PNAS COMMENTARY

Programming material logic using magnetically controlled bistability

Tian Chen[a,1]

Anyone who has ever flipped a light switch has an innate understanding of mechanical bistability whereby a mechanical system possesses two stable equilibrium states. With sufficient energy input, the system will transition from one stable state to the other and vice versa. While common place in mechanical devices such as light switches, it would seem strange for a material (e.g., rubber) to exhibit bistability. Yet numerous investigations have demonstrated bistability in artificial materials or "metamaterials" by manipulating the geometry of the constituent units. These bistable metamaterials exhibit a number of useful properties such as energy absorption (1) and shape change (2). In these works, the stability landscape (e.g., how much energy is required for state transition) is engrained in the material architecture upon fabrication and can no longer be altered. In PNAS, Pal and Sitti (3) demonstrate a bistable mechanism whose stress–strain behavior is programmable in-field. They achieve this by permanently magnetizing flexible beams with particular magnetization profiles. By changing the external magnetic field strength during testing, they demonstrate that the mechanical behavior and the stability landscape of the curved beams can be predictably programmed on-demand. An array of these beams in turn are used to demonstrate programmable computational logic by varying the external fields.

The notion of programmability forms the foundation of modern computers. Devices such as field programmable gate array and EEPROM allow reprogrammable digital information processing. This capability in turn fueled the digital revolution in the 20th century. Of late, researchers in mechanics of materials have begun investigating whether physical characteristics of a material can be similarly reprogrammed. Specifically, recent works are proposing simple and reversible means to "program" mechanical behaviors such as stiffness, strength, or geometry on-demand. Examples include liquid evaporation to change lattice topology (4), magnetic interaction to control the shape of a surface (5), and manipulating pressure to tune stiffness (6).

In the past few years, there has been a flurry of activities that utilize magneto-mechanical bistability to achieve advanced forms of material-based programmability (7). When we think of magnets, we imagine a metallic cylinder that attracts to metallic surfaces. Permanent magnets like these can be formed by sintering neodymium–iron–boron (NdFeB) alloys. This precursor is then magnetically saturated under a strong magnetic field (in a magnetizer). Given the hysteric behavior of NdFeB, a remanent magnetization is imparted. One limitation is that the magnetizers themselves typically offer rather simple magnetization profiles (bipolar, quadrupolar, and so on). As NdFeB is a brittle material, engineers do not usually regard magnets as being deformable. Recently, magnetorheological elastomers (MREs) fabricated using 3D printing demonstrated extreme deformability while maintaining magnetization. While the underlying physics remains the same, the deformability of MREs enables previously infeasible design freedom. MREs are fabricated by impregnating ferromagnetic particles (e.g., NdFeB) in an elastomeric matrix (8) (Fig. 1*A*). This MRE precursor allows the design of arbitrarily complex magnetization profiles (9). Combining this with a tunable external magnetic field may enable intricate deformation behaviors.

With the goal to achieve programmable bistability using MREs, Pal and Sitti impose two different magnetization profiles onto flat silicone beams, 1) parallel and reversed, and 2) orthogonal to surface (Fig. 1 *B* and *C*). Once magnetized, the beams are clamped at the two ends and placed in a static and uniform magnetic field of strength $|\mathbf{B}|$. To characterize the mechanical response, a vertical indentation is applied at the apex (Fig. 1*A* shows the fabrication and testing of profile #1). One can visualize the magneto-elastic interaction as the turning of the magnetization vectors within the material toward being parallel to the external magnetic field vector. Given that the magnetized particles are bonded to the silicone, they collectively apply a torque $\vec{T}$ to the elastic beam.

In the first profile (Fig. 1*B*), also proposed by Abbasi et al. (10) in a recent publication, a prescribed lateral shortening causes the initially flat beam to "pop-out" into a curved shape (Fig. 1*B*). Under the vertical indentation, the beam transitions from an up-curve to a down-curve or vice versa. The rotational direction of the magnetically induced torque does not change under this deformation. Rather, a change in the external field strength $|\mathbf{B}|$ results in a predictable vertical shift in the force displacement curve and causes one equilibrium state to be more energetically favorable than the other. With a sufficiently large field, the system loses bistability entirely.

In the second profile (Fig. 1*C*), no shortening is prescribed. Rather, the imposition of the external field causes the clamped flat beam to be at an unstable equilibrium. The magnetization vector in the material is exactly antiparallel to the external field vector; consequently, the particles do not know whether to turn clockwise or counterclockwise to align with the field. Physically, with a small perturbation,

Author affiliations: [a]Cullen College of Engineering, Department of Mechanical Engineering, University of Houston, Houston, TX 77204

Author contributions: T.C. wrote the paper.

The author declares no competing interest.

Copyright © 2023 the Author(s). Published by PNAS. This article is distributed under Creative Commons Attribution-NonCommercial-NoDerivatives License 4.0 (CC BY-NC-ND).

See companion article, "Programmable mechanical devices through magnetically tunable bistable elements," 10.1073/pnas.2212489120.

[1]Email: tianchen@uh.edu.

Published April 18, 2023.

Downloaded from https://www.pnas.org by 92.41.158.105 on August 12, 2026 from IP address 92.41.158.105.

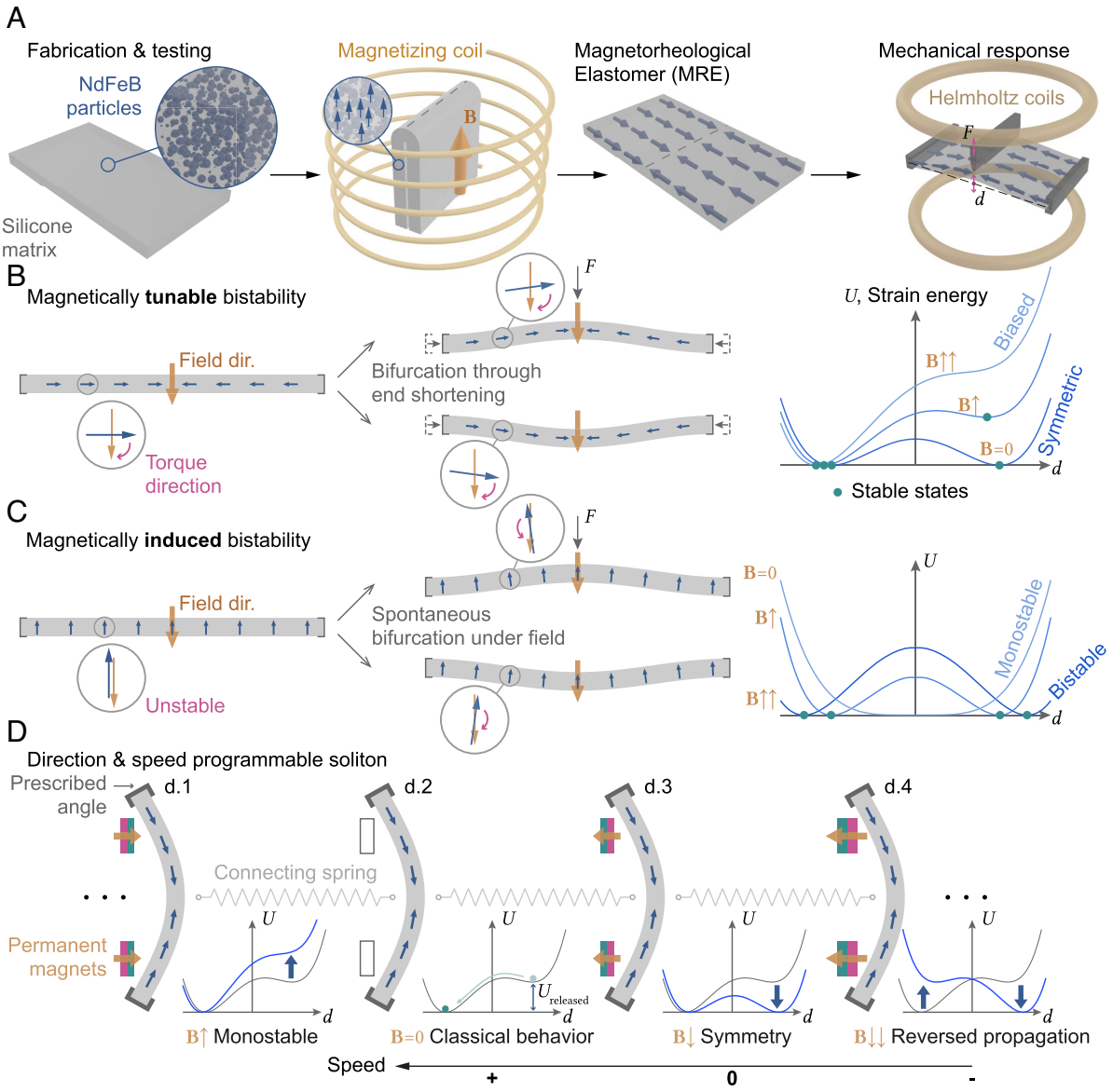


Fig. 1. Magnetically programmable bistability in curved beams. (*A*) The fabrication of the beams begins by impregnating a soft material matrix with ferromagnetic particles. This precursor is then cured and magnetized in a strong field to form the MRE. The resulting structure is then mechanically characterized under a magnetic field. (*B*) A parallel magnetization is used to demonstrate tunable bistability. The magnetic field applies a distributed torque to the beam, biasing it toward one (of the two) equilibrium states. (*C*) An orthogonal magnetization is used to instill bistability. Under a magnetic field antiparallel to the material magnetization, the otherwise monostable beam becomes unstable in the flat state and spontaneously buckles up or down. (*D*) An array of curved beams is connected together in series to demonstrate the propagation of a mechanical signal. By placing permanent magnets to locally control the field around each beam, the propagation characteristics (speed and direction) can be programmed on-demand.

the beam spontaneously "snaps" to one of the states, curving up or down. Both the geometry at the stable states and the energetic cost of transition become a function of the field strength. An indention applied to the system results in a familiar bistable strain energy curve that is indistinguishable from a naturally bistable curved beam. This is significant as, without the magnetic field, the beam is not curved or bistable at all!

Going one step further, Pal and Sitti tile beams magnetized in profile #1 in a linear array to demonstrate programmable mechanical wave propagation (Fig. 1*D*). The notion that bistability can be used to stably propagate a mechanical signal was first explored by Raney et al. (11) By connecting multiple asymmetric bistable elements in series and placing each in the less-stable state, energy is stored in each element. When the first element is triggered (via a mechanical impulse) to transition into the more stable (of the two) state, energy is released to trigger the next element in the series, causing a cascade of transitions (Fig. 1*D.2*). Two limitations were stated in this seminal work, namely both the direction and the speed of propagation were fixed after manufacturing and can no longer be changed without physically modifying the system. Here, by installing permanent magnets with each curved beam, Pal and Sitti were able to control both the speed and direction smoothly. By increasing the external field strength in the direction of the beam magnetization (Fig. 1*D.1*), the propagation speed increases as one of the states becomes less and less favorable, until the beam loses bistability. Conversely, the speed is reduced when the field strength

Downloaded from https://www.pnas.org by 92.41.158.105 on August 12, 2026 from IP address 92.41.158.105.

is increased in the other direction until both states become equally favorable and the propagation stops (Fig. 1*D.3*). With further increases, the direction of propagation reverses as the previously unfavorable state becomes the more favorable one under the field (Fig. 1*D.4*). Using this programmability, Pal and Sitti demonstrate a mechanical logic block that can behave as an AND or an OR gate. By locally controlling the magnetic field, the logic block may propagate the signal with a mechanical impulse on both inputs (AND) or when only one of the inputs is triggered (OR). This is reminiscent of a configurable logic block which is a fundamental component of field-programmable gate array.

In PNAS, Pal and Sitti demonstrate a bistable mechanism whose stress–strain behavior is programmable in-field.

Pal and Sitti demonstrate the impressive ability to remotely program the bistable mechanics of an otherwise static material. This is an important addition to the nascent field of material-based programmability. At an abstract level, the proposed device is a form of volatile mechanical memory as it requires the presence of a magnetic field during operation. While energy intensive, these devices are rapidly refreshable. In terms of design, the authors provide a means to smoothly tune the mechanical response using the field strength as a continuous variable. This is in contrast to combinatorial design frameworks (12–14) and may potentially enable reduced-order simulations and gradient-based optimizations (15). While the information density in this and other material-based programmable systems is far lower than their digital counterparts, one may argue that Moore's law may apply equally well here. More explicitly, the goal of this collection of work may be to use material-based intelligence to process mechanical information (e.g., earthquake as a mechanical signal) and optimize mechanical response (e.g., reducing stiffness) while bypassing digital controllers all together.

ACKNOWLEDGMENTS. My research is supported by the Advanced Manufacturing Institute at the University of Houston, Grant 2091-H0579-B2380-NA (69831). I also wish to thank Daniel Floryan for his suggestions on the manuscript.

1. S. Shan *et al.*, Multistable architected materials for trapping elastic strain energy. *Adv. Mater.* **27**, 4296–4301 (2015).
2. T. Chen, J. Panetta, M. Schnaubelt, M. Pauly, Bistable auxetic surface structures. *ACM Trans. Graph* **40**, 1–9 (2021).
3. A. Pal, M. Sitti, Programmable mechanical devices through magnetically tunable bistable elements. *Proc. Natl. Acad. Sci. U.S.A.* **120**, e2212489120 (2023).
4. S. Li *et al.*, Liquid-induced topological transformations of cellular microstructures. *Nature* **592**, 386–391 (2021).
5. Y. Bai *et al.*, A dynamically reprogrammable surface with self-evolving shape morphing. *Nature* **609**, 701–708 (2022).
6. Y. Wang, L. Li, D. Hofmann, J. E. Andrade, C. Daraio, Structured fabrics with tunable mechanical properties. *Nature* **596**, 238–243 (2021).
7. T. Chen, M. Pauly, P. M. Reis, A reprogrammable mechanical metamaterial with stable memory. *Nature* **589**, 386–390 (2021).
8. Y. Kim, H. Yuk, R. Zhao, S. A. Chester, X. Zhao, Printing ferromagnetic domains for untethered fast-transforming soft materials. *Nature* **558**, 274–279 (2018).
9. Z. Zhao, X. S. Zhang, Topology optimization of hard-magnetic soft materials. *J. Mech. Phys. Solids* **158**, 104628 (2022).
10. A. Abbasi, T. G. Sano, D. Yan, P. M. Reis, Snap buckling of bistable beams under combined mechanical and magnetic loading. *Philos. Trans. A Math. Phys. Eng. Sci.* **381**, 20220029 (2023).
11. J. R. Raney *et al.*, Stable propagation of mechanical signals in soft media using stored elastic energy. *Proc. Natl. Acad. Sci. U.S.A.* **113**, 9722–9727 (2016).
12. D. M. Sussman *et al.*, Algorithmic lattice kirigami: A route to pluripotent materials. *Proc. Natl. Acad. Sci. U.S.A.* **112**, 7449–7453 (2015).
13. C. Coulais, E. Teomy, K. De Reus, Y. Shokef, M. Van Hecke, Combinatorial design of textured mechanical metamaterials. *Nature* **535**, 529–532 (2016).
14. A. Bossart, D. M. Dykstra, J. Van der Laan, C. Coulais, Oligomodal metamaterials with multifunctional mechanics. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2018610118 (2021).
15. L. Huang, D. L. Michels, Surface-only ferrofluids. *ACM Trans. Graph* **39**, 1–17 (2020).

Downloaded from https://www.pnas.org by 92.41.158.105 on August 12, 2026 from IP address 92.41.158.105.