Neri Oxman

Neri Oxman/MIT Mediated Matter Group and Stratasys in collaboration with Professor W Craig Carter/ MIT Department of Materials Science and Engineering, Gemini, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, 2014

Templating Design for Biology

The complex relationship between biology and design can be understood as two uniquely distinct yet complementing approaches. While the biological world expresses form and function from the bottom up through self-organisation, cell differentiation, growth, remodelling and regeneration, design practice operates from the top down, establishing constraints that inform or guide form generation and construction.

and Biology for Design

Architect **Neri Oxman**, Associate Professor and Head of the Mediated Matter Group at the MIT Media Lab, introduces how new advances in additive manufacturing coupled with emerging capabilities in materials science and synthetic biology are today empowering designers to combine top-down design procedures with bottom-up digital or physical growth across spatial and temporal scales.

Top view of the final design, 3D-printed by Stratasys with Objet500 Connex3 Color multi-material 3D printing technology, and CNC milling by SITU Fabrication. An acoustic chaise longue, Gemini's surface varies its rigidity, opacity and colour.

In order to fully employ the new competencies provided by advances in science and technology, we must first define and demonstrate ways that enable top-down templating of bottom-up processes. This dual approach can increase the dimensionality of the design space by enabling the creation of multifunctional structures with high spatial resolution expressed in additive manufacturing and sophisticated computational algorithms.[1] Below are four approaches by the MIT Media Lab's Mediated Matter Group for templating design for biology and biology for design by inventing and deploying novel digital fabrication tools and technologies. Templates are defined here as top-down material (for example, physical scaffolds) or immaterial (environmental forces) frameworks that can inform or direct bottom-up processes.[2] The projects are organised by the complexity of the media being templated, starting with morphological templating, transitioning into biochemical templating and culminating with biological as well as synthetic-biological templating. Each unfolds the technical challenges associated with templating bits, genes and atoms to inform design with biological principles on the one hand, and augment these designs with biological functionality on the other. The article concludes with the future prospect of designing biology itself.

Static Shape and Property Templating Through Compound Fabrication

The seed geometry of the *Ornithogalum dubium* (also known as Star of Bethlehem) flower is characterised by a star-shaped cellular structure with interlocking units connecting one cell to another.[3] This unique geometry enables an increased surface-area-to-volume ratio, a principle that can be employed, for example, to increase sound absorption or enable tight spatial packing.[4]

Gemini, created by Neri Oxman and Stratasys in collaboration with Professor W Craig Carter for the 'Vocal Vibrations' installation at La Laboratoire, Paris, in 2014, is a chaise longue designed as a semi-anechoic chamber. Comprising a 3D photo-polymeric skin and a wooden shell constructed using a compound fabrication approach[5] that combines multi-material 3D printing with CNC milling, its texture is informed by the weight distribution of a typical person with the goal of delivering structural support and comfort on the one hand, and maximising the absorption of sound emanating from exterior sources of noise on the other.[6] To achieve the increased surface-area-to-volume ratio required for the reduction of the signal strength, this biological pattern was emulated through the computational implementation of an inhomogeneous Poisson process, and then templated by the overall geometrical constraints, desired material properties and sound absorption across the surface area of the chaise.

To implement the templating technique, the mechanical and acoustical properties of the 3D-printed texture first devolved quantities and their gradients from the density, size, shape and material choice of each cell. The density of cells on the chair's surface, for example, were derived from an estimate

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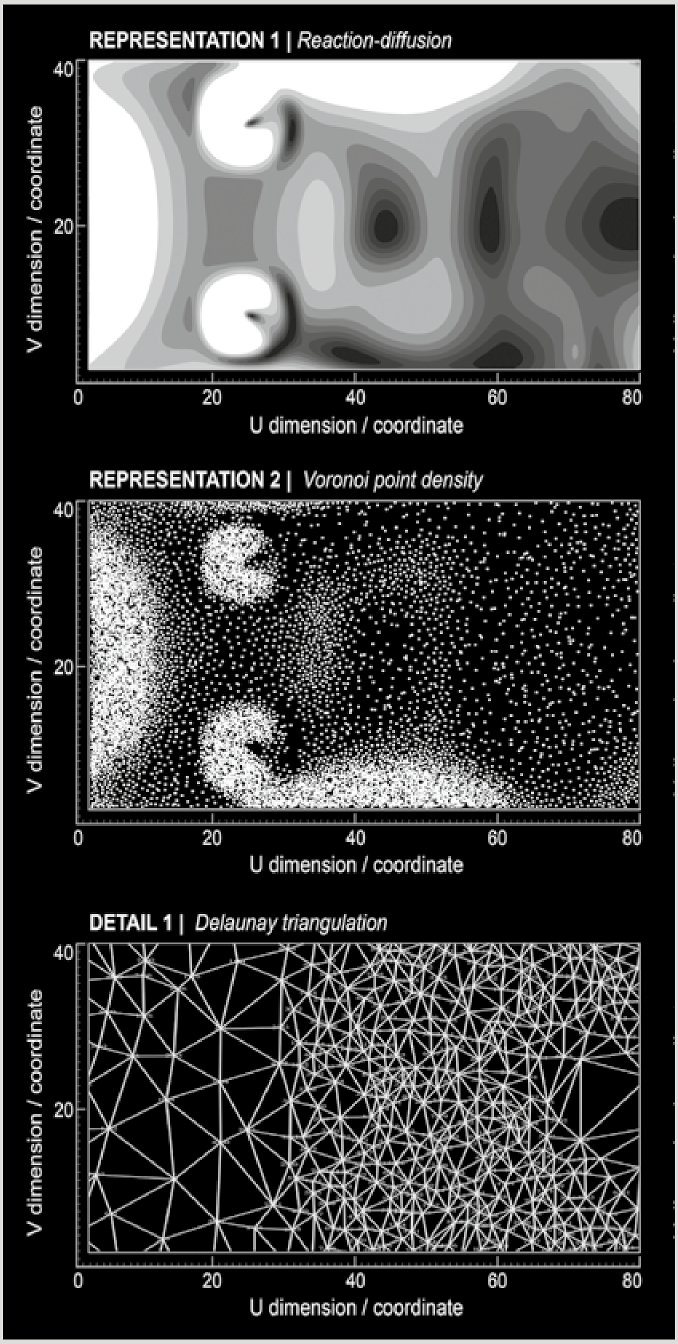
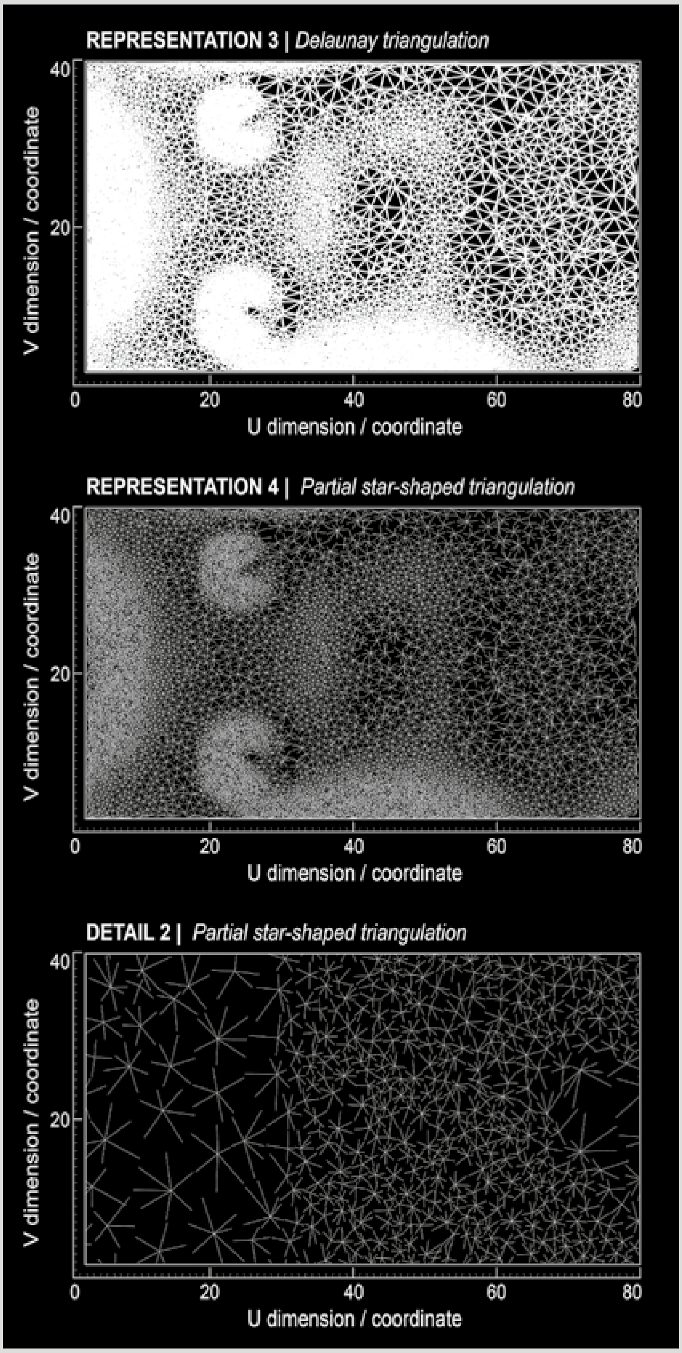
below and opposite left: Static shape and property templating representations of Gemini including: (1) reaction–diffusion; (2) Voronoi point density; (3) Delaunay triangulation; and (4) partial star-based triangulation.

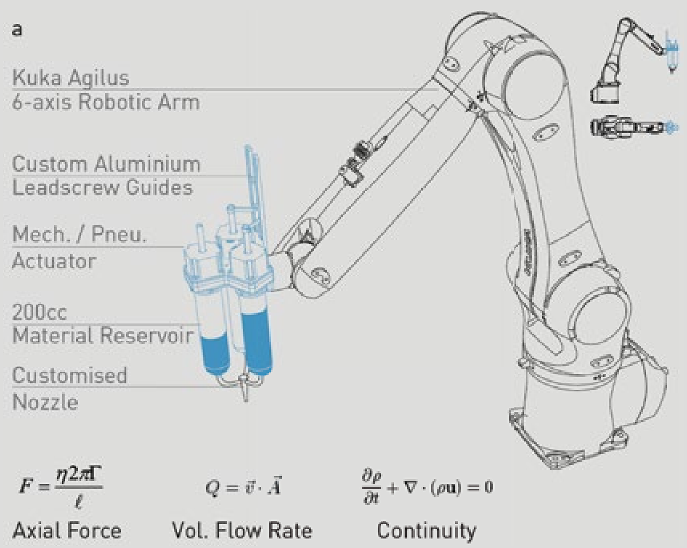


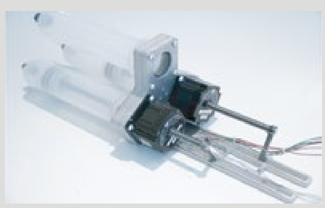


of the pressure distribution due to a sitting body and a simulation of the diffusion of that pressure within the chair's surface. Secondly, the morphology and shape of each cell derived from an algorithm that, simultaneously, maximised the interlacing contact between neighbouring cells and minimised the distance of any part of the cell to its root structure. Algorithms for material choices for each cell were generated so as to optimise for structural integrity and user comfort. The resulting object thus represents a case of geometrical templating of a large set of quantities mapped onto a two-dimensional manifold that is embedded in three dimensions.

Dynamic Shape and Property Templating Through Robotic Additive Manufacturing

The beak of the Humboldt squid is extremely stiff at its tip, yet when surrounded by water the base is 100 times more compliant, enabling it to continuously fuse with the surrounding soft tissue. Stiffness gradients combined with aqueous environment are key to enabling dynamic adaptation of material and geometrical features over space and time. Inspired by aqueous material gradation, the Mediated Matter Group's Water-based Fabrication Platform offers a new perspective on water-based manufacturing, combining a crustacean-derived material with robotic fabrication to form constructs that utilise graded material properties for hydration-guided self-assembly.[7]



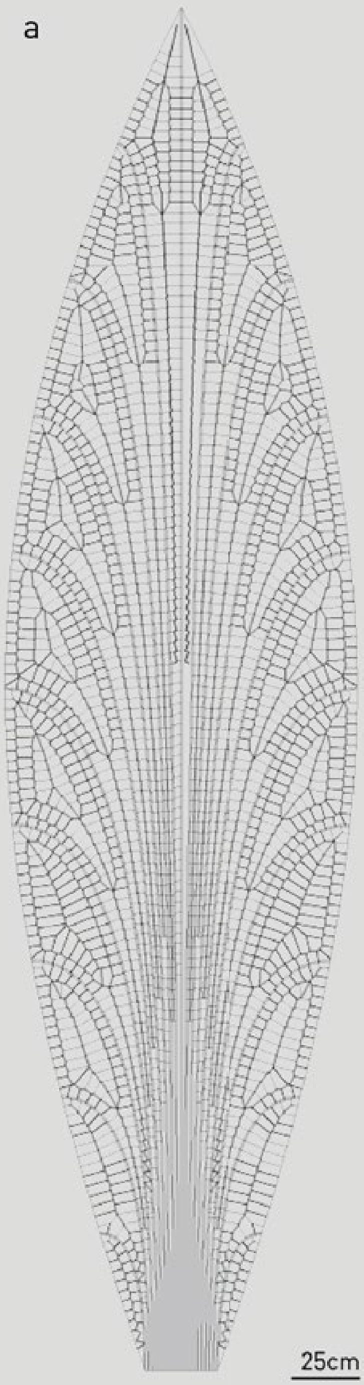


MIT Mediated Matter Group, Water-based Fabrication Platform, MIT Media Lab, School of Architecture and Planning, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, 2014-

Mechanical setup for dynamic shape and property templating through robotic additive manufacturing. A custom-designed portable multi-chamber extrusion system is mounted as an end-effector of an industrial robotic arm to enable synchronisation between robotic positioning and materials deposition.

MIT Mediated Matter Group, Water-based Fabrication Platform, MIT Media Lab, School of Architecture and Planning, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, 2014–

below and opposite top: Overall shape formation is achieved through geometrical and material property templating deploying a robotically controlled multi-material nozzle.



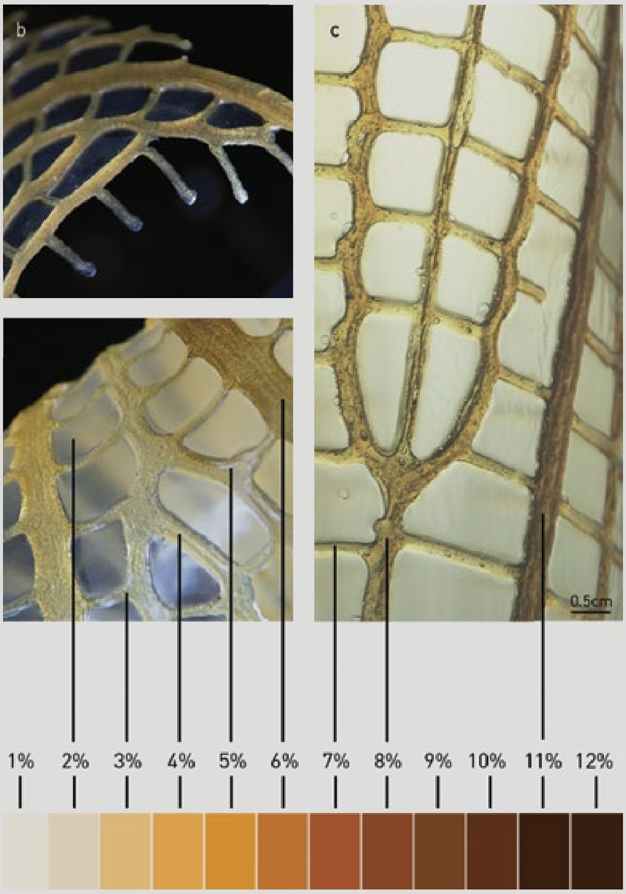
As part of the group's ongoing research, a robotically controlled extrusion system was designed to deposit biodegradable composites with functional mechanical and optical gradients across length scales. A seamless computational workflow was then implemented for the design and direct digital fabrication of multi-material and multi-scale structured objects, to encode domain-specific meta-data relating to local, regional and global feature resolution. Shape-informing variable flow rates and material properties were associated with mesh-free geometric primitives. The system utilises water to process high-strength bioplastic materials and to control their properties over time. 2D additively manufactured 4-metre (12-foot) long structural components provide the template for 3D shape formation. Once templated, components are form-found through evaporation patterns given by geometrical arrangement and hierarchical distribution of material properties. Each will take shape upon contact with air, and biodegrade upon contact with water.

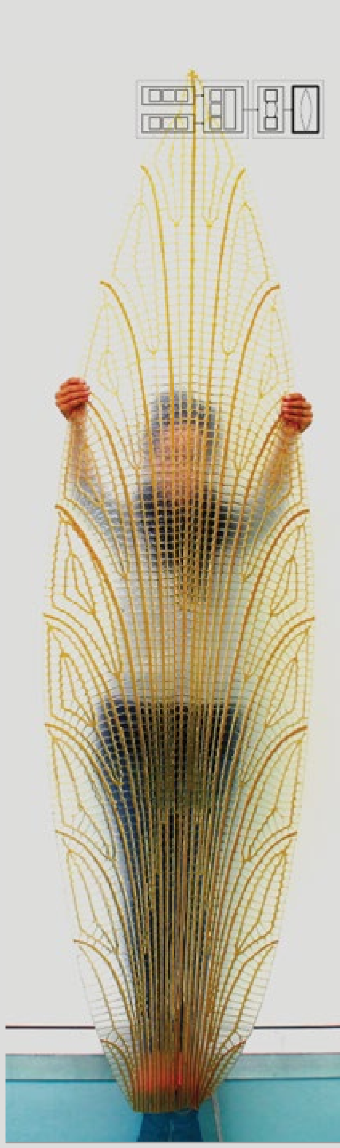
Organismic Templating Through Robotic Fibre Spinning

The domesticated silkworm *Bombyx mori* can be thought of as a biological multi-axes, multi-material, 3D fibre-spinning apparatus. It spins a single kilometre-long thread of raw silk filament over 72 hours to generate a complex structure, the cocoon, for metamorphosis. Alas, silk cocoons are often boiled in order to separate the fibres (fibroin) from the matrix (sericin), which makes the cocoon easier to unravel and the silk simpler to wind.[8] However, when presented with a relatively flat surface the silkworm will spin a flattened patch while healthily metamorphosing, and this inspired Mediated Matter Group to deploy silkworms over an existing scaffold in order to spin a structure made of natural silk without boiling the moth or its cocoon. Moreover, further experiments confirmed that spinning configurations and fibre density distribution varied according to the morphological features of the 'templating environment'.[9]

The scaffold structure comprised 26 polygonal panels made of silk threads laid down by a computer-numerically controlled (CNC) machine.[10] A swarm of 6,500 silkworms was then positioned at the bottom rim of the scaffold, spinning flat non-woven silk patches as they locally reinforced the gaps across the CNC-deposited fibres to create the Silk Pavilion. Following pupation, the silkworms were removed; the resulting moths can produce 1.5 million eggs with the potential of constructing up to 250 additional pavilions.

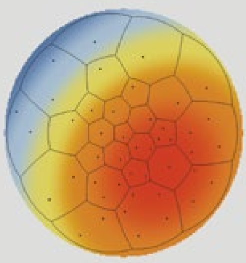
A season-specific sun-path diagram mapping solar trajectories in space templated the location, size and density of apertures within the primary templating structure in order to lock in rays of natural light entering the pavilion from the south and east elevations. Controlled heat distribution enabled a relatively equal spread of fibres over the surface area of the structure.

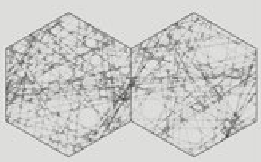


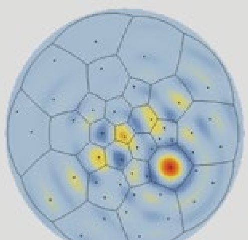


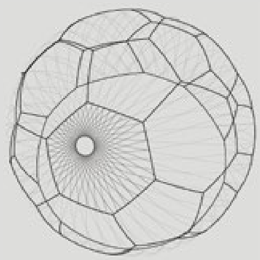
MIT Mediated Matter Group, Silk Pavilion, MIT Media Lab, School of Architecture and Planning, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, 2013

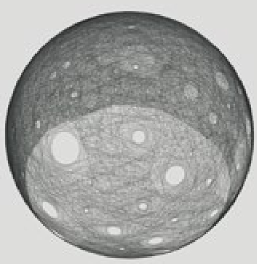
below: Organismic templating representations of robotic fibre spinning. The overall form of the dome structure and its fibrous organisation was informed by a sun-path diagram – a form of environmental templating – relevant to the date on which organismic deployment took place. Silkworms migrated to colder darker surface patches making them stronger and denser, which in turn informed the robotically spun fibre density distribution.

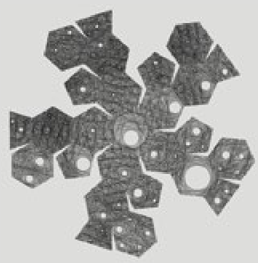












Micro-organismic Templating Through Bitmap Printing

Microorganisms can today be synthetically engineered to produce biofuels, upregulate the production of sucrose, excrete precursors of medical drugs or identify a growing tumour. Related opportunities for digital fabrication in product scale, however, have to date remained largely unexplored. The Mediated Matter Group has recently undertaken this challenge, combining 3D printing and synthetic biology with the goal of creating a new class of functional living materials for product and architectural design.

Wanderers: Wearables for Interplanetary Pilgrims is a speculative design collection including four wearables created for sustaining life on other planets. Designed as capillary structures that can be infused with synthetically engineered microorganisms, the aim is to turn the hostile environments found on other planets into possibly habitable ones. They do so by generating and growing – bottom-up – sufficient quantities of biomass, water, air and light necessary for sustaining life. Some are designed to photosynthesise, converting daylight into energy, while others bio-mineralise to strengthen and augment human bone. Each design was conceived as a 'codex' of the animate and inanimate with an origin and a destination: the origin being engineered organisms, which multiply to create the wearable within a 3D printed 'organ'; and the destination being a unique planet in the solar system for which the wearable is designed. The origin and the destination engage multiple scales, from the atomic to the cosmic, in a setting where, with the exception of planet Earth, no life is known to exist.

The project is the first of its kind to achieve volumetric property gradients in extremely high resolution (a few microns), enabling the design of micro-channels for micro-organismic containment using a process known as bitmap printing. Here, material composition is designed on voxel resolution and used to fabricate an object with locally varying properties such as colour, rigidity or opacity. Voxel resolution is set by the printer's native resolution, rendering the need for path planning obsolete. Controlling geometry and material property variation at the resolution of the printer provides greater control over structure–property relationships.

MIT Mediated Matter Group, Silk Pavilion, MIT Media Lab, School of Architecture and Planning, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, 2013

Views of organismic templating: 6,500 silkworms were deployed on top of the variable-density robotically spun template.

Templating Biology for Design and Design for Biology

Digital design today has progressed to a point where we can achieve high spatial resolution and material complexity in form generation and manufacturing. Coupled with the emergence of research areas such as synthetic biology, bottom-up design procedures – both digital and physical – are aiding the transition from biologically inspired, to biologically engineered design. This shift in practice requires new methods that offer top-down templates employed to assemble entities for bottom-up formation in a scalable and parallel manner. Ultimately, these two procedural trajectories will become tightly mapped onto each other, enabling the production of cyborg tissues at building scales. AD

Neri Oxman/MIT Mediated Matter Group with Christoph Bader and Dominik Kolb, Mushtari - Wanderers: Wearables for Interplanetary Pilgrims, MIT Media Lab, School of Architecture and Planning, Massachusetts Institute of Technology (MIT), Cambridge, Massachusetts, 2014

top: Detail of micro-organismic template through bitmap printing.

below: Front view of Mushtari, a prototype for the photosynthetic wearable included in the Wanderers: Wearables for Interplanetary Pilgrims collection. Produced by Stratasys on the Objet500 Connex3 3D printing system.

Notes

1. Neri Oxman, 'Structuring Materiality: Design Fabrication of Heterogeneous Materials', AD *The New Structuralism*, July/August (no 4), 2010, pp 78–85; and Neri Oxman, Steven Keating and Elizabeth Tsai, 'Functionally Graded Rapid Prototyping', in Paulo Jorge da Silva Bartolo, *Innovative Developments in Virtual and Physical Prototyping: Proceedings of the 5th International Conference on Advanced Research in Virtual and Rapid Prototyping*, CRC Press (Leira), 2011, pp 485–7.
2. The Merriam Webster Dictionary defines the term as 'a pattern or mold used as a guide to the form of a piece being made': www.merriam-webster.com/dictionary/template.
3. Alexander Campbell Martin, 'The Comparative Internal Morphology of Seeds', *American Midland Naturalist*, 36 (3), 1946, pp 513–660.
4. Neri Oxman *et al*, 'Gemini: Engaging Experiential and Feature Scales Through Multimaterial Digital Design and Hybrid Additive–Subtractive Fabrication', *3D Printing and Additive Manufacturing*, 1 (3), 2014, pp 108–14.
5. Steven Keating and Neri Oxman, 'Compound Fabrication: A Multi-functional Robotic Platform for Digital Design and Fabrication', *Robotics and Computer-Integrated Manufacturing*, 29 (6), 2013, pp 439–48.
6. Neri Oxman *et al*, 'Gemini: Engaging Experiential and Feature Scales Through Multimaterial Digital Design and Hybrid Additive–Subtractive Fabrication'. *3D Printing and Additive Manufacturing*, 1 (3), 2014, pp 108–14.
7. Laia Mogas-Soldevila, Jorge Duro-Royo and Neri Oxman, 'Water-Based Robotic Fabrication: Large-Scale Additive Manufacturing of Functionally Graded Hydrogel Composites via Multichamber Extrusion', *3D Printing and Additive Manufacturing*, 1 (3), 2014, pp 141–51.
8. Hyoung-Joon Jin and David L Kaplan, 'Mechanism of Silk Processing in Insects and Spiders', *Nature*, 424 (6952), 2003, pp 1057–61.
9. Neri Oxman *et al*, 'Biological Computation for Digital Design and Fabrication', *Computation and Performance:* Proceedings of the 31st eCAADe Conference, Vol 1, Delft University of Technology (Delft), 2013, pp 585–94.
10. Neri Oxman *et al*, 'Robotically Controlled Fiber-based Manufacturing as Case Study for Biomimetic Digital Fabrication', in Helena Bartolo et al, *Green Design, Materials and Manufacturing Processes*, CRC Press (London), 2013, pp 473–8.