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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.
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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

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