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SCIENCE OCT 30, 2024 8:00 AM

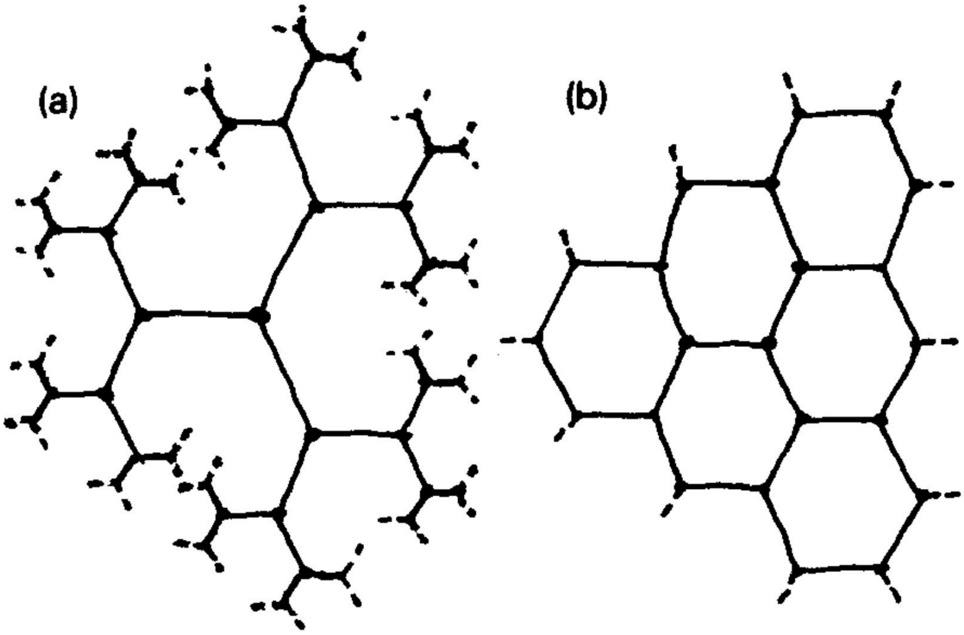
Programmable Matter

The story of dumb stuff doing smart things.

Programmable wood [9] and Jammed particles [12]

Introduction

The term “Programmable Matter” was originally coined by two computer scientists, Tommaso Toffoli and Norman Margolus, in 1991 when referring to CAM-8, a “scalable cellular automata machine” or “fine-grained multiprocessor” which “embodies the concept of programmable matter” [7]. I know what you’re thinking, the title made this sound much more fun. Don’t worry, we’ll get to the whiskey barrels and microrobots in due time. For now, just know that as the field of programmable matter has matured, the definition and practice of programmable materials has become more accessible [8].



Diagrams from Tommaso Toffoli and Norman Margolus' paper [7]

Today, programmable matter is more widely described as materials which are designed to be highly dynamic in a precise, sequential predetermined way, on-demand [8]. These dynamics can refer to the material's shape, physical or functional properties, or both. Skyler Tibbits, founder and director of the MIT Self-Assembly Lab, defines programmable matter simply as "a physical material structure that is embedded with information and physical capabilities like logic, actuation, or sensing" [15].

Essentially, **programmable matter is material designed to respond a certain way to some condition.**

By this definition, 1991 seemed too recent of a start for the story of programmable matter. To get a better idea of where programmable matter comes from, we can look for historical occasions when the properties of a material were at the heart of a technology. In his book "Things Fall Together", Tibbits notes how "craftspeople have used wood's inherent properties when making furniture or building joints, ship hulls, or whiskey barrels" [3]. Could wooden barrels, whose oak planks gradually flavoured ancient wine, be an early example of programmable matter?

A Brief Analysis of Programmable Matter through the Lens of Wooden Barrel History

Basically, no. This is for two main reasons. Firstly, the early wooden barrels were more about the barrel than the wood. Around 350 BCE, the Romans realised that they could steal cutting-edge barrel technology from the Celts and roll their goods rather than lift them in their “amphorae” [4]. Beyond the knowledge required to manipulate wood into wine barrel, other material properties were of little interest. Programmable matter is fundamentally about the properties of materials.

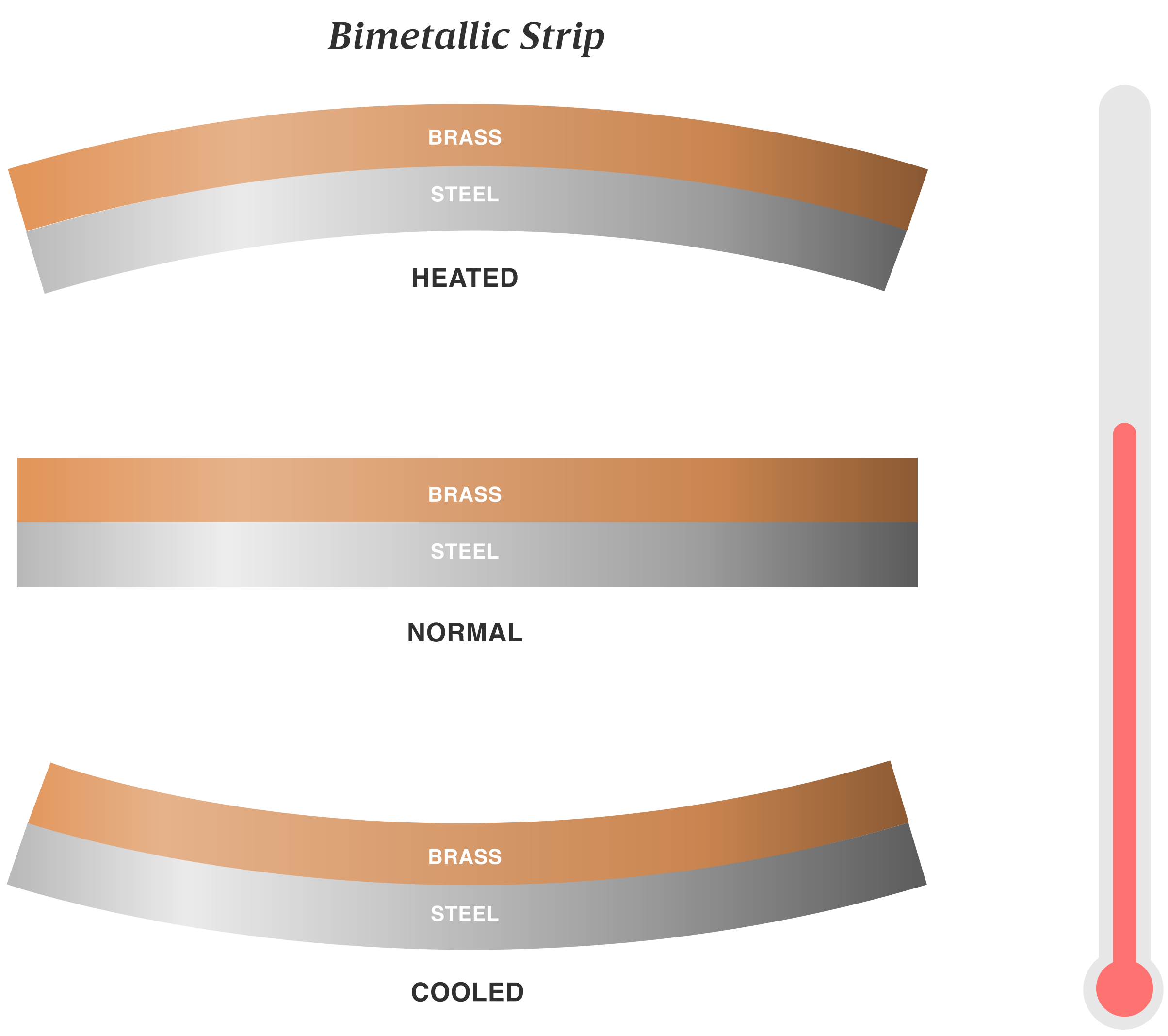
Secondly, even in the times of Captain James Cook, when a deliberate focus was placed on the ‘seasoning’ of wood to prevent barrels from changing shape, the idea was to prevent dynamics rather than create them. In Cook’s third journey, he discovered that “inadequately seasoned” wood was the cause of barrel warping which led to several casks of mouldy bread [5]. Unfortunately for the sailors, this also did not count as programmable matter because it was not on-demand.

A Predecessor to Programmable Matter

My borderline embarrassing deep dive into the history of wooden barrels was serendipitously rewarded when I learned that the very same ship which carried Captain Cook and the barrels also carried John Harrison’s Marine Chronometer, the first time-keeping device capable of withstanding the violent motions and temperature changes of the open sea [6].

John Harrison’s H4 Marine Chronometer
Image Credit -- Royal Museums Greenwich
https://www.rmg.co.uk/collections/objects/rmgc-object-79142

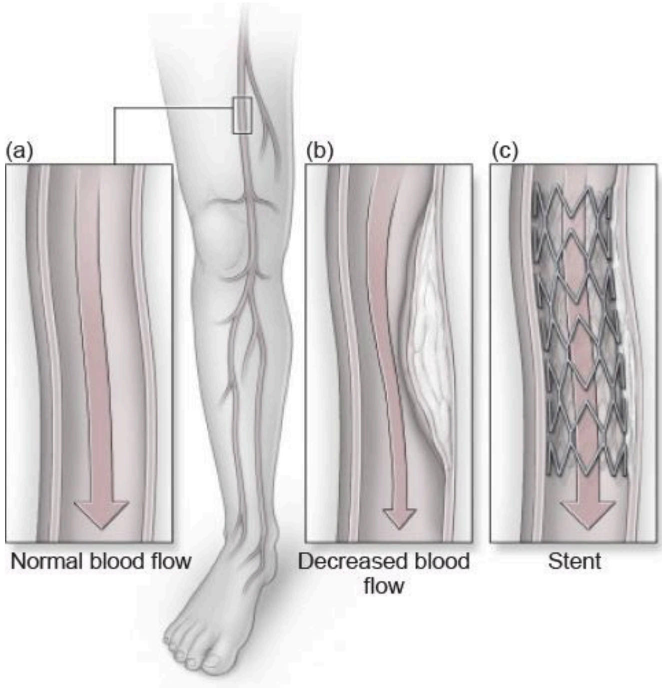
Before John Harrison, pendulum driven clocks were defeated by the rocking of vessels upon waves, and spring powered clocks were at the mercy of thermally expanding or contracting metals [6]. Harrison solved the problem of temperature sensitive timekeepers first with his gridiron pendulum and later with his more compact bimetallic strip. These devices took two metals, brass and steel, which expand at different rates for a given change in temperature and used the known difference to counteract temperature error. Unlike the wooden barrels, the Marine Chronometer was programmed to react both dynamically and precisely to changing conditions.



Bimetallic Strip Diagram
Credit -- Lucas Kiewek

Contemporary Programmable Matter

Today, programmable matter has been modestly integrated into everyday life. Harrison's bimetallic strip can be found in home thermostats and circuit breakers. Your orthodontist may prescribe a device made from Nitinol, a material which can transform into a preprogrammed shape when exposed to body temperature [17].



Example of how Nitinol can be used in medical applications [17]

"Things Fall Together" talks about how the industrial revolution and its simplification and standardisation of components may be to blame for programmable matter's relegation to often niche materials and use-cases. As advanced manufacturing technologies become more mainstream, simplified and standardised components are becoming less of an economic concern [18]. Therefore, it is worthwhile to become acquainted with what the state-of-the-art of programmable matter research has in store for us.

State-of-the-Art

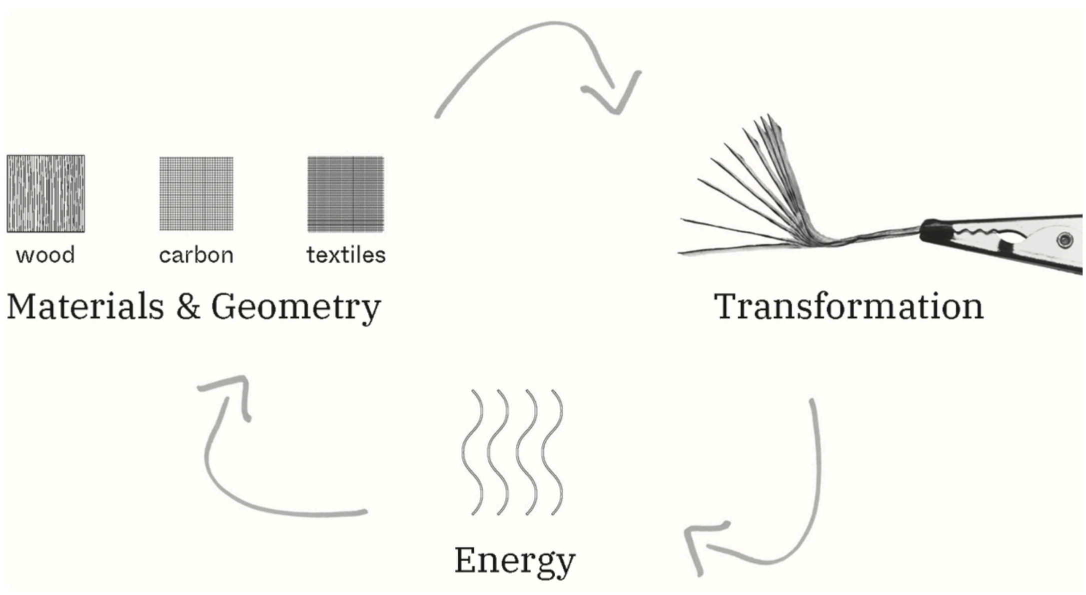
A good place to start is the MIT Self-Assembly Lab, where Tibbits and his team are looking into three main areas [15]:

Shape Change
Material systems that can adjust their geometry by design.

Phase Change
Material systems that can reversibly transition from liquid to solid and back.

Self-Assembly
A process by which disordered parts build an ordered structure through only local interaction.

For each area, I will provide examples from the Self-Assembly Lab and from other researchers.



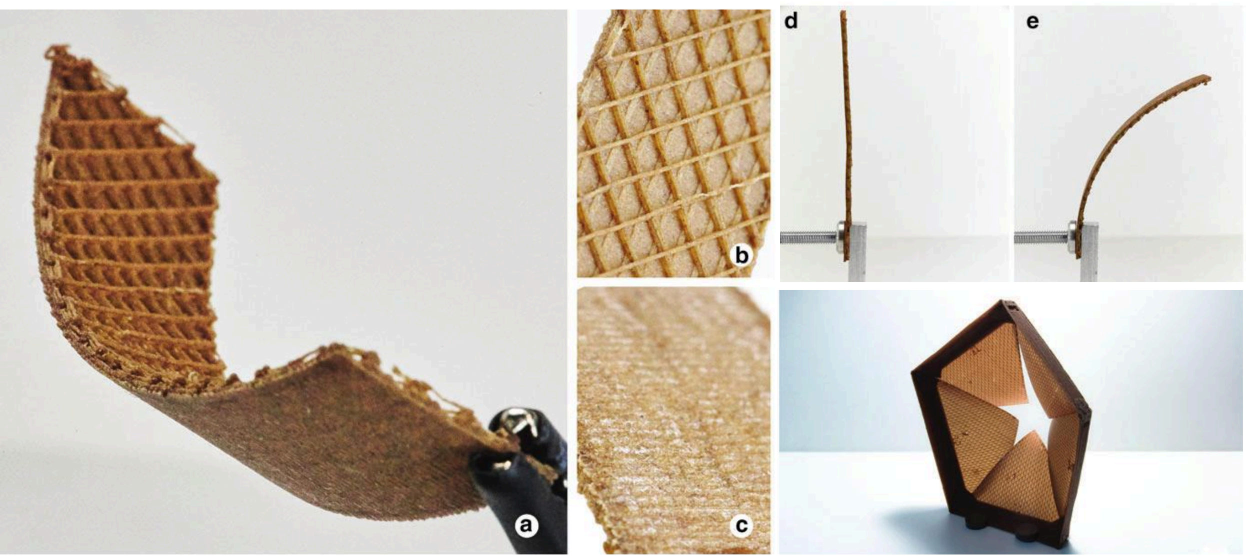
A diagram showing the key ingredients for programmable materials: materials, geometry, and energy to create physical transformations. *Credit:* Self-Assembly Lab, MIT

Shape Change

Shape Changing Wooden Bowl by Christophe Guberan and the Self-Assembly Lab, MIT [9]

Active Wood

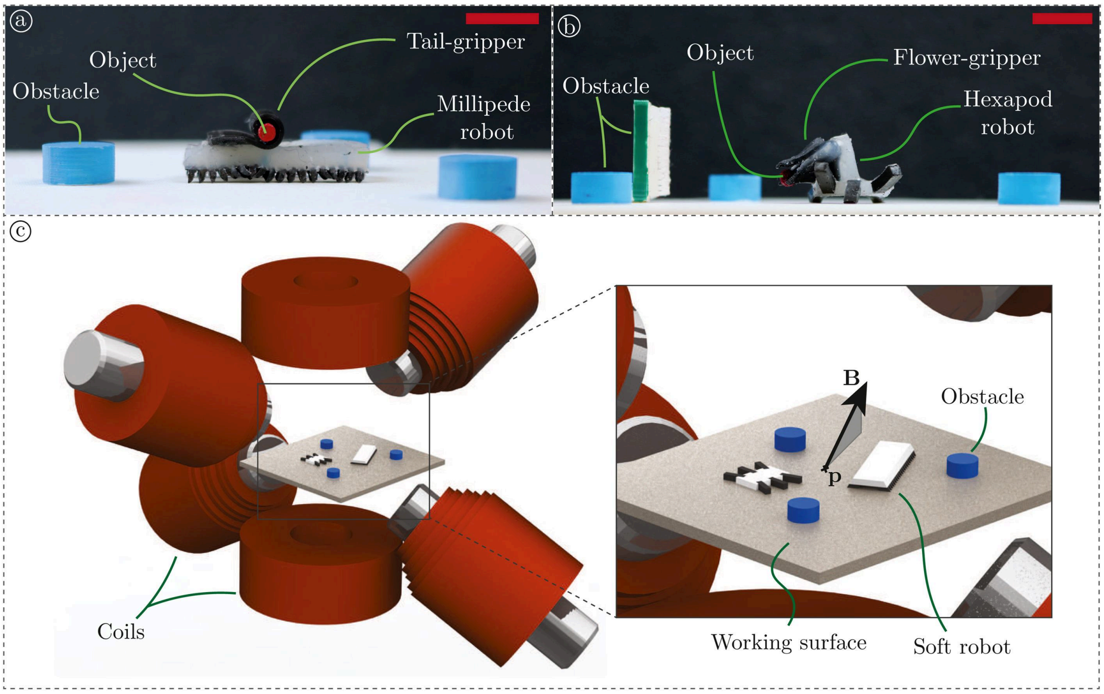
If you have ever seen a spilled drink result in warped floorboards, you have an intuition for how moisture and woodgrain can interact to cause shape change. In “3D-Printed Wood: Programming Hygroscopic Material Transformations” David Correa et al. shows how by 3D printing particular grain structures (yes out of wood) the deformation of the wood can be controlled [9]. In collaboration with the product designer Christophe Guberan [10], the Self-Assembly Lab created bowls and baskets which are printed flat but transform into the desired shape after being transported in a moist plastic bag. Shipping becomes assembly.



Detailed images of wood grain curling [9]

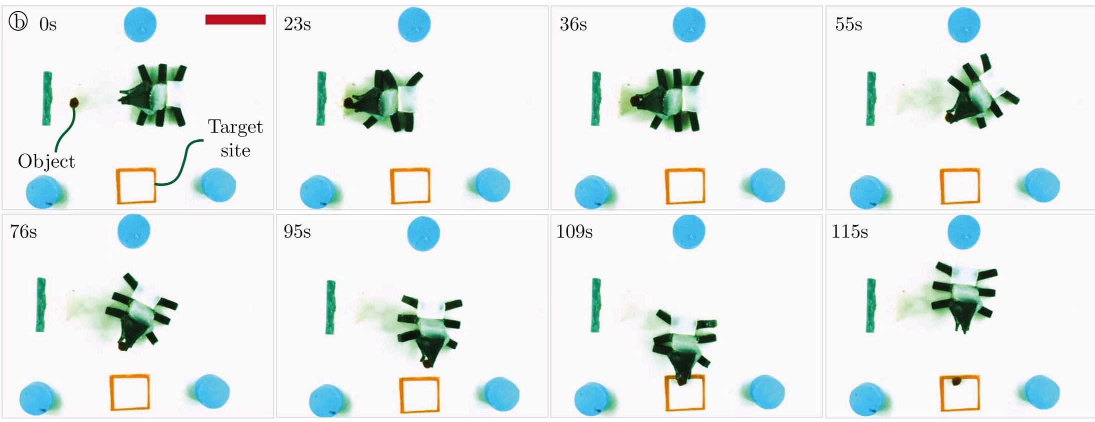
Magnetic Silicone

Waiting for wood to absorb water can be slow, what if you wanted a programmable material which reacts instantly? The Surgical Robotics Laboratory at the University of Twente used composite silicone rubber with magnetic powder to create untethered soft robots capable of locomotion and grasping [11]. The researchers understood that when you place a ferromagnetic object within a strong magnetic field, the object will be magnetised in alignment with the magnetic field.



Diagrams of the magnetic soft robots and their actuation system [11]

By mixing ferromagnetic powder into silicone, magnetising it in a particular folded shape, then unfolding it, the researchers were able to program certain behaviour into the silicone [11]. Once programmed, the object would conform to the predetermined shape when exposed to a magnetic field. The hope is that untethered, magnetically actuated soft robots could become useful in the future of minimally invasive surgery.



Magnetic soft robot engaging in locomotion and grasping [11]

Phase Change

Different examples of materials that can exhibit liquid-like and solid behaviour when jammed [12]

Jammed Structures

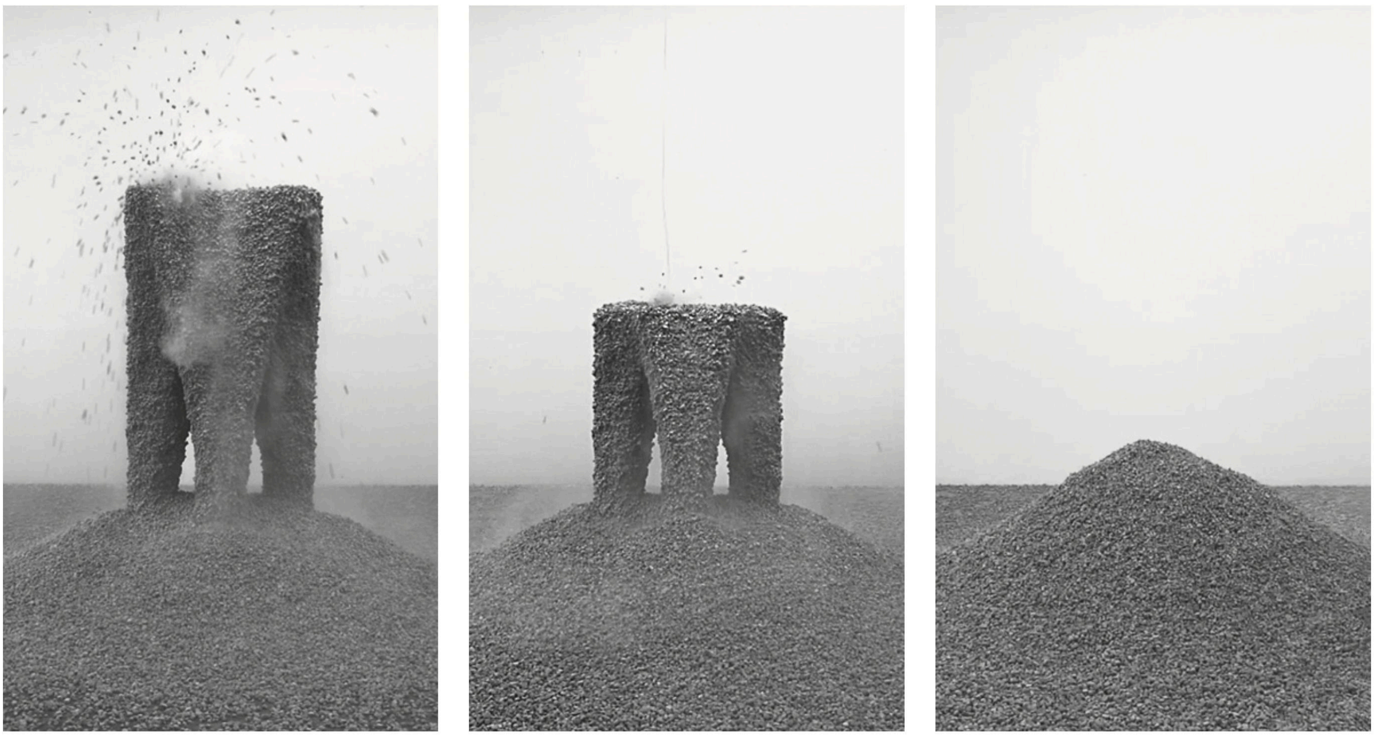
If you have ever played with sand, you may have noticed that sand becomes much harder when you jump on it. This phenomenon is known as 'particle jamming', and it was used by the Self-Assembly Lab and the group of Gramazio Kohler at ETH to create a four-metre tall, load bearing column out of a pile of rocks and a string [12].

A four-metre tall, load bearing column out of a pile of rocks and a string [12]

This works because the rocks are strong under compressive forces while the string is good at withstanding tensile forces. Under certain 'constraining force conditions', they become "jammed" and behave more like a solid than their previous, liquid-like state. Why do all this?

A zigzag wall was built with only loose rocks and coconut husks using a slip-forming method to promote granular jamming in a fast, efficient, and reversible manner. *Credit:* Self-Assembly Lab, MIT, Google

As the paper “Jammed architectural structures: towards large-scale reversible construction” describes, these materials do not require any curing time to become structural and are completely reversible [12]. The shape of the structure can be programmed by the pattern in which the string is placed, and when the structure is no longer wanted, all that must be done is to pull out the string.



The disassembly of the four-meter-tall tower built from only loose rocks and string using the principle of granular jamming. The tower was disintegrated by simply winding up the string to allow the tower to return to a pile of rocks and a spool of string. *Credit:* Gramazio Kohler Research, ETH Zurich, and Self-Assembly Lab, MIT

Phase Change Materials

Other work on phase change materials (PCMs) involves diving into concepts such as amorphous crystalline structures and latent heat which may require an entire blog post to describe. The basic idea is that changes occur in PCMs at the chemical scale. These changes can determine properties such as refractive index, making PCMs useful for tuning light-based neural networks [17]. They can also allow the PCM to release heat under specific conditions, making them useful for greenhouse temperature control [13].

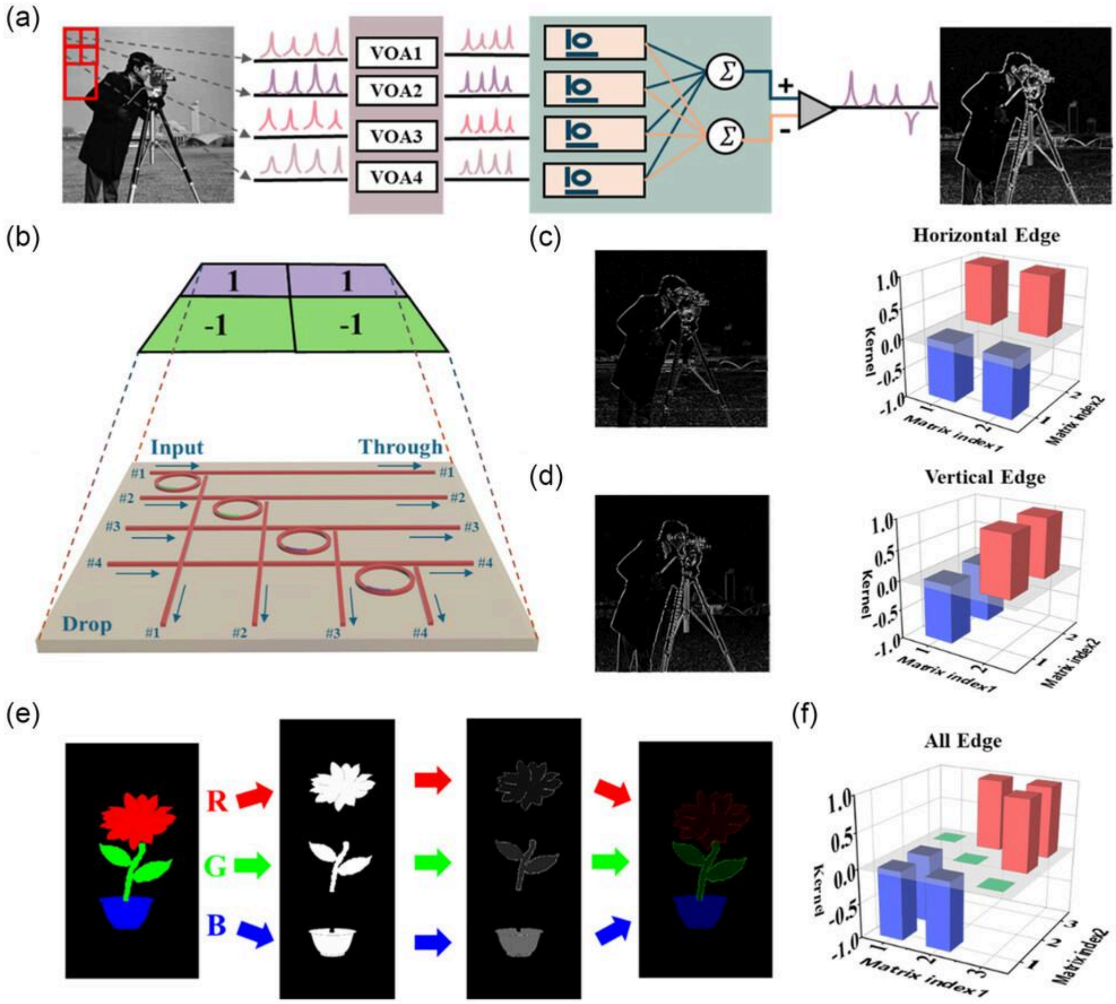
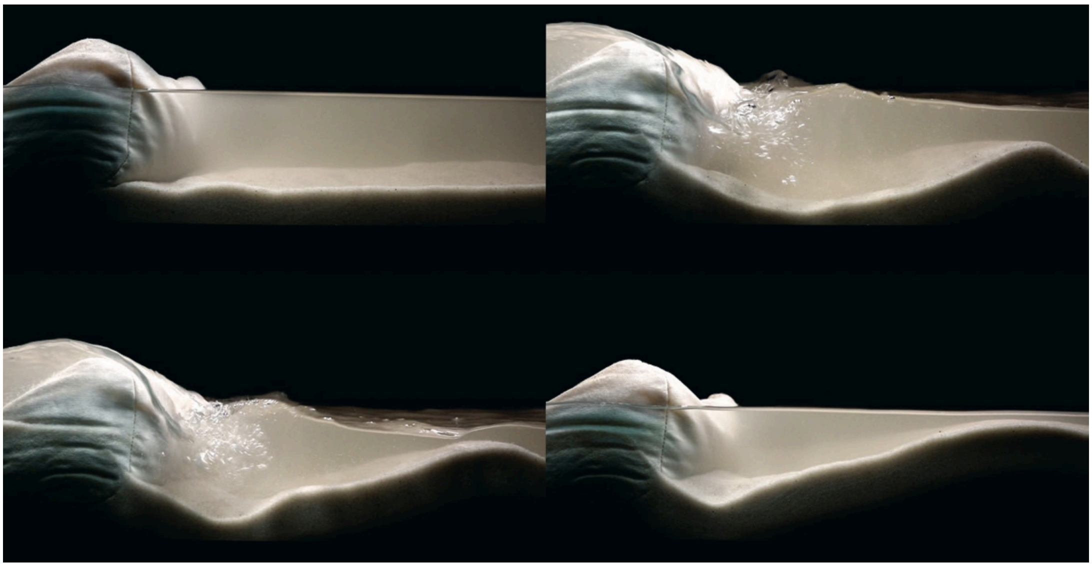


Diagram depicting an optical neural network which can be adjusted by the phase changing properties of GST, a material made from Germanium, Antimony, and Tellurium [17]

Self-Assembly

Growing Islands

Sea level rise places particular pressure on island nations such as the Maldives to mitigate land loss [19]. Current methods to combat this include “dredging” which involves launching sand from the sea floor onto the beach. Looking for an alternative which does not strain coral ecosystems, researchers at the Self-Assembly Lab studied how sand banks form naturally and found that sand banks could be grown by placing certain shapes, particularly ramps, in the ocean and letting the waves do the work [14].



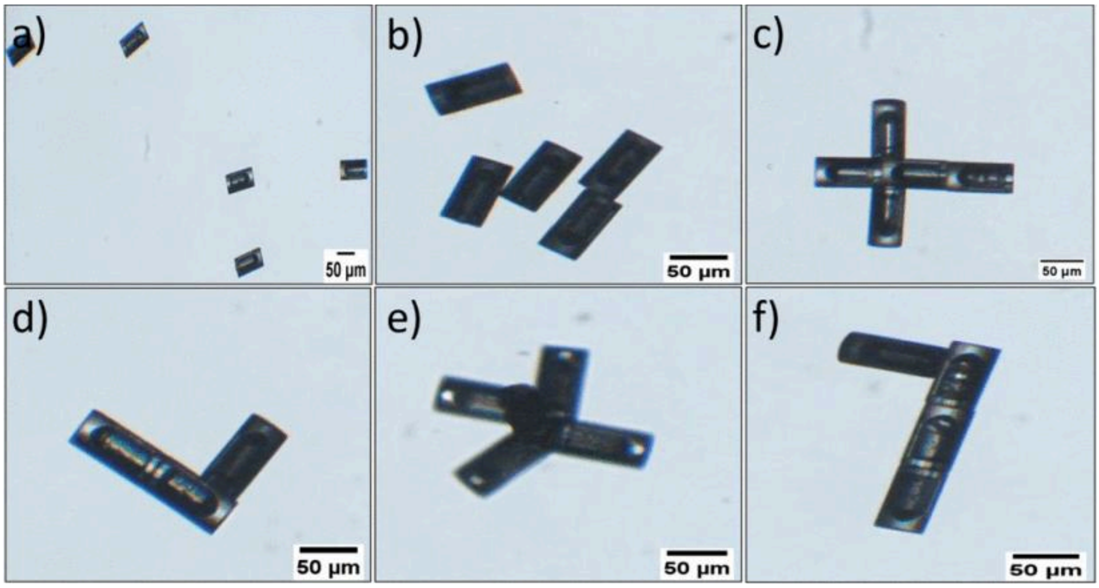
Lab tank testing of ramp geometries [14]

In the lab, the researchers studied how the ramp angle and monsoon forces could affect the accumulation of sand. In October of 2019, they took the experiment to the field and installed two large-scale wedges (10m x 4m x 2m each) made from geotextiles and filled with sand on a target site in the Maldives [14]. Four months later, they found that the wedges had promisingly accumulated 0.5m of sand accumulation over an area of 20m by 30m (300 cubic metres).

Submersible geometry that was deployed in the Maldives [14]

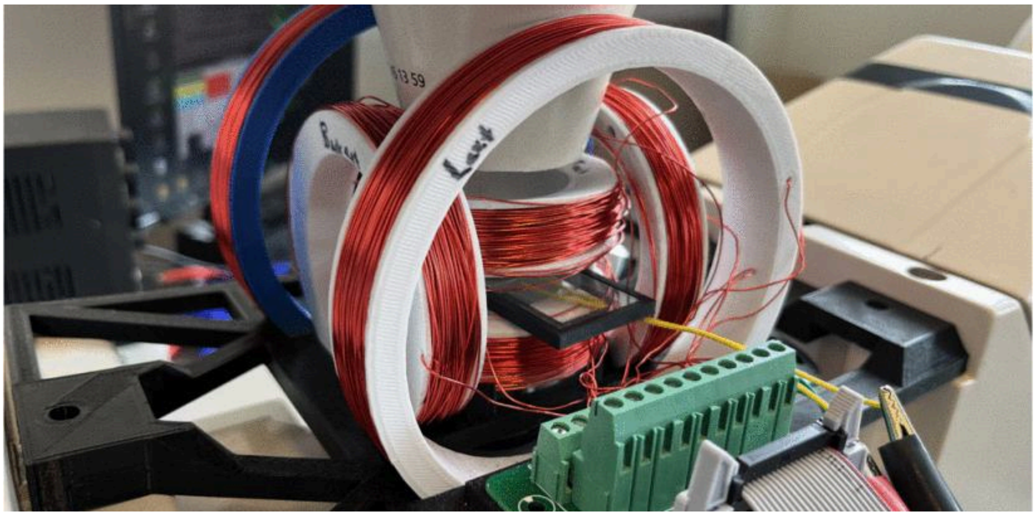
Micro Robots

On the opposite side of the scale spectrum, Cherukumilli et al. created 40-micron long microrobots (about 10x smaller than a grain of sand) capable of self-assembly and untethered control [2]. The microrobots are half-coated in a 100 nm layer of nickel, allowing their orientation to be controlled by an applied magnetic field. This has the added benefit of creating magnetic interactions between the robots which can create and maintain various configurations of microrobot structures.



Different configurations of microrobot structures after magnetic field is applied [2]

The position of the robots can be adjusted using acoustic propulsion, where a bubble trapped inside of a specially shaped cavity within the microrobot resonates with an applied acoustic field to create thrust [2]. The shape and material of these robots have been programmed so that they can receive commands, arrange into configurations, and be compatible with biology. This technology could be used to address challenges in drug delivery, microsurgery, and tissue engineering.



Experimental setup for microrobot paper [2]

Limitations of Programmable Matter

While these exciting technologies can seem straight out of a sci-fi film, a paper titled “Programmable materials: Current trends, challenges, and perspectives” by Giulia Scalet reminds us that nothing comes without its limitations. Programmable matter is currently limited by the following five factors [8]:

Stimuli
The most common stimulus for programmable material, heat, tends to have a slow response time which can limit real-life applications. The need for diverse and effective stimuli remains a challenge in the field [8].

Materials
Many of the main materials used to create programmable matter such as polymers, hydrogels, or metals are only capable of reacting to a certain set of stimuli such as temperature or PH. Furthermore, materials can also struggle with incurring irreversible changes or performing as expected under extreme conditions [8].

Control
It can be difficult to use programmable matter to achieve precise movement and accomplish sequential tasks. In the magnetic silicone soft robot example, the control of the locomotion and the gripping were not entirely independent as they both reacted to surrounding magnetic fields. Even in simple applications, complex modelling and simulation tools may be needed to effectively implement a control system [8].

Energy
While some programmable materials get their energy independently from natural sources such as body temperature or humidity, many require continuous or varied magnetic, electric, or even pneumatic sources to function. This reliance may limit their applicability to the real world [8].

Manufacturing
Many programmable materials are created using 4D printing (Invented by Skyler Tibbits). The cost and access to this technology can be prohibitive. Furthermore, current fabrication methods do not allow for the standardisation and scalability required for the economic feasibility of creating the complex geometries involved in programmable matter [8].

Final Thoughts

So, what's the point of all of this? Programmable Matter is gradually addressing a problem which has been limiting the scale at which we can apply intelligent systems: code runs on computers [20].

At a certain point, putting chips and servos and batteries in everything becomes impractical.

Maybe we can build a future where every brick in a building or string in a sweater has an Intel Core i98, or maybe we learn how to code with chemistry and crystals and carbon.

We could write simple instructions into the grain of wood chips and the molecules in a magnet and call it a "fine-grained multiprocessor" and live in a world where matter is more than structural.

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