Mechanical computing

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Mechanical mechanisms have been used to process information for millennia, with famous examples ranging from the Antikythera mechanism of the Ancient Greeks to the analytical machines of Charles Babbage. More recently, electronic forms of computation and information processing have overtaken these mechanical forms, owing to better potential for miniaturization and integration. However, several unconventional computing approaches have recently been introduced, which blend ideas of information processing, materials science and robotics. This has raised the possibility of new mechanical computing systems that augment traditional electronic computing by interacting with and adapting to their environment. Here we discuss the use of mechanical mechanisms, and associated nonlinearities, as a means of processing information, with a view towards a framework in which adaptable materials and structures act as a distributed information processing network, even enabling information processing to be viewed as a material property, alongside traditional material properties such as strength and stiffness. We focus on approaches to abstract digital logic in mechanical systems, discuss how these systems differ from traditional electronic computing, and highlight the challenges and opportunities that they present.

History provides numerous examples of computation via clever mechanical mechanisms, including the Antikythera mechanism of the Ancient Greeks[1], the analytical machines of Charles Babbage[2] and the differential analyser of Vannevar Bush[3]. For the most part, these older mechanical forms of computation have long since been replaced by more efficient electronic forms. Recently, there has been a rise in unconventional computing approaches that blend ideas from information processing, chemistry, biology, materials science and robotics into new information processing platforms. Examples include neuromorphic computing[4], DNA computing[5], robotic materials[6], morphological computation[7–9], optical computing[10,11], microwave-based quantum gates[12,13], and pneumatic or microfluidic logic circuits[14–18]. There has also been a growing recognition that some natural systems (such as the Venus flytrap[19–21]) may be viewed as unconventional computation platforms. These systems differ greatly from the von Neumann architecture of classical computing and digital electronic hardware (in Fig. 1, the conventional computer is mapped from the Turing machine, a model for universal computation, to the physical silicon substrate; further explanation is provided in Box 1). They are also capable of interacting with and adapting to their environment in unprecedented ways (Fig. 1b).

As a case study, we focus on emerging research on the use of mechanical mechanisms as a means of processing information, a concept that has become plausible owing to advances in additive manufacturing, materials science and structural engineering. Unlike the gears and linkages of ancient mechanical computers, these new mechanical computing systems use various subtle mechanisms to sense, interact and process information from their environment. In this way, information processing may be viewed as a material property, alongside traditional material properties such as strength and stiffness. However, with the information processing intrinsically part of the composition and geometry, new design rules and computing techniques beyond traditional von Neumann architectures will be required (Fig. 1a).

In this Perspective, we use a three-layer framework for computation (Box 1) to outline the process of information abstraction in computing systems and highlight innovations for mechanical computing in each layer. Using combinatorial logic as an instructive computing model (Fig. 1a), we first consider the abstraction of mechanical binary digits (bits) in the physical substrate layer (see Fig. 1c for an origami-based example), highlighting static and dynamic representations (section 'Mechanical bit abstractions'). Next, we consider how the above mechanisms may be combined or networked to achieve more complex computation (section 'Mechanical computing architectures') and to potentially implement specific engineered architectures. Then we consider how these systems interact (input/output) with the surrounding environment and/or other subsystems (section 'Environmental interactions and input/output'), and the advantages this presents over conventional computing approaches. We conclude by summarizing the challenges and opportunities on the horizon and opportunities for broader community engagement going forward (section 'Challenges and opportunities').

Mechanical bit abstractions

To leverage materials for information processing, the physical material must be structured to instantiate an abstract computational process. Developing these material-to-computation abstractions are core issues

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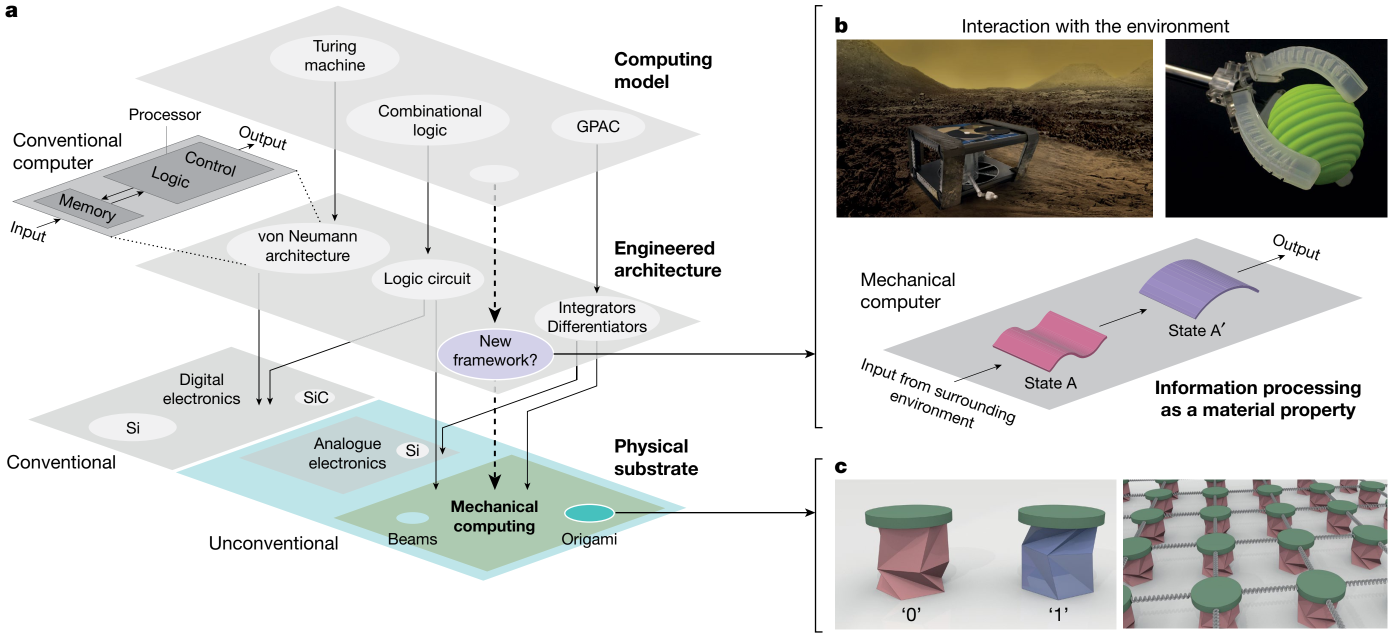

Fig. 1 | Three-level hierarchy of a computational system. a, Building a computer using a three-level model. The top layer is the computing model (for example, a Turing machine, combinatorial logic or general-purpose analogue computer (GPAC)). The middle layer is the engineered architecture, which represents an abstract platform in which a computing model is implemented (for example, von Neumann architecture (see inset)[125] or logic circuit). The bottom layer is the physical substrate, which realizes a design in a physical system. **b**, In mechanical computing systems, information processing is a material property that interacts with the environment and performs computation. Top left, a rover inspired by mechanical computers for extreme environments[126] (image credit, NASA/JPL-Caltech). Top right, soft robotic grippers with embedded sensors that can sense pressure, temperature, and so on (image reprinted with permission from ref. [116], Wiley). **c**, A mechanical computing system may be realized using various mechanical building blocks. For example, this origami-inspired unit represents binary information ('0' or '1') using different deformation modes (left) in a two-dimensional network (right) (image reprinted with permission from ref. [38], Springer Nature).

associated with defining the meaning and opportunity space of physical computation[22,23]. As the complexity of the targeted abstract computation increases, so does the complexity of the design required to instantiate it. In light of this, binary operations are the dominant computational abstractions used in modern computing systems, owing to their relative simplicity, robustness and scalability. In electronic systems, transistors function as a bit (Fig. 1a), systematically switching between the 'on' and 'off' states to represent, process and store information. By contrast, unconventional computing systems operate on architectures that do not necessarily require digital representation[24]. Various new research areas, such as morphological computing[7–9], wave-based mechanical metamaterials[25–27] and neuromorphic systems[4], explicitly make use of analogue computing principles.

Following the goal of illustrating pervasive challenges, we limit the scope to mechanical computing approaches that embody digital abstractions of information. One of the benefits of mechanical computing is the opportunity to define diverse digital abstractions of information from the physical system. In this section, we discuss two different strategies for representing digital states in mechanical systems: non-volatile systems, which undergo quasi-static deformation between equilibrium states, thereby storing discrete state information without external energy; and volatile systems, which are abstractions from dynamic systems and require external energy to maintain the information state.

Non-volatile systems

Mechanical realizations of non-volatile, digital computing have predominantly assumed a binary form using bistable configurations. Such bistability is readily obtained by introducing geometric nonlinearity into a mechanical structure. Under certain loading and constraints, even simple beams may be designed to support two stable configurations[28–33]. For example, if planar tilted beams are confined perpendicular to their loading direction (Fig. 2a, b), they may snap between two stable configurations, which can be assigned a '0' or '1' state. By using mechanical snap-through between these two states, the binary information can be manipulated. When the deformation is limited to the elastic regime, the transition to bistability is governed by scale-independent geometric parameters and boundary conditions rather than material properties. Hence, beam-based bistabilities have been exploited in several materials (such as silica and soft materials) and form factors to realize mechanical bits[34–37]. Similarly, bistability may be realized in origami-based structures[38–54], enabling the structure to have distinct '0' and '1' states, as above. For example, a mechanical bit has been defined in triangulated cylindrical origami structures by transitioning between two stable states through cross-sectional rotation (Fig. 2c[38]). Another origami example is the waterbomb fold pattern (Fig. 2d[55]), which uses bistability to 'pop' between up ('1') and down ('0') equilibrium states of the centre vertex of the fold pattern. The multistable energy landscape of the origami structures, and their ability to form modular assemblies, is a helpful intuition-building construct for identifying and developing mechanical computing devices.

Binary representations are important in electronic computation, and have facilitated immense information densities through the miniaturization and computational scaling of a single bit. Although some mechanical bit implementations may be compatible with a miniaturization approach, increasing the number of stable configurations[56–58] (that is, changing the base of the computation) is probably a more tractable path to increasing information density. For example, mechanical mechanisms that are tristable (for example, rotating squares[58]) or quadstable (for example, origami[43]) could be used as non-volatile computing devices with greater information density than binary equivalents (see Supplementary Information for additional discussion).

Volatile systems

In the non-volatile examples of the previous section, digital abstraction is tied to quasi-static transitions between equilibrium configurations

BOX 1

Information processing

When thinking about building a computational system, a ‘computer’, it is helpful to describe three levels: the model of computation, the architecture and the physical substrate.

The model of computation

The model of computation is an abstract, usually mathematical, model of how the computational process unfolds. There are many models of computation. Classically, there is a progression of models of increasing computational power: combinational logic, finite state machines, pushdown automata with an unbounded memory stack, and Turing machines with an unbounded memory tape. Other classical models, such as lambda calculus, are equivalent in power to the Turing machine model. These models are discrete in state space (symbols) and in time. Other discrete-space discrete-time models, such as cellular automata, have the same theoretical computational power as Turing machines, but may map to an architecture more suited to different implementations and problems. Quantum computational models have greater efficiency, but not greater computational power, than Turing machines (they can solve some problems faster, but they cannot solve non-Turing-computable problems).

Continuous-space discrete-time computational models, such as coupled map lattices and some neural network models, are typically based on underlying difference equations. Continuous-space continuous-time models, such as some spiking neural network models, reaction–diffusion models, Shannon’s general-purpose analogue computer, Rubel’s general-purpose extended analogue computer and continuous-time quantum computational models, are typically based on underlying differential equations.

The architecture

An architecture is an abstract design for how a model of computation may be realized (implemented) in hardware. It focuses on a set of basic components and how they are connected. For example, the combinational logic model maps naturally to an architecture that comprises a universal set of logic gates connected into a circuit. The classical von Neumann architecture, which describes how a central processing unit controls and performs computational operations, with random-access memory that contains a stored program and data, is not a natural mapping of the Turing machine (which has sequential memory access). Instead, it has a more natural mapping to an efficient hardware implementation. Other architectures, such as those underlying graphics processing units and field-programmable gate arrays, are alternative designs for classical computing. An architecture need not be realized directly in hardware; it may be a form of virtual machine implemented in software in another architecture. For example, cellular automata and neural networks are typically implemented in classical architectures.

The physical substrate

The physical substrate (hardware) realizes an architecture and its model of computation—it forms the physical computer. The standard substrate for realizing the von Neumann architecture is digital electronics. (Technically, because the von Neumann architecture, in principle and its realizations in practice, does not have unbounded memory, it has the computational power of a finite-state machine, not a Turing machine. This tension between theoretical computational power and finitary physical limitations tends to be glossed over in practice.)

There are many other substrates that support a range of architectures, including nonlinear materials, analogue electronics, magnetic materials, optics, chemicals, biochemicals, biological organisms and mechanical devices. The earliest engineered computers were mechanical clockwork systems, including the Antikythera device, Babbage’s difference engine and the differential analyser. In recent decades, all these approaches have been referred to as ‘unconventional’ computing, owing the enormous success of ‘conventional’ silicon-based digital electronics. Yet, thanks to advances in manufacturing, materials and design, unconventional computing has recently begun to receive a great deal of attention. Here we focus primarily on digital architectures that enable information processing via mechanical mechanisms and stimuli-responsive materials.

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of a multistable structure. However, digital abstraction of information and manipulation of the bit state may also be achieved via the dynamic response of a mechanical system, for example, phase, frequency or amplitude. A well-studied example is a clamped beam under harmonic excitation[59–64], which behaves as a mechanical resonator. In Fig. 2e we show structural oscillations of a clamped–clamped beam integrated with a piezoelectric actuator. The bit information is expressed by the two stable phases, 0 and π[59]. Another example based on beam vibration is a microcantilever with stiffening behaviour that arises as a result of geometric nonlinearities at large amplitudes[65]. This nonlinear behaviour results in distinct dynamic responses depending on whether there is a forwards or backwards sweep in the input drive voltage (a hysteretic response; Fig. 2f). Therefore, if the system is operated at a certain drive strength in this hysteretic response regime and the input drive voltage is modulated, the dynamic response will be one of the two distinct stable states (high amplitude or low amplitude), depending on whether a forwards or backwards sweep in the input voltage is used.

The burgeoning field of mechanical metamaterials presents a large toolset of methods and building blocks to control the flow of mechanical energy, guide mechanical waves and tune the frequency band structure[66–73]. Precise control of these dynamic phenomena, through advances in conceptual design and experimental validation, provides a testbed for mechanical computing abstractions. For example, a pop-up structure is studied in ref. [74] that exhibits tuneable transmission depending on its structural configuration (that is, a pop-up state that allows the propagation of input signals, or a flat state where elastic waves are prohibited; Fig. 2g). By constructing an array of the unit cells, the researchers designed a mechanical transistor and demonstrated various logic-gate operations based on transmission dynamics. Similarly, granular acoustic switches have been proposed[75], which digitize the state information by using the nonlinearity of the system to tune the frequency response (Fig. 2h). Multifrequency information, together with the phase and amplitude control discussed above, could be used to abstract and manipulate multiple mechanical bits in parallel. In addition to the use of elastic waves, acoustic logic operations based on non-reciprocal propagation of sound pressure have been proposed[76,77]. These examples highlight the diverse digital abstractions possible in dynamic mechanical systems and offer an alternative view of mechanical information processing.

Bit retention in volatile systems requires sustained energy input, typically through a continuous harmonic excitation or other driving force. The volatility provides flexible bit manipulation, such as driving multibit logic operations as discussed above, and flexible bit abstraction, because the bit state can be (re-)assigned for different driving frequencies, amplitudes and so on. By contrast, the bistable mechanisms

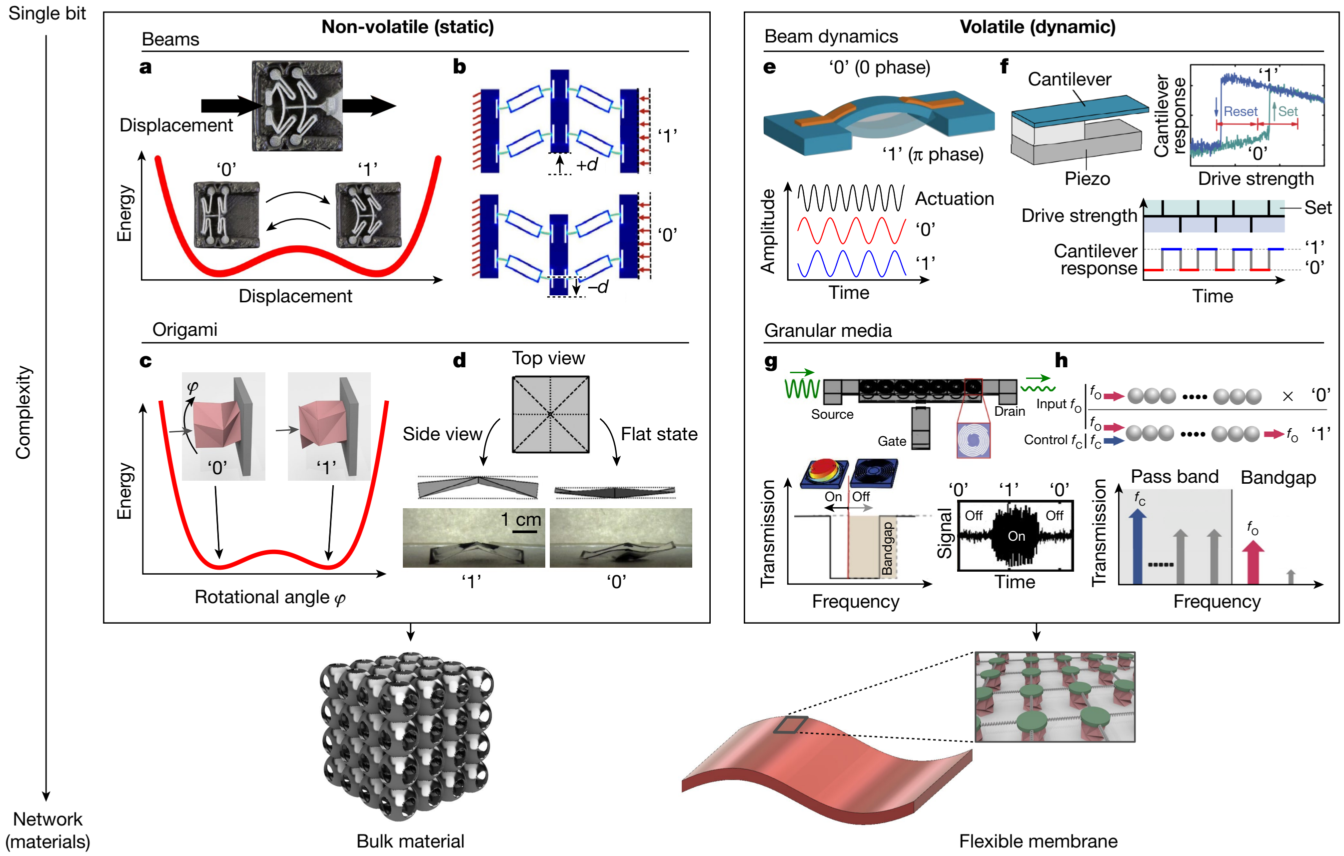

Fig. 2 | Non-volatile and volatile mechanical bit abstractions as building blocks for mechanical computing. a, b, One of the approaches to retaining information without an external power source is to use bistable behaviour based on geometric nonlinearities, such as a unit cell composed of clamped beams (**a**; reprinted with permission from ref. [34], ACM), which can transform between undeformed ('0') and deformed ('1') configurations, or a bistable flexure mechanism (**b**; reprinted with permission from ref. [35]; Springer Nature). *d*, displacement. **c, d,** Origami may also be used to design non-volatile mechanical memory, as demonstrated by a triangulated cylindrical origami-based structure (**c**; reprinted with permission from ref. [38], Springer Nature) and waterbomb origami (**d**; reprinted with permission from ref. [55], National Academy of Sciences). **e, f,** Volatile logic may be encoded in beam dynamics, as demonstrated in electromechanical beams (**e**; reprinted with permission from ref. [59], Springer Nature) and in microcantilevers with stiffening behaviour (**f**; reprinted with permission from ref. [65], AIP Publishing). **g, h,** Other examples of volatile mechanical devices include a one-dimensional array of spiral spring cells with a magnetic mass (**g**, reprinted with permission from ref. [74], National Academy of Sciences) and granular chains (**h**; reprinted with permission from ref. [75], Springer Nature).

of non-volatile systems retain bit information without additional energy input, but require additional mechanisms to reconfigure the system (for example, control of loading or constraint conditions in a beam-based system). New metrics are needed to map the trade-off between computational versatility and mechanical energy consumption in mechanical computing devices. Hybrid systems present an opportunity to harness the strengths of both, by combining the programming flexibility and operational sensitivity of volatile systems with the stable memory storage of non-volatile systems. Although simple hybrid approaches could use non-volatile subsystems as memory and volatile subsystems as processors (analogous to the classical von Neumann architecture in Fig. 1a), it remains an open question how these subsystems could be combined in more creative ways to attain new functionality. The discovery of new mechanical logic networking principles and architectures that implement hybrid bit information is an open challenge.

Mechanical computing architectures

To perform more complex computing operations, the mechanical computing units discussed above require assembly into larger, integrated networks. Although replicating electronic computers is not the underlying goal of research in alternative computing approaches such as mechanical computing, the principles of digital logic design from electronic computing systems provide a robust foundation of theory and circuit simplification schemes to guide the development of mechanical logic analogues. AND, OR and NOT gates may be combined to achieve universal logic; NAND and NOR gates are each able to achieve universal logic merely through combinations of themselves (functionally complete). The design of universal gates in mechanical logic systems is an important benchmark for demonstrating computational utility and for revealing the physical constraints of networking these building blocks in one, two and three dimensions.

The simplest examples of mechanical computing systems are one-dimensional chains of mechanical bits, such as linkage systems[64,78–81] or granular chains[74,75]. For example, if two units composed of spiral springs with lumped masses (see Fig. 2g for the single element) are connected in series, this one-dimensional chain structure may exhibit AND-gate behaviour; that is, no output signal is obtained unless input signals ('1') are applied to both units (Fig. 3a, upper inset)[74]. On the other hand, if the two units are connected in parallel, the system may serve as an OR gate (Fig. 3a, lower inset). In addition, NOR-, XOR-, NAND- and NOT-gate behaviours may be achieved by combining multiple units. The above examples are volatile, but one-dimensional non-volatile logic systems have also been constructed, including functionally complete logic gates (see ref. [35] for an example of a NAND gate). In these one-dimensional systems, the output of one unit is connected to the input of the next unit. Therefore, input information is typically processed unidirectionally from one end of the chain to the other.

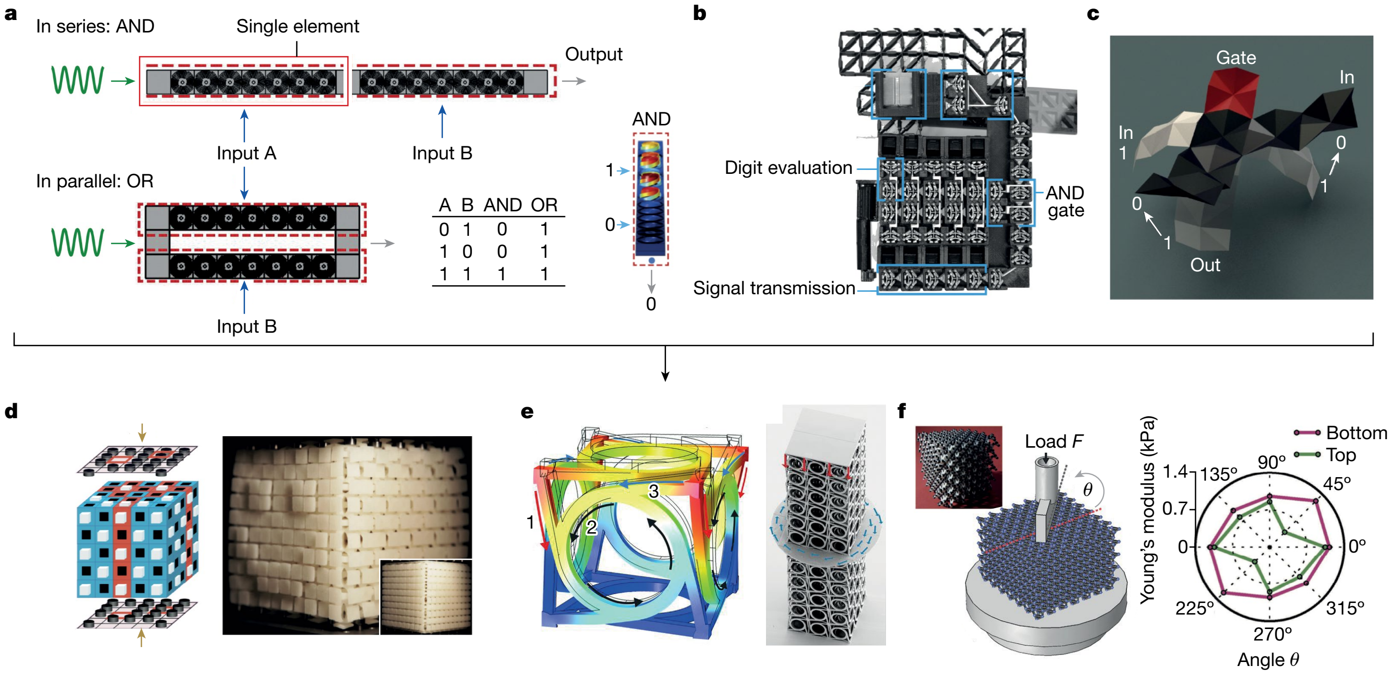

Fig. 3 | Networking mechanical computing units for digital logic. By using single-bit mechanical memory units as building blocks, we can construct one-dimensional chains (**a**) and two-dimensional planar structures (**b**, **c**) to create classical digital logic gates and networks of these. **a**, One-dimensional array of spiral spring cells with a magnetic mass (reprinted with permission from ref. [74], National Academy of Sciences). **b**, **c**, Two-dimensional configurations have been designed using modules of constrained beam elements (**b**; reprinted with permission from ref. [34], ACM) and tessellations of waterbomb origami unit cells (**c**; reprinted with permission from ref. [55], National Academy of Sciences). **d**–**f**, Although three-dimensional networks for mechanical information processing have not yet been widely explored, strategies for their implementation may be derived from the deformation mechanisms and unconventional properties of three-dimensional mechanical metamaterials, such as a combinatorial design for programmed shape change (**d**; reprinted with permission from ref. [87], Springer Nature), three-dimensional chiral metamaterials with compression–twist coupling behaviour (**e**; reproduced with permission from ref. [88], American Association for the Advancement of Science) and topological materials with elastic polarization (**f**; reproduced with permission from ref. [96], Wiley).

The limitation of linear information paths in one-dimensional systems motivates the development of two- and three-dimensional systems, in which signal branching and interactions beyond nearest neighbours are possible. Several two-dimensional systems have been demonstrated[38,55,82–84]. Figure 3b,c illustrates examples of planar systems that consist of constrained beams[34] (Fig. 3b) or waterbomb origami[55] (Fig. 3c). For example, modules composed of constrained beams (Fig. 2a) may be arranged as a grid-like planar system (Fig. 3b), which enables the implementation of multiple logic operations. Parallel connections of two modules could coordinate to pass or block a signal or emulate an AND gate by propagating the snap-through behaviour[34]. Similarly, waterbomb origami may be connected side by side to form a system of multiple bits that perform simple logic operations, depending on the configurations of the unit cells[55]. Unlike in one-dimensional systems, these mechanical computing units may interact with multiple nearest neighbours in both dimensions, allowing information to propagate across the two-dimensional plane, instead of in only one dimension. This feature may be used to control multiple bits in parallel and could enable new functionality or mechanical computing architectures. Extending to two and three dimensions not only increases the degrees of freedom of mechanical systems but also allows new logic state assignments that arise from the coupling of degrees of freedom. For example, mechanical substrates that are effectively two-dimensional in nature, such as lattice or origami structures, may take on complex and multistable three-dimensional conformations as a result of the coupling of twisting and bending motions, and in-plane deformations. The mapping between the sequence and structure of cell deformation and global, stable configurations may also emulate logic, as demonstrated recently in an elastomeric sheet with embedded bistable domes[85]. Therefore, two- and three-dimensional systems offer not only an extension or tiling of one-dimensional logic elements but also a platform to assign new kinematic mechanisms and three-dimensional deformations with a logic state.

Three-dimensional mechanical computing systems have not been studied extensively. However, numerous previously reported one- and two-dimensional architectures could naturally be extended to three dimensions[86] and used to control the mechanical flow of information in unprecedented ways. Recent advances in 3D printing could enable the fabrication of more complex three-dimensional mechanical systems that have been recently conceptualized. For example, by using a combinatorial approach, a metacube structure composed of cubic unit cells has been proposed[87]. This structure exhibits a programmed pattern on its side surface under axial compression (Fig. 3d). Not only linear motions but also coupling between axial and rotational deformations have been demonstrated[88] (Fig. 3e), allowing vertical deformation to induce transverse or lateral motions in three-dimensional space. In addition to these static responses, there are opportunities to process information using the dynamic properties of a mechanical system, such as topological phases or phase transitions, which were originally studied in condensed matter physics. These emerging 'topological mechanical metamaterials' can be designed to provide robust control of wave dynamics in planar networks and volumetric systems[74,89–95] (for example, three-dimensional systems with elastic polarization[96]; Fig. 3f). Owing to the localization of waves (for example, topological edge modes), such systems could enable various operations relevant to information processing; for example, mechanical diodes could be tailored to route mechanical signals in a specific direction, to switch or reroute signals, or to isolate a complex routeing pathway.

The development of mechanical computing architectures involves several challenges, which will require clear understanding of the fundamental abstraction layer discussed above (section 'Mechanical bit abstractions') and new design rules for circuit and component-level

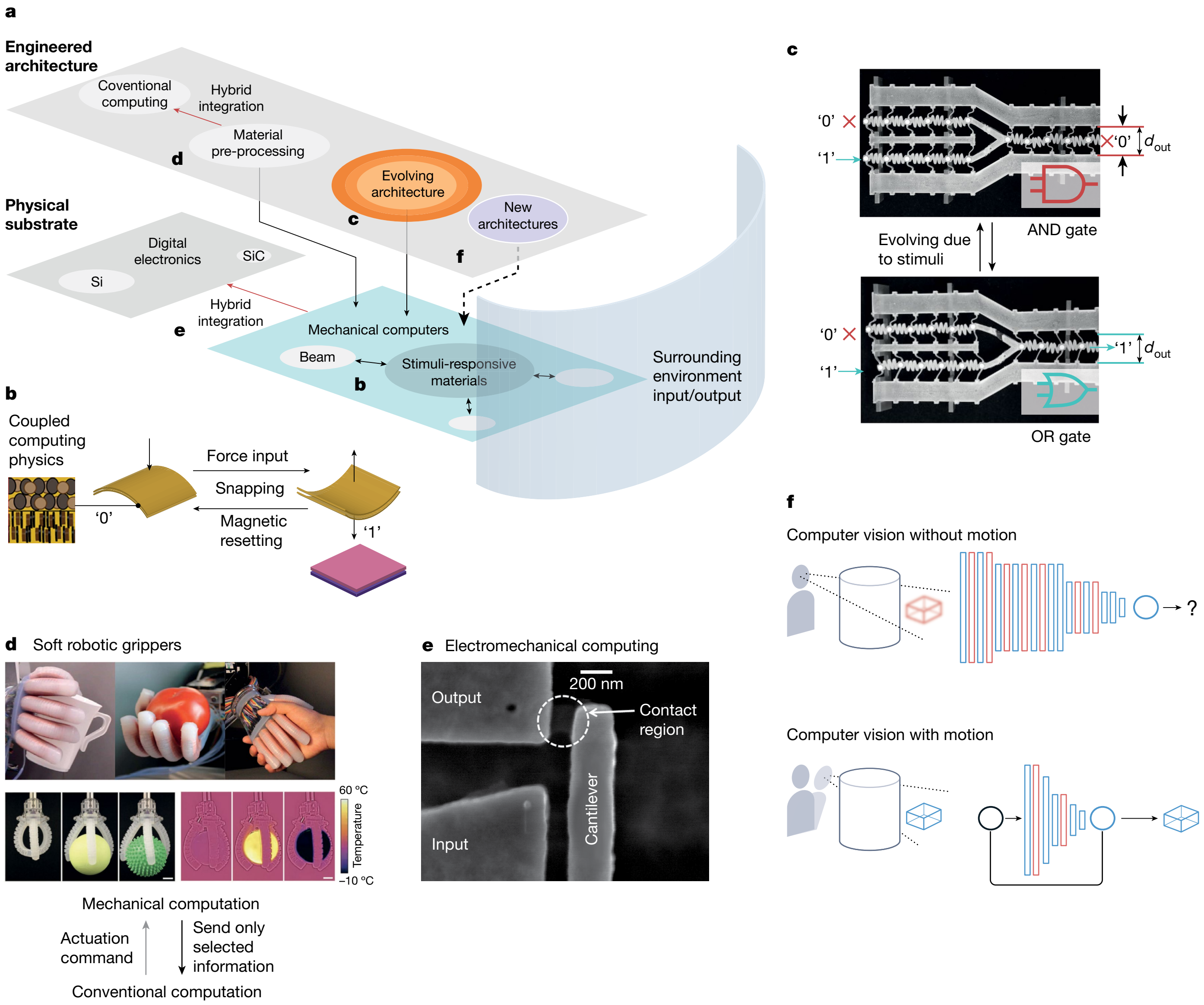

Fig. 4 | Environmental interactions. a, Schematic of the advantages and opportunities of mechanical computing coupling directly with the physical environment. Abstractions and mappings to higher computing layers are needed to precisely define the computational contribution of new substrates and physics. **b**, Coupled computing physics provides the opportunity to combine physics and sensory input in the abstraction layer of the physical substrate, for example, multiple inputs (force and magnetic field) to manipulate the binary state (reprinted with permission from ref. [104], American Chemical Society). **c**, Evolving architecture enables environmental stimuli to reprogram the computing architecture, for example, a mechanical logic gate switching between AND and OR behaviour in response to external mechanical loading d_{out} (reprinted with permission from ref. [37], National Academy of Sciences). **d**, Material pre-processing leverages mechanics to synthesize environmental input for integration with conventional architecture, for example, soft robotic grippers with embedded sensory functions that detect target object shapes (top; reprinted with permission from ref. [115], American Association for the Advancement of Science) or that process different textures and temperatures (middle; reprinted with permission from ref. [116], Wiley). **e**, Electromechanical silicon carbide switch, highlighting coupled mechanics and electrostatics for high-temperature computing applications (reprinted with permission from ref. [117], American Association for the Advancement of Science). **f**, Illustration of a computer-vision task to classify the shape of a partially occluded cube, with (bottom) and without (top) the aid of mechanical motion. Motion to avoid a visual occlusion reduces the conventional computing cost of a machine-learning-based vision classifier for this task by enabling a camera to see all of an object. However, it is unclear what architecture and computing model should be used to assess the trade-offs between conventional computation and mechanical motion.

integration. For example, the kinematics of the bit abstraction places constraints on the gate assembly, because inputs and outputs may be mechanically incompatible for certain gate combinations. Owing to these constraints, circuit designs from electronic digital logic may not translate to bottom-up gate assembly in a mechanical logic system. One approach to this challenge, inspired by the electronics community, is to develop design tools for these constraints. For example, instead of a single AND-gate design, perhaps the design of an AND-gate structure is optimized on the basis of the gate types connected to it. Similarly, a top-down design approach may be more tractable for certain mechanical logic implementations, where higher-level functionality (for example, a full or half adder) could be designed directly rather than by assembling the individual logic gates that are known to collectively produce the equivalent functionality. Topology optimization, pseudo-rigid body models and graph-based techniques for mechanism design[97–100] are promising approaches to these more complex logic structures, with the potential benefit of reducing gate interconnections, incompatibilities and the overall energy requirements of the mechanical computing devices.

Mechanical logic networks are also constrained by the number of accessible interactions between gates, limiting the number of inputs that an output signal can drive (also known as the problem of fan-out in electronic circuits). Damping and other losses may further limit the distance of force propagation, which could constrain the overall size of the mechanical computing network. These limitations afford approaches where the order or sequence of mechanical loading may enable multiple mechanical logic networks to co-exist within the same structure, effectively increasing the computational utility for the same size of network. For example, an elastomeric sheet populated with bistable domes was shown[85] to exhibit distinct three-dimensional conformations based on the order of dome inversion not just the specific combination of inverted domes. Sequence-dependent effects of this nature could lead to complex and branched logic networks, which may redefine the current understanding of these mechanical networking constraints. Mechanical computing systems also have the advantage of a direct interface with the environment, which may include a large set of physics and timescales of interaction. Leveraging this additional design dimension of computing physics has the potential to relax the fan-out constraint (using non-contact interactions such as magnetics) and recoup energy losses (harvesting environmental sources such as thermal cycles) while simultaneously integrating these cues into the computing task of the device. In the following section, we explore how computing frameworks that integrate stimuli-responsive materials and additional physics into the logic flow present a possible strategy for combining computation and function in mechanical systems.

Environmental interactions and input/output

In the first three sections, we discussed an operational framework in which abstract computational models may be physically realized in networked mechanical systems. We discussed how mechanical mechanisms enabled by geometric nonlinearity could produce mechanical systems with switchable, discrete information states. However, we have not yet discussed what, beyond mechanical loading, might induce the mechanical systems to change state. In this section, we consider the ways in which these unconventional computing systems might interface with their environment and with other subsystems. What are the inputs and outputs relevant to mechanical or material computing systems with coupled physics? How might mechanical computing augment digital electronic systems to improve the performance of engineered systems? What computing architectures are needed to fully integrate multiple, diverse environmental inputs? To navigate these questions, we evaluate environmental interactions in the physical substrate and architecture levels, highlighting future opportunities for mechanical computing. In Fig. 4a we provide examples of relevant interactions (either with the external environment or with other subsystems). These interactions may be triggered via stimuli-responsive materials or structures in a layer. In mechanical systems, such active materials are analogues to conventional sensors or actuators. In this framework, a specific computation (such as a logic-gate operation) may be performed by connecting physical substrate and engineered architecture layers.

In conventional digital computers, silicon is a substrate for electronic components but is not designed to change or to respond to the environment. Instead, environmental inputs are obtained via modular sensors, distinct from the computing device, which transduce physical quantities such as temperature or light intensity into an electronic signal that the computer subsequently operates on. By contrast, mechanical computing systems may be constructed from adaptive materials that respond directly (bend, twist and so on) to environmental inputs that correspond to the active materials used in the system. Examples include electronic signals (for example, using dielectric elastomer actuators[101,102] or liquid metal[103]), mechanical stimuli[34,104], chemical stimuli[21,105], acoustic pressure[83] and humidity gradients[55]. In addition, mechanical deformation may be triggered in shape-memory polymers and liquid-crystal elastomers in response to temperature changes[106,107] and/or light[108]; polymers can be designed to respond mechanically to pH[109] and magnetic fields[110–112]. Moreover, multiple input sources may be combined for operation (for example, mechanical force and magnetic field to manipulate bit information[104]; Fig. 4b). This could enable computation in new form factors and operating environments[113]. Multiresponsive systems may also be designed to account for the order of stimuli, allowing time to serve as a design parameter to logically couple or decouple stimuli[21].

In distinct contrast with input/output in traditional digital electronics, the changes that occur to the mechanical computing system as a result of environmental inputs are not limited to the physical substrate layer—they can also affect the engineered architecture layer. For example, the application of external force may be used to morph a mechanical logic gate from an AND gate to an OR gate, and vice versa (Fig. 4c)[37]. Evolving the computing architecture in response to environmental input enables mechanical computing platforms to be reprogrammed, with the potential of intra- and inter-switching in and between architecture classes. Collectively, these examples highlight the novelty of mechanical computing concepts, not only in granting access to new operational environments, but, more importantly, in expanding the definition of and methods for how information is abstracted and processed.

Understanding materials in terms of their information processing capabilities could affect every aspect of automation systems that interact with their environment. Robotic systems may be expected to be equipped with classical centralized computing when physically feasible; yet, for various scenarios, this may not be plausible or optimal. For example, it is typically not possible for micrometre-scale robots[114] to rely entirely on traditional electronic computing. Even with classical computing available, robots will rely on physical properties to perform material pre-processing to reduce the centralized computational load. For example, a soft robotic hand[115] that assesses fruit ripeness through a temporal–spatial integration of the mechanical deformation during contact effectively augments the computing task of the robot through a form of mechanical filtering (Fig. 4d, top). This filtering concept may be expanded to other features, such as texture, temperature and shape, as demonstrated[116] in another soft robotic gripper (Fig. 4d, middle). Together, these examples highlight the opportunity to consolidate sensing and computing into the structure and physics of the device, performing materials-enabled computation in the relevant physics and timescales of the target application. This congruence between the computing task and the physical task motivates the augmentation of conventional computing with unconventional computing substrates, to improve energy consumption and information collection.

Challenges and opportunities

Although many recent publications have shown the feasibility and potential for storing and processing binary information as a material property, there remain challenges and associated opportunities for advancing the field of mechanical computing. In this section, we explore some current and future research directions related to the realization of unconventional computing in mechanical systems, using the three-layer model of computation (Fig. 1) to guide the discussion.

Beyond binary abstraction

Advances in additive manufacturing, materials science and mechanical metamaterials have led to new ways of thinking about materials. As presented here, the research community has begun to think about ways in which information processing may be thought of as a material property. Abstracting information processing is an underutilized opportunity in mechanical systems. The mechanical mechanisms described in section 'Mechanical bit abstractions' underscore this point and serve as an instructive guide to identifying new ways to embed and abstract information. Extending the number of states, such as by using tristable mechanisms in which discrete states take a value of 0, 1 or 2, is one promising next step. Exploiting the frequency response spectrum is another. Far more complex multistable or volatile mechanisms are also possible, allowing the representation of more than just binary information. These non-traditional discrete representations present opportunities for the mechanics and materials communities to work with computational theorists to explore new abstractions and mappings between computing layers.

Compilers

In conventional computing, the choice of architecture and substrate is biased by the inherent (and justifiable) demand for a universal computing platform, which has focused investment into (and led to remarkable success for) a handful of core technologies. However, a universal computing machine is not optimal for every application. The mechanical computing examples highlighted above demonstrate that even simple logic calculations could enhance the operation of a device without serving as a general-purpose computer. To tap into this computing potential, design tools are needed to move up and down between computing layers in Fig. 4a, not only to fit new materials and physics into established computing models but also to identify the computing abstractions that are most compatible with the physical substrate, whether localized, dispersed or some hierarchical combination. This relates to conventional compilers, which translate a higher-level programming language into a lower-level language more closely tied to the operation of the physical substrate (that is, silicon-based digital electronics for traditional computing systems). This is a key step in telling a universal computer how it should operate. By contrast, an analogous compiler for a mechanical computing system would need to algorithmically generate an appropriate computational substrate layer (Fig. 1, Fig. 4); that is, it must generate a design for a three-dimensional mechanical system that reconciles its mechanical kinematics and energy constraints and ensures that the system embodies sensing, computing and actuating functions in its arrangement of active materials. An initial example of a mechanical logic compiler[34] involves a design editor to minimize the size of the mechanical logic network to achieve a target logic operation. Expanding the capability of the compiler to integrate diverse environmental input/output, computing models, spatially dispersed nodes, fabrication constraints and hybrid integration with conventional electronics presents a challenge, and potential bottleneck, for the advancement of mechanical computing concepts. Most unconventional computing systems, including mechanical logic, are programmed at a very low level, because substrate-specific design and abstraction rules have not had time to mature. Codifying the compiler design rules for these unconventional substrates is an open challenge for the materials, design and computing communities.

Exploring new unconventional computing

Opportunities to innovate exist at all three layers of the computing framework (Fig. 1). In the physical substrate, new abstractions are being identified through combinations of materials, physics, geometry and timing to access new operation regimes. For example, by combining the physics of electrostatics with contact mechanics, submicrometre-scale electromechanical switches made from silicon carbide enable digital logic computations at extreme temperatures (more than 500 °C)[117], outside the typical operating temperature of conventional electronics (Fig. 4e). The engineered architecture layer may also interact directly with the environment (Fig. 4c), presenting an opportunity to embed self-reconfigurable computing architectures in mechanical systems. The range of computational tasks this will enable has yet to be investigated. For instance, a periodic, temporal cue from the environment might be able to trigger the material computing system to convert from a digital to an analogue interpretation or to produce some form of digital–analogue hybrid. Lastly, innovations in the computational model layer will have the dual benefits of establishing new computing constructs to guide the discovery of unconventional computing materials and of stimulating new ways of characterizing and thinking about materials. For example, multistable beam networks are physically continuous, with temporally and spatially varying internal stress and strain states under deformation. However, it is the discrete configurations of the multistabilities, not the continuous state variables, that are used to emulate logic operations in the examples discussed here. The focus on the discrete properties of the beam array motivates the application of discrete mathematics techniques, such as graph theory, not only to scan for computing potential but also to provide a new lens to characterize and benchmark the behaviour of the underlying material structure.

Metrics to assess mechanical computers

New computing and material performance metrics are needed to classify and benchmark the collective innovations across these computing layers (see, for example, ref. [118] for a discussion on quantifying unconventional computing resources). Conventional metrics focus largely on processing speed, bit density and input/output package miniaturization. Mechanical computing performs poorly against these benchmarks. Miniaturization has been pursued for mechanical computing using micro- and nano-electromechanical systems[119–122] and could provide benefits (such as robustness against harsh environments or high temperatures[117]); however, the relevant fabrication approaches for micro- and nano-electromechanical systems come with their own set of constraints that would limit the complexity of a mechanical logic network and the types of materials (and hence sensors) that could be integrated. Instead, alternative metrics are needed, to better capture the strengths of mechanical and other unconventional computing concepts and to assess the effect of hybridization with conventional electronics. For example, the intrinsic integration of the computation in the physical material or device offers efficiencies and insertion opportunities that would be challenging for conventional approaches. Metrics that reflect this advantage could include the number of data-type conversions between input and output computations, the spatial proximity of the computation to the input signal and the relevance of the computing physics and timescales to the computing application. A dynamic mechanical load operating on the timescale of hertz may not require state assessment of the order of megahertz or greater. Rather than continually querying for the current configuration, it may be more efficient to have the material or structure directly detect, assess and process the mechanical event. Efficiency and integration benefits of this nature lack the precision and concreteness of the benchmarks currently used for conventional computing, but are necessary for placing mechanical computing concepts in an appropriate context.

Developing methods to establish the computational equivalence of these alternative metrics in augmenting conventional computing systems is also an important next step. For instance, machine vision—and vision-based object classification—relies heavily on sophisticated algorithms to robustly handle occlusion, distortion and other environmentally driven image degradation. These algorithms come at high computational and, implicitly, energetic expense. However, vision systems that move meet the same object identification requirements through mechanical motion, by looking around an occlusion rather than by using classifiers intended for limited data. In addition, mechanical motion augments the view of the object relative to previously collected images, which may improve the efficiency of classification[123]. In Fig. 4f, we illustrate such a situation, in which a camera must either identify an object—the cube—from a partial image or move to avoid the visual occlusion created by the cylinder. That machine learning uses mechanical motion to improve data collection and learning efficiency[124] highlights the need for new architectures and computational models to precisely define the interactions between the mechanical properties of new material substrates and computational requirements.

Integration, efficiency and material compatibility metrics will also provide clear evaluation criteria for the merits of using stimuli-responsive materials to directly harness environmental interactions in the computational abstraction. Bottlenecks in information processing often occur at the points of data conversion between physical type (mapping sensor physics to computation physics) or computational representation (analogue to digital). Mechanical computing may mitigate this bottleneck by merging the sensing and computing physics into a single domain. However, timescale incompatibilities are likely to arise as additional physical stimuli are integrated into the computation, owing to the distinct timescales associated with each stimuli-responsive phenomenon. For example, a sudden change in temperature or voltage may equilibrate throughout the system more rapidly than a change in the chemical environment due to diffusion (which also introduces time dependence based on feature size). These differences could be used to produce effects such as spatially and temporally distributed reprogramming in response to local environmental cues, but will require careful design at the architecture level to retain the meaning and utility of the computation. Understanding the advantages of sensory consolidation at the physical substrate layer will be key to deciding whether to use conventional, unconventional or hybrid computing approaches.

Conclusion

Treating information processing as a material property will introduce multidisciplinary challenges that will require new theoretical approaches and practical design tools, as discussed above. Solutions are therefore likely to be found at the interfaces between materials science, information theory, computer science, additive manufacturing and robotics. Our intent is that the framework highlighted here, along with the specific mechanical computing examples that we reviewed, will inspire the discovery of new material computing systems and encourage the community to view information processing as a material property.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-021-03623-y.

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