Universal Mechanical Polycomputation in Granular Matter

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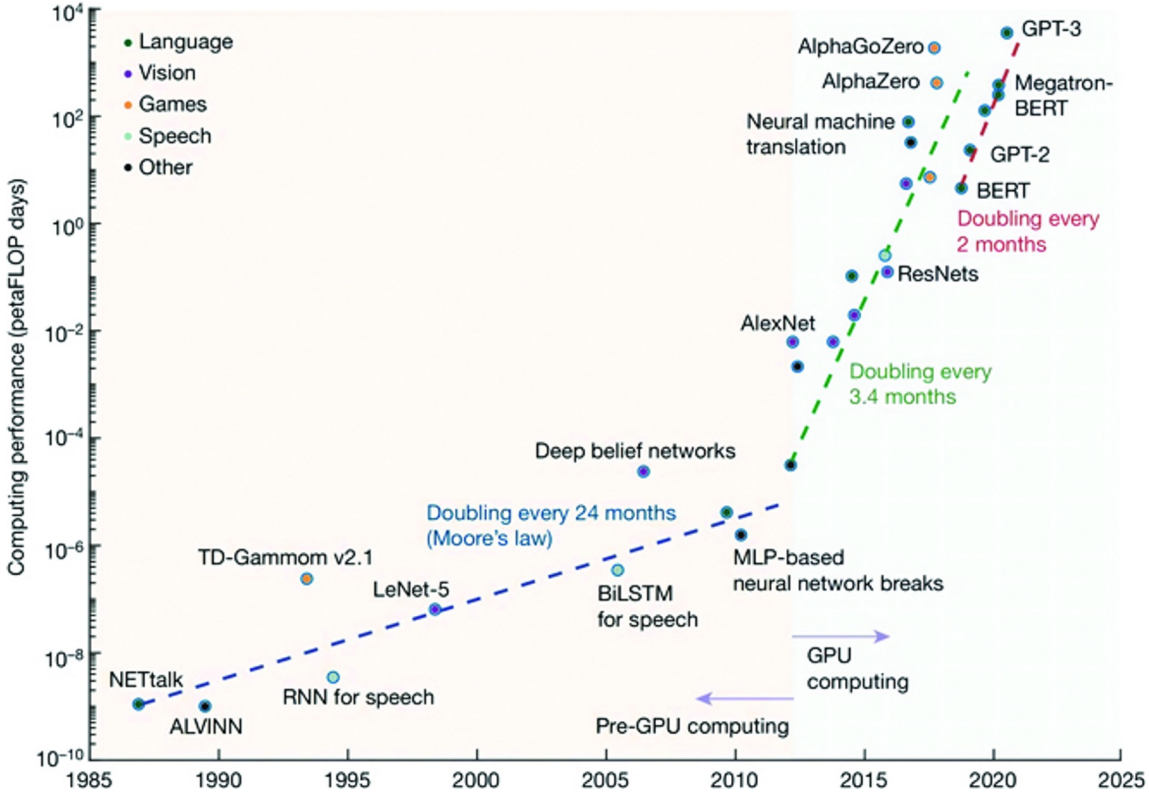
Corey S. O'Hern[2], Rebecca Kramer-Bottiglio[2], Josh Bongard[1]

[1] University of Vermont, Department of Computer Science
[2] Yale University, Department of Mechanical Engineering and Materials Science

The University of Vermont

Yale University

Computational demands are increasing rapidly



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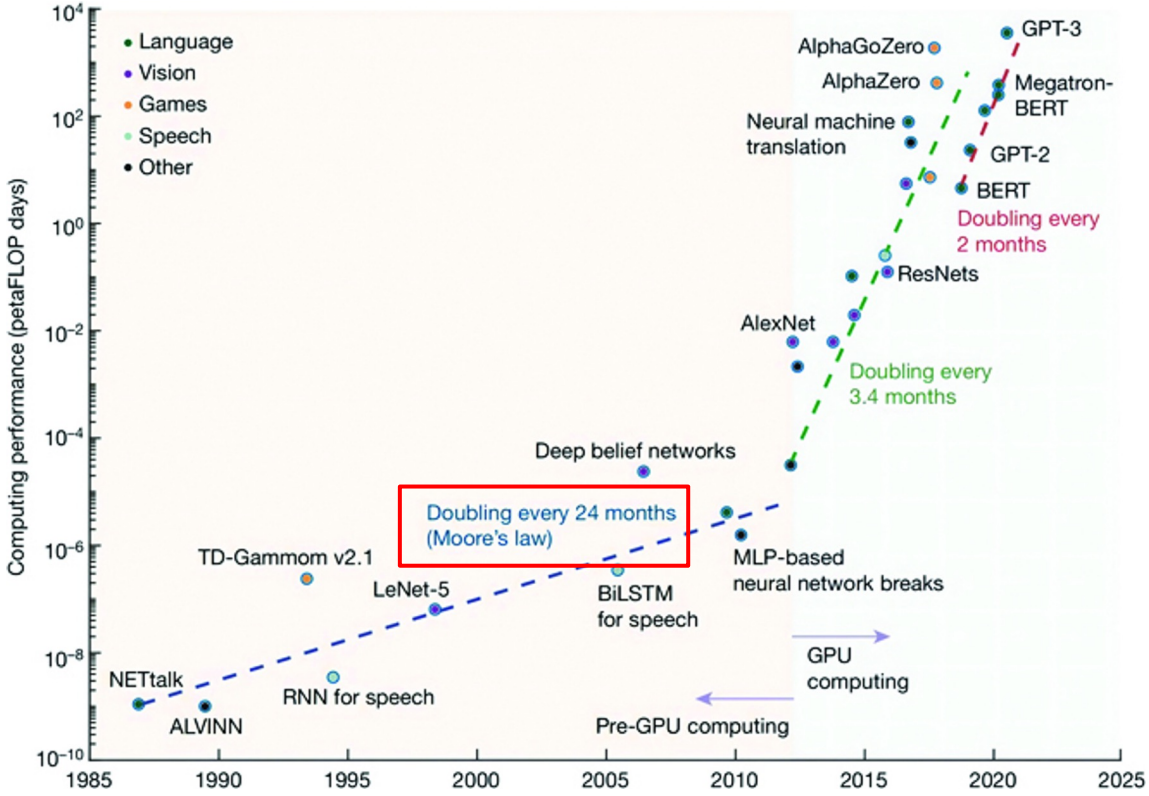

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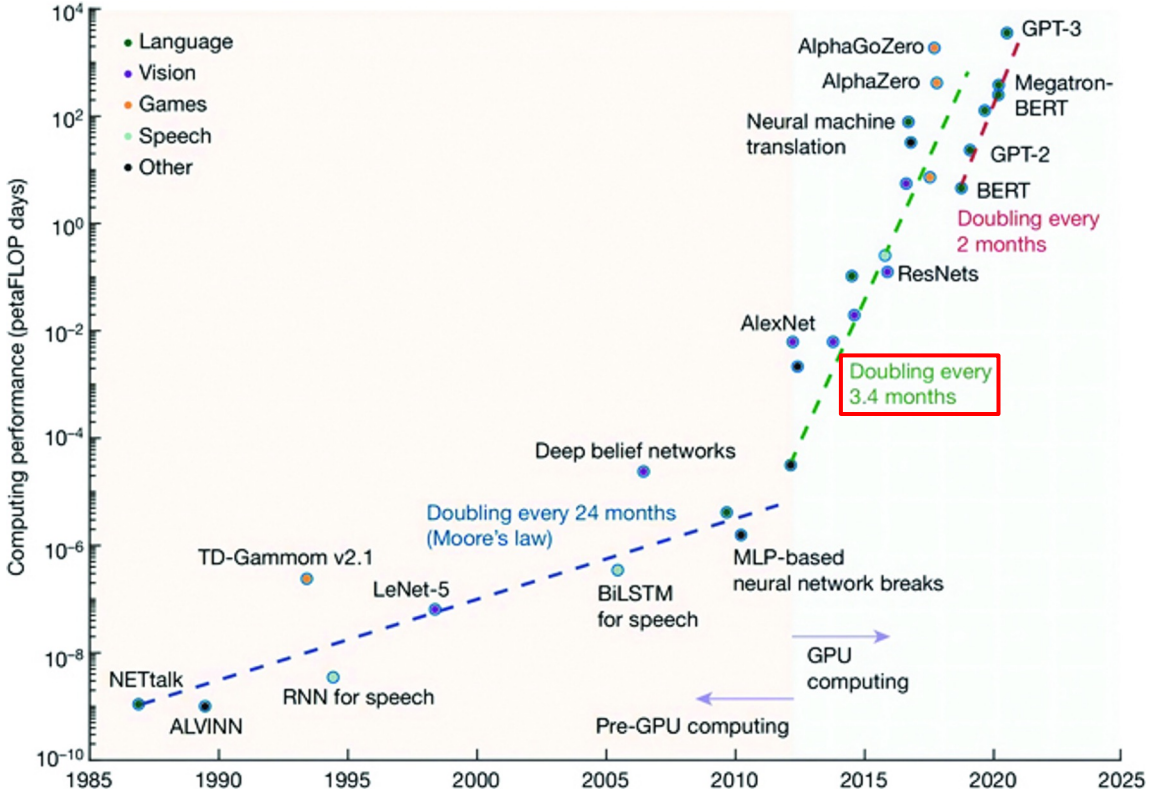

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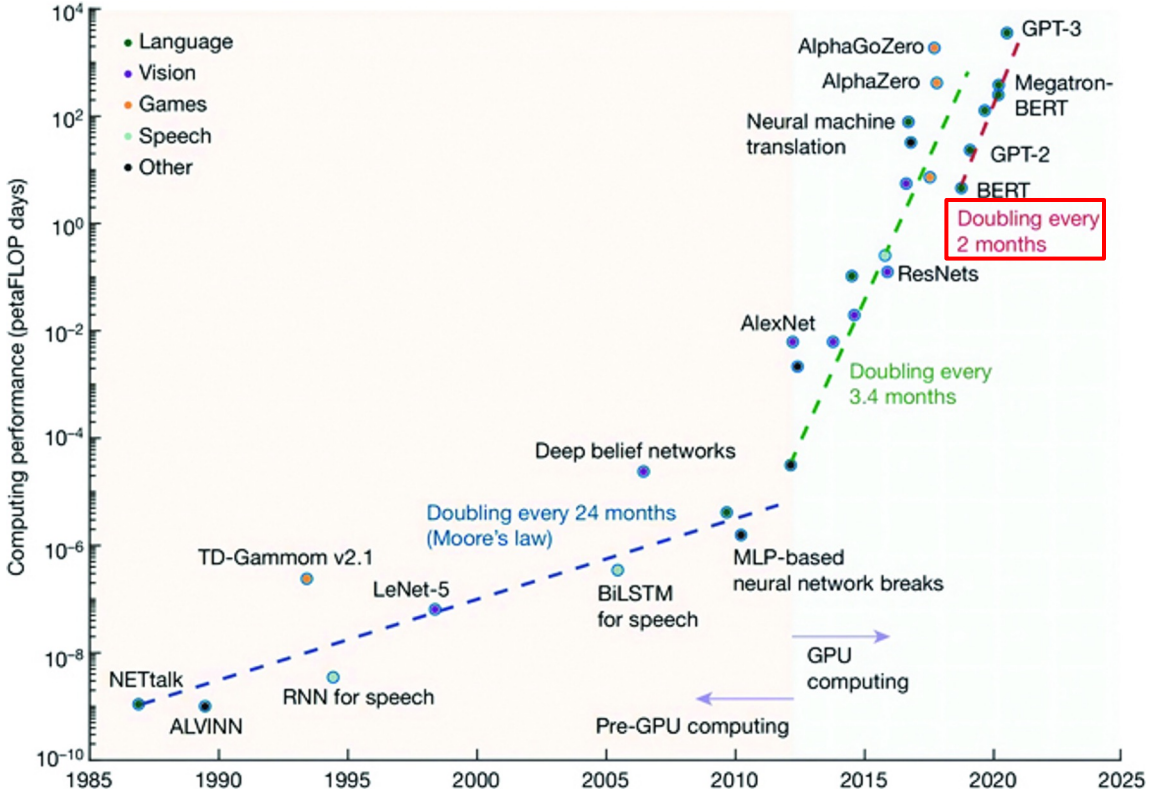

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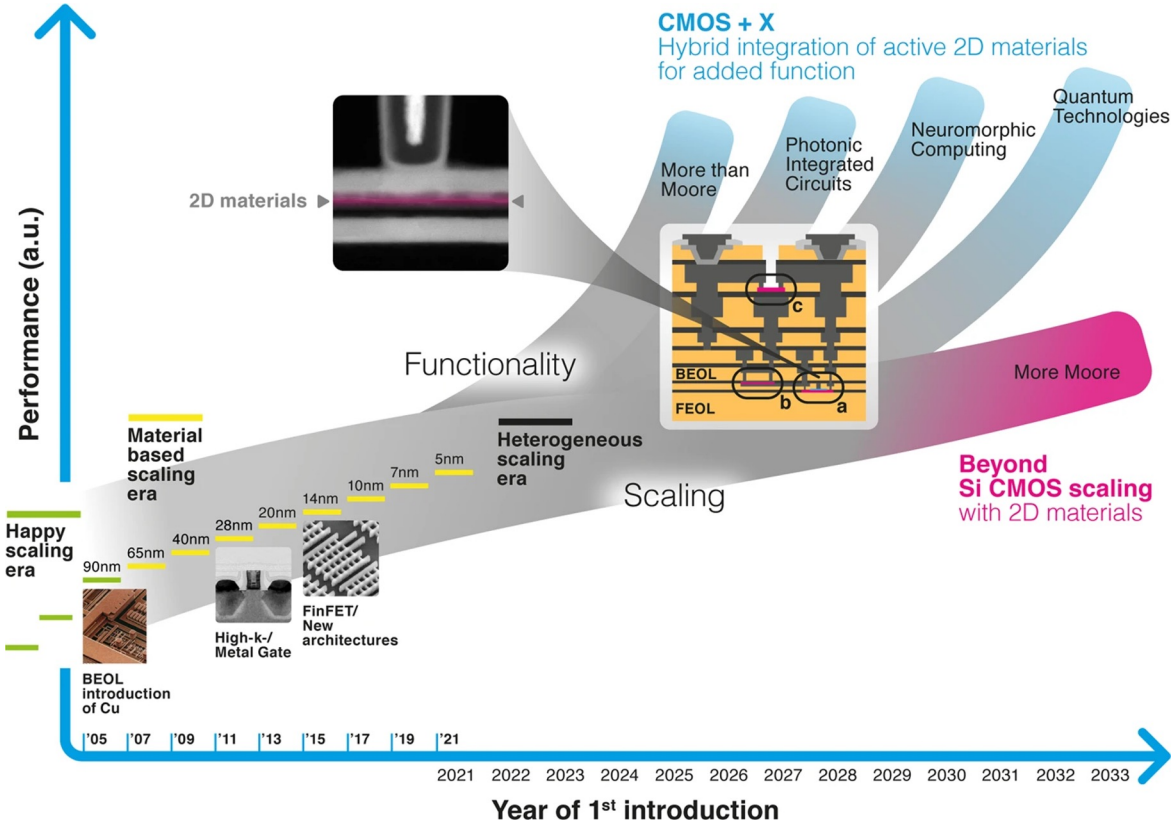
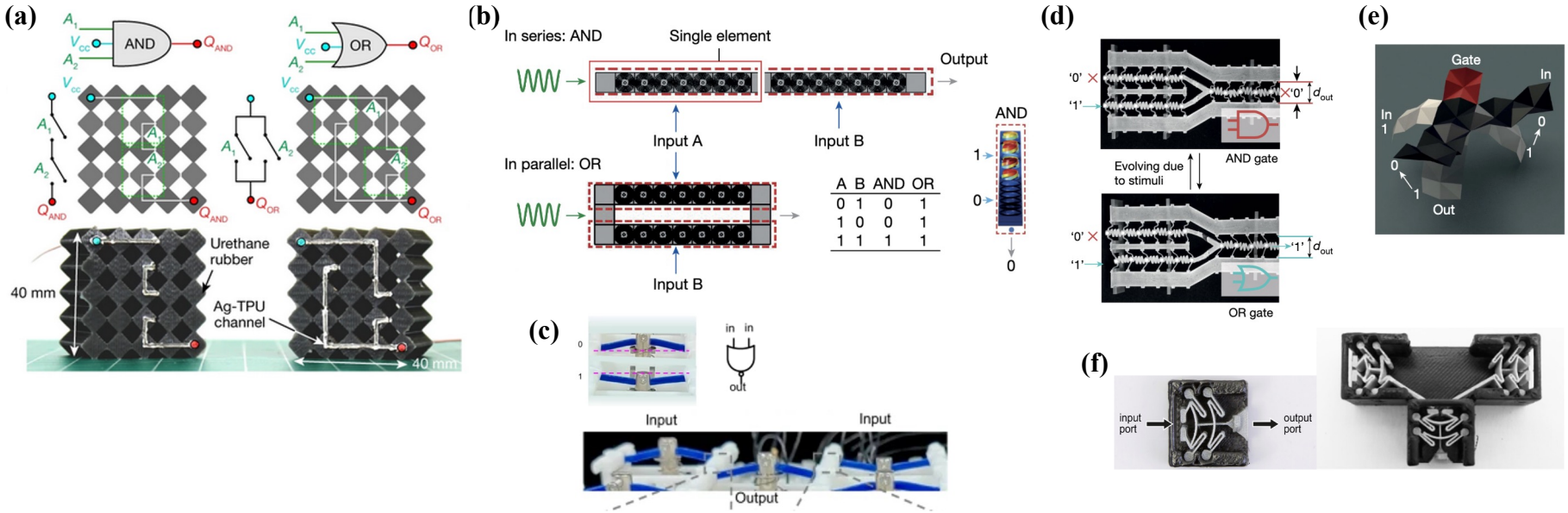
A New Beginning for Information Technology



[Lemme, Max C., et al. "2D materials for future heterogeneous electronics." *Nature communications* 13.1 (2022): 1392.]

A New Beginning for Information Technology:
Computing with Metamaterials



[a] El Helou, C., Grossmann, B., Tabor, C.E. *et al.* Mechanical integrated circuit materials. *Nature* **608**, 699–703 (2022).

[b] Bilal, Osama R., et al. "Bistable metamaterial for switching and cascading elastic vibrations." *Proceedings of the National Academy of Sciences*).

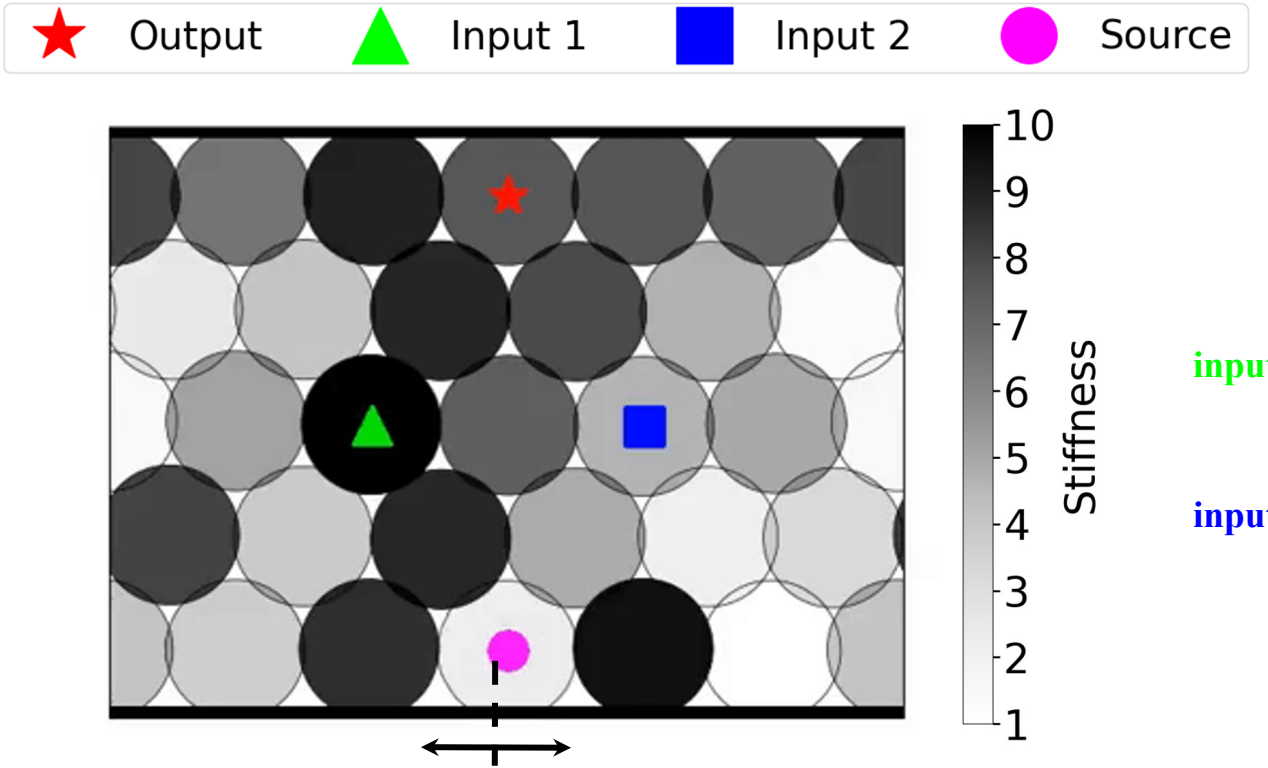
[c] Mei, T., Meng, Z., Zhao, K. *et al.* A mechanical metamaterial with reprogrammable logical functions. *Nat Commun* **12**, 7234 (2021).

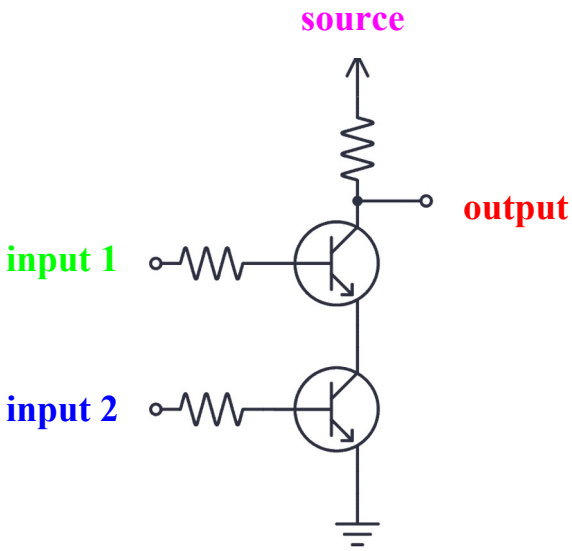
[d] Raney, Jordan R., et al. "Stable propagation of mechanical signals in soft media using stored elastic energy." *Proceedings of the National Academy of Sciences*, (2016).

[e] Treml, Benjamin, et al. "Origami mechanologic." *Proceedings of the National Academy of Sciences* 115, no. 27 (2018).

[f] Ion, Alexandra, et al. "Digital mechanical metamaterials." *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 2017.

The Task: Computing with Granular Matter





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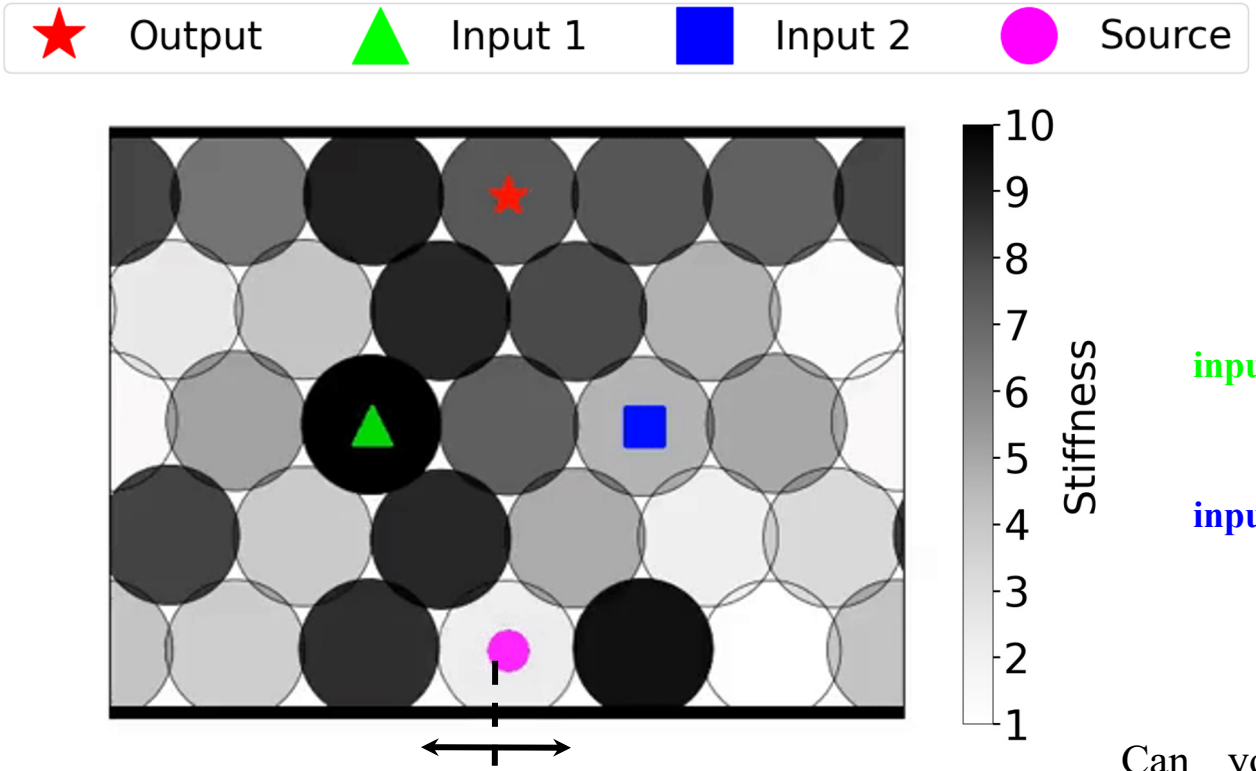
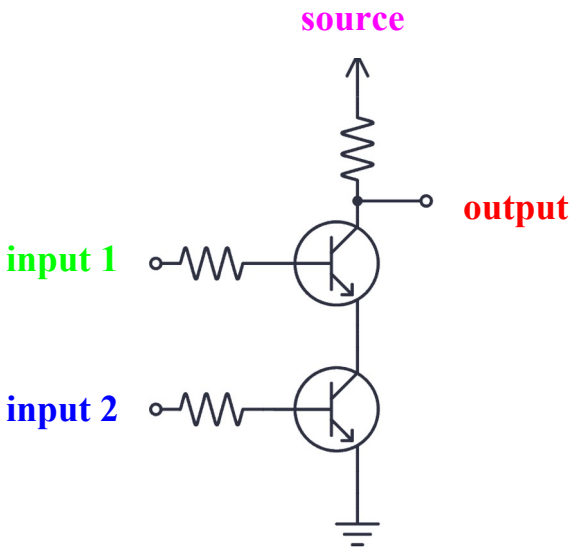
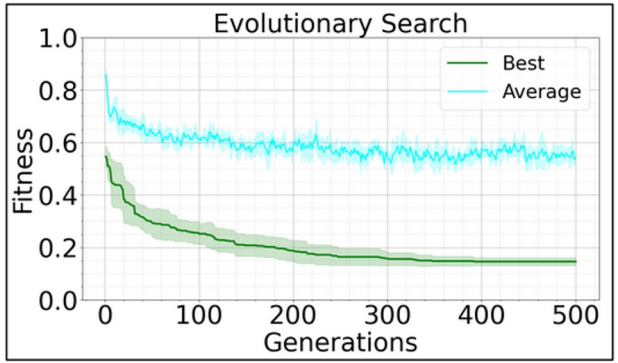


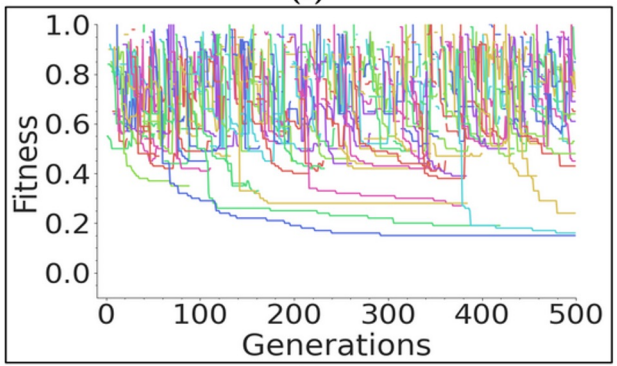


Can you find a configuration of particles that acts as a NAND gate?

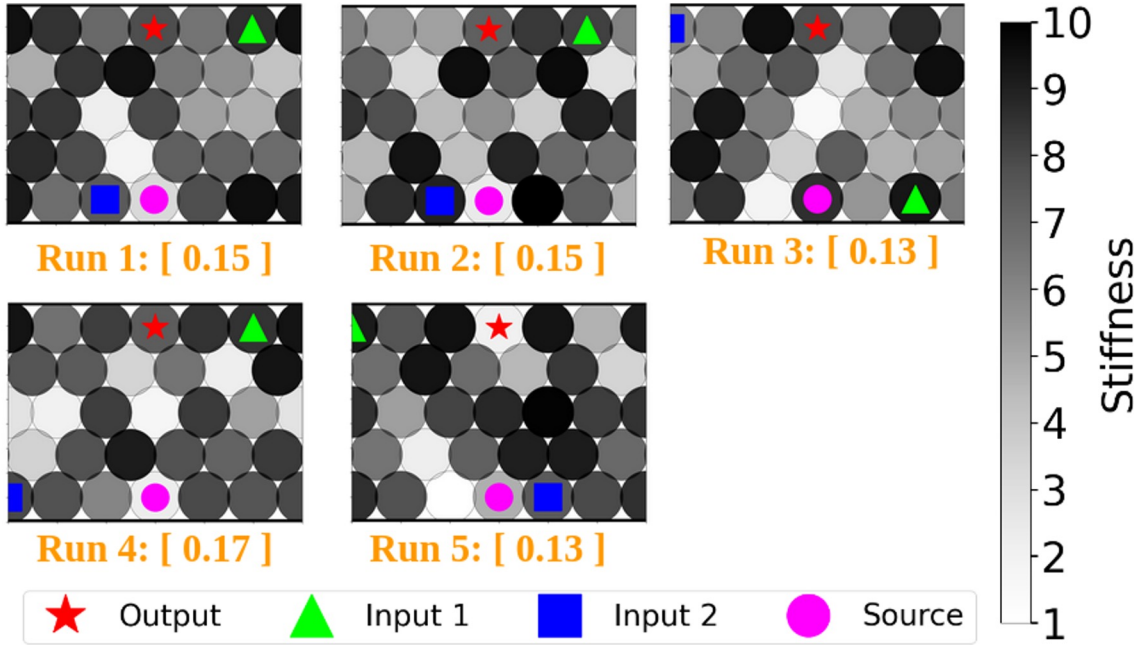
Evolutionary Computation for Designing Computational Material

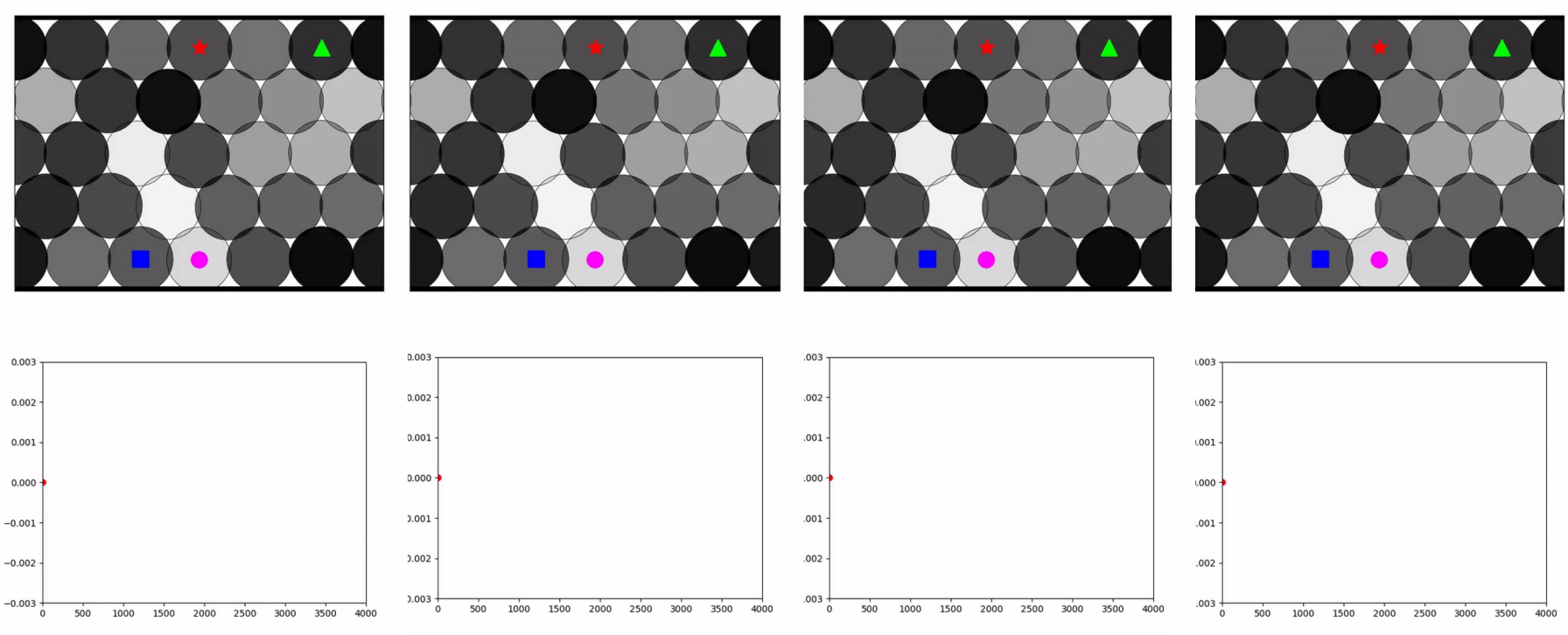


(a)



(b)




Stiffness
10
9
8
7
6
5
4
3
2
1
00
01
10
11
Output
Input 1
Input 2
Source

The Case for Humies Awards

Criterion A: The result was patented as an invention in the past, is an improvement over a patented invention, or would qualify today as a patentable new invention.

- We believe the granular metamaterial designs found by artificial evolution qualify as a patentable invention.

Jaeger, Heinrich, et al. "Methods of Designing Aggregates Optimized for Specified Properties." U.S. Patent Application No. 14/239,090.
Engheta, Nader, et al. "Metastructures for solving equations with waves." U.S. Patent No. 11,494,461. 8 Nov. 2022.
Dillavou, Samuel, et al. "Coupled networks for physics-based machine learning." U.S. Patent Application No. 17/750,072.
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- We believe the granular metamaterial designs found by artificial evolution qualify as a patentable invention.
- The computational capabilities of our designs which enable superposition of multiple logical functions in one granular metamaterial, the high dimensional parameter space and the complexity of emerging patterns make these designs unique compared to previous work.

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Criterion D: The result is publishable in its own right as a new scientific result — independent of the fact that the result was mechanically created.

- Despite recent advances in the field, in none of the previous works is the computational unit automatically optimized to perform computation, let alone how best to densely pack computation in new ways into materials is explored.

- We think that our result is valuable on its own as a new scientific discovery.

The Case for Humies Awards

Criterion G: The result solves a problem of indisputable difficulty in its field.

- The non-intuitive nature of embedding computation into granular metamaterial is evidenced by the lack of obvious common patterns across the evolved materials that best embody the logic gates.

- This emphasizes the utility of automated design in this domain: designing a configuration of particles to behave as a logic gate is a rather difficult if not impossible task to accomplish without the aid of computer optimization.

We believe this paper may stand out in 2 ways:

1. Our work shows a significant step forward for designing computational material by unveiling the potential of polycomputation in granular matter.

Most of the work in the field of metamaterial design have been essentially a human-driven process of trial and error to design materials with desired properties.

The invention of transistors is considered one of the greatest technological achievements of the human age.

Field Effect Transistor patent filed (1926)

Image source: www.britannica.com

First bipolar transistor (1947)

One-transistor DRAM cell invented (1968)

First MOSFET (1960)

VLSI era

1940 1950 1960 1970 1980 1990 2000 2010 2020

First transistor computers that featured boards filled with discrete transistors (1955)

CMOS invented (1963)

IC invented (1958)

First micro-processor (1971)

First commercially available microcomputer kit (1975)

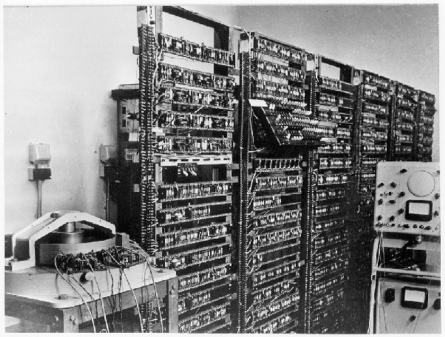

Image source: http://curation.cs.manchester.ac.uk/

[IEEE Electron Devices Society, Newsletter, January 2023]

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- The high-dimensional design space and the unintuitive relationship between microstructure and the desired macroscale behavior makes the inverse design problem formidable.

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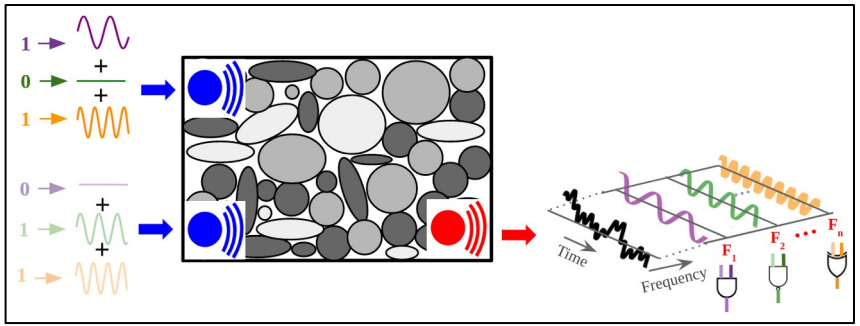
- The high-dimensional design space and the unintuitive relationship between microstructure and the desired macroscale behavior makes the inverse design problem formidable.

- In our research, for the first time, we showed the successful application of evolutionary algorithms for designing computational granular metamaterials.



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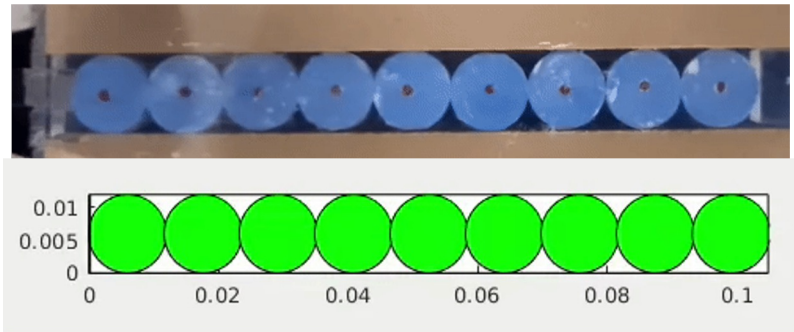
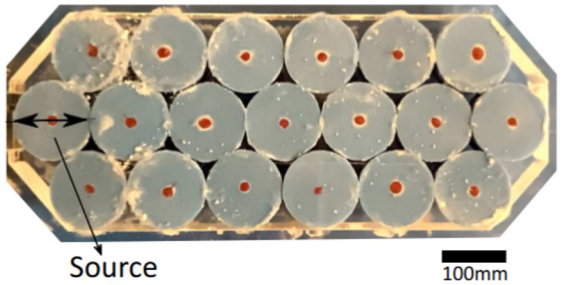
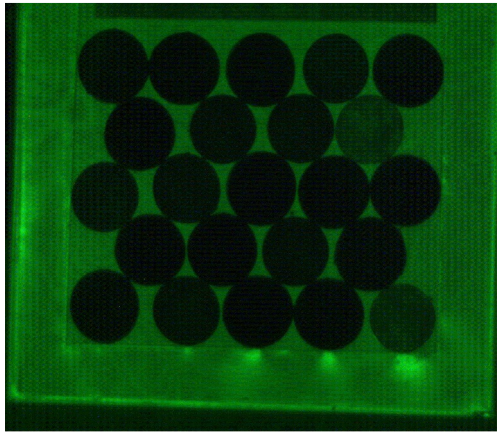
it is possible that given the discrete nature of granular metamaterials compared to continuous media, crossing the reality gap may prove easier







Collaborators:

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Rebecca Kramer-Bottiglio

Josh Bongard

THE UNIVERSITY OF VERMONT
ADVANCED COMPUTING CENTER

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- Parsa, Atoosa, Dong Wang, Corey S. O'Hern, Mark D. Shattuck, Rebecca Kramer-Bottiglio, and Josh Bongard. "**Evolving programmable computational metamaterials**." In *Proceedings of the Genetic and Evolutionary Computation Conference*, pp. 122-129. 2022.