

Mechanical hysterons with tunable interactions of general sign

Corresponding Author: Professor Joseph Paulsen

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This paper presents a general mechanical design platform comprising rigid bars and linear springs that successfully transforms the abstract hysteron model into a physical implementation. By adjusting the connections between rigid bars using springs of varying stiffness and rest lengths, the system materializes tunable interactions (frustrated or cooperative, reciprocal or non-reciprocal) between bistable units, enabling many intriguing pathways (e.g., latching and multiperiodic) previously demonstrated only in simulations. The reported results are interesting and could potentially provide new possibilities for designing materials with memory, computing, and learning capabilities. The paper is generally well-written, though several issues should be addressed to strengthen the contribution:

1. The author demonstrates the merits of their system by showcasing interesting deformation pathways previously unachievable by metamaterials. However, the author also refers to their system as a "material" in certain sections of the manuscript (e.g., line 110). The system reported is more accurately characterized as a mechanical assembly or device rather than a (meta)material in the conventional sense. I would suggest being more precise in descriptions throughout the manuscript to avoid conceptual confusion.
2. The author develops both a kinematic model and a reduced model to explain how the system realizes complex interactions between units and to predict system response. However, experimental videos and snapshots indicate that the springs seem to be prestretched before being mounted to connect the rigid bars. Neither model appears to account for the effects of different prestrain levels applied to the springs. Could the authors provide a more detailed explanation/analysis on how spring prestrain influences system response in both experiments and theoretical models? This clarification would strengthen the connection between theory and experiment.
3. The design approach for multiperiodic response appears somewhat ad hoc rather than following general design principles. While it demonstrates that interactions in this system are more complex than in other demonstrations (e.g., additional interactions between elements 1 and 3), the description of how to achieve such counting behavior is overly simplified. A more comprehensive explanation of how to realize such responses and how this system can be generalized to more complex systems with larger periodicity would benefit both the broader audience and the scientific community.

Reviewer #2

(Remarks to the Author)

The paper translates the abstract model describing interactions between hysterons into a mechanical system made of rigid bars and linear springs. It uses this mechanical platform to demonstrate the full generality of the abstract model first for a pair of interacting hysterons and then for a collection of multiple hysterons. The results show that the switching thresholds for one hysteron are dependent on the state of the other, and that a rich hysteretic landscape emerges by coupling uncrossing and crossing springs. The mechanical system is also leveraged to demonstrate non-reciprocity of hysteron interactions as well as latching, a phenomenon that has recently emerged in the study of amorphous solids forming memories of asymmetric driving.

The paper presents an engaging educational approach that initiates with the fundamental demonstration of a non-interacting

single rotor and progresses towards the more complex coupling of multiple mechanical hysterons, with the aim of achieving specific computations on sequences of mechanical inputs for the processing of mechanical information. It provides a solid demonstration platform, and it is well-structured and well-written.

The novelty per se is not as high, given most of the phenomena have already been investigated in other material systems, such as corrugated sheets, biholar domains, and origami bellows. Yet, the spring-bar system adopted here has broad applicability, as it can effectively demonstrate a rich set of hysteretic interactions and tunability of general sign. This paper will undoubtedly appeal to the condensed matter community; in fact, it could also be a very good fit for publication in physics journals.

The following are recommendations for improvement.

The hysteron design is introduced without elucidating the rationale behind the selection of the spring-bar arrangement and the coupling—whether crossed or uncrossed—of the rod with the supplementary springs. To some extent, the description appears to be presented as a fact. It is recommended to provide a justification for this particular design choice and to elaborate on the significance of creating such types of couplings for cooperative interactions. Although the results indicate that this design is feasible, an account of the reasoning employed by the author in developing this bistable unit system, which constitutes one among several alternatives, should be included.

The author states that two additional transition graphs are possible for “mixed” interactions, where the signs of J_{ij} and J_{ji} differ, but there is no way to realize such interactions in the system. Can the author explain the reason of this limitation and propose a rationale/strategy to address it? What are the key factors that control the unsuccess on this front, and what can be done to circumvent this limitation.

Statistical uncertainty: All experimental data are presented as individual data points. Although the correspondence between theoretical predictions and experimental outcomes is satisfactory, it is advised that, where feasible, the variability of results pertaining to experimental repeatability be incorporated. This practice is customary in research driven by experimental investigations.

Clarity of visuals. Although the position for $\theta = 0$ is indicated in the text (vertical position), I recommend visualizing θ in figure 1. I would also include the coordinate system in figure 1 as to refer to when explaining the relation in the text involving the y variable.

Typo

mounted a distance $>$ at a distance

References. The author uses references to add footnote-type description. See for example references 24 -27 and others. I am not sure this practice is allowed in this journal

Reviewer #3

(Remarks to the Author)

The manuscript exhibits a mechanical embodiment of the general coupled hysterons model previously introduced in the literature. The system discussed by the authors consists of rigid bars mounted on rotational axis, where the rotational degree of freedom is bounded by hard stops. The bars are coupled through linear springs to their neighbours and a global drive, resulting in bistable hysteretic units, or hysterons, with a large design space for their couplings. The authors show in particular that their system can reproduce reciprocal and non-reciprocal interactions, which is a key feature of the theory. Furthermore, they develop a clear theoretical mapping from physical parameters to abstract hysteron properties and couplings. Then they proceed to make the practical demonstrations of targeted collective behaviours and computational capabilities like counting and memory latching, deduced from the study of the initial model in earlier publications.

The manuscript is well written, scientifically rigorous, and the technicalities are rather thoroughly presented. However, it should be explicitly acknowledged that the manuscript primarily demonstrates proofs of concept and practical realisations rather than introducing fundamentally new scientific principles or theories. In particular, it is unclear why the authors do not perform a more thorough parametric study, that could lead to at least attempting at a phase diagram.

Additionally, the present system is so small that it is obviously within reach of simulations. We feel that the authors endeavour may have a significantly larger impact if the experimental system could be scaled up, in order to reach regimes that would otherwise require involved computational resources.

We would also like to mention that despite its elegance and versatility, the mechanical system introduced here is a chain, and thus behaves like a one-dimensional material. We feel like the lack of spatial dimensionality might severely limit the range of actual material collective behaviours it is susceptible to mimic. Demonstration of 2D effects would greatly enhance the reach of this study.

In the perspective of metamaterials and scalability, it would also make this work more impactful to display a form of material embodiment, maybe involving additive manufacturing, as the present form of the system is rather abstract and “resembles” the theory very closely.

In my opinion, this is a very interesting line of thoughts, but too early to meet the standards of Nature Communications.

However, I would gladly reconsider this position if progress could be made on the points mentioned above.

Reviewer #4

(Remarks to the Author)

This manuscript presents a mechanical platform for constructing interacting hysterons with tunable, non-reciprocal interactions. Using a system of rigid rotors and linear springs, the authors demonstrate programmable bistable elements whose switching thresholds can be continuously tuned and made dependent on the state of other hysterons. They map this mechanical implementation onto abstract hysteron models with arbitrary interaction matrices and show experimental realizations of latching behavior, counting, and modulo-2 logic. The work is conceptually elegant and technically sound, supported by both experimental and theoretical models.

Strength:

1. The same platform is used to demonstrate multiple behaviors — from simple hysteresis to latching, counting, and logic cycling — by tuning geometric parameters. This highlights the versatility and generality of the system.
2. The mechanical implementations are well-crafted and convincingly demonstrate the phenomena described.
3. The kinematic model and its small-angle reduction are well presented and agree with experimental results. This adds credibility and predictive power to the platform.

Points for improvement:

1. The demonstrated systems involve up to four hysterons. It is unclear how the complexity of tuning scales with larger networks. For example: Can the method be practically extended to 10s or 100s of elements? Are there design heuristics or learning-based strategies for configuring large systems? A brief discussion of these points would enhance the broader relevance.
2. The setups involve careful alignment. It would be helpful to clarify: How robust is the system to noise or misalignment? Can these mechanical elements be miniaturized or implemented in soft materials for integration into real-world systems?
3. The model is entirely quasi-static. However, in physical implementation, transitions involve fast motion and likely energy loss. A brief discussion of how damping or inertial effects might influence state transitions or memory stability would be valuable.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The author has properly addressed all of my concerns. I therefore recommend publication in Nature Communications.

(Remarks on code availability)

The author has provided a clear code-availability statement, and the accompanying dataset and code appear to be well organized and usable. However, the Figshare link in Ref 45 is currently inaccessible. The author should double-check and update the link accordingly.

Reviewer #2

(Remarks to the Author)

The author has addressed my comments and provided clear, well-reasoned responses in the rebuttal letter. The manuscript has also been revised to incorporate elaborations on the points I raised, which significantly enhance the clarity and coherence of the work. The additions make the arguments more accessible. I am satisfied with the revisions and deem the manuscript to meet the required standards. I recommend the paper for publication.

(Remarks on code availability)

Reviewer #3

(Remarks to the Author)

The authors addressed my concerns, and their work is certainly worth publishing in Nature Communications.

(Remarks on code availability)

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REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

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>I thank the reviewer for their careful reading of the work. I have removed the term “metamaterial” on the (old) line 110. I did not notice any other instances of this term in the manuscript.

2. The author develops both a kinematic model and a reduced model to explain how the system realizes complex interactions between units and to predict system response. However, experimental videos and snapshots indicate that the springs seem to be prestretched before being mounted to connect the rigid bars. Neither model appears to account for the effects of different prestrain levels applied to the springs. Could the authors provide a more detailed explanation/analysis on how spring prestrain influences system response in both experiments and theoretical models? This clarification would strengthen the connection between theory and experiment.

>The reviewer is correct that all springs are prestretched before being mounted; this is necessary as the springs are not suitable for compression. This is already accounted for in the kinematic model; we assign the force following Hooke's law with $F = -k(l - x_0)$ with x_0 the spring rest length, and k and x_0 are measured independently for each spring. I have revised the text in several places to make this aspect of the kinematic model more clear.

As for the reduced model, the SI shows that x_0 drops out of the net torque for parallel springs, so long as matched pairs of springs are used with equal spring constants and rest lengths. This is easy to achieve with off-the-shelf extension springs. For crossed springs, the value of x_0 drops out in the net torque if either of two limits are satisfied; x_0 small compared to the mounting position ℓ or rotor spacing, w . The suitability of this latter approximation is tested in Fig. S3. All the above findings are stated more clearly in the revised manuscript.

3. The design approach for multiperiodic response appears somewhat ad hoc rather than following general design principles. While it demonstrates that interactions in this system are more complex than in other demonstrations (e.g., additional interactions between elements 1 and 3), the description of how to achieve such counting behavior is overly simplified. A more comprehensive explanation of how to realize such responses and how this system can be generalized to more complex systems with larger periodicity would benefit both the broader audience and the scientific community.

>Indeed, our approach to building multi-periodicity was the following: (1) identify parameters in simulations of the abstract hysteron model that lead to multi-periodicity, and then (2) target these interactions and thresholds in the lab. This serves to demonstrate the precision and fidelity that can be achieved with this rotor hysteron design. By contrast, finding a general design principle for achieving a targeted transition graph is a major challenge for the field, which is establishing its own body of work (c.f. Refs. 39-41 in the revised manuscript). It is worth emphasizing that the value of that body of work is limited without some guarantees that arbitrary parameters can be realized, as we now show in this study.

We hope that our experimental platform can also guide and inform more systematic methods for targeting collective hysteron behaviors, and we outline in the final paragraph of our manuscript how this might unfold, e.g. through the confluence of two emerging areas in the field: abstract hysteron models and “physical learning”. Our study identifies a robust experimental and theoretical sandbox that can push the field in this direction.

Reviewer #2 (Remarks to the Author):

The paper translates the abstract model describing interactions between hysterons into a mechanical system made of rigid bars and linear springs. It uses this mechanical platform to demonstrate the full generality of the abstract model first for a pair of interacting hysterons and then for a collection of multiple hysterons. The results show that the switching thresholds for one hysteron are dependent on the state of the other, and that a rich hysteretic landscape emerges by coupling uncrossing and crossing springs. The mechanical system is also leveraged to demonstrate non-reciprocity of hysteron interactions as well as latching, a phenomenon that has recently emerged in the study of amorphous solids forming memories of asymmetric driving.

The paper presents an engaging educational approach that initiates with the fundamental demonstration of a non-interacting single rotor and progresses towards the more complex coupling of multiple mechanical hysterons, with the aim of achieving specific computations on sequences of mechanical inputs for the processing of mechanical information. It provides a solid demonstration platform, and it is well-structured and well-written.

The novelty per se is not as high, given most of the phenomena have already been investigated in other material systems, such as corrugated sheets, biholar domains, and origami bellows. Yet, the spring-bar system adopted here has broad applicability, as it can effectively demonstrate a rich set of hysteretic interactions and tunability of general sign. This paper will undoubtedly appeal to the condensed matter community; in fact, it could also be a very good fit for publication in physics journals.

>Developing a pedagogical narrative was indeed a major goal of the author; I am grateful that the reviewer sees this value in the work. I am also grateful that the reviewer appreciates the “broad applicability” of our spring-bar system, as well as its particular appeal to physicists.

What I want to emphasize about those previous systems (corrugated sheets, biholar domains, origami bellows, ...) is that those experiments are great, but taken together, they do not suggest a general solution to the inverse design problem. Indeed, an important value of this work is to demonstrate *how much functionality can be crammed into one simple system*. I think this satisfies a hunger in the community as grapples with questions such as “what are the rules for combinations of hysteron interactions that respect the first law of thermodynamics?” (c.f. Ref. 39). By building in the lab a single system that achieves non-reciprocal, tunable interactions that can be cooperative or frustrated, we immediately settle some important questions of what is physically possible for hysterons built from passive, overdamped elements.

The following are recommendations for improvement.

The hysteron design is introduced without elucidating the rationale behind the selection of the spring-bar arrangement and the coupling—whether crossed or uncrossed—of the rod with the supplementary springs. To some extent, the description appears to be presented as a fact. It is recommended to provide a justification for this particular design choice and to elaborate on the significance of creating such types of couplings for cooperative interactions. Although the results indicate that this design is feasible, an account of the reasoning employed by the author in developing this bistable unit system, which constitutes one among several alternatives, should be included.

>We thank the reviewer for pushing us to improve the manuscript in this regard. Indeed, the design reported here was not inevitable; there are many designs being developed, using e.g. origami modules or buckled beams as the mechanical bits. What was missing from the field were strong, tunable, general interactions. We landed on a rotor spring system because it allows you to place forces (and hence torques) where you want them. It is difficult to outline the exact process, however, as it was a creative process guided by principles of simplicity and tunability. And, some of the attractive features of the interacting system came as happy surprises (such as the linearity of the interactions, even at arbitrary angles, which we now point out more clearly).

Nevertheless, we agree with the reviewer that we can do better in describing how certain couplings (parallel versus crossed) lead to particular interactions. We now motivate the interactions through torque balance, in the final paragraph of the Section titled “Hysteron design”.

The author states that two additional transition graphs are possible for “mixed” interactions, where the signs of J_{ij} and J_{ji} differ, but there is no way to realize such interactions in the system. Can the author explain the reason of this limitation and propose a rationale/strategy to address it? What are the key factors that control the unsucccess on this front, and what can be done to circumvent this limitation.

>The apparent absence of “mixed” interactions is an intriguing topic that we are still exploring. We were able to make some incremental progress since submitting this manuscript, and our

preliminary results suggests that mixed interactions might be possible in a certain region of parameter space, although the magnitudes of the mixed interactions appear to be weak. As such, it is not yet clear whether the two “missing” transition graphs could be built. Rather than muddy the waters by speculating further in this manuscript, we plan to work on this in a follow-up study. We highlight this open question in the revised Discussion.

Statistical uncertainty: All experimental data are presented as individual data points. Although the correspondence between theoretical predictions and experimental outcomes is satisfactory, it is advised that, where feasible, the variability of results pertaining to experimental repeatability be incorporated. This practice is customary in research driven by experimental investigations.

>The experimental uncertainty for all experimental thresholds was at a consistent level of ± 0.1 cm. This value is small compared with the symbol size, so that the uncertainty is difficult to display graphically. This information is now reported more prominently in the figure captions. (It was previously buried in the Methods section.)

Clarity of visuals. Although the position for $\theta = 0$ is indicated in the text (vertical position), I recommend visualizing θ in figure 1. I would also include the coordinate system in figure 1 as to refer to when explaining the relation in the text involving the y variable.

>We thank the reviewer for this helpful feedback. We have marked θ_1 in Fig. 1A and Fig. 1D. We have also added a coordinate system to Fig. 1A.

Typo

mounted a distance $>$ at a distance

>We thank the reviewer for their careful reading. This typo is fixed.

References. The author uses references to add footnote-type description. See for example references 24 -27 and others. I am not sure this practice is allowed in this journal

>I can rewrite these footnotes as parentheticals if necessary.

Reviewer #3 (Remarks to the Author):

The manuscript exhibits a mechanical embodiment of the general coupled hysterons model previously introduced in the literature. The system discussed by the authors consists of rigid bars mounted on rotational axis, where the rotational degree of freedom is bounded by hard stops. The bars are coupled through linear springs to their neighbours and a global drive, resulting in bistable hysteretic units, or hysterons, with a large design space for their couplings. The authors show in particular that their system can reproduce reciprocal and non-reciprocal interactions, which is a key feature of the theory. Furthermore, they develop a clear theoretical mapping from physical parameters to abstract hysteron properties and couplings. Then they proceed to make the practical demonstrations of targeted collective behaviours and computational capabilities like counting and memory latching, deduced from the study of the initial model in earlier

publications.

The manuscript is well written, scientifically rigorous, and the technicalities are rather thoroughly presented. However, it should be explicitly acknowledged that the manuscript primarily demonstrates proofs of concept and practical realisations rather than introducing fundamentally new scientific principles or theories. In particular, it is unclear why the authors do not perform a more thorough parametric study, that could lead to at least attempting at a phase diagram.

>I thank the reviewer for their careful reading and evaluation of our work. I disagree, however, with the implication that proofs of concept are inferior to fundamental principles or theories. This is a field where models have long outpaced experiments. By demonstrating in the lab the wide variety of transition graphs that can be achieved with a modest set of simple components, we implicate a vast, untapped space that could be reached with more elaborate components and designs, more unit cells, or higher-dimensional lattices. Most of this space is off-limits to previous experimental designs and approaches.

Second, due to the sheer number of tunable parameters, a systematic parametric study quickly becomes overwhelming to explore and display. Even with just two rotors, there are three variables related to the mounting positions and angles plus two variables related to the springs (see Fig. S1C). To address this, the philosophy of Fig. S1 was to walk through multiple transition graphs by changing just one parameter at a time. These represent one-dimensional slices through a high-dimensional phase space, as shown by the groupings in Fig. S1B and in Supplementary Videos 2-5. Figure 2A presents another slice through parameter space by varying ℓ and keeping all other parameters constant.

The enormity of this phase space poses an interesting question: How should one navigate this space to target different functionalities? One possible solution is in the emerging field of “physical learning”; we outline this enticing future direction in the Results and Discussion.

Additionally, the present system is so small that it is obviously within reach of simulations. We feel that the authors endeavour may have a significantly larger impact if the experimental system could be scaled up, in order to reach regimes that would otherwise require involved computational resources.

>In principle we agree, and we hope to access such system sizes in future work. But, the fact that we hit upon a system with a wide range of behaviors, yet simple enough in its design to be simulated, built in the lab, and easily replicated by other groups, is a strength of the work.

We would also like to mention that despite its elegance and versatility, the mechanical system introduced here is a chain, and thus behaves like a one-dimensional material. We feel like the lack of spatial dimensionality might severely limit the range of actual material collective behaviours it is susceptible to mimic. Demonstration of 2D effects would greatly enhance the reach of this study.

>Our mechanical platform surely does not take advantage of all the degrees of freedom that a future designed structure could. Indeed, we arrange our components in a one-dimensional chain.

But I view this as a strength, not a weakness – the goal of our design was to see what range of interactions and behaviors could be achieved with a modest hysteron design. I think part of the impact of the work is showing how much one can already do in 1D. Expanding to 2D presents an exciting future direction, which can likely be done by building on our minimal 1D design.

In the perspective of metamaterials and scalability, it would also make this work more impactful to display a form of material embodiment, maybe involving additive manufacturing, as the present form of the system is rather abstract and “resembles” the theory very closely.

>Material embodiment is a very exciting possibility that the community at large is eager to achieve, but despite concerted effort, has not yet been possible in hysteron-based designs. One impact of this work is to show what interactions are possible between hysteretic bistable units, and to do so cleanly and thoroughly, so that such implementations (which take into account various design constraints and performance goals), can follow next. The “nonlocal” (elevated spring) interactions demonstrated here, and our use of torques as the mechanical coupling, seem to be the magic ingredients.

In my opinion, this is a very interesting line of thoughts, but too early to meet the standards of Nature Communications. However, I would gladly reconsider this position if progress could be made on the points mentioned above.

Reviewer #4 (Remarks to the Author):

This manuscript presents a mechanical platform for constructing interacting hysterons with tunable, non-reciprocal interactions. Using a system of rigid rotors and linear springs, the authors demonstrate programmable bistable elements whose switching thresholds can be continuously tuned and made dependent on the state of other hysterons. They map this mechanical implementation onto abstract hysteron models with arbitrary interaction matrices and show experimental realizations of latching behavior, counting, and modulo-2 logic. The work is conceptually elegant and technically sound, supported by both experimental and theoretical models.

Strength:

1. The same platform is used to demonstrate multiple behaviors — from simple hysteresis to latching, counting, and logic cycling — by tuning geometric parameters. This highlights the versatility and generality of the system.
2. The mechanical implementations are well-crafted and convincingly demonstrate the phenomena described.
3. The kinematic model and its small-angle reduction are well presented and agree with experimental results. This adds credibility and predictive power to the platform.

Points for improvement:

1. The demonstrated systems involve up to four hysterons. It is unclear how the complexity of tuning scales with larger networks. For example: Can the method be practically extended to 10s or 100s of elements? Are there design heuristics or learning-based strategies for configuring large

systems? A brief discussion of these points would enhance the broader relevance.

>How to design or train the collective behaviors of larger systems is a very important question that this research community is grappling with, primarily through simulations and theory (c.f. Refs. 39-41 in our revised manuscript). We contribute some modest ideas along these lines in the Discussion, but ultimately that is outside the scope of this contribution. What we are excited to show here is an experimental platform that can in principle be scaled up to larger system sizes, as these ideas are developed in the community. We think our contribution will generate excitement, and also provide useful and timely constraints on what a theory should or shouldn't assume about what is buildable and measurable.

2. The setups involve careful alignment. It would be helpful to clarify: How robust is the system to noise or misalignment? Can these mechanical elements be miniaturized or implemented in soft materials for integration into real-world systems?

>Sensitivity to misalignment is highly dependent on what behavior one is trying to achieve. A useful way to think about these issues is through the inequalities implied by various state transitions, which partition a high-dimensional parameter space into polytopes. Some transition graphs (corresponding to the interior of these polytopes) can fit a larger ball within them; they are more robust to errors in the parameters themselves.

As an anecdotal example, the period-2 response of Fig. 6 is sensitive to small (millimeter-level) displacements of the mounting points of some of the springs. But, once the period-2 behavior is found and the screws are tightened, the system dependably stays in that limit cycle. I feel this makes the system an interesting candidate for exploring physical learning.

Miniaturization is a fascinating direction, and we hope to generate the excitement for others to take our platform in this direction.

3. The model is entirely quasi-static. However, in physical implementation, transitions involve fast motion and likely energy loss. A brief discussion of how damping or inertial effects might influence state transitions or memory stability would be valuable.

>Our approach here was to separate any competing transitions in the system by 0.1 cm or more, to avoid so-called “race conditions”. Then, by moving the driving rod slowly, each time a transition is triggered it can hit the stopper post and dissipate its energy before the next transition is prompted. Dynamic effects bring in other interesting questions (c.f., Jules et al., Comm, Phys. 6, 2023); here we focus on the already rich quasistatic regime of driving.