Programmable Materials (2023), **Vol. 1**:e3 1–2
doi:10.1017/pma.2023.3

EDITORIAL

Programmable Materials

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Received: 20 February 2023; **Accepted:** 20 February 2023

Programmable Materials represent a new and vast frontier in the field of materials science and engineering, as they incorporate algorithms into their design and structure, thus enabling them to have functionalities and abilities beyond just physical properties. Especially functional and smart materials, as well as the concept of meta materials, has enhanced the design space tremendously, while at the same time, modern manufacturing techniques and AI-assisted materials design have brought the necessary structural control to implement such algorithms. The design of *Programmable Materials* means to facilitate changes within the molecular as well as mesoscopic meta materials' structure to react, for example, on thermal or mechanical inputs. This allows a different quality of interaction with the environment. Here, *Programmable Materials* can draw inspiration from biological systems, which have complex physical computing mechanisms that allow them to adapt to changing environments, can self-repair, and even 'learn' from repetitive external stimuli.

Nevertheless, designing such functionality or even abilities into artificial materials require a radically different view on materials, as in classical engineering, changing properties in materials typically are a problem and not an opportunity. Instead, mechanisms that allow to change the structural state due to external or internal signals need to be identified and characterised in terms of their potential use for *Programmable Materials*. Furthermore, their interplay at the different available size and time scales needs to be mastered. To reach the full potential similar to biological model systems, it requires the understanding and control of complex algorithms based on a hierarchical design.

Being able to design materials that can process information have the potential to answer many challenges within society as well as through radically innovative industrial applications. Programmable shape morphing concepts enable new designs for adaptive aerodynamics to save energy, programmable damping can change how shoes or helmets are constructed, programmable stiffness can enhance soft robotics as well as the design of exoskeletons for workers or elderly people, tuneable acoustics can improve coworking in shared offices or the quality of life in crowded cities, and adaptive thermal conductivity improves autonomous thermal management of houses or batteries. More importantly, a modular design will simplify recyclable sustainable systems designs.

To bring technological innovations to life, several scientific challenges need to be met: (1) Identification and characterisation of physical, chemical and mechanical mechanisms on different scales (e.g., molecular and mesoscopic), and how they react with a physical output on different inputs (e.g., mechanical load, temperature, humidity and pH). (2) Developing concepts for transferring, storing, retrieving and transforming information by structural changes within *Programmable Materials*. (3) Combine different mechanisms into computing modules, resembling classes (similar to, e.g., an

Fast Fourier Transform (FFT)) and add them into more complex algorithms. (4) Identify such compute classes for different base materials (e.g., polymers, metals and ceramics) and the necessary processing routes (e.g., multimaterial additive manufacturing and foil stacking) to compile them into applications (e.g., by system designers, mathematical optimization) with interfaces to larger systems. (5) Describe algorithms in an abstract and materials agnostic language. (6) Identify algorithms, system functions and abilities for engineering use cases or from biological model systems, where *Programmable Materials* can lead to breakthrough innovations and pose these as challenges to the community.

Bringing *Programmable Materials* to life will require a major interdisciplinary effort within and between different scientific fields and with the *Journal of Programmable Materials*, we will offer a scientific platform that allows us to find solutions for these challenges and enable unique innovative and sustainable applications.

Cite this article: Eberl, C. (2023). Programmable Materials. *Programmable Materials*, **1**, e3, https://doi.org/10.1017/pma.2023.3