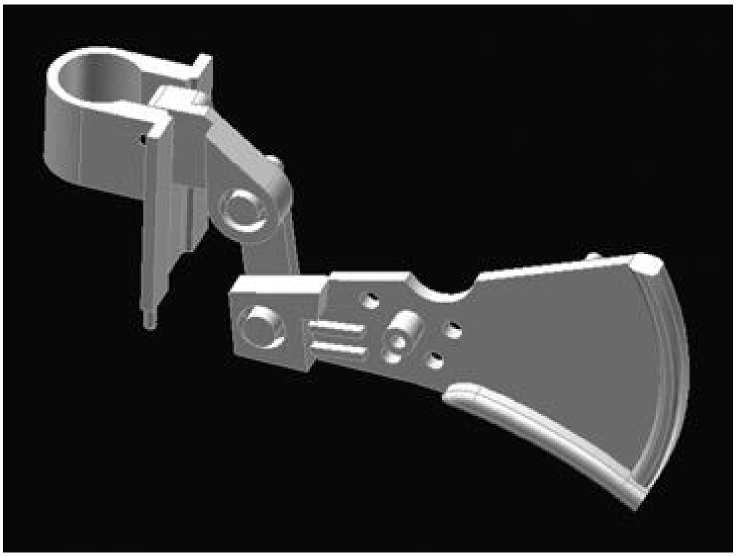


Figure 8.9: Plastic trigger from glue gun.

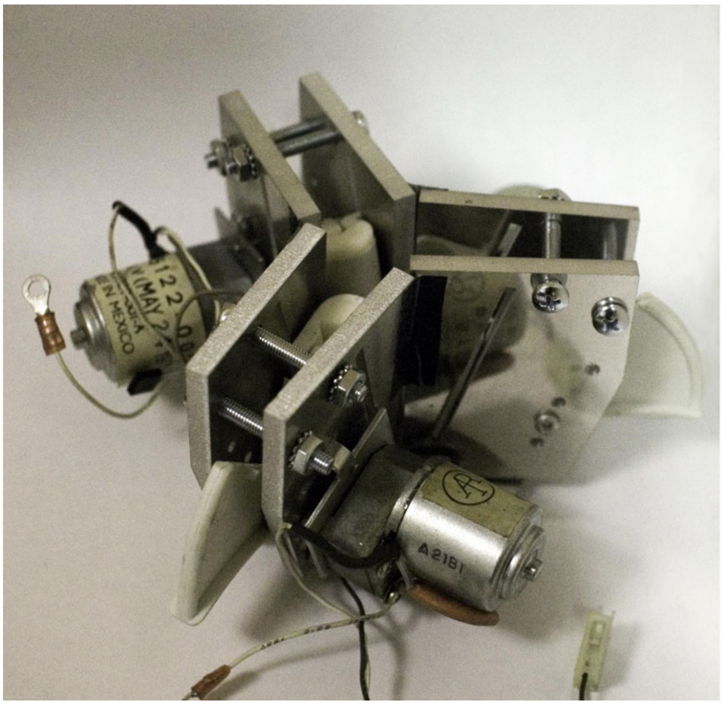


Figure 8.10: Individual pusher assemblies mounted to base-plate.

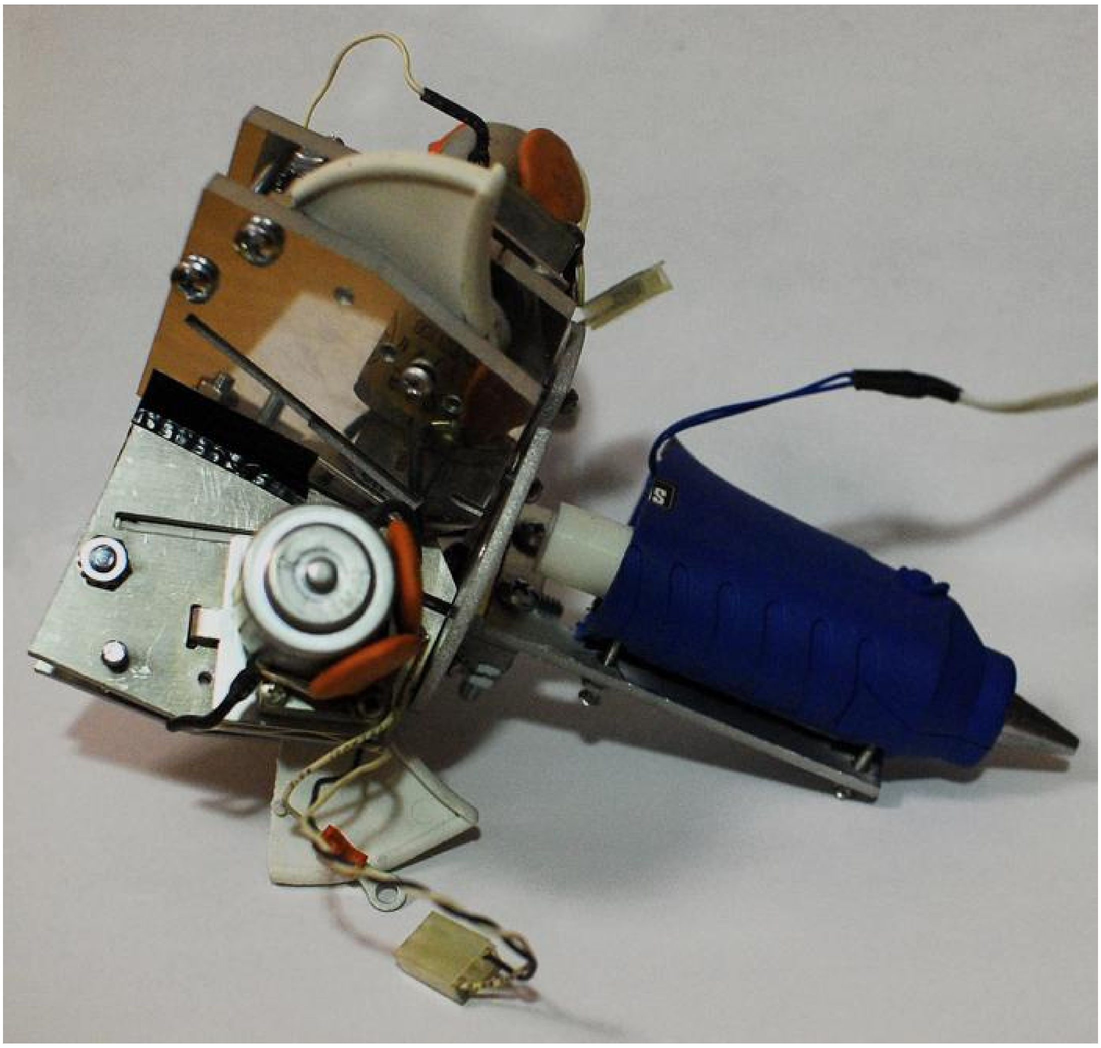


Figure 8.11: Final assembly (not including a stand or CNC movement

CHAPTER 9

CONTRIBUTIONS
Material-based Design Computation: towards Nature's Way

> *"Nothing is built on stone; all is built on sand, but we must build as if the sand were stone"*
>
> **— Jorge Luis Borges**

> *"In other words, what we call Form is a ratio of magnitudes referred to direction in space...We are dealing with Form in a very concrete way. To Aristotle it was a metaphysical concept; to us it is a quasi-mechanical effect on Matter of the operation of chemico-physical forces. To Aristotle its Form was the essence, the archetype, the very "nature" of a thing, and Matter and Form were an inseparable duality. Even now, when we divide our science into Physiology and Morphology, we are harking back to the old Aristotelian antithesis."*
>
> **— D'Arcy Thompson**

9.1 Introduction

In the following chapter we review the theoretical, methodological, and technological contributions of the thesis. The implications of these contributions are considered in the context of architectural design, product design and material design. Motivated by the desire to consider the possible future contributions of this field to sustainable design, the orientation of this analysis has been to promote the proposed methods and technologies of performative design as a means to achieve a novel form-generation approach inspired by Nature.

Common to these contributions, therefore, is a mandate to promote a *potentially* sustainable design approach inspired by Nature that supports the negotiation of multiple performance criteria in the various stages of form-generation while at the same time allowing for the seamless integration between modeling, analysis and fabrication environments. This design approach has been termed by the author, *Natural Design*.

The theoretical contributions refer to the body of experiments promoting and evaluating the foundations of *Material-based Design Computation* through digital form-generation informed by material properties and behavior. *Material-based Design Computation* as a potential field of knowledge is viewed here as the enabling theoretical and technical approach for *Natural Design*.

The chapter is organized into various sections classifying the contributions as theoretical, methodological and technological. Theoretical contributions refer to the theoretical foundations of both *Material-based Design Computation* and of *Natural Design* while methodological contributions refer to the enabling assumptions, methods and techniques afforded by *Material-based Design Computation*. The methodological contributions refer to the methods and technical means supporting this design approach through the introduction of design environments included under the categories of *Tiling Behavior*, *Finite Element Synthesis*, and *Variable Property Fabrication*.

Finally, the theoretical and methodological contributions culminate in the invention of a new technology currently under development and testing in industrial contexts. *Variable Property Rapid Prototyping* (Oxman 2009) has been developed and implemented as a novel technology which enables the controlled variation of material properties during the process of material deposition in a 3-D printing application. This technology combines a novel software environment termed *Variable Property Modeling* (VPM) with a mechanical output tool designed as a 3-D printer. VPRP allows for physical prototyping of graduated properties in product design scale based on the design and fabrication logic of *Functionally Graded Materials* (FGMs).

Within those processes of computational design directly associated with materials, it is the computational potential for the distribution of material structure (structurally, spatially and materially) that has been an objective of the research and has become a unique attribute of *Material Computation*.

The technical contributions include the analysis of forms allowing property variation in response to mechanical, thermal, or lighting conditions; the fabrication of forms with material property and thickness variation over a surface; and the development of a new device, entitled VPRP, which promotes the fabrication of forms with continuously varying properties corresponding to certain given external, (environmental) constraints.

9.1.1 Natural Design

At the heart of this research lies the following syllogism:

Given that Nature applies strategies of material *distribution* in order to satisfy multiple classes of site-specific structural and environmental performance simultaneously; given that in Nature we find full integration between “modeling” (genetic code), “analysis” (adaptation) and “fabrication” (growth); and given that Nature is demonstrably sustainable; then architecture and design may become substantially more sustainable when adopting Nature’s design and material strategies.

Contrary to Nature’s strategies of material distribution, the milieu of architectural design and construction to date is predominantly based on strategies of material assembly and property assignment rather than strategies of material *distribution* and property graduation. Clearly, since a novel strategy to processes of design generation has immense implications on the construction industry, the body of theoretical and methodological discussion following the contributions sections demands that we revisit the way in which architectural design operates as a whole.

In previous chapters we have proposed that since the industrial revolution, glass and steel remain the quintessential modern materials from which to design buildings and cities. As a result functional material allotment is promoted: steel traditionally serves the *structural* functions of the building while glass serves the *environmental* functions of the building. This holds true for the use of other materials and products, including advanced structural composites across various design challenges in domains central, but not exclusive to, architecture such as product design, medical device design, and the design of construction tools, techniques and technologies. It is mainly due to the conventions defined by, and within, the fabrication and construction industries that modular components and assembly tool kits for building practice are promoted.

Perhaps the most significant implications celebrated by the introduction of *Natural Design* into design practice and education, is the potential withering away of the module and the component and the arrival of a new way of generating and constructing design objects without assemblies. More about this towards the conclusions as we contemplate the future of architectural design.

9.1.2 Material-based Design Computation

Material-based Design Computation is the body of theoretical, methodological and technical contributions that enable and support *Natural Design*. This body of knowledge encompasses the characteristics of objects and buildings naturally designed, and suggests methods by which to achieve them given their potential performance superiority over conventional practice and having observed their advantages as demonstrated through the experimental research.

Guided by the general thesis that design based merely on geometrical shape does not generally promote sustainable design; *Material-based Design Computation* offers certain form-generation processes, introduced in various stages of the design,that integrate physical properties prior to materializing the final design output. In this way, the designer may correspond to, and negotiate between, multiple types of performance as demanded by the design environment. Such classes of performances include both engineering and architectural performance, distinguished in this thesis as two separate classes of parameters. Material properties are typically assigned only after the 3D form has been generated, in order to fulfil functional and aesthetic objectives as well as to satisfy given building codes. As a result, form, structure and material are treated as disintegrated constituents of the design object. *Material-based Design Computation* promotes generative design processes based on material properties and behavior responding to specific performance constraints. As a result, the generation process allows for multi-performance criteria to be considered and for the integration between form and its material constituents to be achieved within various stages of the design process.

Beyond the possibility to address performance criteria early in the design process, the methods allow for the integration of modeling, analysis and fabrication environments culminating in a new fabrication invention that allows the simultaneously mapping, forming-generating and 3-D printing of parts with graduated material properties as defined by the environment. Design in this way, is perceived virtually as a *second nature*.

9.2 Material-based Design Computation: Theoretical Contributions

9.2.1 New Sustainable Design Approach

While the practical application varies among disciplines, the common principles of sustainable approaches to design continue to revolve around strategies of improving the efficiency of already existing forms (McLennan 2006). For instance, design standards promote the use of low-impact materials; those that are non-toxic, sustainably produced, or recycled materials which require little energy to process. Alternatively, guidelines suggest the use of manufacturing processes requiring less energy. Most of these codes are precisely *that* codes indicating what ways might best increase efficiency by reducing waste and energy (Anastas and Zimmerman 2003). However, what is now beginning to be considered as “sustainability science” still seems to avoid disciplinary content. As a result of this tendency towards improving the design status quo, the methodological integration between form-generation, evaluation and fabrication (Oxman 2007; Oxman 2007; Oxman and Rosenberg 2007) has not yet emerged as a logical alternative. Not once in Hannover’s Bill of Rights for the Planet is such integration mentioned or referred to while considering its potentially radical positive impact on sustainable design (McDonough and Braungart 1992).

Rather than separately considering form, structure and material in the process of design, this thesis suggests an alternative approach for the generation of form merging its three constituents and assigning them equal value in the design process (Oxman 2007; Oxman 2007; Oxman and Rosenberg 2007). Engineering performance is thus considered early in the design generation process, along with the potential consideration of material impact on efficiency increase and waste decrease. Moreover, rather than considering materials as *inferior* to the generation of form, the thesis speculates upon the potential positive implications of design guided by material properties and behavior; that is, design that originates from material properties rather than design that is terminated with their assignment.

Furthermore and most importantly, in this research, it has been demonstrated that a *graduated material approach*, which promotes the heterogeneous distribution of materials as a function of their anticipated function, allows for the potential to negotiate between multiple properties within the same object (considering structure, light, humidity, sound etc) as well as the achievement of potentially highly optimized structures customized to fit their particular environment as defined by the designer. All of this can be achieved through the integration of digital and physical media in the various stages of design generation.

9.2.2 Computationally-driven Form-Finding

Physically driven form-generation processes are not novel. They have been around for many years in various forms serving a wide range of different purposes. Most notable, and of relevance to this thesis, are the experiments carried out by Frei Otto and his teams in the late 1950's (Otto, Rasch et al. 1995). Becoming the world's leading authority on lightweight tensile and membrane structures, Otto pioneered advances in structural mechanics and civil engineering (Otto, Nerdinger et al. 2005). The collective body of experiments testing the forms that emerge out of the interaction between material and load is known today as "form-finding" (Otto, Glaeser et al. 1972). However, as Otto and his team members were uniquely interested in *structural* efficiency, and given that most of these experiments were executed in the *physical* domain without the aid of computational tools, the scope and impact of these processes was somewhat limited.

In this research I have explored the role of computationally-enabled form-finding processes in the generation of form informed by factors that are not limited to structural constraints. The experiments developed in this thesis demonstrate that *multiple* performances – including structural and environmental – may be accommodated in the process of form-finding, generaion and optimization. Through the development of specific methods and tools, this research opens up possibilities for the generation of form based not on a singular criterion, but on multiple performance criteria negotiated to express a specific set of functions. In this respect, the thesis specifically provides for architectural performance criteria to be incorporated in processes of formal exploration.

9.2.3 Engineering Performance vs. Architectural Performance

Various attempts have been made to define the role of *form-finding* contrary to that of *form-making*, the latter being a formally and aesthetically motivated design process. When considering the relevant literature sources presented in this thesis it becomes clear that such a distinction thrives on the partitioning between architect and engineer. Defined in this thesis as the process whereby form precedes the analysis of programmatic influences and design constraints, form-making is associated with processes of inspiration and refinement. Hence, form without explicit function might be considered the most extreme expression of form-making (i.e. architecture as sculptural art). Alternatively, extreme form-finding, serving the generation of form that is exclusively determined by function, may be regarded as the pure expressions of applied engineering. Clearly, architectural design methodologies known to date fall between these two extremes, and it has been argued that many canonical works result from design processes that optimally balance form-making and form-finding.

In this thesis it has been proposed that various criteria which may not be considered for instance as engineering criteria may still be incorporated into the form-generation process. Central to this position is the distinction between architectural and engineering performance, both of which serve the architect in creative discoveries of formal nature. Here is it imperative to mention that unlike Nature, design processes are motivated by constraints that are not always objectively defined.

Contained within such distinction are parameters such as physiological comfort (in the case of *Beast*) and pain (in the case of *Carpal Skin*) which are based on conditions subjectively and specifically defined by the user or patient. In these explorations, engineering performance parameters (such as functions optimized for the minimum material to accommodate for the maximum loading conditions) and architectural performance parameters (such as functions optimized for particular effects of light facilitated by the relative translucency offered by a material) are integrated within a singular and consistent form-generation process.

9.3 Material-based Design Computation: Methodological Contributions

Methodological contributions focus on strategies of formal generation through simulated-growth, subdivision, or a combination of both. In other words, all experiments have been generated by the graduated assignment of physical properties relative to specific performance constraints defined by the designer either when combined with some algorithmic process defining formal generation (i.e. cellular automata combined with FE analysis) or when applied as a subdivision (tessellation) strategy given initial surface features. Variable property modeling, analysis and fabrication are respectively mapped to three methods for formal subdivision and growth informed by the interaction between material properties and the environment.

9.3.1 Variable Property Modeling: Tiling Behavior (Subdivision)

Tiling-behavior is a methodological approach to form-generation allowing the designer the assignment of physical performance criteria to geometrically tessellated doubly-curved surfaces. The method developed in this research enables the designer to integrate material properties and behavior as part of the modeling process, while corresponding to a multitude of fitness functions. Specific work presented focused on the generation and implementation of a voronoi-based finite-element analysis application termed V-FEM (Oxman 2009) as an approach to tiling behavior. It promotes an alternative to traditional optimization algorithms that are applied on top of an already existing model. In other words, the V-FEM method promotes an integral approach to generation through optimization, whereby a finite element-like method is inherently linked to behavioral data and geometrical organization.

Tiling has been the subject of many innovative design projects in both academic and practical frameworks, as it closely relates to issues of fabrication and assembly of components. This work represents an attempt to rethink the role of tiling not as a formal maneuver for the rationalization of form materialization but, rather, as a means to incorporate physical behavioral constraints early on in design. It does so by introducing a theoretical and technical approach, entitled *Tiling Behavior*, which explores the integration of tessellation generation with a finite element method approach to mechanical optimization, entitled *V-FEM*.

The Voronoi cells applied in the project, *Beast*, were obtained by Dirichlet tessellation of complex 3-D surface representations. This process involves the discretization of a heterogeneous curvature domain, based on the location of a finite set of behavioral heterogeneities that are defined by mechanical behavior.

The UV re-compression algorithm implemented in this work demonstrated how to apply a Voronoi mapping on a highly complex, doubly curved 3-D NURBS surface. The need for such an algorithm was introduced by the difficulties presented in using projections, and resulted in extreme UV-squeezing conditions where point cloud density increases at regions of large squeezing. The solution involved the transformation of a uniform Voronoi point cloud mapped on the 3-D surface into a non-uniform point cloud on the UV plane. The Voronoi construction in the UV plane produces odd-looking cells on the UV-plane, but a uniform Voronoi pattern on the 3-D surface. Such a recompression algorithm may potentially be generalized to include other types of tiling patterns based on complex point cloud registrations.

Complex models that correspond to a multitude of fitness functions require sophisticated tools for their evaluation. Project *Beast* focused on the generation and implementation of V-FEM as an approach to behavior tiling. However, the structural and environmental evaluation of this tool has yet to be developed. A shape-annealing approach to tile typology that considers the dynamic growth of tiles as a function of vector mapping appears to offer one such promising direction. Finally, the method demonstrates that geometrical tessellation can be informed by physical constraints beyond its general application as a rationalizing strategy for fabrication purposes.

9.3.2 Variable Property Analysis: Finite Element Synthesis (Subdivision and Growth)

Finite element analysis methods and their practical applications[9.1] are primarily applied to evaluate a given design relative to some objective function. Currently advanced applications exist that support the integration of form-generation and evaluation from a structural perspective. Such are, for instance, tools developed for automobile shape optimization routines based on the types of loads considered, their magnitudes and directions. However, despite their generative advantage, such tools have yet to incorporate *multiple* performance criteria as part of the form-generation process.

The *Finite Synthesis Method (FSM)* was developed as a theoretical approach and methodology supporting the integration of modeling and analysis routines in the process of form-generation. It affords the designer the ability to consider analysis tools for their generative impact while corresponding to various performance criteria. In order to further implement this approach within a design environment, the concept of *material elements* has been introduced, whereby each element as defined by the FE application may contain, in addition to its structural data, information regarding other performance criteria that are of interest to the designer. In this regard, each *material element* is regarded as a tensor element defined by indices negotiating various objective functions. This method supports the distribution of properties across the entire surface area of the design object relative to the various architectural and engineering performance criteria addressed.

Beyond the notion of performance-driven interpretations based on computational geometry methods, this work has also engaged with the notion of computational analysis as a source for strategizing material distribution. Rather than breaking down the design into a series of componentized elements aiming at straightforward and simplified assemblies, the experiments undertaken in this research demonstrate an alternative approach favoring material distribution over strategies of composition.

To conclude, analytical tools are computed as geometrical statements. These statements may serve as bridging (or “multi-objective”) representations between geometry and performance, geometry and construction, and geometry and manufacturing. With the project *Raycounting*, the research sought to demonstrate such an approach by reconstructing two analysis tools for structural and environmental performance with additional functionality.

In presenting the prospects for an emerging professional profile of *informed tool-making* this work seeks to promote a new model for contemplating form and practicing design. If such a prospect is legitimate,

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[9.1] Numerical techniques for finding approximate solutions involving various domains (such as air, water etc) in which the design object is sited and by which its performance is informed then it is the knowledge of computational geometry that is becoming one of the significant forms of disciplinary knowledge of the new computational design professional.

9.3.3 Variable Property Fabrication: Multi-Material 3-D Printing (Growth)

The FSM approach assumes and facilitates the distribution of multiple material properties as a function of site-specific constraints of various types. In other words, for each material element, the size and shape of which is defined within the FE software, there exists a list of related properties specifically defined for that element. The next step is to fabricate the designed object such that all material criteria defined for each element would be manifest within the physical object. The *variable property fabrication* method was developed to support the physical production of design objects while maintaining the distribution of properties.

Currently there exist no fabrication technologies that allow for the production of objects with gradually varying structural properties. This thesis demonstrated that such a need is justified given the potential advantages in terms material and mechanical efficiencies. In addition, the thesis has confirmed that an integrated approach to form-generation where fabrication processes play an active role in the form-generation process, allows for more efficient products and building parts to be fabricated allowing the designer to include evaluative functions early in the design process.

9.4 Material-based Design Computation: Technological Contributions

9.4.1 Variable Property Rapid Prototyping

Since its introduction in the late 1980s, layered manufacturing has become increasingly common and efficient as a means of delivering functional and visually representative prototypes in relatively short amounts of time using CAD files as input. However, most layered manufacturing technologies known today produce only single material, constant property prototypes from a limited array of materials.

While conventional layered manufacturing technologies have given us the opportunity to create complex models in relatively short periods of time, the technology is also very limiting, often reducing material selection to an array of highly brittle, inelastic materials. Objet Geometries, an international 3D printing company, recently introduced their Connex Series, a line of 3D printers that use Polyjet Matrix TM Technology to allow the creation of dual material prototypes. This technology has also allowed the generation of composite material prototypes of varying stiffness. However, single material, varying property layered manufacturing technology has not yet been introduced.

The technology offered by *Variable Property Rapid Prototyping* (VPRP) represents an alternative approach to layer-manufacturing, namely, a layered manufacturing product that, while using a single material, produces a design object of varying material properties.

VPRP is a novel approach and method introducing the ability to dynamically mix and vary the ratios of different materials in order to produce a continuous gradient in a 3-D printed part. This ability expands the potential of prototyping, since the variation of properties allows for optimization of material properties relative to their structural performance as well as more accurate evaluations of the intended final product, such as stress testing. Dynamic gradients also contribute to efficient conservation of material usage. The VPRP pending patent (Oxman 2009) establishes a novel nozzle that can produce a continuous gradient, using colors as a substitute for material properties.

VPRP could potentially be applied to support materials within the printing process. Support materials are designed as temporary deposited structures that allow for a stable build to be prototyped. These structures, for the most part, are removed from the final model by decomposition, melting, heating or mechanical removal. However, such constructions are extremely wasteful. The ability to 3D print with variable properties may potentially eliminate the need to extrude support material by varying the relative thickness of the functional part in regions of under cuts and/or geometrical perimeters which require more strength in order to self-stabilize in the build process and also as the part dries out. Moreover, an intermediary step towards the application of such ideas could potentially be applied to existing support materials themselves; by offering variable property support, parts could be excavated with ease as stronger support pieces cling to more fragile areas within the print.

Finally, VPRP represents the first rapid prototyping technology which allows for modifying material properties such as strength, stiffness, density and elasticity as continuous gradients across the surface and volume area of a functional component in construction scale. Given that such variations are typically achieved as discrete changes in physical behavior[9.2] they often result in material waste and lack of functional precision. VPRP introduces the ability to dynamically mix, grade, and vary the ratios of different materials in order to produce a continuous gradient, highly optimized to fit its structural performance with an efficient use of materials, reduction of waste, and the production of a highly customizable features with added functionalities.

9.4.2 Eco-Maxels: A Variable Property Modeling Environment

In addition, VPRP also explores a new approach to fabrication that challenges the concept of Computer-Aided Manufacturing (CAM) by introducing a software application that, rather than providing a means of digitizing the geometry of a completed design, allows engineers and designers to create and design structures that are defined at various points by their material behavior as opposed to their geometry.

Most of today's Rapid Prototyping technologies create products in a point-by-point fashion. Selective-laser-sintering (SLS) and stereolithography (SLA), for instance, initiate prototype solidification at areas of contact between the stock material and the laser as the laser traverses the X, Y and Z planes. Other layer manufacturing technologies, such as 3D Systems' In Vision machine and Objet Geometry's machine, deposit the material point by point. In these systems, the prototype is constructed drop by drop using a modified inkjet system. When supplied with one or more extra jets, both systems could build graded material parts, also known as "functionally graded materials" (FGM's). This type of graded internal structure is only possible when taking an additive approach to manufacturing. However, it is still impossible to represent FGM's in a CAD environment. Most commercial CAD systems are in the category of 'B-rep' modelers. This means that the inside of the 'solids' using these modeling techniques are as empty as the volumes surrounding the solid. Therefore, for most CAD systems, even though they are known as 'solid' modelers, they are, in fact just surface representation protocols of the geometry defining the 3D form. All RP production formats, STL predominantly, are thus numerical representations of those geometries.

The Variable Printing Method (VPM) offers a novel approach to modeling and fabrication of 3D solids as it offers a way to represent the internal structure/composition of the form at individual points within the volume of the part. Currently, this method is explored by using colors as a representation of material properties. In the future, we anticipate that 3D printers will be designed as "FGM machines" which are provided with information to 'print' the desired graded material distribution.

It is expected that new CAD systems such as the VPM environment could also be applied for the design or Functionally Graded Materials using the same application logic in micro scales. Such developments

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[9.2] Such changes are achieved by printing multiple components with different properties, defining delineations between materials, and assembling them only *after* the fabrication process has been completed will most probably occur independently from other developments in CAD for rapid prototyping and manufacturing.

It is also expected that such innovations in rapid prototyping technologies will find their way into rapid manufacturing parallel to the development of more structural materials and an increase in scale. Currently, all developments in rapid manufacturing have been aligned with and dependent upon, traditional CAD environments. However, the VPM environment contributes to a radical shift from contour modeling composition modeling, allowing for new capabilities in performance modeling, with a decrease in material waste and an increase in efficiency.

A voxel represents a volume element in volume graphics just as a pixel denotes a picture element in raster graphics. Voxelization is the process of converting a geometrically represented 3d object into a voxel model. Kaufman proposed that graphics is ready to shift paradigms from 2 d raster graphics to 3d volume graphics with implications similar to these of the earlier shift from vector to raster graphics. Voxel research however has mostly focused at the informative display of volume data. We propose here a voxel based approach to geometric modeling for new layered manufacturing technologies.

The voxel-based approach for geometric modeling supported by the concept of *Eco-Maxels* offers a powerful methodology for the new variable prototyping technology. It has several advantages over conventional modeling methods, stemming chiefly from the close resemblance between a voxel model of an object and the object fabricated using an LM technology. The design of an interactive environment for voxels sculpting is the critical factor that will bring out the full power of the voxel-based approach to geometric modeling and is the focus of our current efforts.

The voxel based approach can exploit a major capability of LM equipment: the fabrication of composite objects. The range of materials that current commercial LM systems handle is limited but growing. It is very likely that in the near future, LM technology will mature to fabricate a single component from multiple materials. Conventional design tools are not oriented to the design of composite objects. Specialized tools are used in areas such as the aircraft industry in which composite materials play a major role. However, advances in LM technologies promise to bring composites into the domain of the average mechanical component.

A voxel based modeler can ultimately provide the capability to design a composite object with materials selectively placed at individual voxels. There is no need to compute the complex geometries of the interleaved materials because each slice of the voxel buffer can be directly read out during fabrication and several masks per layer can be created to deposit the different materials. Such capabilities will be indispensable as the technology of micro-electro-mechanical systems mature. A voxel will then be of molecular dimensions.

With voxel-based modeling, a solution is feasible because of the direct relationship between a voxel and the basic additive resolution of the LM equipment. The relationship implies that the surface area of the resulting object can be estimated by identifying the exposed voxels in the model, adding the area contributed by the voxel faces on the boundary, and using suitable filters to simulate the effects of merging and coagulation behaviors in the real material. Properties such as friction coefficients, surface roughness, and contact area between interacting parts can be estimated and accommodated.

Finally, another important contribution of the voxel-based approach, in contrast to traditional vector modeling, is that it eliminates the need for an intermediate format as well as for a post processing step beyond the designer's control[9.3].

[9.3] Typically, the component is modeled, and then analyzed using a finite-element analysis module. The design must then be iterated to account for the analysis results and the model is output in a given format for fabrication. Because of discretization processes inherent in layered manufacturing the resulting component could have properties different from what the CAD analysis predicted.

9.5 Current Limitations

9.5.1 Tabula Rasa: Design by Immaculate Conception?

An important assumption underlying this research is that form may be generated without explicit geometrical content (that is: form), but rather as the byproduct of matching material parameters and environmental constraints. The main design model proposed in this thesis supports such a process by considering the landscape of design possibilities as the interaction between force and matter, and between energy and matter. Eco-maxels are conceived of as the units by which to technically achieve such a concept of design. However, this model is yet to be developed as a robust design platform. Due to the difficulty of defining the origin of form within each of the experiments, I have alluded to strategies that combine more traditional form-generation with analytical iterations.

It is important to note that the mechanics calculations, for most part of the experiments presented in Chapter 7, are limited to the linear-elastic response of materials. Further experiments should be carried that explore various types of material and responses in correspondence to the types of forces exerted.

Regarding experiments focusing on surface subdivision: having focused on the customized reconstruction of analytical tools and their ability to contribute to explorations driven by performance parameters, the main limitations of this thesis remain its dependency on the initial form to be analyzed. In other words, this application assumes the initial generation of preliminary geometry constructed by the user, and applies the evaluation and modification on top of it. The question relating to the origin(s) of form remains to be discussed and engaged with in another context. And indeed, the notion of where generation ends and evaluation begins will forever remain complex, and perhaps so it should.

9.5.2 Cells, Tissues, Organs: The Limits of Distribution

In this thesis I have chosen to experiment with design challenges that are relatively small in scale from an architectural perspective: furniture pieces, medical devices and building components. In this regards it was relatively easy to dismiss resolving larger scale componentizations and assemblies in favor of smaller scale heterogeneity and distribution. However, when applied to the design of buildings, new challenges present themselves as walls join their respective floors and ceilings, if indeed they must. Throughout this treatise I have expressed the desire to consider all of a building's components as continuous site-specific extensions of a given material logic. Indeed, the main questions raised by this research have typically revolved around the desire to translate bottom-up formation processes across multiple length scales such that an organizational consistency between micro, meso and macro scale (i.e. the case of bone) prevails.

In his *Conversations with Students*, Kahn calls upon us to "consider the momentous event in architecture when the wall parted and the column became"(Kahn 1998). *Natural Design* proposes that such an "event" is synonymous with formation triggered by environmental constraints. In this regard the distinction between "wall" and "column" is attributed to the variation of forces their magnitudes and directions as matter (however this matter may be physically defined) distributes itself locally to account for the load presented to it. In the future, such typological classes will be omitted from an architect's glossary and in their place will appear classes of procedural routines by which to relate material substance to energy. A time will come where buildings may be constructed as bones.

9.5.3 Nature Minus Growth: Considering Static and Dynamic Material Architectures

Motivated by the idea that architectural form may be generated by the interaction between matter and energy, it is rather straightforward to imagine how concepts developed in this thesis may potentially be applied to dynamic objects that respond and adapt to their environment in real time. However, since the subject of this investigation focused on form-generation processes that are informed by material properties and behavior *prior* to form's materialization, I have chosen to focus on the generation of static objects and explore these emerging forms as templates of their environment. Another motivation has been the desire to examine natural materials specifically cellular solids and the way in which their micro and meso-structural organizations have been informed by load and other constraints. This has made it possible to circumvent domains of kinetic structures activated by add-on electronic devices and to focus on natural processes, structures and materials.

Clearly, the question of how to convert and implement some of these ideas in the context of what is today termed *responsive environments* appears to be a promising and challenging path for the future.

9.6 Design Implications

9.6.1 The Death of the Module: Design without Assemblies

The modernist tradition typically promoted the division of functions implicit in the architectural elements: their pre-assigned forms, structures and materials (i.e. the separation between structure and façade and the assignment of steel columns and glass walls respectively to each function). Coupled with automation in construction, this logic gave birth to an architecture that is easily mass produced, assembled and built of replicated modules. Despite its obvious advantages, the application of the modular logic of building holds some fundamental limitations when it considering requirements driven by site-specific functionality and customization.

Alternatively, design based upon performance and conditions of habitation promotes customization through formal, structural and material heterogeneity. Our ability to quantify a building's structural and environmental performance allows the designer to account for site-specific differences of use and behavior.

Given such ability to predict and respond to performance criteria and desired effects, this research holds implications for shifting design practice from *homogeneous modular design* driven by the *logic of material assembly* to *heterogeneous differentiated design* driven by *material distribution*. In this approach, matter is distributed where needed responding to its structural, environmental or, indeed, social performance. In fostering material integration of architectural elements across various scales, architectural elements such as structure and façade are no longer divorced in function and/or behavior, but rather negotiated through the informed distribution of matter.

Perhaps the most significant consequence of design that is informed by performance is the incorporation of difference: gradients of structural and material effects emerge modulating their thickness, transparency, porosity and thermal absorption according to their assigned function or desired condition of stability (structure) and comfort (environmental conditions).

9.6.2 Modeling is Analysis is Fabrication: Design without Representation

To dream that a desert house may form itself from sand as defined by the forces of the wind, or that an igloo may self-assemble as arctic water freezes would require that we achieve seamless integration between processes of environmental surveillance, modeling and construction.

The design world has forever negotiated between the separated practices of form-generation, analysis and fabrication. This schism between the design and engineering disciplines (as well as their respective tools and technologies) has yielded with it an image of a layered and streamlined practice where time and matter are wasted as we move through many layers of design translation from conception to materialization. We have seen that in Nature such distinctions do not exist: the form of an organism is directly informed by its growing substance and the way in which it responds to its environment. As far out a statement as this may seem to be, I have attempted to present some concepts and methods by which such integration between process domains might be achieved as we design structures that are more efficient and effective with regards to the functions they are intended to satisfy.

Supported by the body of work entitled *Material-based Design Computation*, this research calls for a shift from a geometric-centric approach to form generation (dominated by the hierarchy of modeling, analysis and fabrication) to material-based processes (where procedural hierarchies are non-hierarchical and context-specific). Such a shift entails that we account for and include material properties and behavior prior to the premeditated and environmentally irresponsible commitments to form.

9.6.3 Sustainable Fabrication: Design without Waste

The integration between the natural and the artificial environment is not trivial inasmuch as it is desirable. The general view within the construction industry is that given its pervasive nature it is almost impossible to imagine a sustainable construction industry without the absence of automation and the prevalence of the vernacular. This is understandable considering that both globally and in the United States of America (USA), the construction industry is one of the main contributors to the depletion of natural resources and a major cause of unwanted side effects such as air and water pollution, solid waste, deforestation, toxic wastes, health hazards, global warming, and other negative consequences. Although this view is changing with the growing understanding of how important and indeed instrumental natural phenomena are or could be in an industrialized society, the utilization of environmental gains in building-construction automation has been hampered by the absence of a detailed understanding of natural phenomena, as well as the ability to experimentally implement it in design.

Initially aimed at reducing material waste, enhancing structural efficiency and minimizing overall environmental impact *Variable-Property Rapid Prototyping* is currently being developed and implemented as a design technology innovation, re-thinking the relation between fabrication and ecology, by offering a novel design fabrication technology that is able to produce lightweight materials with continuously varying mechanical properties. This technology offers to significantly reduce material and energy waste in the design of products and buildings by constructing structures with varied properties using lighter, stronger materials and avoiding redundant deposition. The aim is that such products and building envelopes will be designed to use significantly less fossil fuel energy to construct and operate than they would typically consume. Local assignment of materials promotes lower energy usage in buildings, blockage of radiation heat from sunlight, passive ventilation, improved occupant comfort, and space utilization. In the design of products such strategies promote high levels of customization. The fundamental concept is a first-generation rapid manufacturing tool for depositing material with gradually varying physical properties such as density or elasticity per unit volume informed by structural and environmental fitness constraints.

Finally, the awareness of environmental impacts is growing and many movements seeking to address sustainability concerns are gaining momentum. Since buildings represent more than 50 percent of the nation's wealth in the USA, it is imperative that we consider how the principles of *Natural Design* might be incorporated not only in the design of products but also in the design of fabrication and construction processes. VPRP represents a pilot project in this direction in hope that many such efforts may be embraced, promoted and implemented as we practice a more natural approach to the design of environments.

9.7 Summary: Material-based Design Computation and the Open Boundary

The major objective in establishing the conceptual and theoretical foundations of Material-based Design Computation (MDC) has been to establish an approach to the design of computational environments which might inculcate material attributes directly into the process of computationally supported design, during its various stages. As we have stated, the huge recent advances of more than a decade's development in computationally supported design have been geometric-centric in nature. This has propagated a dichotomy of form-making and *a posteriori* materialization which has become schismatic. MDC has been envisioned as a body of theory, methods, techniques and technologies which might enable computing directly with material attributes in processes of design synthesis, that is, in the *generation of form*. As a basic assumption of the research I have attempted to frame MDC as a performance-based model of design. In recognition of the various important precedents for formulating models of design, I have attempted to emulate Nature's Way in theorizing and developing computational means for supporting material-based form finding and generation. In the most concise sense, the definition, theorizing, experimentation and validation of these research assumptions have done much towards the more ambitious goal of establishing the field. But I believe that these ambitions, when coupled with the technological developments that have been invented as the fruitful side effects of the experimental method of the research perhaps justify the claim to having invented and established a new field.

Beyond the direct scientific contributions of MDC there has been an intrinsic belief that MDC, being framed within the principles of Nature-emulated models of design, might potentially provide the attributes of nature in eco-efficiency and sustainability. Thus MDC was intentionally conceived as a design medium to achieve what I have termed *Natural Design*. A material-based design approach to form-generation deriving from the potential of the design paradigm and technology of gradated, or gradient, materiality is the second area of contribution of the work. Partially realized in the case studies, validation of these methods of design and their attributes at architectural scales remain to be strengthened in future work. Having said this, the combination of MDC and its attributes in contributing a design method to produce Natural Design may potentially be considered a new paradigm of design relevant to a variety of fields including architecture, product design, and the less conventional, but as yet undefined, futures of *material design*. MDC as a paradigm of *Natural Design* can provide a *second nature*, or a means to envision design (the science of the artificial) as *natural artifice*.

Along the way, among the most significant of the three areas of contributions, was the dissolution of disciplinary boundaries, or the foundation of a meaningful *open boundary* between architecture, design studies, design computation, and material science. The open boundary condition between these fields grants the discussion of future research and potential contributions of the field a special importance due to the scientific and applicative potential of certain of these inter-disciplinary relationships. But then again, such is the nature of design innovation.

SERGE
Promise me, Julia...build. Build what’s possible, build nobly.

JULIA
I promise.

Megalopolis
by Francis Ford Coppola
Scene 167

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