Smart materials that are actually smart

1. **Combinatorial design of textured mechanical metamaterials**
   Authors: Corentin Coulais, Eial Teomy, Koen de Reus, Yair Shokef and Martin van Hecke
   Nature 535, 529 – 532 (2016)

2. **Designing self-powered materials systems that perform pattern recognition**
   Authors: Yan Fang, Victor V. Yashin, Steven P. Levitan and Anna C. Balazs
   Chem. Commun., 53, 7692 (2017)

Recommended with a Commentary by Christian Santangelo, University of Massachusetts Amherst

As I type this commentary on my computer, I am reminded that the revolutionary advances in electronics over the past sixty years has made computing ubiquitous in our lives. Yet, the desktop computer on which I am typing can draw up to 200 Watts of power while the laptop I will probably switch to as I continue writing later will draw 60 Watts of power. In contrast, the human brain, which is not too shabby as a computing device, uses only an estimated 20 Watts of power [1]. Beyond this, there is a growing sense that many of the computers of the future will be distributed throughout our environment as soft, flexible, wearable devices and in the form of smart materials. Unlike the smart materials of today, future smart materials will be "smart" in the sense that they will be autonomously *sense* their environment, *decide* how to respond, and *actuate* to perform a task according to the environmental cues. As examples, one might think of clotting agents that detect and heal pipeline ruptures, or health and infrastructure monitoring devices. To remain flexible and reduce weight, these future materials must perform under low or even intermittent power, perhaps even harnessing ambient noise, rather than drawing on bulky batteries. On the other hand, the types of processing that is required need not be nearly as complex as what is required to compile a LaTeXdocument, suggesting that, perhaps, smart materials need not perform their computations at the speed or complexity we might desire from our cell phones.

What would a soft computer look like? One possibility is based on the self-assembly of DNA tiles with specifically-tailored interactions in some kind of "smart soup" [2]. Yet, even as far back as the earlier 19th century, Charles Babbage proposed another computing paradigm, the difference engine [3]. The difference engine was a hypothetic computing device (since built and demonstrated [3]) which, through the turning of gears and motion of rigid other elements, performs computations entirely mechanically. Of course, this device is not soft, is not small, and essentially reproduces the kind of computation already performed far more rapidly by even the simplest electronic computer. Yet, Babbage's difference engine evokes the possibility of harnessing elasticity and mechanics to perform computational tasks.

The first paper I am commented on, by Coulais *et al.*, takes a step toward using the flexibility of mechanical metamaterials, elastic structures designed to have a specific mechanical response under load, in order to create soft structures that recall patterns "holistically." The structure they designed appears to be a monolithic cube coated with panels but, under the hood there is a complex three dimensional pattern of mechanical voxels designed so that, when the cube is squeezed, the surface panels pop out in a specified pattern. The patterns are holistic in the sense that, even with damage to specific structural elements inside the cube, the desired pattern still emerges. This might be viewed as analogous to how the human brain recalls entire memories from just their components. In principle, even more is possible with appropriately designed mechanisms. It is known, for example, that a universal computer built entirely from mechanical parts, much as Charles Babbage might have originally envisioned, is at least possible [3, 4]. Whether or not a more complex, mechanical computing device could be realized in a soft material is, as far as I know, an entirely open question, but one that could and should be explored as this field moves forward.

With additional complexity and the introduction of activity, even recognition can be performed by a soft device. In the second recommend paper, Fang *et al.* propose a more complex device made from several interacting parts, which in their paper they simulate (but do not build). The basic unit of activity comes from an oscillating reaction known as the Belousov-Zhabotinsky reaction (BZ). They propose for the reaction to occur inside a gel which can then respond mechanically to the oscillations, something that has been demonstrated experimentally at least [5]. Fang *et al.* propose to couple their BZ gel system to a piezoelectric cantilever that is then coupled electronically to other gel-piezoelectric devices which can be used, for example, as the pixels of an image. Crucially, the entire device is powered by the chemical gradients that also drive the BZ reaction – there are no additional power requirements.

Once the BZ reaction starts in each individual pixel, the gel oscillates between being swelled and unswelled. When it swells, it deforms the cantilever, and this generates an electric displacement field, $\mathbf{D}$, inside the material (as in Fig. 1). Electrodes are placed so that there is a potential difference generated across them. The piezoelectric polarization can be aligned so that the same deformation can produce either a positive or negative potential difference on the electrodes as desired. Note that, through the converse piezoelectric effect, a voltage across the electrodes also causes the piezoelectric cantilevers to deform and pull on the BZ gels. Thus, by wiring the electrodes together serially, there is a chain of feedback from chemistry to mechanics to electrical and back again, providing a mechanism to passively couple the oscillations of the BZ gels. Since it will be the coupling between BZ gels that is important, one could imagine other mechanisms to couple the gels together. Notice, however, that different couplings are generated by changing the orientation of the piezoelectric cantilevers – hence the sign of the voltage difference can be used to "program" how the BZ gels actually interact. These differences in coupling control how the different BZ gels eventually synchronize - in-phase or out-of phase. It is this phase information that acts as an information carrier for the device. For example, the authors propose encoding an image by coloring all the swollen gels black and all the unswollen gels white. Therefore, arranging the piezoelectric polarizations controls the synchronization so that each pixel produces a

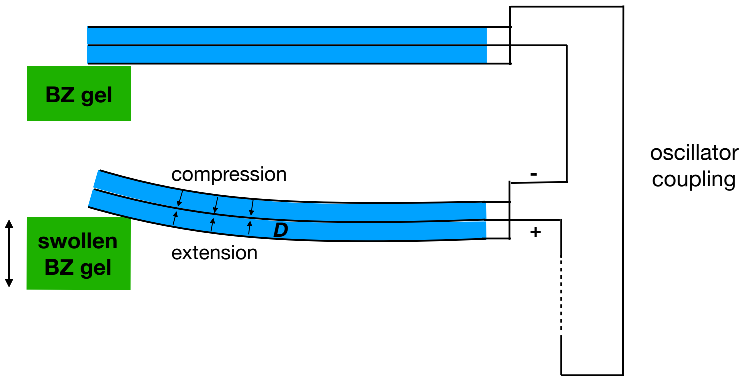

Figure 1: An example of the device proposed by Fang *et al.*, adapted from their paper. The swelling of the BZ gels induce electric fields inside the piezoelectrics that produce an internal electric field. The electric field drives currents that are coupled together by the wiring. The feedback between chemistry, mechanics and electronics couples the BZ oscillators together to control how they synchronize. The synchronization of the BZ oscillators encodes information about the memory to be stored.

pattern of black and white to form an image. Of course, only the relative phase matters – interchanging black with white everywhere changes nothing.

What this paper demonstrates is that the piezoelectric polarization determines how the BZ oscillators will converge to a pattern of synchronization. Moreover, the speed at which they converge to this image depends on how the oscillation phase are initially synchronized. They propose that the convergence time provides a means of testing patterns (or partial patterns) in terms of how similar they are to the stored memory. For example, initializing the BZ oscillators to nearly the same phase as the stored pattern quickly converges to the stored pattern; initializing them randomly will cause the device to take longer to converge. One of the striking things about this device is that it could serve as a *test* of a pattern (or partial pattern) that could then lead to an action downstream.

Looking forward, these papers raise several questions. First, of course, is what are the limitations of soft computers and where might they be profitably used? Second, what other types of devices, for sensing, decisions might be possible? Third, what type of power consumption would these truly require? Finally, can the complex mechanical metamaterial designs from the first paper be combined with activity, perhaps in the form of the BZ oscillations of the second paper, to create truly smart but soft materials?

References

[1] B. Sengupta and M.B. Stemmler, "Power consumption during neuronal computation.," Proceedings of the IEEE, 102, pp.738-750, (2014).

[2] Chengde Mao, Thomas H. LaBean, John H. Reif and Nadrian C. Seeman, "Logical computation using algorithmic self-assembly of DNA triple-crossover molecules," Nature 407, 493–496 (2000)

[3] Doron Swade, "Redeeming Charles Babbage's Mechanical Computer," Scientific American, 268, 86–91 (1993).

[4] Ralph C. Merkle, Robert A. Freitas Jr., Tad Hogg, Thomas E. Moore, Matthew S. Moses, James Ryley, "Mechanical Computing Systems Using Only Links and Rotary Joints," arXiv:1801.03534.

[5] Ye Zhang, Ning Zhou, Ning Li, Megan Sun, Dongshin Kim, Seth Fraden, Irving R. Epstein, and Bing Xu, "Giant Volume Change of Active Gels under Continuous Flow," J. Am. Chem. Soc., 136, 7341–7347 (2014)