

Neri Oxman, Beast: Prototype for a Chaise Lounge, Boston Museum of Science, Boston, Massachusetts, 2008 opposite left: 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 its stress, strain and comfort profile. An algorithm then assigns one out of five materials for ohysical construction.

Neri Oxman, Monocoque: Prototype for a Structural Skin, Museum of Modern Art (MoMA), New York, 2007

opposite right: Monocoque illustrates a process for stiffness distribution informed by structural load based on a Voronoi algorithm. 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

In her (nature's) inventions nothing is lacking, and nothing is superfluous.

Leonardo da Vinci

Nature is demonstrably sustainable. Her challenges have been resolved over eons with 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.

### Structuring Difference: Nature's Way

Natural structures possess the highest level of seamless integration and precision with which they serve their functions. 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 fibres.1 Combined with extra-cellular matrices, these structural biomaterials form microstructures engineered to adapt to prearranged external constraints introduced upon them during growth and/or throughout their life span.<sup>2</sup> Such constraints generally include combinations of structural, environmental and corporeal performance. Since all biological materials are made of fibres, their multifunctionality 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.3 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 distribute material properties by way of locally optimising regions of varied external requirements, such as bone's ability to remodel under altering mechanical loads, or 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. This property is called 'anisotropy', and it is due to 'anisotropic structuring' that nature can create sustainable structures efficiently.

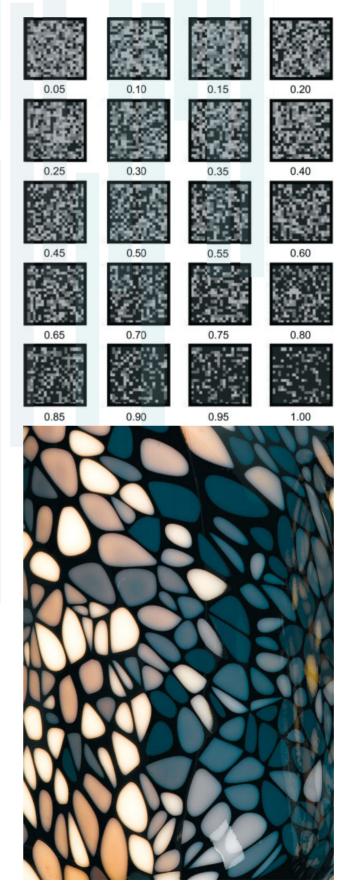
## From Discrete to Continuous Heterogeneous Material Architectures

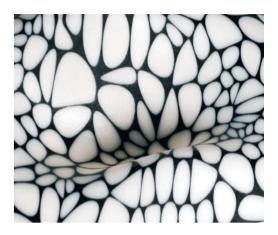
Compared to nature, our own material strategies appear to be much less effective, and mostly wasteful. Since the industrialised age, the construction industry has been dependant on discrete solutions for distinct functions.<sup>4</sup> Building skins are a great example of such a claim. Steel and glass 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 customised. 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?

## Form First, Structure First, Material First: New Materialism

The image of the architect as form-giver has for centuries dominated the profession. In most cases, structural strategies are addressed by way of post-rationalisation in support of the building's utility captured by spatial properties. In this light, material selection and application are dependent on structural solutions. Such views emphasise the hierarchical nature of the design process with form being the first article of production, driving both structural and material strategies. Frank Gehry's architecture provides many such examples; 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 prioritises the function of structure as the main driver of formal expression.

'Structure first' is manifested particularly in projects of 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





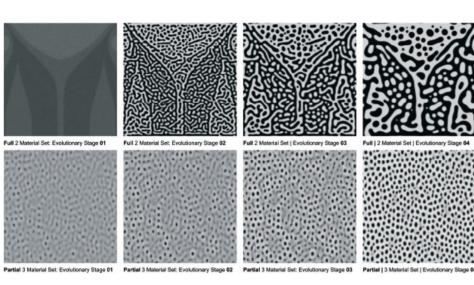
bottom-up as material informs structure which, in turn, informs the shape of naturally designed specimens. Such is the case, for instance, with bones and other cellular structures, the shape of which is directly informed by the materials from which they are made. In nature, in most cases, material comes first. How can a 'material first' approach be accommodated by design?

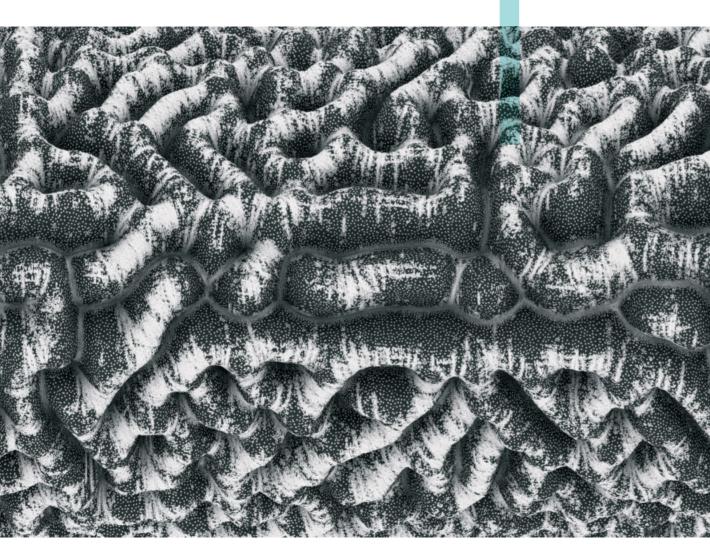
With the assistance of advances in structural and material engineering entering contemporary discourse, architectural culture appears poised for transformation. Designers now seek to advance nature's strategies in structuring matter by designing synthetic multifunctional materials competing with evolution's unrestricted timeframe of design process. Fitness, not form, is what actually matters. Welcome the new materiality.

## The New Materiality: Defining a Novel Technology of Variable Property Design Fabrication

Variable property design (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 here termed 'synthetic anisotropy' – an 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. Theoretical and technical foundations for this approach have been termed 'material-based design computation.<sup>5</sup>

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 technologies to fabricate and construct them. The following projects illustrate an array of implementations for this approach in the design of a furniture product, a medical device and a fabrication technology. All projects integrate the components of modelling, analysis and fabrication with a particular focus on the development of one such component in each of the projects.





Neri Oxman, Carpal Skin: Prototype for a Carpel

Tunnel Syndrome Splint, Boston Museum of

Physical model of prototype. Material

ons informed by size, scale, direction and

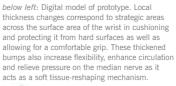
netween soft and stiff materials. The charts

nputed on top of an optimised unfolded

sentation of the frontal and dorsal planes of attent's hand and refolded following mater ament to construct the 3-D glove.

Science, Boston, Massachusetts, 2008

opposite bottom: 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 allow for passive yet consistent pulling and stretching simultaneously.



below right: 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.





### Variable Property Modelling (VPM): Chaise-Performative (Boston Museum of Science, 2009)

A single continuous surface acting both as structure and skin is locally modulated to provide for both support and comfort. This design for a chaise longue corresponds to structural, environmental, and corporeal performance by adapting its thickness, pattern density and stiffness to load, curvature and skin-pressured areas respectively. The technical objective was to introduce a quantitative characterisation and analysis of VPM as it is applied to a tiling algorithm using Voronoi cell tessellation. Stiffer materials are positioned in surface areas under compression, and softer, more flexible materials in surface areas under tension.

# Variable Property Analysis (VPA): Carpal Skin (Boston Museum of Science, 2009)

Similar to the manner by which load or temperature can be plotted and computationally optimised to fit their function, physical pain may also be mapped in the design and production of medical assistive devices such as pain-reducing splints. Carpal Skin is a prototype for a treatment glove for 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. Nighttime wrist splinting is the recommended treatment for most patients before going into carpal tunnel release surgery. The main problem with current glove solutions is their lack of customised features in relation to the patient's distribution of pain. Carpal Skin is a process by which to map the pain profile of a particular patient - intensity and duration - and distribute hard and soft materials corresponding to the patient's anatomical and physiological requirements. The relative distribution of softer and stiffer materials across the glove's surface area allows limiting central and lateral bending motions locally in a highly customised fashion.

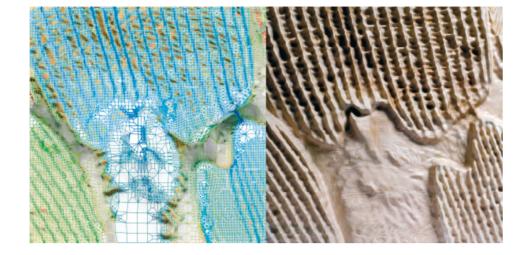
### Variable Property Fabrication (VPF)

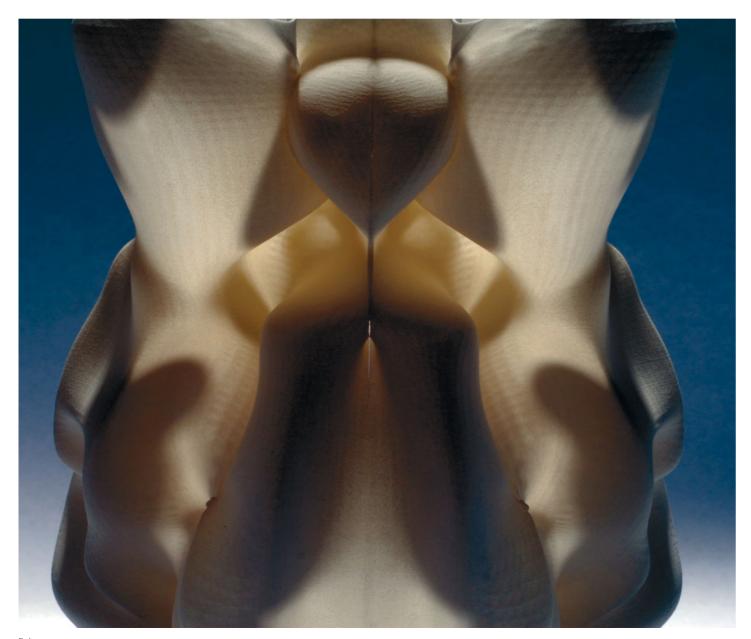
Currently, there exists no rapid prototyping technology that allows for a continuous modification of material properties such as strength, stiffness, density and elasticity as continuous gradients across the surface and volume area of a functional component. Such variations are usually achieved as discrete changes in physical behaviour by printing 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 fabrication aims at introducing a novel material deposition 3-D printing technology8 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 optimised to fit its structural performance with an efficient use of materials, reduction of waste and the production of highly customised features with added functionality.

#### Materials are the New Software

Since its emergence in the 1960s, computer-aided design (CAD) in its many transformations has afforded the designer an almost effortless manipulation of shapes generally detached from their fabrication in material form. Such processes promote the application of material subsequent to the generation of form. Even when supported by high-fidelity analytical tools for analysis and optimisation, these processes are predominantly linked to geometrical manipulations in three dimensions. The work presented here calls for a shift from a geometric-centric to a material-based approach in computationally enabled form-generation.

Variable property fabrication of materials with heterogeneous properties across a wide array of scales and applications holds a profound place in the future of



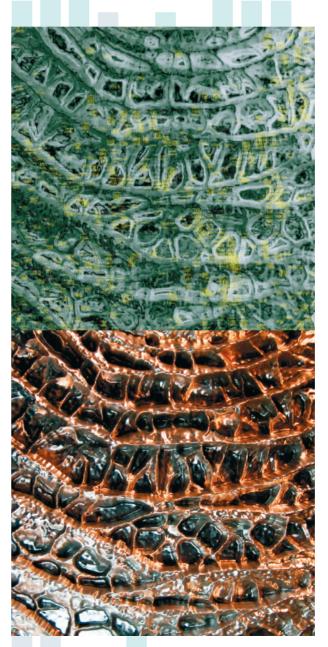


Neri Oxman, Raycounting, Museum of Modern Art (MoMA), New York, 2007 opposite bottom: Raycounting is a method for originating form by registering the intensity and orientation of light rays.

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

Neri Oxman, Subterrain: Variable Property Analysis and Fabrication of a Butterfly Wing, Museum of Modern Art (MoMA), New York, 2007 opposite top: An object-oriented application determines the material's behaviour 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 fibre directionality assignment and layering strategies are employed for areas requiring structural stiffness as defined by the designer.

Neri Oxman, [X, Y, Z, S, S, T] (pronounced 'exist'): Variable Property Analysis and Fabrication of Natural Specimens, 2008 below: Aluminium and low carbon steel composite. The 6-D model includes 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.



design and engineering. The ability to synthetically engineer and fabricate such materials using VPF strategies appears to be incredibly promising as it increases the product's structural and environmental performance, enhances material efficiency, promotes material economy and optimises material distribution. Among other contributions, material-based design computation<sup>7</sup> promotes a design approach through digital fabrication of heterogeneous materials customised to fit their structural and environmental functions. The practice of architecture is at last reawakening to its new role as (a) second nature.  $\varpi$ 

#### Notes

- 1. Janine M Benyus, *Biomimicry: Innovation Inspired by Nature*, HarperCollins Publishers Inc (New York), 1997.
- 2. Julian Vincent, Structural Biomaterials, Princeton University Press (Princeton, NJ), 1982.
- 3. Steven Vogel, Comparative Biomechanics: Life's Physical World, Princeton University Press (Princeton, NJ), 2003.
- 4. Neri Oxman, 'Oublier Domino: On the evolution of architectural theory from spatial to performance-based programming', First International Conference on Critical Digital: What Matters(s)?, Harvard University Graduate School of Design (Cambridge, MA), 18–19 April 2008, pp 393–402.
- 5. Some relevant foundations of material-based design computation appear in: Neri Oxman and JL Rosenberg. 'Material-based design computation: an inquiry into digital simulation of physical material properties as design generators', *International Journal of Architectural Computing* (IJAC), Vol 5, No 1, 2007, pp 26–44; Neri Oxman, 'Get real: towards performance-driven computational geometry', *International Journal of Architectural Computing*, Vol 5, No 4, 2007, pp 663–84; Neri Oxman, 'fab finding: predicting the future', Proceedings of the 25th eCAADe Conference, Frankfurt am Main, 26–29 September 2007, pp 785–92.
- 6. Neri Oxman, 'Material-based design computation: Tiling behavior', reForm: Building a Better Tomorrow, Proceedings of the 29th Annual Conference of the Association for Computer Aided Design in Architecture, Chicago, 22–25 October 2009, pp 122–9.
- 7. Material and mathematical studies were carried out in collaboration with Professor Craig Carter and Professor Lorna Gibson from the Department of Materials Science and Engineering at MIT.
- 8. 2010, MIT patent pending.

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