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Designer Matter: A perspective

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ABSTRACT

The surge of modern techniques to fabricate structured materials paired with our ever deeper understanding of complex forms of matter present us with the opportunity to make and study dramatically new forms of designed materials and structures. This movement is being fueled by recent and rapid developments in a variety of fields, including soft matter, materials science, computer assisted design and digital fabrication. Here, we present an overview of these recent trends based on a multidisciplinary meeting on *Designer Matter* that we organized June 22nd–June 24th, 2015, at AMOLF, Amsterdam.

1. Introduction

The ongoing convergence of novel conceptual approaches, theoretical advances, computational tools and experimental techniques is revolutionizing our ability to design and fabricate new classes of materials and structures. As a result, we are witnessing the rapid emergence of new materials that share the common characteristic of the prominent role of structure at the mesoscopic scale, intermediate between the material continuum at the macroscale and the size of the constituent building blocks that define the microscale. Digital fabrication has been a particularly important catalyst in this movement as it allows for the fabrication of structures with arbitrary three-dimensional (3D) geometries, across length scales, made out of a wide ranges of materials. Simultaneously, the democratization of computational capabilities has empowered even small research groups to realistically model complex materials structures by molecular dynamics, finite element modeling, topology optimization and evolutionary algorithms. In parallel, the community is undergoing a paradigm shift that recognizes disorder, mechanical instabilities and strong geometric nonlinearities as novel opportunities for function rather than regarding them as routes towards failure. Much of this effort has contributed to a revival of Solid and Structural Mechanics. Finally, a deepened theoretical understanding of the rich physics of soft materials has opened new vistas to realize complex, or even programmable, functionality. Together, these advances enable an unprecedented level of flexibility and control of the (mechanical) properties of structured materials and the resulting mechanical response.

The new output that has emanated from the movement described above has been referred to as transformative matter, mediated matter©, smart matter, active matter, metamatter or machine matter. Here, we refer to these various trends by the encompassing term *designer matter* (DM). The crucial role of meso-scale structure distin-

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guishes DM from more traditional materials science and chemistry, which focus on the smallest scales to manipulate the ordering of building blocks such as atoms and molecules. These domain boundaries are, however, not sharp, as illustrated by the recent and exciting research on supramolecular chemistry, biophysics and nanoscience [1–5].

Mesoscale geometric motifs (*e.g.*, obtained through jamming, folding, buckling and other instabilities) are often translatable across a wide range of physical sizes and systems, highlighting the transdisciplinary nature of DM. As a result, there has been an intensified conversation and collaboration across disciplines, ranging from engineering mechanics, physics, materials science, chemistry, architecture and even art. In recent years, the exchanges between these communities have been bubbling as demonstrated by the many related symposia in leading conferences of the American Physical Society (*e.g.*, the '*Extreme Mechanics*' focus sessions ongoing since 2008 and the special outreach session '*From Function to Form - Matter by Design*' at the 2014 March Meeting), the Materials Research Society, as well as the '*Soft Materials and Structures*' minisymposia at the American Society of Mechanical Engineers, and the Society of Engineering Science.

Motivated by the all of this burgeoning research activity, and inspired by a similar workshop in 2012 [6], we organized a workshop under the umbrella of '*Designer Matter*' at AMOLF (a Dutch national research institute) in Amsterdam, the Netherlands, during June 22nd–24th, 2015. The goals of the workshop were: (i) explore the current state of the field; (ii) establish connections more broadly than usual (*e.g.*, including architecture and high-end gastronomy); and (iii) identify novel research opportunities. The DM workshop consisted of 19 invited talks by leading experts in the field and 14 short talks by junior researchers (see Supplementary Information, SI, for complete list of participants and the titles of their talks). The broad range of topics covered metamaterials, flexible electronics, folding and self-folding structures (origami), structural design, soft robotics, granular materials, complex fluids, architecture, and gastronomy. The overarching theme of the workshop was *shape*, with the following trio of sub-themes: *structure*, *design*, and *fabrication*. Here, we provide a perspective on DM by reviewing some of the main issues that emerged during the workshop, as well as a list of opportunities/challenges, and an outlook. Selected references are used to reflect a cross section of the research presented at the workshop rather than provide an extensive review of the various topics covered.

2. Main thrusts of the *designer matter* workshop

2.1. The role of structure

The question – '*How does a solid object of a given geometry and material composition respond to load?*' – is quintessential in engineering mechanics. There has been a recent upsurge in interest on this question for objects that possess a carefully designed meso-structure, which can lead to novel material properties and effective behavior at the macroscale that does not occur in ordinary bulk materials. Examples include negative Poisson's ratios in mechanics [7,8] and negative index of refraction in optics [9,10]. Moreover, actively changing this meso-structure can enable the tuning of these properties and therefore produce novel modes of functionality. The study of such *metamaterials* has become an active field of research. One of the exciting possibilities of metamaterials is their usage for cloaking, whereby a region of space filled by the material can be effectively isolated so that its properties or even its existence cannot be probed or detected from the outside. A well-known example is optical cloaking, although the highly desirable combination of multidirectional, broad band and low loss cloaking remains a formidable challenge. More recently, instances of thermal, electrical, acoustic and mechanical cloaking have also been realized [10,11]. In this context, it is worth pointing out that mechanical cloaking is particularly challenging to implement due to the tensorial nature of the elastic fields. Nevertheless, the problems mentioned thus far can be rationalized within a linear framework.

Nonlinear metamaterials allow for an even broader spectrum of functionality, that has yet to be fully exploited and explored. One promising example is the breaking of reciprocity, where wave propagation from point A to B is different from B to A. This feature is a crucial ingredient for single frequency cellular communications, and hence of great technological relevance. Individual elements that break reciprocity have been realized recently [12], and when connected, such elements can form a 2D topological insulator [13].

Mechanical metamaterials are another rapidly evolving branch of nonlinear metamaterials. Much like resonances can give rise to special optical properties, mechanical instabilities can be harnessed to generate new modes of functionality and enhanced mechanical properties. In this context, an emerging class of system is that of buckling-based metamaterials. A series of recent examples involve 2D and 3D elastic media containing a periodic array of voids, whose ligaments (slender beams that separate two neighboring voids) can be reversibly switched to buckle periodically under external stimuli and yield auxetic behavior [8,14]. The pattern transformation of the voids can also be used for the reversible folding of curved structures, as recently demonstrated for spheres [15] (for encapsulation) and cylinders [16] (to excite bending and twisting modes). The dynamics of elastic buckling (or *snapping* [17]) is used for movement of biological systems [18,19] but has also been exploited for surfaces with switchable optical properties [20] and microfluidic pumps [21]. Mechanical metamaterials can also leverage the tunable nature of elastic instabilities, for example by creating discontinuous buckling in 'metabeams' [22], and programming specific modes of deformation [23].

Origami-inspired metamaterials exploit the wide range of shape transformations available through folding in structures comprised of networks of hinges and creases. Advances in this area are often inspired by classical origami of flat sheets of paper that can be folded into arbitrary complex shapes. Whereas the mathematics of origami has long been a topic of active research [24], the mechanics of folding structures has only recently started to receive detailed attention, with an emphasis on programmable response [25], multistability [26] and topological insulation [27].

An emerging application of ultra-thin material sheets with morphable shape is in flexible electronics [28]. Exploiting the low bending stiffness of slender design layouts made out of materials that are otherwise stiff and brittle in bulk (*e.g.* in silicon) is opening unprecedented opportunities for flexible, switchable and tunable electronic devices that can conform to surfaces with complex geometries [29]. Potentially, even more revolutionary is the concept of embedding flexible electronic devices into soft biological tissue or laminating them on top of tissue such as skin, for example as electronically functional tattoos that can transmit medically relevant information about their wearer [30,31].

2.2. New perspectives to design

Design is central to many branches of engineering, including civil, aerospace and mechanical, as well as product design, robotics and architecture. A (somewhat biased) selection of reviews that have identified new trends in design include: soft robotics [32], complex fluids [33], jamming for material design [34], and materials that couple sensing, actuation, computation, and communication [35].

Designing a material by starting from a target set of desired properties (also known as the *inverse problem* [36]) is a well-established problem in materials science. It is, however, generally ill-posed and making progress requires a combination of (computational) strategies to strengthen intuition. Computational power has now reached a level where parameter spaces can be explored systematically and extensively [37,38], as embodied by *the Materials Project* [39,40]. As an alternative route, topology optimization techniques have been very successful for design in structural mechanics [41,42], but have also branched out to a variety of other fields, such as in the design of patient-specific large craniofacial segmental bone replacements [43]. However, these numerical techniques are typically not well suited for strongly nonlinear problems, such as the metamaterials that are based on buckling mentioned above, where geometric nonlinearities dominate. Another emergent direction in computational design has been the use of genetic and evolutionary design algorithms [34]. For example, these various computational techniques have been able to uncover new and unexpected shapes that optimize the strength to weight ratio of metallic joints that can be fabricated using additive manufacturing [44]. They have also led to the discovery of granular particle shapes that, in aggregate, result in novel and counterintuitive behavior such as strain stiffening [45].

This combination of systematic exploration of parameter space, topology optimization and artificial evolution can be used to develop intuition and a deeper understanding of the emergence of effective properties in complexly structured matter. One example of the many surprises is the recent discovery of a decoupling of the contributions to the resistance to compression and shear of disordered network materials, which can be used to tune the elastic response into extreme corners of parameter space [46]. Other examples include the use of geometric methods to capture and predict the response on mechanical metamaterials [23]. In addition to the many, exciting open problems in this area, including the need to further develop design algorithms that can deal with the inverse problem efficiently, an ongoing debate concerns the ideal balance between brute force computational approaches to optimization and intuition-driven explorations of parameter space.

Rational design principles have also been applied to devise new classes of hydrogels with unprecedented mechanical properties [47–49]. Here, enhanced and delayed dissipation was achieved through interpenetrating short-chain and long-chain polymer networks that simultaneously yield the remarkable resilience and toughness of these materials. It has been shown that these tough hydrogels can be 3D-printed into complex structures that are suitable for long-term cell culturing [50].

2.3. Fabrication: top-down vs. bottom-up

In the quest to design and fabricate materials with intricate internal geometric structure, either a *top-down* or a *bottom-up* approach can be followed.

Top-down digital fabrication techniques include both subtractive manufacturing processes (*e.g.*, computerized numerical control machining and laser-cutting) and additive manufacturing techniques, also known as 3D printing. Numerous 3D printing technologies exist that span a wide range of length scales, from direct laser writing (DLW) with sub-micrometric voxels [51,52] to robotic fabrication in architecture [53]. In principle, these techniques enable the fabrication of any 3D structure that can be designed digitally. In practice, however, limiting factors include: physical constraints (*e.g.*, gravity and sequential layering), speed, parallelization, material selection, multi-material composites and integration with biological tissue.

An exciting new direction is the fabrication of objects that, upon printing, can evolve with time due to external stimuli (*e.g.*, electricity, temperature or swelling), which has come to be known as 4D printing [54,55]. Despite the growing catalog of printable materials, its range is still limited, in particular for commercial products. Nevertheless, even some of the commercial materials allow for surprising (and originally unintended) functions such as shape memory effects [56]. This calls for a more thorough characterization of the physical–chemical properties of printable materials, and it appears that there are plenty of opportunities for novel usages that *hack* the originally targeted material properties.

Bottom-up fabrication is radically different and is of particular interest at the small length scales where self-assembly can be exploited and/or when large parallelization with high yield is desirable. A key underlying idea is that functionality emerges from the interaction of a large number of building blocks during the assembly process. To paraphrase Tom Witten (University of Chicago) during the workshop, a design principle within this bottom-up approach can be described as: '*We do something simple, nature does something subtle, and something complex and beautiful* *happens*'. Self-assembly can be as simple and spontaneous as in the drying of a coffee stain [57]. More complex processes have become an active area of research in colloidal suspensions [58,59]. Significant control can be achieved by biasing or directing the self-assembly process. For example, directional drying of a colloidal suspension can be used to create ultrathin nanoparticle-based ribbons [60] that can then be cross-linked into sheets to resemble woven fabrics [61]. A different kind of biasing involves manipulating the concentrations of different species participating in a self-assembly process. Recent theoretical developments have highlighted opportunities for achieving high-yield self-replication of complex particle assemblies [62]. Self-(un)folding of microscopic systems, with high yield, is another topic that has received increasing attention [63–66].

An exciting challenge in this area is to combine bottom-up and top-down approaches by exploiting and extending nanofabrication principles to larger length scales, and exploiting a wider availability of smart materials (*e.g.*, shape memory polymers [67], swelling hydrogels [68] and self-healing materials [69]).

A field where the assembly of structures certainly has had a long history is architecture. Traditional architectural strategies might be labeled as decidedly bottom-up (although not self-) assembly. Indeed, current approaches practice the extreme limit of directed assembly. Typically all the elements, from bricks to windows to trusses, are still placed individually and under the direct control by and/or interaction with humans. However, the introduction of robotic and large-scale digital fabrication techniques is shifting this paradigm. This includes robotic assembly of masonry, including the usage of small drones [70], or macro-scale analogs of molecular self-assembly [71]. A second paradigm being challenged is the requirement of structural regularity and order. Ideas originally developed within the context of jamming in disordered granular media are providing a framework for new approaches in architecture that radically break with traditional building techniques. For example, *aggregate architecture*' makes it possible to create, by simple pouring, freestanding structures that can adapt to varying load conditions and can be easily reconfigured or recycled [72].

3. Outlook

Empowered by new technological advances in digital fabrication and computer assisted design, together with novel theoretical frameworks and approaches, we envision an exciting future for the design and discovery of novel materials and structures with unprecedented properties and functions. Progress in this area will most likely happen at the porous boundaries between research domains and will benefit from pollination across disciplines, from engineering, to physics, chemistry, materials science, architecture and mathematics. Bringing together a diverse set of domains, as well as their techniques and conceptual frameworks, will be a challenging endeavor, but one which the community feels has great potential. Perhaps most interesting, and clearly evidenced during this workshop on DM, is the fact that common ideas and frameworks can have relevance across a strikingly large range of physical size scales, from nanometer-size systems to truly macroscopic architectural structures.

Looking ahead, progress will require tackling a number of challenges. Some in the community believe that it would be beneficial to the field for a set of fundamental and unifying questions to be identified in order to provide focus. Developing a set of theoretical constructs that get us closer to the ultimate target of rational design is a goal worth pursuing. Combining top-down (digital fabrication) with bottom-up (self-assembly and emergence) design approaches would unfold a wide array of new opportunities. There are also several open questions that are more specific. For example, given that geometry is a primary ingredient in many of the problems under investigation, how do we couple what are mostly scale-invariant phenomena with other ingredients such as gravity (at the cm-scale), capillarity (at the mm-scale), electrostatics (at the scale of 100s of microns) or van der Waals interactions (at even smaller scales)? Can hierarchical approaches be devised and exploited for multi-scale fabrication and operation? Biology has taught us that this is possible but it is not yet clear how we can formalize design strategies that will allow us to go beyond what is presently feasible.

Despite the strong sense of potential for practical applications, many in the workshop raised the need for a few '*signature apps*' to be identified (*e.g.*, in medicine, robotics, flexible electronics or architecture) even if their actual use may still be far out into the future. Having a well identified target of this kind, which the community could rally around, would provide impetuous to the field and drive work on problems that have societal relevance. Engineering applications provide constraints that can themselves be enhancers in the process of discovery. Moreover, the drive for simplicity can enhance creativity. Discovery may also be enhanced by a balance between systematic and serendipitous exploration. In a similar vein, computational investigations (where all the ingredients are input *a priori*) need to be well balanced by explorative work (where one often tries to remove and control factors, but sometimes the unexpected occurs). What is certain is that we have an exciting path ahead for engineering-inspired science and science-enabled engineering in the general area of the design of innovative materials and structures.

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Appendix A. Supplementary data

Supplementary material related to this article can be found online at http://dx.doi.org/10.1016/j.eml.2015.09.004.

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