That matter is secondary to shape constitutes the fallacy of design after craft. By nature, and in its rite, the material practice of craft is informed by matter, its method of fabrication, and by the environment (Semper, 1851). As in Nature, when creation begins with matter, morphogenesis, or the generation of form, is a process engendered by the physical forces of Nature (Thompson, 1942; Thom, 1975). Similarly, in the framework of this essay, Material is not considered a subordinate attribute of form, but rather its progenitor. Such is the story of form told from the point of view of matter, and it begins, naturally, with form’s predicament.

**Form’s Predicament: A Brief History**

Over the long trajectory of architectural design history, the design and production of artifacts has been characterized by a growing separation between form and matter. In contradistinction to craft in which material and form are organically intertwined into a tradition of making, modern design and production have historically evolved away from this integration, or in its absence, towards the compartmentalization of form-making as a process independent of its sources in material knowledge (Sennett, 2008). At least since the Renaissance, with the emergence of architectural theories, form generation has become somewhat of a self-directed and 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 has become, within the logic of the modernist tradition, an agency secondary to form.

The Industrial Revolution lay 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, detached and independent of environmental forces and influences. The values promoted by ancient crafts (not unlike Nature’s way), 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 appeared 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 and engineering (Jencks, 1984).
The Digital Revolution, which marked the shift 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. This new design space afforded much liberation in 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 "non-standard" form.

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**Designing (with) Nature: Towards a New Materiality**

Today, perhaps under the imperatives of growing recognition of the ecological failures of modern design, inspired by the growing presence of advanced fabrication methods, design culture is witnessing a *new materiality*. Within the last decade in both industrial design and architecture, a new body of knowledge is emerging within architectural praxis. 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. With the growing relevance of “materialization”, new frontiers of material science and digital fabrication 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 a new paradigm inspired by the *Troika* structure of craft, at the interaction of Materials Science, Digital Fabrication and the environment.

*Material Ecology* is an emerging field in design denoting informed relations between products, buildings, systems, and their environment (Oxman, 2010). Defined as the study and design of products and processes integrating environmentally aware computational form-generation and digital fabrication, the field operates at the intersection of Biology, Material Science & Engineering, and Computer Science with emphasis on environmentally informed digital design and fabrication.

**Bitmap Printing: Fabricating Nature**

With the advent of digital fabrication techniques and technologies, digital material representations such as voxels (3-D pixels) and maxels (a portmanteau of the words 'material' and 'voxel') have come to represent material ingredients, for instance in the context of additive manufacturing processes. Designers are now able to compute material properties and behavior integrated into form-generation procedures.
Motivated by the prospect of designing material behavior, a novel design and technological approach for biologically-inspired layered fabrication entitled *Bitmap Printing* (Figure 1) has been defined, implemented and explored by the author, in collaboration with Objet Ltd., The Mathworks and in the context of new design work commissioned by the Centre Pompidou (Paris).

**Figure 1**: The bitmap printing technique allows for the capturing of material property data in high resolution as a collection of bitmap files printed in 16µ resolution. Left: Curvature informed material distribution (from blue to green); Right: Relative height informed material distribution (red to yellow). Design: Neri Oxman in collaboration with Prof. W. Craig Carter, Objet Ltd., and The Mathworks, Centre Pompidou, Paris 2012. Photo credit: Yoram Reshef

In this collection, 18 prototypes for the human body were fabricated, designed to augment human function such as enhancing strength, promoting flexibility, providing for comfort, or exploring some functional combination. The aim was to implement material property and behavior combinations accommodating for multiple functions in the design of human armors including helmets, corsets, hip splints and various prosthetic devices. Specifically, the work explored strategies for the integration of protective functions with flexibility and comfort implementing functional gradient digital fabrication (Oxman, 2011, C). These experiments lay the methodological foundations for the generation of heterogeneous and functional prototype development using structural materials for humanoid armor. In order to address geometrical constraints and allow for material organization modulation, both anatomical and physiological mapping were executed during the analysis and the synthesis stages.
**Anatomical & Physiological Mappings (Analysis):**
Combining global organismal hierarchies informed by anatomical data with local tissue composition mappings informed by physiological data (i.e. µCT scans) the aim was to achieve a fully integrated armor which varies its mechanical, chemical, environmental and thermal properties accommodating geometrical (anatomical) features and physical (physiological) properties (Oxman, 2009).

**Anatomical & Physiological Fabrication Strategy (Synthesis):**
On global anatomical scale, basic geometrical data describing the anatomical features as transformable meshes were extracted. This network of curves and surfaces guided the distribution of material properties as behavioral patches relating to the skeletal and muscular systems. On the local physiological scale, µCT scan data converted to material distribution data informed the allocation of stiff and soft materials. A novel digital fabrication method entitled *Bitmap Printing* that facilitates the 3d printing of 16µ physical bits was implemented to support high-resolution digital fabrication of heterogeneous functional material gradients (Figure 2). Each material component within the overall armor construction was designed and printed with varying physical properties informed by multi-scalar mappings.

![Figure 2: Examples of bitmap printing demonstrating formal variation in color, thickness, porosity (right) and material property variation in 16 µ scale (left). Design: Neri Oxman in collaboration with Prof. Craig Carter, Objet Ltd., and The Mathworks, Centre Pompidou, Paris 2012. Photo credit: Yoram Reshef](image)

The following example illustrates the *Bitmap Printing* concept and technique, developed in collaboration with Objet, Ltd., The Mathworks and Uformia for Centre Georges Pompidou (1012).

The final head shield introduces variable thickness of the shell, informed by anatomical and physiological data derived from real human skull µCT scan data. Medical scan data of a human head is selected from an open repository. Two sets of data are created and trimmed from the scan using medical imagining software simulating the hard tissue (skull) and the soft tissue (skin and muscle) (Fryazinov, 2011). Combined, these two data sets make up the bone-to-skin threshold informing helmet thickness and material
composition according to its biological counterpart such that bony perturbations in the skull are shielded with soft lamellas designed as spatial sutures (Figure 3).

**Figure 3**: Tissue composition data extracted from µCT scan analysis informs geometrical and physical material properties in the design of a helmet. Design: Neri Oxman in collaboration with Prof. Craig Carter, Objet Ltd., The Mathworks, and Turlif Vilbrandt, Centre Pompidou, Paris 2012. Photo credit: Yoram Reshef

**Figure 4**: Tissue composition data extracted from µCT scan analysis informs geometrical and physical material properties in the design of a helmet. Design: Neri Oxman in collaboration with Prof. Craig Carter, Objet Ltd., The Mathworks, and Turlif Vilbrandt, Centre Pompidou, Paris 2012. Photo credit: Yoram Reshef
What Does a Pixel Want to Be? Towards a Material Ecology

The ability to design, analyze and fabricate using a single material unit implies unity of physical and digital matter, enabling nearly seamless mappings between environmental constraints, fabrication methods and material expression (Oxman, 2010, 2011A, B). Such unity - like that found in natural bone, a bird’s nest, a typical African hut and a woven basket - might promote a truly ecological design paradigm, facilitating formal expression constrained by, and supportive of, its hosting environment.

Like Kahn’s brick arch (Kahn, 1969), the units of digital matter may be informed with various functions on their way to become and contribute to larger material organizations. The designer’s voxel is equivalent to Kahn’s brick, in that when combined, these material units can self-organize by way of mediating their physical properties with their external environment.

Ultimately, the faculty to author new forms of expression will depend on the craft triptych (matter, fabrication, and environment) and its integration into the design practice as an undifferentiated scheme, able to process matter into shape as informed by the environment. Once achieved, architectural design will have arrived at an ecology of the artificial: a Material Ecology.

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