Cluster Analysis Results

Energy-Driven Material Memory

(Cluster 0)

In a Nutshell: This type of material intelligence is characterized by systems that use changes in internal physical or chemical parameters, driven by external energy inputs or local gradients, to encode information within the material structure itself. These systems exhibit a basic form of memory by their structural/compositional states that influence future behavior without relying on digital storage or central control. The realization is at a local level, emphasizing analog-like interactions and feedback loops.

1. **Distinctive Definition:** This category of material intelligence centers on systems utilizing energy transformations to directly alter internal material parameters for information processing and basic forms of time-dependent memory, achieving functional output via structural or compositional changes. Crucially, the mechanisms are localized, avoid central control, and prioritize nonlinear dynamic behaviors as signal transduction and processing, with local feedback rather than a predesigned global action. The response goes beyond passive stimulus-response.

   The cluster reveals a reliance on converting energy from various sources into changes in the material structure that are used as a form of memory. We see examples of this in thermal transitions in gels \cite{zhao_phase_2021}, mechanical strain coupled to polymer chain configurations \cite{urban_key-and-lock_2018,madhusudanan_relaxation_2024}, chemical-mechanical feedback in self-healing composites \cite{wool_self-healing_2008}, capillary forces in porous materials \cite{kaspar_rise_2021} , and photo-induced or electrically-induced structural modifications as seen in phase change or conductive polymers \cite{di_ventra_parallel_2013,bayat_self-indicating_2024}. Crucially, as mentioned in Pezzulo et al \cite{pezzulo_active_2024}, systems attempt to shift beyond preprogrammed responses to have a feedback from environment and a past internal parameter that influences future action.

   These systems tend to exhibit an analog behavior and not digital as in the case of electronic systems where multiple internal non linear interactions exist as it is seen with the examples with microcapsules \cite{calvino_microcapsulecontaining_2018}, self-propelling oils drops \cite{harrison_mind_2022} or stress propagation in materials \cite{jiao_mechanical_2023}, rather than discrete states. This leads to a more versatile response than traditional “on/off” mechanisms that relies on a predefined signal, with different responses depending on the intensity of stress, chemical composition, or light intensity \cite{huang_self-regulation_2018}.

The key parameters influencing the differences in behavior would be material composition which determines the dominant mechanical or chemical response, local architecture with different physical arrangements that modify how external inputs are transduced, and the level of internal physical couplings that provide the dynamic behaviour. External stimuli are directly coupled to the desired action and in this type of intelligence external inputs play the role of a "trigger" for material changes and thus their behavior, requiring very little energy at the input itself. These systems respond to stimuli as diverse as thermal changes \cite{zhao_phase_2021}, mechanical stress that can be induced by force or light \cite{jiao_mechanical_2023,madhusudanan_relaxation_2024}, pH or chemical gradients that induce swelling or changes in conductivity in conductive polymers \cite{urban_key-and-lock_2018}, light with photo-thermal effects for phase change or with photochemical reactions for isomerization based transformations \cite{bayat_self-indicating_2024,xiao_artificial_2020}, changes in magnetic environment that control the spin state of components \cite{stamps_active_2024}, or a simple diffusion process as with microcapsules \cite{calvino_microcapsulecontaining_2018}.

The core criteria for this type of material intelligence are: (1) the use of internal structural or compositional changes of the material, not as an isolated sensing process, but as the mechanism by which “memory” and “responses” are generated via a physical or chemical state, (2) a significant emphasis on local feedback loops as a means of information processing and action, (3) an inherent time dependence in memory retention, with past interactions influencing future actions within same structural elements, (4) limited or no dependence on external digital controllers or pre-defined programming or centralized processing, and (5) no defined signal transduction outside of the material itself acting as a transmission element, the structural or internal parameter of material itself acting as a link between one unit and the next, with a strong influence of environment as a way to trigger a response.

2. **Core Concept:** From a Category Theory perspective, the general mechanism in this ‘material intelligence’ can be seen as a transformation of external energy into a material state, which then maps this internal state into a change in some physical parameter of the material with a functional output, with very limited or no external control loop. The transformation process prioritizes local interactions through a network-based architecture with coupled nonlinear response elements and feedback generated by internal material properties. The essential component is not a discrete signal, or external controller, but it is always related a a change in a physical variable intrinsic to the material itself during a functional response using a nonlinear approach with small elements coupled to each other.

   The shared principles across the publications in this cluster include: (1) **Local**

Interactions: Components interact directly with the neighboring units through physical or chemical couplings (mechanical stress, chemical diffusion, energy fluxes without long-range signal transmission \cite{bayat_self-indicating_2024,jiao_mechanical_2023}, creating what is defined as embodied intelligence with a physics-based feedback, so that all system behaviour is determined by physics and not external software as mentioned in \cite{pezzulo_active_2024} (2) **Active Structural Memory:** Information is stored not only as a static recording but also as a time-dependent influence over material behaviour, via structural or compositional changes (e.g., polymer chain configurations, stress states, chemical compositions, changes in topology etc \cite{madhusudanan_relaxation_2024,zhang_active_2024}). This “memory” shapes responses in future actions, allowing for some form of adaptation to previous stimuli similar to a reinforcement learning system with minimal computing units with no software, (3) **Analog Computation**: The system performs a type of computation through the inherently analog physical processes in material parameters and not via digital circuits (e.g., phase transitions, local phase change, swelling effects, reaction speeds, stresses). (4) **Local Feedback loops**: all designs include or at least suggest feedback loops where the internal parameter change is responsible to action by changing its material properties instead of explicit electric circuit or post processing or software control and (5) **Self-organization :** A high degree of self-organization with minimal dependence on predefined connections, with a dynamic system.

The architecture is self-organized with local feedback loops. These could be from a change of a physical parameter directly connected to an action, as seen with pH swelling and induced local acidification \cite{pezzulo_active_2024}. Or with different examples of mechanically compliant systems that induces a change in local electrical or chemical properties due to that effect, as well as with time dependent mechanical changes from thermal phase transitions that change its physical state \cite{zhao_phase_2021}. Local rules and a physical coupling system are an essential requirement to implement desired responses.

A minimal design rule would dictate the coupling of internal parameters that are set by external influences via a local rule system, linking the energy exchange and information flow at a material level; i.e. an input parameter, will cause a change at a specific location creating a “memory” for latter actions while also changing system properties for an emergent behavior without a predesigned global action or without a global central processing unit. All operations are limited to the local scale so a small structural unit will have an internal behavior that is locally controlled only by local inputs that will modify its properties (composition morphology stress etc). Also the minimal system should operate without any external controller.

A "minimal design implementation" would involve a composite material where a thermo-responsive polymer is coupled with a phase change material (PCM). The polymer would expand or contract based on local heat generated by a small change of state in the PCM. The PCM is activated by a specific threshold temperature as an external input. The expansion state will not only directly provide actuation, it can create a change in stress or even change the diffusion properties, generating an inherent feedback that would change device properties or generate a new form of internal signal to generate a cascade of changes with no electronic circuitry. The structure itself will encode the past interactions, based on the local PCM structural state.

3. **Readiness:** Current realizations, while promising, fall short of the "cognizant matter" ideal. Most systems achieve a form of passive memory where structural changes are recorded, but they don't actively learn or adapt. For example, while the shape-memory and thermal transitions at phase change material described in \cite{zhao_phase_2021} record a past thermal input, this record does not directly change future responses or create a system with autonomous behavior to set new system parameters. Similarly, phase change materials or memristors do store a kind of "memory" of a past input via some chemical or electrical parameters, as cited in \cite{di_ventra_parallel_2013}, but they lack an ability to integrate this memory with actuation for a more complex response, or an internal processing without external control.

   The most glaring limitations exist in the ability to truly create feedback and information processing loops and have material learn from past interactions. The self-healing polymers shown in \cite{urban_key-and-lock_2018} can repair damage, but that process is always the same and does not change its behavior due the previous interaction. They are responsive and not adaptive and learning, as described in the proposed framework. Although these designs may be very useful, they respond but do not learn; they act but do not integrate information and decision for a truly autonomous behavior, highlighting current designs to be a form of a physical feedback rather than a truly intelligent material system as defined on theory by \cite{pezzulo_active_2024}, and with other theoretical publications with similar goals, as seen in \cite{harrison_mind_2022}.

   Systems that rely on environmental interactions as the core element for action such as a metasponge that expands based on liquid uptake as shown in \cite{soto_programmable_2023} or the light controllable material described by Zhang et al. \cite{zhang_active_2024}, have clear limitations in terms of complexity in their response. These responses are linked to current environment and not to an internal memory that would modulate a different response as a function of the past interactions, also a clear requirement of a more "intelligent" system able to change based on past behaviors, a goal of cognizant matter that goes beyond just an output by feedback. Most existing systems in this list are limited to a stimulus response type of action as stated in \cite{mcevoy_materials_2015} "Instead of seeing a soft material simply a body, an encapsulation method for a set of predefined responses based on specific external controls or stimuli… start exploring their inherent characteristics by implementing all

functionalities to work synergistically to create a smart behavior". They don´t fully integrate internal memory to drive action or computation as it is clearly stated by \cite{mcevoy_materials_2015} which the cited work does respond to stimuli but lack internal coupling to perform an action. Also as stated in the framework for this type of intelligent material the system should "change its properties by direct interaction with the environmental physical or chemical conditions" with the emphasis in the "interaction" mechanism with the environment which is absent in most designs by its simple passive response to environment rather than a direct interaction which changes both environment and material, with all processes controlled mostly by external parameters. Therefore a shift is required from passive responsivity to an active self-regulatory behaviour.
The emphasis is that current physical realizations are still predominantly relying on passive material responses rather than active behaviors driven by an internal regulatory system, as required for a truly "cognizant material".

4. **Challenges:** The primary challenges stem from the difficulty of combining multiple properties within a single material while retaining precise control and robustness.

    - **Material Control:** Precisely tailoring the material properties to achieve desired behaviors is difficult. The publications rely often on known properties of existing material and not new type of design techniques. For example obtaining precise spatial control, especially when creating complex, non-linear, or dynamic interfaces remains difficult with low implementation of concepts to do so, mostly relying on simple methods of material distribution in a composite or molecular structure that is often predetermined. This lack of control could be the major hurdle towards creation of such complex systems.

    - **Fabrication:** Most of the systems described lack details on fabrication techniques where precise structural arrangement is mostly crucial for information handling specially concerning the distribution of different elements or complex topologies as presented in the theoretical frameworks. Creating systems that operate at a desired scale, especially scaling up or creating micro and nano implementations that require precise nanoscale or microscale control during the fabrication with a direct correspondence to function and no external digital processing unit that can have its own limitations due to scaling down, is also a major problem. The scalability is limited as all these designs operate at different material configurations, requiring different method of constructions, so the general fabrication protocols are often missing.

    - **Stability and Robustness:** Maintaining long-term structural integrity and functional performance in different or harsh environments is challenging. Maintaining long term time stability of dynamic structures, such as molecular gradients, polymer entanglements etc is also a major challenge. System robustness in different temperature or humidity conditions are often presented in theory only or mentioned very briefly in discussion as in \cite{urban_key-and-lock_2018}. Most systems work at specific conditions with low adaptability, limiting their use in realistic settings that may have changes in the experimental conditions.

- **Efficiency:** Designs for true intelligent systems require material properties as the most important factor in their design. Most rely on processes with little to no energy conversion but rely on a response. The efficiency of energy transfer or energy transformation (chemical, mechanical, light) is usually low as no particular mechanism was introduced to prioritize it as is only used for signal transduction between its components and without using any complex computations or external control which usually increase the inefficiency. Also the implementation of analog type of components as basic element will require a deep revisit in the current implementation and its efficiency and stability in long operations. The economic viability for mass production of complex hierarchical systems with multiple interactions is also questionable using the proposed methodologies.

- **Absence of internal dynamics**: The publications often highlight the need for time-dependent memory and self-organization, but many designs lack an internal "clock" or dynamics that would permit the system to be self-regulating, mostly responding to external cues only and not performing action depending on an internal time constant.

These limitations restrict potential applications, especially for systems requiring precise, robust, and autonomous behaviors with complex responses outside of laboratory settings. The lack of detailed experimental evidence for self-regulatory properties and self-driven behaviours and data on the actual long term stability of internal parameters of such complex system that are directly linked to their functionality also needs to be addressed.

5. **Reflective Insights:** This cluster highlights current designs that are on the borderline between classic smart materials and new paradigms for intelligent matter, using coupled physics as computing components with novel features to be explored. The presented approaches often start from "easy to understand" ideas such as simple phase transitions or diffusion process with a low number of components and design limitations. There is a lack of designs that implement a hierarchical architecture with multiple feedback loops, creating a truly open system architecture, and a very limited research in this area. There is very limited work on how such elements can be coupled, and more experiments are needed to support such ideas, as most designs are just individual solutions to specific goals with very limited design flexibility or an integrated set of multi-functions as proposed for true intelligent systems as described by \cite{mcevoy_materials_2015}.

The presented examples often focus on creating components, not integrated systems, as it is seen in the description by \cite{di_ventra_parallel_2013}, requiring more emphasis to the overall design rules than implementation of materials-only solutions for specific problems. The memory mechanisms based on material properties and not on digital means as proposed in \cite{reiter_memorizing_2020} represent an innovative approach, but these mostly are not implemented at scale or linked to an active response mechanism for more complex behaviors with self-regulation as proposed in \cite{huang_self-regulation_2018, nelson_delivering_2023}. There is also lack of designs that integrate multiple inputs simultaneously with the same elements.

Future evolution requires a shift in emphasis from passive responsivity to active self-regulatory systems with feedback, multi stability, memory and complex interaction. The systems should also have local energy harvesting, and all information processing must take place within the material structure itself, not simply with external read-out devices. Furthermore the ability to interact with environment not for passive response purpose but to gather data is a central pillar, as stated in many different points in this review, of a truly “cognizant” type of material. The most promising concept is designing materials where information storage and processing happen via dynamic material properties change that allows them to react to outside stimuli but also learn and respond differently depending on history or internal state without external control but relying on local rules, creating self-regulated and coupled systems. It is necessary to move beyond designing individual components toward the creation of integrated systems based on material properties themselves. Therefore more research is needed to develop a new physical methodology that will provide new set of tools to guide this new paradigm of material research to build true "cognizant matter.". These may require a re-evaluation of the fundamental concepts in materials science. While some progress can be achieved with incremental improvements, complete breakthroughs in material design, self-assembly, and non-linear dynamics will be needed to truly implement this vision of material intelligence. The current challenge lies more in conceptual and design limitations than on minor improvements in methods of fabrication and component implementation, but are essential for new type of explorations.

Dynamic local interaction processing.

(Cluster 1)

In a Nutshell: This cluster of "material intelligence" explores systems where information is encoded and processed through the dynamic interplay of self-propelled agents, be they living organisms or synthetic particles. These systems lack long-term structured memory, relying instead on transient spatial or orientational states and local interactions to drive collective behaviors. The intelligence arises from the emergent patterns resulting from these continuous interactions and adjustments rather than pre-programmed control.

1. Distinctive Definition:

This type of intelligent matter, encompassing natural systems like ant colonies \cite{theraulaz_spatial_2002} or fish schools \cite{puy_signatures_2024, couzin_collective_2009}, and synthetic active particles \cite{negi_collective_2024-1, ziepke_acoustic_2024,goh_noisy_2022}, is characterized by **dynamic, non-material information encoding** and **local reactive actuation**. Unlike traditional smart materials with pre-defined stimulus-response behaviors, this type relies on the transient spatial or orientational states of its constituent agents (or “particles”) as the primary carrier of information. This information is not stored in a static, persistent structure, but is continually changing as agents interact. The key is how locally sensed parameters directly modify the agent trajectory. For example, in active particles, the relative positions or orientations of neighbors within a "vision cone" dictate the particle's next action \cite{negi_collective_2024-1}. Similarly, fish schools coordinate motion via velocity alignment and changes in heading direction of neighboring fish \cite{puy_selective_2024, puy_perceived_2024} or ants form trails through pheromone deposition changing local probabilities for following the path in a self reinforcing fashion \cite{theraulaz_spatial_2002}. The universal features are the local sensing and immediate use of that information for a physical reaction, generating a feedback loop. The primary difference in the systems’ behavior resides in the specifics of the sensing modality and actuation rules: active particles are based on engineered rules, fish and birds use visual input and hydrodynamic or aero-dynamic interactions, and ants employ chemical trails and physical movement. However, common parameters are spatial density of agents , agent velocity \cite{masila_emergence_2023}, relative position and orientation of neighbors \cite{negi_emergent_2022,goh_noisy_2022} and parameters that control agent responsivity to that given sensory input. The most suitable external stimuli for this type of material intelligence are gradients that influence the local agent state such as light for light-sensitive particles \cite{schmickl_how_2016, iyer_directed_2024}, or chemical changes that attract or repel agents. The key distinguishing criteria is that no memory of a specific event is encoded in a non-volatile material state, but is achieved via local action with dynamic continuous state update. This leads to complex behaviors not by pre programming each state, but as a continuous update of existing information based on local rules of interaction. .

2. Core Concept:

From a Category Theory perspective, this type of material intelligence can be conceptualized as a system of interacting 'objects' (the agents) with morphisms defined by their local interactions with each other. The shared principle across all publications is that these systems exploit dynamic spatial configurations or specific dynamic states as a form of transient “memory” that actively modulates future behavior. The key components are: (1) **self-propelled agents,** (2) a local sensory system that measures a property like relative distance or orientation, and (3) **local interactions** that define rules for adjustment of the state of the agent. This interaction is not a digital computation but a physical reaction via physical forces. For instance, in acoustic swarms, elements emit acoustic waves that propagate in the medium altering agent direction or internal oscillations \cite{ziepke_acoustic_2024}. These rules transform the sensory input into a force altering the agents motion direction or configuration in an analog continuous fashion without threshold-based switching behavior. In terms of architecture, there is an emerging self-organization of the elements that allows complex collective behaviors, where the dynamic state of each component or agent is modulated locally \cite{march-pons_consensus_2024,mugica_scale-free_2022}. The core for the "intelligent" behavior is the feedback mechanisms that emerge from **local interactions** between agents in physical proximity. These interaction rules, based on physical parameters like distance and relative orientation, generate a force that is coupled in a non trivial manner with sensing input that guides the output of each component. This is a minimal computing element based on physical interaction rules. The system, as a whole, does not operate towards achieving a predesigned state like traditional smart materials but its output is a continuous consequence or an 'emergent' property of that particular local rule set. Feedback loops are not classical ones where some specific output feeds back into a defined input, but a continuous update of the current state of all components based on local physics. A minimal design rule could be described as: “*Every agent will continuously sense and react to its local environment by modulating its energy state based on a set of rules that couple sensing to action which also defines the type of interaction*” . A minimal implementation could consist of active particles with a limited "vision" range, performing continuous sensing of the local spatial density of other particles and generating a force for turning. Their direction is constantly modulated by interactions where they act and react in a continuous manner without need of an external controller.

3. Readiness:

The examined systems demonstrate aspects crucial for “cognizant matter,” especially in the utilization of active elements and the absence of centralized controllers and a form of analogue computations. However, they often fall short of creating self regulated adaptive responses that are not directly linked with current input. While spatial information encoding as a form of short term state memory is achieved, they lack long-term memory based on structural changes (as proposed in the background description) \cite{negi_collective_2024}. For instance, while ant colonies exhibit a form of memory through their pheromone trails \cite{theraulaz_spatial_2002}, this is not a truly long lasting memory which does not modulate future response beyond the current phernomone concentrations. Similarly, active Brownian particles change configuration and move with a given direction based on current neighbors, and not any record of past positions \cite{negi_emergent_2022,goh_noisy_2022}. The most relevant publication on this cluster \cite{negi_collective_2024-1} highlights this limitation where motion is derived from direct local interaction without integrated memory, which is not present at the single particle level but which might be encoded at a higher, collective level but with no mechanism to modulate individual units based on that. This shows that present design is limited in having a true long term memory via a material system that can actively adjust the system future behavior. While local interactions and feedback are present, such as in fish schools when single fish changes its movement affecting the neighboring fishes

\cite{puy_perceived_2024}, the information processing is not beyond the instantaneous interactions and without local learning rules beyond the direct local response. Furthermore, most systems react rather than learn based on prior events. They do not display adaptation or self-improvement based on history. For example in the simulation of pursuit evasion with particle system \cite{goh_noisy_2022-1,goh_noisy_2022}, there is no ability for the pursuer to learn over time from past trials which is a required feature of what has been defined as a 'cognizant matter. Most of these models are more suited for a limited set of behaviors, with an externally imposed operation, and without a truly open ended dynamic response for adaptation to environment..

4. Challenges:

One key technological hurdle in mimicking these systems is the controlled fabrication of self-propelled, locally interactive components with tunable properties. While micro and nanoparticles with light- \cite{schmickl_how_2016, iyer_directed_2024} or other-responsive surfaces are becoming more feasible, their mass production and integration into larger structures remain challenging. Controlling the exact shape, composition, and interaction rules of each agent is difficult especially if the goal is to create a new material rather than a system built by external intervention. Ensuring the robustness and stability of these systems in varying environments is another challenge, as minor variations, temperature, chemical noise, or physical constrains can alter the dynamics of material behaviors. For example, the fish school experiments demonstrate that spatial boundaries influence the emergent collective motion \cite{puy_signatures_2024}. Scaling up these systems also presents significant limitations as the number of interactions increases, and can lead to chaotic or unexpected behaviors specially if system is designed for a very specific set of operations and behaviors. The efficiency of these implementations, particularly in terms of energy use, is also a pressing concern, as the continuous self-propulsion often requires a constant energy input as noted for active Brownian particles or active microswimmers \cite{negi_collective_2024, masila_emergence_2023}. The economic value is also limited as current methods are more expensive compared to systems with pre designed behavior or static structures that can be implemented in large scales. A specific obstacle is that current self propelled systems such as active particles \cite{negi_collective_2024}, or simulated agents \cite{masila_emergence_2023}, rely on continuous external energy input and they do not harvest the energy from external environment limiting their potential for autonomous long term operation. Similarly, in all presented cases the lack of long term memory will cause issues in complex decision tasks or problem solving behaviors that require some kind of past internal recording to inform and select future action or responses.

5. Reflective Insights:

Analyzing the disparate examples reveals a common thread: the power of local interactions and dynamic self-organization in achieving "intelligent" behaviors without central control.

There is a strong link between biological self-organization principles and the dynamic nature of the emergent material states in synthetic active systems, however current technologies are limited by the low degree of dynamic complexity as the control is not encoded into the material proprieties but into external rule systems. While material systems are still far from the complexity and adaptability of biological systems like ant colonies \cite{theraulaz_spatial_2002} or fish schools \cite{couzin_collective_2009,puy_selective_2024}, they confirm that behaviors, like pattern formation, memory, locomotion and dynamic selection of states, can come from very simple rules and physical interactions. However, a key limitation is that those local rules, even though they are leading to complex behaviors, are fixed and they do not adapt or change during their operation due to an active integrated memory system. Innovative solutions rely on creating coupled multi-state systems with a response that is coupled to internal property of a given material where that property acts both as output and as an input. . The greatest potential for further evolution lies in developing materials that can not only sense and respond but also store temporal information, combine various different type of environmental signals (chemical, light, mechanical, etc.), and even learn from their interactions. To achieve this a shift in knowledge is required, moving from current limited implementations by preprogrammed actions, towards designing materials with an **intrinsic learning ability** that would allow a new form of embodied material intelligence and a path to achieve the defined properties for cognizant matter. This would require a better understanding of the fundamental physics that can generate those complex interactions to enable a new generation of materials. The least potential lies in systems with very limited capabilities that are based on simple responses that don't integrate memory states in their operation. This would include most implementations of active particles since they react using a fixed, predesigned set of rules without further modifications over their operation and mostly without a form of real memory based on material states. Such limited responses, or systems based on software instructions have shown significant limitations to perform complex decision-making that require a truly adaptable response that is present in living organisms but are still beyond the scope of most material implementation. Incremental improvements on existing techniques are unlikely to produce those desired intelligent behaviors, requiring instead a focus on new physical system and design principles to build complex information processing materials based on the core principles set by theoretical frameworks and nature itself.

Mechanically mediated responsive systems

(Cluster 2)

In a Nutshell: This cluster of publications explores a type of material intelligence centered on the transformation of mechanical energy, where external stimuli, typically forces or vibrations, induce changes in the material's internal configuration, resulting in actuation and altered system dynamics. This form of intelligence encodes information in geometric arrangements, mechanical contacts, and transient dynamic states, achieving responses through local interactions and, in some cases, by coupling with external control loops in an analog fashion. This is primarily achieved via passive physical mechanism driven responses with limited long term memory or selfregulation.

1. **Distinctive Definition:** This category of material intelligence can be rigorously defined as a *mechanically mediated responsive system*, where the primary operational principle lies in the direct transduction of mechanical energy into changes in material structure and system behavior. The key mechanisms involve: 1) **Mechanical transduction**: converting external mechanical stimuli (forces, vibrations, or pressure) into internal strain, kinetic energy, or structural deformation. 2) **Geometric Encoding**: Imprinting information within the material through its shape, linkages, or spatial distribution of elements, defining the specific response to external stimuli. 3) **Transient Information**: utilizing the changes of the geometrical configuration as time-dependent output rather than static properties, providing a short term time-dependent form of encoded information. 4) **Analogous Computation**: Transforming the external mechanical input into a distributed processing via physical interactions that modulate responses by their own physical parameters, without digital components. The observed behaviors within this cluster focus on actuation, ranging from locomotion [e.g., \cite{hu_small-scale_2018}, \cite{warkentin_locomoting_2018}, \cite{goldman_robot_2024}] to pattern formation \cite{bordiga_automated_2024} and mechanical computing \cite{lee_mechanical_2022}. While the stimulus-response can be quite diverse, the underlying mechanisms show a remarkable similarity. For example, both metamaterials subject to mechanical compression \cite{xi_emergent_2024-1}, \cite{mertan_no-brainer_2025} and soft robots actuated by magnetic fields \cite{hu_small-scale_2018}, \cite{wang_robo-matter_2024} all utilize mechanical forces to induce changes in geometry that result in altered dynamics. The differences in behavior arise primarily from the specific geometric configurations, material properties (stiffness, elasticity) and the way that those properties are physically coupled in the architecture and what specific external stimulus is used to operate this physical transformation. The most suitable external stimuli are therefore mechanical which include: compressive forces, contact interactions, vibrations, external magnets, or pressure. This class of intelligence is not defined *per se* by external feedback but by an implicit relationship with the system internal physical parameters and properties, and the external stimuli acting as a continuous flow of energy and action. The criteria for this type of material intelligence emphasize: a) the requirement for a clear material-based mechanical transduction; b) preprogrammed geometric configurations and material properties that define the response; c) a reliance in analog computation where the physical structure changes via physical forces (contact, stress or strain) resulting in complex behaviours due to nonlinearities in physical response.

2. **Core Concept:** This form of material intelligence can be understood using Category Theory as a functor that maps inputs (mechanical forces) to outputs (system dynamics).

Specific principles and components unify the diverse physical implementations. These include: 1) **Energy Input Transducer**: A component (active or passive) that converts the external mechanical input to internal kinetic or strain energy. 2) **Structural Encoding**: A predefined geometry, either in links \cite{goldman_robot_2024}, voxels \cite{milana_morphological_2022}, metamaterial units \cite{mertan_no-brainer_2025}, \cite{xi_emergent_2024-1}, membranes \cite{bordiga_automated_2024}, or magnetic distribution \cite{hu_small-scale_2018}, which dictates how the material will respond based on that energy transfer. 3) **Mechanical Coupling**: Physical connections and interactions between components that propagate energy and information through the material. 4) **Nonlinear Response:** Most physical implementations rely on nonlinearities derived from the material or physical interaction itself to guide deformation or physical behaviour (e.g. buckling transitions \cite{milana_morphological_2022}, geometrical constraints in linkages and metamaterials \cite{goldman_robot_2024}, \cite{mertan_no-brainer_2025}). The core for intelligent behavior resides in the *dynamic interplay* between the energy transduction, encoded geometry, and the material's physical response leading to a nonlinear physical response from the material structure. The prevalent architectures are *modular and network-based*, with a common design strategy of linking multiple local units (e.g. robots, voxels, metamaterial units, memory units) together creating a large system with distributed action. Feedback loops are either very short term due to physical parameters such as stress strain or velocity or rely on external computer controls \cite{sabelhaus_-situ_2022},\cite{lee_mechanical_2022}. To create local self sustained feedback loops, the material itself should change via the action with a time scale that allows future events to respond to past ones, without external controllers. A *minimal design rule* would emphasize: The material responds locally to external constraints or stimuli by transforming mechanical energy into structural rearrangements. These changes couple mechanically to the output, with such transformation creating a feedback that modulates further responses without external assistance or digital control. For an example, a "minimal design" could use a layered composite, where one layer swells upon mechanical stress, simultaneously altering the strain rate of the material itself while also changing internal pressure via local deformation by a nonlinear mechanical coupling, such as a buckling type transition, and this change can modulate future deformation characteristics, resulting in a self-regulating dynamic system capable of performing mechanical actions.

3. **Readiness:** Considering the ideal of "cognizant matter," the current cluster realizations are far from achieving the necessary complexity and self-regulation. While these systems demonstrate responsivity to external mechanical stimuli and implement energy conversion, they primarily operate based on pre-defined responses lacking a sophisticated level of internal self regulation or feedback. Memory is mainly transient, stored in the current structural state which is immediately overwritten using continuous signals [\cite{milana_morphological_2022}] or in electrical components outside material \cite{riley_neuromorphic_2022, lee_mechanical_2022}. They do not actively learn from

past events or adapt their internal properties based on experience that is a core requirement for that definition. For example, in \cite{warkentin_locomoting_2018}, the robotic system responds through a fixed program, relying mostly in indirect communication between robotic units with no physical memory based on material properties. The main limitation in these examples is the lack of proper coupling between the system memory (which is often not a material property) and the system's action, which prevents higher forms of learning and self-regulation and the dependence on external energy sources to implement action and memory which limits potential long term autonomy. There is a lack of hierarchical organization, where multiple types of feedback loops can establish self regulation that generates complex material behavior as it can be potentially encoded in living systems, where many components contribute in various feedback mechanisms. In most cases, the information processing is implicit in the structural geometry rather than an active, adaptable, or self-regulating mechanism. In particular, the feedback in most systems rely mostly on external controllers and are not part of the material structure and do not modify any material properties. Finally there is absence of intrinsic long term memory mechanism that is part of the material that is integrated with its internal mechanisms and that does not require external power or control to function where information can be stored in the structure via slow relaxation processes \cite{Self-healing materials: a review, The memorizing capacity of polymers}. Therefore the current implementations are still mostly on what can be defined as responsive material rather than a cognizant matter, as defined in the background information.

4. **Challenges:** Several technological hurdles restrict the advancements of this kind of material intelligence. Precise control over material properties remains a significant issue, with most properties as fixed parameters at start time of action. Achieving consistent and reproducible structural configurations with different levels of complexity, and at different scales, is severely limited by existing fabrication techniques. The robustness or structural stability is very limited to operation in very specific range of parameters, and they show a poor performance in terms of adaptation capabilities to different and unforeseen external conditions, where a more complex material response would become essential. Scaling up such systems represents further challenges as it requires that mechanical interactions between multiple components would have to be uniform and reproducible in same material properties as a requirement for operation that is, in most cases, not fully possible, or not feasible with low cost. The majority of systems have poor integration and a strong dependence on external controllers, resulting in an inefficient system with high power consumption \cite{sabelhaus_-situ_2022}, \cite{lee_mechanical_2022}. Also, the implementations are mostly based in pre-defined parameters with limited capacity for self-organization or adaptation, requiring precise component design and parameters implemented from the exterior rather than material self made control. The lack of memory in material properties or complex system architecture does not allow for dynamic adaptation and complex behaviors in more dynamic external environmental conditions. A

major limitation is the linear sequence of operation: stimuli (external pressure, vibrations, contact forces), response at material level (change in shape or configuration), action (such as locomotion or actuation) . This linear sequence is often set by fixed material and design parameters which allows for limited response capabilities thus reducing the overall versatility of these types of “intelligent materials”. The analyzed examples lack robustness due to the reliance on very specific mechanical interactions which do not allow complex and adaptive response.

5. **Reflective Insights:** The surveyed studies point to a common path: an attempt to construct a new form of functionality that bypasses digital electronics by harnessing physical forces instead of electrical signals. There are two contrasting approaches in the designs: passive designs which use pre-programmed shapes, and active designs based on external controls. In active designs, the material itself is passive, with all active elements positioned outside it \cite{lee_mechanical_2022}, which offers highly precise operation while compromising system autonomy and integration. Passive designs operate similarly to metamaterials or robots, relying primarily in pre-programmed geometry and materials, yet with limited control or long term memory \cite{mertan_no-brainer_2025, xi_emergent_2024-1, warkentin_locomoting_2018}. Both approaches however, fall short from a true autonomous implementation. A novel implementation strategy would require integrating the action, computation and memory inside the material and making the response also part of the active structure of the material itself without external control. This requires a complete shift from a linear sequential approach to one that utilizes complex non-linear couplings and feedback mechanisms. The most potential for further evolution is in creating designs where the "memory" becomes part of an active mechanism or internal parameter of the material itself, which modifies and shapes its response, in conjunction with more complex system architectures that have different types of feedback loops integrated from many different material properties to establish complex forms of self-regulation and adaptation as it occurs in living systems. On the other hand, the least potential area resides in designs where control and memory elements are still outside of the materials structure requiring complex software loops or external manipulation as seen with implementations that rely on micro servos motors \cite{warkentin_locomoting_2018} or external controllers \cite{lee_mechanical_2022}, as this implies a complex assembly and limited scalability that also reduces the potential for future adaptation or change by the material itself. A complete shift is needed in the methodology where the material becomes not merely a responsive medium but an active agent. This is achieved if the processing, memory, actuation, and sensing are all seamlessly integrated within its internal physical structure (geometry, composition, and dynamic couplings) rather than externally hard-coded. Future research should, therefore, focus on the integration of these characteristics synergistically to have a truly smart system at the material level beyond simple stimulus-response behavior through local selfregulation based on internal parameters rather than external interventions.

Ionic gradient material intelligence

(Cluster 3)

In a Nutshell: This cluster explores material intelligence realized through the manipulation and transduction of ionic concentrations, predominantly in microfluidic environments. Information is encoded in spatial and temporal variations of ion distributions, which are used to modulate processes such as fluid flow, conductance, and particle sorting. These systems demonstrate analog memory through the history-dependent ionic gradients and are typically actuated by chemical or electrical stimuli.

1. **Distinctive Definition:** This category of material intelligence is characterized by the *dynamic manipulation of ionic concentrations and the subsequent conversion of these distributions into functional responses*. Key to its operation is the use of *ionic fluxes and resulting gradients as the primary mechanism for information encoding and processing*. The systems utilize various physical phenomena including electrokinetics, concentration polarization, ion exchange, and surface tension gradients to achieve their functions. These mechanisms are distinctly non-electronic, highlighting a departure from traditional solid-state devices. Instead of relying on electron flow, these implementations directly exploit the thermodynamics and transport properties of ions. The output manifests primarily as fluid flow, changes in conductance or particle movement, all driven by ionic gradients. The behavior and response differences are largely dictated by the specific implementation, i.e. use of microfluidic channels, Nafion membranes, or oil-water interfaces, as well as properties of the ions themselves. Parameters such as applied voltage, salt concentration, pH, and the geometric constraints of the device strongly influence the system. Suitable external stimuli encompass electrical fields, chemical gradients, pressure gradients, and light (though not prominent in this cluster), all of which can modulate ionic transport and concentrations. This form of material intelligence distinguishes itself from others through its use of ionic transport as a form of “computation”, with memory, action, and sensing being tightly integrated into a single physical process; contrasting with the usual sensor-controller-actuator paradigm.

2. **Core Concept:** In category theory, the general concept of this type of intelligence can be described as a transformation of ionic landscapes into functional behavior. The essential components common across publications in this cluster (universal features) are: (1) a medium where ions can move (e.g. microchannels, aqueous solution) (2) a source of ionic species and (3) a method for creating concentration gradients i.e. voltage bias, differential diffusion or a chemical potential. The *core mechanism* for intelligent behaviour is the *creation and manipulation of non-equilibrium ionic concentration profiles*, which then drive an action through forces exerted on other components (e.g charged particles, liquids) or changes in device behaviour (e.g. conductance changes). The architecture of these

systems varies depending on their purpose; for example, some utilize microfluidic channels with specific shapes to enhance concentration polarization \cite{barnaveli_pressure-gated_2024, robin_long-term_2023}; others rely on the self-assembly of molecules at interfaces to produce movement, such as in droplet-based systems \cite{hanczyc_fatty_2007, cejkova_dynamics_2014, fraxedas_collective_2024}. The common architecture framework however is primarily a *self-organized* one and not a modular one as the "functional" units use the media itself and the boundary conditions for creating non-linear effects and the integration of information processing is done through physics of coupled gradients and not via active control via digital devices. To formulate a minimal design rule, the system should consist of: (a) a source of ions; (b) a means to create ion concentration differences and (c) a physical phenomenon that connects these gradients to the desired functional output (e.g. changes of conductivity, fluid flow). Feedback loops are not implemented in the traditional system design sense, instead they are created by the physics of the coupled phenomena where local events (ion concentration) influence local parameters (conductivity) which in turn will change future ion distributions. The minimal operational characteristics required for new implementations include: (i) achieving a desired time dependency of ionic fluxes or gradients using the material properties or the environment; (ii) ability to control the amplitude of signals by material properties and (iii) a direct physical coupling between ionic gradients and the output parameters. A minimal design example would be a microchannel with spatially varying surface charge; this would allow for control of electroosmotic flow by creating regions of high and low ion accumulation with varying flow rates via different voltage or chemical pulse patterns.

3. **Readiness:** The current realizations of this type of material intelligence fall short of achieving the ideal of "cognizant matter," as proposed in the introduction. Several publications show memory encoding via ionic distribution that is then linked to an output action through some physical phenomenon. While some of the systems utilize non-equilibrium states to encode 'memory' and integrate the input with some system's output, they still lack self-regulation and autonomous adaptation based on past interactions with an environment. For example, although the devices in \cite{kamsma_brain-inspired_2024, kamsma_iontronic_2023} use ionic currents to produce memristive responses, these still rely on a pre-defined electrical signal from external source and do not show self-adaptation after initial fabrication. Moreover, many systems lack embedded computational elements required for local signal processing; instead, they mostly show a direct, passive response to a specific set of predefined stimuli. For example, while droplet systems such as \cite{cejkova_dynamics_2014, hanczyc_fatty_2007} demonstrate autonomous movement, such systems lack a long-term memory as the material is being constantly transformed by the external environment losing ability to change functionality based on history. While \cite{esplandiu_electrophoretic_2020, esplandiu_radial_2022} do show a way to create some kind of 'decision' by differential particle trajectories based on an external electrical field, these systems do not feature any internal feedback loop or

local processing which can actively change any parameter from the implementation. In essence, current implementations use time-dependent gradients of ionic concentrations to carry signals but they lack the capacity for self-modification, learning or choice and instead respond in a predictable fashion to externally implemented parameters. In contrast, truly "cognizant matter" should actively change its parameters based on past interactions and be capable of selecting different actions, using a memory that is coupled directly to output action without external controllers.

4. **Challenges:** A major hurdle lies in the limited control over ionic transport at the micro- and nanoscale. While microfluidic channels offer some control, manipulating ionic fluxes with high precision remains difficult. Fabrication of complex 3D architectures with spatially modulated surface charges or chemical functionalities with high reproducibility is another significant challenge. System stability and robustness in different environments are often compromised because they rely on specific combinations of temperature, pH, and ionic concentration that are hard to control outside of well defined lab environments. Scaling these systems up while maintaining performance is an additional barrier due to their often complex coupled interactions that can become highly non-linear using a larger system surface or volume. Furthermore, the current implementations are not efficient in terms of energy usage and production time; many require external power supplies or slow, high precision fabrication processes. For example, many systems that use Nafion \cite{esplandiu_electrophoretic_2020, luo_highly_2023} depend on external chemical reactions which can diminish the “memory effect” while using microfluidic channel based systems \cite{boniface_self-propulsion_2019, barnaveli_pressure-gated_2024} have limitations in terms of scalability and integration into useful devices. Most importantly, as highlighted in the provided text snippets, the reliance on passive response and external control signals rather than intrinsic self-regulation creates a major limit in obtaining a truly intelligent response that is linked with its internal properties and history of use. The limitations highlighted in the analyzed papers include: the lack of long-term memory mechanisms (beyond simple gradients relaxation via diffusion) and the lack of internal feedback loops needed for adaptive intelligent behavior as also discussed in the general ideal (also present in Background), which ultimately results in materials with response that is only a result of pre-designed interactions.

5. **Reflective Insights:** The reviewed publications reveal a common thread: the use of ionic gradients as a flexible means to couple sensing, memory, and actuation into one single unit that is a direct result of material properties. However, there is no direct integration among these areas as usually the mechanism used for ionic gradients, the readout parameters and the method used for outputs does not intercommunicate with each other. Systems based on microfluidic channels such as \cite{kamsma_chemically_2024, kamsma_iontronic_2023} and those using oil-water interface such as \cite{fraxedas_collective_2024, horibe_mode_2011} have some clear implementation differences that are not trivial. The former relies on precise fabrication and careful tuning

of experimental parameters while the later relies on the self-organized dynamics of molecular assembly. A limitation across all the implementations, however, is their reliance on pre-set boundary conditions (geometry, material properties) and externally programmed signals as well the fact that the memory is not embedded in the structure in terms of, composition, phase transition, stress or similar effects and hence it is mostly linked to local gradients or short time effects. The most promising direction for future research would involve moving towards systems with multi-functional self-organized architectures where the information can be processed locally without an external controller. Specifically more research is needed on the use of dynamically changing chemical phases that can create long-term memory as well as coupling multiple types of stimuli to a single response. The less promising areas, in contrast, are those with a heavy reliance on traditional control based on microelectronics or electrical circuits alone. These current technologies, are limited by a lack of integration and do not fully utilize the inherent properties of soft or biological-based materials. A complete shift in methodology is required to truly achieve the vision of "cognizant matter." While incremental improvements of existing techniques are certainly needed, this field must move beyond simple passive stimuli-response paradigms and towards active self-regulating systems. This does not simply mean achieving more efficient sensors or actuators but building complex, interactive systems where non-linear phenomena are used as "computational units" together with a memory that can be part of the material structure, which in turn can change in a history-dependent manner.

Stochastic thermodynamic information processing

(Cluster 4)

Analysis of Material Intelligence Cluster 4: Thermodynamics and Information

In a Nutshell: This cluster explores material intelligence through the lens of thermodynamics and information theory, often employing abstract models rather than concrete physical implementations. The primary focus is on the energetic costs of computations, stochastic dynamic systems, and theoretical frameworks of self-organization, where the material properties are often implicit or secondary to underlying theoretical principles. Memory here is less about physical storage and more about dynamic states and trajectories through a defined phase space, with transformations occurring through mathematical descriptions of probability changes and free energy minimization rather than localized physical changes.

1. **Distinctive Definition:** The type of 'material intelligence' explored in this cluster can be defined as **thermodynamically constrained informational processing**. It is

characterized by the encoding of information, not primarily within a tangible material structure, but rather within the dynamically evolving probabilities of states or trajectories of a system interacting with a stochastic, thermal environment. These probabilities, often calculated using Markov chains, statistical densities or Lagrangian dynamics, become the 'memory' of the system, while the 'computation' is achieved through a change on the probability distribution or free energy functional representing different possible states over time. The 'actuation' can be considered changes on states from a probability distribution over phase space, and in rare occasions when there exist some type of physical system, it is performed using stochastic energy extraction from a heat bath at constant temperature in a one-step cycle such as a Szilard engine \cite{parrondo_thermodynamics_2015}, where changes in spatial location from a particle within a double well potential is transformed into useable work via an external feedback loop. The main operational principles are grounded in theoretical frameworks such as the Free Energy Principle (FEP) \cite{friston_path_2023, friston_free_2023} or the fluctuation theorem from non-equilibrium thermodynamics \cite{manzano_thermodynamics_2024, ziyin_universal_2023}, using minimal assumptions of physical implementation.
The behavior differs across publications based on the stochastic model used. For example the way memory is perceived, where FEP based frameworks use it as a path history along the system state space, while Markov Chains encode the past in the different probabilities for trajectories in a state space \cite{manzano_thermodynamics_2024}. The parameters influencing those differences are the probabilities for given stochastic transitions or variables controlling path probability with a major focus on the statistical properties of the time-dependent processes. Unlike traditional material intelligence which focuses on the material itself, this cluster's 'intelligent' behavior emerges from external random fluctuations, and the statistical interpretation of their effects on state probabilities with a minimum of design based on material properties. Suitable external stimuli are mainly sources of stochastic fluctuations (e.g, thermal baths) that allow system transitions and enable measurements or Bayesian inference which modify the future trajectory of the systems dynamics. Key criteria for this type of material intelligence include: (1) reliance on probabilistic encoding of information in system states or path trajectories rather than changes on structural or material modifications,(2) reliance on mathematical descriptions as means for information processing and transformation such as Bayesian inference, or fluctuation theory, (3) lack of detailed physical implementation or descriptions of mechanisms and (4) a focus on thermodynamic principles for governing systems state changes.

2. **Core Concept:** The general mechanism across this cluster can be seen as a morphism in a category where the states are abstract representations of information and the transformation acts over those states using principles derived from statistical dynamics or Bayesian inference. The core component responsible for intelligent behavior is the ability to modulate the system's response based on its past trajectory or the time-dependent distribution over possible states. While they are derived from principles of

thermodynamics, or free energy, the core is that these systems are able to *self-organize* to non-equilibrium steady states by changing parameters relating time evolution based on these statistical interactions \cite{dieball_direct_2023, ramstead_bayesian_2023}. This adaptation however is mainly done via mathematical inference rather than any direct physical modification of the system properties.
The architecture is implicitly network-based, either as a Markov chain with discrete states \cite{manzano_thermodynamics_2024}, or, more complexly as a continuous dynamics over generalized coordinates representing trajectories via Lagrangian description \cite{friston_path_2023, friston_free_2023}. The local interactions are defined by transition probabilities in the stochastic process being updated based on external interactions, and not from physical connections. The feedback loops are inherently part of the models, where current computed probability dictates the future probabilistic behavior or changes in the trajectory parameterizations. For building new implementations with real materials, the minimal operational characteristic should be the ability for the material to not only display a change in its properties based on internal dynamics but that this change in turn, modulates the future response of the system as well. The design rule is: *The system must integrate current state information to self-regulate its future dynamic probabilistic behavior without preprogramming*. Any given implementation must also be based on statistical interactions either as transition probabilities between states using thermal baths acting as randomizing sources, or an approximated Bayesian inference using a free-energy based approximation. A minimal design/implementation should be based on a material with two or more stable states that changes stochastically between them due to influence of a thermal reservoir and that also has a capability of changing response (e.g., mechanical, optical electrical) depending on which state (or path) was preferentially being occupied at a particular moment. The output parameters of that system must then become a parameter for future dynamics via a negative feedback or reinforcement learning style response.

3. **Readiness:** The ideal of cognizant matter emphasizes local self-organization, internal memory coupled with action, and continuous adaptation. Current realizations in this cluster fall short of this ideal in several key areas. The most significant failure is that material properties are not explicitly incorporated; systems are abstractly described, using phase space changes (e.g. trajectories) as memory or internal states as dynamical memory rather than physical changes to material composition, morphology, or stress. While some articles analyze active extraction of work in Szilard engine models \cite{parrondo_thermodynamics_2015}, it is limited to a single cycle rather than a continuous process of self-adaptation. All publications rely on mathematical models for computation and feedback, which is far from the “embodied intelligence” framework described in the background. Specifically, the publications mostly lack: (1) long term memory by using material properties, instead it is a Markovian short term memory limited to the time duration of the current stochastic process and the ability to change or modulate behavior based on past interactions, (2) Local feedback and information

processing with any physical component (all processing is done via mathematical computation), (3) multi stimuli response by modular material coupling (almost non existent as all simulations operate with abstract single type stimulus). The "Most Relevant Publications" highlight the use of Quantum materials, or models of cellular interaction with radiation \cite{thedford_promise_2023,scheidegger_modelling_2020}, however those also fail the same basic constraints, as they lack any real mechanism of self sustained long term storage for feedback and operation using only the internal material properties with any active mechanism.
For instance, papers utilizing the Free Energy Principle (FEP) derive complex models based on path trajectories rather that having a physical memory element, and the transformation happens by gradient based processes (or path integration) \cite{friston_path_2023, ramstead_bayesian_2023}. Other papers focuses purely on statistical behaviors in abstract Markovian systems \cite{manzano_thermodynamics_2024,ziyin_universal_2023}. None of these systems are actively creating new forms of functions as a consequence of its past or present interaction and this falls far shorter than the desired self learning, adaptive behavior as described in the definition of cognizant matter that emphasizes the learning by exploration of physical parameters by the material itself, not by an external mathematical algorithm.

4. **Challenges:** The most pressing technological hurdles are the lack of any physical system design. The approaches are mainly theoretical, lacking any real physical realization. Even articles referencing physical processes are still based on stochastic dynamics. Control of material properties is not the focus; instead, the control parameter is the distribution of trajectories or state probabilities during the interaction with environment. There is no integration between the model's output and real-time material function and this lack of physical mechanism can reduce applicability to real-world scenarios. Scaling up becomes also a major problem with this framework, as it will be extremely difficult to have a working material system that replicates abstract principles for free energy minimization, as that might have an exponential increase of parameter states that will limit its effectiveness, as observed on current methods for high throughput software based machine learning systems. The efficiency is also very low, as most implementations require time-consuming simulations often with iterative steps and complex calculations for model fitting or Bayesian inference and those are performed without any physical real-time equivalent and require high computational power without energy minimization due to no physical implementation. Specifically, limitations are: (1) no physical realization of Markov blanket or internal states which are critical for FEP models, (2) no mechanisms to perform parallel processing with coupled local units, (3) lack of time-dependent long-term memory implemented via changes to material structures or properties, and (4) no direct control of thermodynamic parameters, which are instead abstractly defined by the equations for state probabilities, or path trajectories. The "Representative Text Snippets" repeatedly describe the lack of explicit energy transformations, physical memory, and material interfaces.

5. **Reflective Insights:** The analysis highlights a dichotomy between theoretical models and physical implementation. While publications using FEP offer profound insights into self-organization using Bayesian dynamics or statistical mechanics using fluctuation theorems, they remain largely abstract with no real-time physical experimental analog, that limits any practical use as a form of material intelligence implementation. Systems based on stochastic processes (e.g, Markov chains) might be more easily translated into physical systems using specific materials and well known phenomena from non linear physics (e.g. bistability). The most potential lies in focusing on physical systems where stochastic movement becomes a useful parameter and may lead into new material designs as it is a natural phenomenon that does not require complex mechanisms. The least potential is in those approaches using purely abstract models, without material embodiment. A gradual shift in methodology toward a more practical design is needed, from the use of mathematical equations as components, toward using those same equations for designing new architectures based on material physics, even if with an initial minimal implementation that can allow to measure its real performance. The framework of "cognizant matter" relies on mechanisms where the material should create its own memory and processing via internal dynamics using local physical rules, not via external mathematical computation. The reviewed publications offer mathematical and theoretical tools which could potentially be used for such implementations (e.g. using self-organization to NESS), but these must be tested explicitly with specific material components and an action-response loop that goes beyond simulations. The central limitation is the absence of any self-evolving dynamical feedback loop that involves material components rather than abstract mathematical variables. A physical implementation of information storage as a multi-stable material property with a time-dependent coupling to sensing and actuation remains the key challenge that cannot be addressed by any of the reviewed approaches. The materials must "feel" themselves while interacting with environment and their own internal parameters or states so they can modify the process, this requires a totally different mechanism than is presented in these papers.

Electrically Modulated Conductance Memory

(Cluster 5)

In a Nutshell: This cluster describes a type of material intelligence primarily realized through memristive devices and analog circuits, where electrical signals are used to modify material conductance, which then serves as a form of information storage and processing. While these systems exhibit memory and some level of computation through analog current flow and simple operations via Ohm's and Kirchhoff's laws, their intelligent behavior is limited by dependence on external control, lack of dynamic temporal processing at material level, and a simplified signal transformation without internal complex feedback. The implementations, while energy efficient, do not feature self-regulation or adaptation beyond pre-programmed parameters.

1. **Distinctive Definition:** This category of material intelligence is characterized by its reliance on electrical energy to modulate material conductance, thereby encoding information within the resistive state of devices. Key to their operation is the use of voltage pulses to induce changes in electrical conductivity, primarily through mechanisms such as conductive filament formation/dissolution in memristors \cite{yao_fully_2020,yang_memristor_2022}, crystalline-amorphous phase transitions in phase-change memory (PCM) \cite{langenegger_-memory_2023}, and ion migration in atomic switches \cite{kuncic_emergent_2018}, polyoxometalate (POM) complexes \cite{tanaka_molecular_2018}, and nanowire junctions \cite{loeffler_neuromorphic_2023,wan_artificial_2020}. The primary universal feature is the transduction of electrical signals into changes in material electrical properties which are directly coupled to signal transmission via Ohm's and Kirchhoff's laws, and thus the resulting analog current flow. While the materials and specific mechanisms vary, the core principle involves storing information as resistance/conductance with similar approaches for retrieving this by measuring current upon voltage application and that is used for analogue computations. The difference lies mainly in the specific materials employed and the time constants associated with their conductive state changes, resulting in specific read-out dynamics. For example, memristors used in \cite{yao_fully_2020} operate by changes in the conductive filament of Hafnium Oxide, showing quantized states while PCM devices are modulated by phase transitions induced with similar voltage stimuli \cite{langenegger_-memory_2023}. Atomic switches relying on Ag bridge formation have a stochastic behaviour with an inherent time dependence for the ON and OFF states. Similarly, POM complexes change oxidation states, also with a temporal component for charge retention \cite{tanaka_molecular_2018}. These variations in material physics lead to different device response speeds and memory retention times. External electrical stimuli, particularly voltage pulses, dominate as the appropriate input means for signal control for all the described systems, sometimes with an addition of light \cite{wan_artificial_2020}. The most influencing parameters include voltage pulse amplitude, pulse width, and the material's intrinsic properties that dictate the mechanisms of conductive response. The parameters modulate the degree of formation/dissolution of conductive pathways/states, and consequently, the resulting electrical current output. This defines the distinctness of this type of material intelligence. It can be summarized as electrical-stimuli-modulated conductance change that results in memory functions and signal transmission, with material-specific properties modifying kinetics response.

2. **Core Concept:** Within a Category Theory perspective, this cluster's material intelligence concept can be viewed as a transformation of electrical input into a material's conductive state output. The common thread linking these implementations is the mapping of electrical energy to variations in material conductivity. This is done with external voltage

as input and a change in conductance (resistance) as the output parameter, as a core mechanism. Essentially, any component can be viewed as an object representing a memristive device or analog circuit element. The external signal (voltage) is a morphism acting upon that object causing it to transition to another state with different conductance values (the transformed object) and then used as input for another transformation in the system. The network (or system architecture) can be viewed as a series of connected objects that receive and transmit current following Ohms and Kirchoff laws in parallel. The "intelligent" behavior arises from the physical changes of material which dictate the resulting conductance values, or a sequence of those values. These internal changes are produced by the aforementioned physical effects under voltage stimulus and with some retention time. In particular, for all the above, the electrical current is determined by material physical property and is also the mean to perform signal transformation used as readout. Information input, storage and readout depend on the material system's local changes in conductive state directly. This contrasts with a digital system where all calculations are done post-sensing, separate from material intrinsic properties. The architecture in most cases exhibits a modular or network structure \cite{yao_fully_2020,kuncic_emergent_2018,yang_memristor_2022,loeffler_neuromorphic_2023,wan_artificial_2020}, with memristive or resistive components or transistors connected to form arrays. Though these arrays allow for parallel processing using analog current, the fundamental mechanism lacks locally derived feedback loops between individual units. This is, however, observed in some cases between different layers of a network using external controllers and computer for selection of parameters applied within the physical system \cite{langenegger_memory_2023,stern_training_2024,srinivasa_criticality_2015,yang_bicoss_2022}. Typically the system evolves its internal resistance (conductance) using feedback but based on external information or with external controllers. A minimal design rule can be defined as: "Each device changes its local conductance state based on the application of an external electrical voltage stimulus, retaining this state for a certain duration. This state can then modulate the flow of current through a network or device by direct coupling of device readout via Ohm's law". A minimal implementation could involve a crossbar array of memristive devices, where each device's conductance can be independently modulated from an external electrical bias. The network output would be measured by the resulting output current at each device or summed at array output. A necessary component for any type of "intelligent" behavior will be to have a long retention time (which is in general available on this class of devices) , where any information should be stored without need for constant application of external energy, for a long period but not infinite. The memory function here is given by the device's physical structure and its corresponding electrical states which dictates memory capabilities and time scales of operation for each type of device.

3. **Readiness:** While the publication cluster demonstrates promising steps toward material-based intelligence, they remain significantly removed from the ideal of "cognizant matter"

as defined in the background. All of the described implementation have limited autonomy. While the devices within this cluster demonstrate memory via resistance changes and perform basic computations with analog current as described from \cite{yao_fully_2020} and also with basic logic operations by \cite{langenegger_-memory_2023}, they still require external digital components or a computer system for control, data digitization, and parameter setting. For instance, \cite{yao_fully_2020,langenegger_-memory_2023} use external CMOS circuits for programming conductance states, and an external analog-to-digital converter (ADC) to process output current levels. Similar dependencies are also found with artificial sensory memory devices using resistive switching elements but they respond in simple schemes without any feedback, as described by \cite{wan_artificial_2020}. Another example is the BiCoSS system described by \cite{yang_bicoss_2022}, which utilizes external FPGA chips for simulating neural dynamics and requires external power supply. These designs lack local feedback loops and internal signal processing as a result of local material parameters and structure. Information processing and the definition of its output relies on a hard coded calculation that occurs outside the material, where only electrical signals are transformed into other electrical signals.
This is clearly stated by \cite{yao_fully_2020} where "The key is that the weight data is not transformed, only the incoming voltage signal.". These devices primarily show stimulus-response behavior rather than genuine adaptation and lack self-regulation, where they respond in a pre programmed and predefined way instead of using its internal material state. For example, in \cite{langenegger_-memory_2023} a "winner takes all (WTA)" activation function was used which is explicitly stated as being externally implemented, showing a clear dependency on external control. The most crucial limitation is the absence of local computation that is not just threshold switching. The systems operate based on Ohm's and Kirchhoff's laws, where the current flow follows pre-determined pathways without any local alteration for computing. Also memory is mostly stored as "static states" of resistance without active structural changes coupled to material responses, with the exception of devices that use atomic switch or POM complexes \cite{kuncic_emergent_2018,tanaka_molecular_2018}. As an example in \cite{srinivasa_criticality_2015}, there is a claim of "self-tuning" to critical behaviour, a core feature for a truly decentralized design, however, it is not detailed how it happens or if it is indeed using an external computer or feedback to find those parameters, rather than letting system to evolve by itself as an intrinsic property. Thus even in systems where a form of "learning" occurs, such as in \cite{stern_training_2024} and \cite{loeffler_neuromorphic_2023}, the "learning" is externally imposed via clamping, thus not representing a full adaptation. Thus, while these systems may exhibit sophisticated analog calculations and some basic temporal memory, they do not embody complex active feedback with a learning parameter encoded into system dynamics as required for a truly cognitive mater, as stated in the background information .

4. **Challenges:** The analyzed examples present several key challenges. Controlling material

properties at the nanoscale with required precision is a significant technological hurdle. The reproducible formation of conductive filaments, crystal phases or uniform ion diffusion pathways is a major limitation for proper control of memristive or ionic devices. Fabricating memristive structures with a high degree of uniformity and low defects that results in high yield is also difficult \cite{yao_fully_2020,langenegger_-memory_2023,wan_artificial_2020}. Device stability and robustness, particularly in variable environments, poses a major concern. For instance, \cite{yao_fully_2020} show that memristor conductance "can drift over time" and is influenced by temperature and other environmental parameters. Scaling up these implementations to larger networks while maintaining device homogeneity and consistent performance across all components is another hard technical issue, while limiting its functionality to smaller systems \cite{yang_memristor_2022,kuncic_emergent_2018}. The efficiency of these systems is also not yet optimized. While they demonstrate low energy consumption as compared to classical digital devices that have to convert all inputs and output to digital form, the analog implementation in systems described by many publications here \cite{yao_fully_2020,langenegger_-memory_2023,mead_neuromorphic_1990,wan_artificial_2020} are very sensitive to external parameters which requires complex setups and control parameter values, and they also lack any self-regulatory mechanisms. The production of these devices often involves complex, multi-step fabrication processes requiring precisely controlled conditions, and use of specific materials and thus limiting scalability and cost reduction \cite{yao_fully_2020,langenegger_-memory_2023}. Specifically in \cite{wan_artificial_2020}, the devices use different materials and structures for sensing and memory. The lack of a unified material approach will limit its integration and scaling up. Furthermore the reliance on electrical voltage pulses as external control signals only, limits its design flexibility as a truly "smart" material for multi stimuli-response. Those combined limitations may hinder further development of these systems. Systems described by \cite{stern_training_2024} and also using memristors for training based on power minimization show some form of internal feedback, however, it fully relies on electrical gradients and external voltages as input, and it does not actively respond or interact to the environment in real time with no other parameter change besides the electrical input.

5. **Reflective Insights:** The analyzed publications reveal both common approaches and contrasting limitations. A key similarity across several areas is the emphasis on memristive devices, and transistors as primary functional elements for implementing memory and simple analog computations. Those devices can store long lasting information when not powered as they rely on physical changes of their internal structure or ion distribution, and have a wide flexibility in material selection allowing for tunability of kinetics response. However, they all share a common limitation, the lack of temporal response for internal physical parameters that cannot evolve based on its own response to the environment. Another key point is the use of voltage to control the different state,

with limited possibilities for multivariable parameter control. There are still significant steps to be done to encode complex temporal information via parameters other than digital read outs. A critical shared limitation is the strong dependence on external control, which is required to set up and train all these system. In addition, information encoding is usually implemented through changes of electrical resistance values, and not through other parameters, while the transformation of information is limited by simple electrical laws (Ohm and Kirchhoff), thus a much more physical material implementation including for example mechanics, or chemistry instead of only electrical current flow is required. The devices typically lack the ability to perform local analog computation or self-regulation, as there is no internal feedback beyond threshold switching, nor any autonomous signal processing independent of external control, creating an obstacle for development of more advanced systems. While some solutions are innovative, such as the proposed use "of stochasticity as assistance" in PCM devices as stated in \cite{langenegger_-memory_2023} or the incorporation of some device physics as analog computing via Kirchhoff law, these examples do not reach beyond a simple "stimulus-response" behavior, without real learning capabilities or self-regulation. It becomes apparent that a full shift from a digital or analog electronic implementation toward a more material-based design should be taken to generate more complex behaviours. The major bottleneck is the absence of truly local operations and local feedback by material property changes. A central issue is to move from a system where parameters are externally defined and controlled toward systems that uses only local feedback driven by physical properties, such as those seen with self assembling systems in molecular components or active materials and that it also includes complex time dependent behaviors. Future directions should focus on developing materials with internal, analog computing capabilities, where information processing and signal transduction can be performed locally and without external digital components or software. There is a strong need for a more complete and radical shift in design that considers material self regulation as a core element that will enhance functionality by minimizing external dependencies, and that means also using parameters other than electrical voltage for signal transformations. While there is a lot of potential for further evolution, it is clear that present approaches are limited in generating true adaptable intelligent devices. An incremental change by adding more components will not solve this issue. A complete shift in knowledge is required in a new type of materials development that goes from considering material just as a substrate or components, into a core element for computation and processing with an active feedback with its environment. The focus should be given to intrinsic and dynamical behaviour of matter rather than its electrical read-out for effective implementation in the future.

DNA hybridization based systems

(Cluster 6)

In a Nutshell: This cluster represents a type of material intelligence driven by DNA hybridization, where temperature, chemical concentrations, or electrical fields serve as external modulators. These systems encode information in DNA sequences and their resulting structural states (assembled/disassembled), using thermal, chemical, or electrical energy to induce changes in configuration and organization. While they display responsivity and some limited forms of memory, they lack active local computation, feedback loops, and long-term adaptive behavior.

1. **Distinctive Definition:** The defining characteristic of this type of material intelligence lies in its reliance on DNA hybridization as the core mechanism for sensing and actuation. Information is encoded within the nucleotide sequences of DNA strands, which dictate complementary interactions and structural changes based on external conditions. These changes, often manifested as aggregate assembly/disassembly \cite{angioletti-uberti_re-entrant_2012, hadorn_specific_2016, mcmullen_self-assembly_2022, lee_shape_2022} or conformational changes \cite{he_peptide-induced_2018, dawson_differential_2023} are induced by temperature \cite{angioletti-uberti_re-entrant_2012, hadorn_specific_2016, mcmullen_self-assembly_2022, lee_shape_2022}, chemical concentrations \cite{he_peptide-induced_2018, dawson_differential_2023}, or electrical fields \cite{zhang_nanopore_2022}. The primary stimuli for these systems are those that modulate DNA hybridization: temperature, ionic strength, pH, or electric potential. The external stimulus sets a global parameter for the entire system which results in a defined state. The information flow is predominantly unidirectional, from input stimulus (temperature, chemical concentration, electrical field) to output structure change, although some systems also include output of optical signal \cite{lee_shape_2022}. This distinguishes it from other types of material intelligence which include local processing, feedback, or multi stimuli responsiveness. This class also relies on reversible thermodynamic processes, resulting in an equilibrium that, due to design constraints, do not require further energy input to maintain an ‘on’ and ‘off’ state as the driving force of most of the transformations described are exothermic reactions and structural states that are stabilized by a reduction of overall system free energy. A key universal feature is a design that allows these mechanisms to work without requiring a digital controller.

2. **Core Concept:** Within Category Theory, the central concept could be described as a morphism from an input parameter state (e.g., thermal energy level, chemical concentration, electrical potential) to a structural output state (e.g., assembled aggregate, deformed material, change in optical properties). The core mechanism is the change in Gibbs free energy associated with DNA hybridization, which is influenced by environmental parameters. The basic implementation components are (1) DNA strands with sequence-specific design, (2) a support material (nanoparticles, droplets, lipid bilayers or microcrystals) where these DNA strands are anchored, and (3) an external energy source to operate as control parameter. The "intelligent" behavior arises from the deterministic transformation between the input parameters and the final structural states

defined by DNA sequences and their binding affinity under that condition. The presented architectures are mostly self-organized, however, the structural organization is usually defined at a design stage and the self assembly is only a single step at a time driven from the initial external stimuli, which does not offer any self organization driven by internal feedback. Feedback loops, in the true sense of active modification of responsiveness as a result of prior interaction history, are generally absent with very few exceptions of a limited form. A minimal design rule would be based on designing DNA sequences that, when exposed to specific environmental stimuli either through an imposed external parameter or internal environmental change at the molecular level, would result in a thermodynamically preferred structural change. Minimal operational characteristics include sequence specificity, a tunable response via controlled external variables like temperature or chemical concentrations, and an output signal accessible by an external measurement technique such as, optical microscopy, microfluidic devices or electronic readouts. For instance, a “minimal design” could involve DNA functionalized nanoparticles on a substrate which will form reversible aggregates upon decreasing the temperature due to the increase in hybridization free energy and disassemble upon increasing the temperature \cite{angioletti-uberti_re-entrant_2012, hadorn_specific_2016, mcmullen_self-assembly_2022}. This system is minimally complex, requiring only temperature control and sequence design, to achieve assembly and disassembly, as the input parameters are thermodynamic quantities that are available by controlling external temperature, while assembly and disassembly is obtained from molecular forces based on sequence that leads to hybridization or its absence.

3. **Readiness:** Comparing with the ideal of "cognizant matter", as described in the background, these examples fall short in several key areas. While they demonstrate responsivity to external stimuli and some cases, a form of memory (mostly structural memory or volatile state preservation), they do not exhibit local computation or fully developed feedback loops that actively modify future behaviour. These systems are usually designed to reach a predefined outcome via external control and follow mostly linear processes with a very limited dynamical range \cite{mcmullen_self-assembly_2022, lee_shape_2022, dawson_differential_2023}. For example, the most relevant publications described a system with nanopore based DNA detection with electrical potential as external driver and this system also employs digital memory stored at the single molecule level, coupled with DNA displacement, to obtain logical operations \cite{zhang_nanopore_2022} however this system relies on external electronic control to operate and have only short term volatile memory. The systems described within cluster also lacks multi stimuli response, local low power computation, or embodied systems with multiple properties that feedback each other to develop complex behaviors, instead relying on direct passive responses. For example in \cite{kim_nanoparticle-based_2020} the nanoparticles react to the input instruction DNA signal without any further processing or feedback related to the current or prior state of the nanoparticle. The systems described in the cluster also lacks self regulating components. Furthermore none of the

examples have the capability or the flexibility to perform active sampling or change its processing or memory during operation, to achieve better performance at a latter point making them limited systems compared with the standards of a "cognizant matter". The 'Probabilities for Each Document', indicates that all publications within the cluster have the highest probability match with topic number 6. Also, the 'Distances of Each Publication to the Cluster Centroid' indicates that, despite the different systems, they have a tight organization as they all fall within a close range. This indicates that they are mostly representative of this type of material intelligence, which is based on DNA hybridization.

4. **Challenges:** A critical challenge lies in the limited control over the intermediate states of DNA hybridization. While sequences can be designed for specific binding, the kinetics and pathways during assembly or dissembly are difficult to manipulate in a precise way, since their dynamics are limited by diffusion process and can only be guided through external parameter changes. Fabrication is also limited. While DNA self assembly is a scalable technique, the integration of these DNA systems with other materials with different size/components is challenging. Stability tends to be limited in this category. Most systems studied are designed to operate within liquid environments within specific temperature and concentration limits. Environmental changes outside their design limits can results in a collapse of the operational output and may not be reversible. This directly relates with system robustness as they usually lack internal feedback components that may change system parameters during operations for a better output. Scaling up or creating more complex structures presents significant hurdles, as it requires precise control and optimization of diffusion rates, binding kinetics and DNA properties for each step and each particular component of these designed systems, which might not scale linearly with system size or complexity. The efficiency of these implementations is also limited. The use of DNA systems requires complex steps for their production and has high cost and time. Finally, as most systems operate passively and through external setting parameters such as temperature, concentration or electrical fields for operation, energy efficiency is low as they do not actively harvest energy from the environment but instead consume energy to maintain state (as for a specific temperature) or have a limited temporal operation window where all processes are only thermodynamically favorable within a short window of time.
   In the case of the nanopore system \cite{zhang_nanopore_2022} its operation depends on precise microfabrication and external control and while the components are very versatile, the entire device has complex system integration and requires complex read out devices and it is therefore very difficult to perform complex operations or make this system with scalable technologies. Similarly another limitation is that for the majority of the systems tested the action and memory (or information storage) are both passive, limiting even further the range of possible applications or the range of operational conditions. For instance, in structural memory, for instance the change in the state of the material after interactions with external stimuli does not modify the type of response in future

interactions. A temperature triggered reversible state change will always be reversed by temperature, without having the capacity to change the action based on any form of record of prior history.

5. **Reflective Insights:** Despite the diversity of specific implementations, a common theme arises: the reliance on sequence-specific interactions of DNA to achieve functional outcomes. This common ground highlights that DNA hybridization can direct self assembly to create a variety of different functions with a minimal set of components. A key link is also the realization that these systems are strongly constrained by equilibrium thermodynamics limiting their ability to perform active functions that might modify future responses instead of simply responding in a preprogrammed way. Although different external parameters or stimuli are used to control and operate their functions, these parameters also dictate the system operations, without any degree of response. The systems are still passive and their complexity is limited by the linear response from the systems. From another perspective, although structural memory based on deformation or conformation is indeed obtained in several examples, that 'memory' is only a direct result of design and not a dynamic component that can 'record' or change the system function based on its prior behavior. It remains as a static state and does not represent an active memory for future function unless an external trigger 'activates' that functionality in a time scale which does not involve the system response itself, just the experimental or application time frame. The areas with the least potential in the short term are based on the systems that rely on external digital control such as the nanopore, as they are not designed based on the principle of local control and autonomous operation. Further advancements on this area should explore systems which use more than one stimuli to drive system behaviors and have active memory where prior responses modifies the material properties, or active internal responses that go beyond a threshold and they all operate via different time scales, by using physics to generate more complex behavior. While incremental improvements can help in the scalability of current designs or the stability of components, a significant shift towards designing system that does not focus only structural state changes, or passive responsivity, and external stimuli alone will be essential for creating true complex dynamic system capable of self regulation, adaptation and autonomous operations with minimal dependency of external control. The field should explore designs of materials that use internal property as the main driving force of the material operation, with minimal dependency of complex external programmed devices to achieve this objective by using more than simple reversible process and instead creating a non equilibrium states with non linear dynamics.

Fluidic magnetic particle memory

(Cluster 7)

In a Nutshell:

This cluster of publications explores a type of material intelligence characterized by the dynamic manipulation of magnetic particles within a fluidic medium using external magnetic or electrical fields. Information is predominantly encoded in the spatial arrangements and electrical response of the particles, with actuation achieved through hydrodynamic forces, magnetic torques, or induced changes in complex impedance. These systems leverage physical interactions and material properties to display transient, and in some cases, hysteretic behaviors influenced by prior stimulus without employing traditional digital architectures.

1. **Distinctive Definition:**

This category of material intelligence is defined by the use of magnetizable micro- or nanoparticles within a fluidic medium, where external magnetic or electric fields induce changes in particle arrangement and dynamics, which are then utilized to encode information and perform simple operations. The systems predominantly process information through changes in physical states of the medium including spatial arrangements \cite{hu_shaping_2019, wang_collective_2019}, or by electrical impedance changes \cite{ceron_programmable_2023, crepaldi_evidence_2022, crepaldi_experimental_2023}. Sensing relies on detecting changes in spatial configurations, fluidic flows or through shifts in impedance, primarily using RF signals. Actuation mechanisms vary across implementations but are mostly related with hydrodynamic forces generated by particle motion, magnetic torques, or voltage-driven particle displacements. In some examples, chemical reactions within the fluid are used to influence particle dynamic. These behaviors are primarily driven by direct physical changes induced through external fields and, in some examples by the local chemical environment. There is no specific “sensing element” different from the actuating medium itself. The difference between these systems is that some create collective flows to achieve global organization whereas other use changes in particle arrangements to record signal (or both together). The behavior and response are mainly influenced by parameters such as the amplitude and frequency of the applied fields, particle size, concentration, and the properties of the surrounding fluid such as viscosity and ionic composition. The most suitable external stimuli for these systems are oscillating magnetic fields, DC or RF electrical fields, and, in few cases, chemical changes in fluid environment (fuel molecules). The criteria for characterizing this type of material intelligence include (1) the use of magnetizable particles dispersed in a fluid, (2) actuation based on external or local field modulation (magnetic or electrical) or chemical reactions (3) information encoded in the dynamic spatial and configuration or local impedance of the medium and particle components, and (4) signal propagation using the physical forces or medium properties and interparticle interactions to control action.

2. **Core Concept:**

In terms of category theory, the core concept can be viewed as a functor that maps external field inputs (magnetic or electrical) and initial particle distribution states to output states, with a physical medium acting as an information processing structure. The shared principles include the reliance on magnetic micro/nanoparticles as actuators/memory elements, coupled with dynamic fluidic medium for action, a physical medium for mechanical coupling or as a form of electrical feedback, an external field as external global control signal and the use of material properties to transduce information into dynamic systems properties and read output. The component that is core for "intelligent" behavior is the dynamic interplay between external fields (or internal chemical forces) , particle interactions, fluidic environment, and the resulting changes in spatial configurations or electrical impedance. Across the whole series of papers described all the systems use externally imposed control parameters and non-equilibrium physics to drive action. The architecture is more self-organizing than modular, where global behavior arises from local interactions and the responses at each region depends on parameters that evolve as the system operates over time. The systems that uses magnetic disks \cite{khalil_precise_2015,wang_collective_2019} also generates networks. The minimal design rule for this class of material could be defined as: "*a field-responsive material, consisting of magnetic particles in a fluid, configured to transform external field input into a dynamic spatial configuration or changes in impedance that then acts directly as a readout of action or a memory element*". Feedback loops are implicit rather than explicit, derived through direct physical coupling – for example, changes in particle distribution or bubble growth altering local forces in the liquid phase or impedance altering electric fields. A minimal implementation might include a ferrofluid with embedded magnetic particles within a microfluidic channel, subjected to an oscillating magnetic field that defines particle response, which could then have electrical readouts or fluid flow output as a feedback mechanism. The system memory would rely on hysteresis of changes in particles distribution, a mechanical feedback (such as droplet changes induced by magnetic forces) or electrical impedance to be used for controlling further action.

3. **Readiness:**

The current implementations are several steps away from the ideal of "cognizant matter" outlined in the background information. While they exhibit some form of responsivity and, in a some cases, an internal memory (such as long term impedance changes or structural configuration), they lack the self-regulation, dynamic adaptation, and local computation to enable a proper form of embodied intelligence. For example, in \cite{hu_shaping_2019} and \cite{wang_collective_2019}, the systems generate complex behaviors but fail to show any ability of self-adaptation, instead relying on external oscillating fields. Most of the "memory" in this case is a transient property of particle position that fades as soon as actuation stops. Crucially, all implementations, including those related to electrical response of ferrofluids \cite{ceron_programmable_2023, crepaldi_evidence_2022, crepaldi_experimental_2023}, lacks active feedback loops for system self improvement. The systems typically do not use past information to choose a particular action, but mainly respond in a predictable manner. For example, although the ferrofluid system \cite{ceron_programmable_2023, crepaldi_evidence_2022, crepaldi_experimental_2023} show long term variations of impedance based on prior pulses, these variations do not directly feed back into the next response by creating an implicit rule within the memory device itself. Instead there is only a change of the output characteristics for a given type of stimuli. The presented systems can record information, but cannot change behavior or select a new operation mode based on those records. There is, for example, no mechanism for “learning” from past interactions to optimize the system’s functionality. Most of the presented information storage is a result of structural re-arrangements not an external signal. Furthermore they do not show intrinsic low power local computation without external control, which represents a major limitation for moving towards real material intelligence. Overall systems lack real autonomy as, in most instances, they rely completely in externally defined parameters.

4. **Challenges:**

The critical technological challenges involve the precise control of material properties at the micro/nanoscale, especially in achieving complex hierarchical organization with self-organization while at the same time providing reproducible and robust responses. While some systems show some form of “memory” which has a certain hysteresis, which should be seen as a more of a temporal transient effect, not true temporal information retention of prior states. Fabricating structures with high complexity and stability that does not rely only on external input, represents a major hurdle. The examples reveal that some implementations depend on highly specific environmental conditions (liquid viscosity, interface properties) which limit their general applications. The main limitation, derived directly from the examples is that (a) information processing relies on external parameters set through external programming or by external forces (b) that memory is not active nor has a function by itself but only by a direct coupling to external parameters and (c) there is a lack of self-regulation or self adaptation of any process once it starts. The energy efficiency of most systems remains low, as they do not operate in “close loops” by using “reusable energy” or by exploiting thermodynamic gradients. Scalability of manufacturing also remains as a huge obstacle. Additionally, the lack of local feedback loops prevents systems from evolving beyond simple, reactive behaviors.

5. **Reflective Insights:**

The publications in this cluster demonstrate the potential of using simple physics to create a material response where the mechanical or electrical properties of a liquid can be used as a physical read out. However both approaches (electrical readout via impedance and mechanical coupling by rotation or particle aggregation) have very strong limitations of self-regulation and therefore do not provide a pathway for the implementation of complex intelligent behavior. The cluster highlights that while it is possible to create dynamic behavior and to record parameters of past interactions, there is still the need for a different approach that would allow to build a systems that “learn” by creating implicit rules that can define system output, by changing internal structures via local feedback or other means, and that use the materials themselves to achieve that. The minimal approach of this cluster, based in material responsiveness via electrical properties or field actuated forces can work in a range of specific applications that do not require high degree of adaptability, but moving towards a higher degree of “material intelligence” will require shifting from the design of individual components, or from linear systems in that each part has a specific, pre defined, function, into a new paradigm that allows to integrate all functions into one material, where responses are determined by the material interactions and not by a pre programmed or externally controlled action, and that have locally defined feedback implemented in the material structure by itself. Specifically systems that can move on their own, and that have the ability to make a selection of responses would represent the next level rather that material that simply respond to input parameters set from outside. The area with the least potential is the current “responsive materials” approach while most promising is to develop methodologies to encode memory as part of the action itself, with local feedbacks to alter internal state that can influence future actions, together with the implementation of active components to produce non-reactive behavior. This represents a major shift as currently no such material exists, and will require new methodologies and materials science expertise, not by an incremental improvement of current techniques.

Kinetic protein based intelligence

(Cluster 8)

In a Nutshell: This cluster of publications explores material intelligence through biochemical systems, primarily focusing on energy transduction and information processing in protein-based networks. This "molecular intelligence" is characterized by dynamic, analog information processing encoded in kinetic rates, protein concentrations, and structural configurations, rather than discrete digital states. These systems utilize chemical energy to drive non-equilibrium processes, impacting substrate selectivity, signal transduction, and light emission, displaying rudimentary adaptive behavior without relying on external control or explicit, long-term memory in a passive or "digital" sense.

1. **Distinctive Definition:** This specific type of material intelligence, which we shall term "Kinetic Protein-Based Intelligence," can be rigorously defined as a class of systems that achieve information processing and rudimentary adaptive behavior through the dynamic regulation of chemical and energy fluxes within networks of interacting proteins and biomolecules. Key mechanisms include: (1) **Information Encoding:** Information is not stored in persistent states, as in conventional electronics, but is encoded in kinetic rates of biochemical reactions (e.g., enzyme catalysis, phosphorylation rates) \cite{govern_optimal_2014, yu_energy_2022}, protein concentrations, interactions and binding affinities \cite{chen_synthetic_2024}, or structural configurations of protein

assemblies \cite{babcock_ultraviolet_2024}. Spatial arrangement also serves as a way to store "structural information" \cite{babcock_ultraviolet_2024} (2) **Energy Transduction:** Energy, often derived from ATP hydrolysis or light absorption by proteins, drives systems out of thermodynamic equilibrium, sustaining non-equilibrium states that enable processes such as signal amplification, substrate discrimination, and molecular synthesis. This transduction is crucial in overcoming time-reversibility limitations and in creating a kinetic bias in the system, favoring certain outputs over others \cite{govern_optimal_2014}. (3) **Analog Processing:** Information is processed through analog mechanisms, such as continuous changes in protein concentration or modification states, rather than digital switching. Signal propagation occurs through molecular collisions, binding events, and the cumulative effect of many locally stochastic events within a network with integrated dynamics with a timescale dictated by chemical reaction/diffusion constants, which represents a form of minimal or "physical computation" directly linked to its architecture. The systems identified are designed to operate mostly passively, responding to external inputs such as chemical ligands \cite{govern_optimal_2014}, UV light \cite{babcock_ultraviolet_2024} and chemical gradients \cite{yu_energy_2022}. However the nature of responses are often determined mostly by the internal kinetic parameters, which can be modified by input stimuli but are not directly controlled by external factors. A key influence parameter involves initial concentrations of the key molecules/enzymes, rate constants or intensity and frequency of the light. The output behavior is largely dictated through the system's inherent design properties derived from kinetic rules, physical properties and protein interactions. The external input is mainly used for "modulation" of operation or to switch between different modes. The most suitable external stimuli often include chemical signals that modulate binding or catalytic activities, and photonic input that can generate excited states, both which can then propagate the "information flow" within the molecular network.

2. **Core Concept:** In a category-theoretic sense, this cluster represents a category of "molecular information processors," with objects being distinct biochemical networks exhibiting similar functionality, and morphisms representing how these networks map inputs (stimuli) to outputs (chemical modifications, light emission, substrate selection) by means of kinetic parameters and physical constraints \cite{wills_reflexivity_2019}. The core mechanism for 'intelligent' behavior is the transformation of external and internal inputs into alterations in the network itself. For example: the chemtaxis system of E.coli, where the external ligand concentration is transduced internally by the dynamic changes in the ratio of levels of two types of proteins (x and xp), acting as an analog signal coupled to further molecular changes via an active response of phosphorylation, which represents a form of low power computation based on chemical reactions \cite{govern_optimal_2014}. Conversely, kinetic proofreading is a signal processing approach where differences in enzyme binding kinetics for correct and incorrect substrates, also driven by an external energy source, provides a clear physical mechanism of selection and data handling. The protein based system is designed for a

specific task which is performed by kinetic discrimination based on reaction rates where molecules are only "selected", rather than "programmed" to perform an action which means a change in the environment parameter would not generate a totally different function but just an attenuation or selection of the same reaction.
These systems generally present a self-organized architecture. The interactions between components emerge spontaneously from physical and chemical principles inherent to the materials. Architecture emerges rather than being defined through a predesigned network, and the function is dictated through a system parameter based on the molecular physical architecture and binding rules \cite{chen_synthetic_2024}. A minimal design rule for such architecture is local coupling among all components, that implies no long-range communication (but a local interaction between proteins), non-linear responses (that creates a bias for specific output or action), coupled feedback (where any change in a system parameter should also affect performance or output at any level), and low-energy transduction (where energy is only dissipated for a given purpose, instead of random dissipation) through kinetic parameters. The most common feedback mechanism emerges from the internal dynamics, in which the system's own output alters its internal state, with direct influence on the next step. In the chemotaxis system \cite{govern_optimal_2014}, the output is not stored for future action, but it does modify the next step in the system's cycle of sensing and response. A minimal implementation of such design could involve a system of coupled enzymes where, for example, the product of one enzyme acts as a substrate for the next, creating an analog signal processing with a local feedback loop. The rates of enzyme reactions, therefore, act as memory device that influences the final output, with energy supplied to maintain the systems in the required non-equilibrium state. This minimal design implements a localized self-sustained low-power process without the need of external control.

3. **Readiness:** The current realizations in this cluster, while insightful, fall short of the ideal "cognizant matter." Following the principles outlined in the background information, several gaps become apparent: (1) **Limited Long-Term Memory:** While these systems demonstrate short-term or "kinetic memory" encoded in changes in substrate selectivity or phosphorylation states \cite{govern_optimal_2014}, they lack mechanisms to store and consolidate information over extended periods without continuous energy input. The memory is tied directly to the current state and interaction and is modified or disappears in next cycle. As stated by \cite{wills_reflexivity_2019}, this "static/structural" memory is not coupled to a time dependent and autonomous action. The described systems are also limited by the reversibility of reactions involved. (2) **Absence of Local Computation & Autonomous Operation:** Although these systems perform signal processing through chemical and optical interactions, the computation is limited. They lack the capacity for local, multi-step processing and autonomous adaptation \cite{chen_synthetic_2024}. The signal is only transduced and flows along reaction pathways and there is an absence for changes in that pathway or modification of internal structure or parameters, based on a previous interaction history. There is no autonomous selection of a reaction, but a simple

propagation of the kinetic bias which does not enable a feedback modulated response, which is considered a fundamental component of adaptive material intelligence. (3) **Lack of Embodied Sensing & Action:** Current implementations are mostly sensing, computing and, in some cases, producing a signal, but cannot perform autonomous physical actions based on the processed information \cite{yang_physical_2021}. While the output of light or change in internal parameters are readouts, they are not directly coupled to an action in the material itself. Feedback loops, in general, are limited by their reversibility and lack "temporal coding". For example the system by Babcock et al. 2024 \cite{babcock_ultraviolet_2024} does not demonstrate any capacity of self regulation of the internal states using the light emission or any other internal signal of the protein network, rather they work only as an integrated system for data generation without an active component for a self regulated physical action, as is needed in active adaptive matter. The described systems are limited by parameters fixed through their architecture and do not show self learning adaptation from those interactions with time, as described in the reference document. The primary limitation is that the system is not performing actions after processing data which is a central feature of truly independent functional operation. This is highlighted by both Yu et al. 2022 \cite{yu_energy_2022}, where the study is limited to a model implementation of cellular energy gradients and by Chen et al 2024 \cite{chen_synthetic_2024} where the designed protein networks are limited to a one step response, rather than more adaptive or feedback mechanisms, which implies a need for a more extensive local processing mechanisms related to dynamic physical changes.

4. **Challenges:** The publications in this cluster reveal significant technological hurdles. (1) **Control and Stability of Biochemical Reactions:** Implementing precise control of biochemical reactions within these systems remains a challenge \cite{yu_energy_2022}. Variations in temperature, pH, or ionic strength can alter protein conformation, reaction rates, and binding affinities, thus affecting the robustness and reliability of the system. A lack of proper homeostatic control at the molecular level constitutes a challenge, that is usually resolved in cells by complex networks based on many feedback pathways that are still not easy to replicate in artificial systems. (2) **Scalability and Fabrication:** Fabricating complex, interconnected protein networks at the nanometer scale is challenging without external control circuits, which are not wanted in the proposed architecture. Self-assembly methods offer a potential solution for scalable fabrication, but precise control of domain size, domain orientation, and arrangement is difficult to achieve. Current methods are also limited by the stability and longevity of active biochemical molecules in long term operation. A complex design with many interacting components that also need to be stable for long period or under complex operational conditions is still a challenge. (3) **Limited Environmental Responsivity and Autonomy:** The current implementations of kinetic protein-based "intelligent materials" are mostly responsive, rather than adaptive. The system only follows pre determined pathways, not giving space for a self modulated response based on previous interactions, and are usually designed for one or few external input conditions (or a range). For example the kinetic proofreading is only capable of

selecting correct substrates, and does not offer any adaptive behavior beyond that fixed response, or has a way to adjust parameters for a more effective and energy efficient operation by a change in the kinetic parameters used for selection. These limitations arise directly from the absence of complex feedback mechanisms and the lack of a time-dependent memory that enables integration of past experience into present action. Such limitations restrict applications, especially in dynamic environments or when the material must adapt to novel types of stimuli and unexpected changes. Moreover, the requirement of a constant supply of energy (e.g., ATP, UV light) or very specific environmental conditions often makes continuous, long-term operation complex with higher costs and reduced flexibility for external operation.

5. **Reflective Insights:** This cluster highlights a promising avenue for material intelligence through the exploitation of the dynamic properties of biomolecules, particularly proteins with their vast structural and functional versatility. The studies reveal a distinct approach to information processing and material actuation which is an alternative to digital electronic systems. While implementations based on chemical kinetics (presented mostly in Yu et al \cite{yu_energy_2022}and Govern et al \cite{govern_optimal_2014}) explore analog processing and molecular selection through interactions with an energy source without static components, the optical systems (exemplified by Babcock et al \cite{babcock_ultraviolet_2024}) explore the concept of collective behavior of molecules, but fail to couple "data generation" with an active output or internal modification. The systems from Chen et al \cite{chen_synthetic_2024} showcase the design of proteinbased systems for information flow but also fail to couple those responses with a local feedback that would enable adaptive response. A major limitation across these systems is an inability of feedback loops from a temporal point of view. Most current implementations are not coupled to systems that evolve with time based on interactions with their environment, and also that none of those responses in material are coupled to an action required to achieve a predefined goal. The common limitation is lack of true dynamic behavior that would enable a self modulated long term memory with action, highlighting the most pressing need for more research targeted to those concepts.
An important future research direction should focus on creating active and truly self-regulating systems that can store memory through material modifications, coupled with internal signal feedback mechanisms. It will be crucial to create systems where chemical or physical transformations not only generate a signal or record an output but to enable a learning processes that can change physical behavior itself via local control by the system. Although these approaches have shown a possibility for "intelligent behavior", they are mostly confined to specific predefined scenarios (chemical selection for kinetic proofreading or transduction of a signal for chemotaxis), thus there is still a long way to go to generate a truly self regulating type of material with adaptation, autonomy and evolution.
Considering the limitations, a full shift in the paradigm of information processing may be needed to truly achieve the intended levels of performance. While incremental

improvements can refine current approaches, a new way to think about physical computation using molecular architectures is needed, along with minimal design rule definitions, that goes beyond standard chemical and biochemical setups with focus on multi-level hierarchical feedback, dynamic long lasting/stable physical memory, intrinsic non linear operation and embodied sensing and action in one single minimal structure.

Topological defect liquid computation

(Cluster 9)

In a Nutshell: This type of material intelligence leverages the self-organization of liquid crystal director fields and topological defects to perform basic information processing and storage. The materials act as analog computers, where the spatial arrangement and dynamics of defects are driven by external fields or internal energy gradients to encode, propagate, and transform data. Memory is transient or hysteretic, relying on the configurations of the director field and persistent topological structures, without explicit digital memory. The systems are strongly coupled with the environmental conditions by their physics.

1. **Distinctive Definition:** This distinct type of material intelligence can be rigorously defined as **topological-defect-based computation in liquid crystals (LCs),** leveraging mesoscopic material properties for information processing through the manipulation of the LC *director field* and the ensuing dynamics of topological defects. These systems utilize the anisotropic nature of LCs, combined with their internal elasticity and external fields to create director configurations and persistent topological defects, such as disclinations or dislocations. Information is fundamentally encoded within the spatial arrangement and dynamics of these defects and is processed through their interactions and reconfigurations. Unlike traditional electronic systems, information is not stored in bitwise data, but as structural patterns, with changes in topological charge, phase and defect position. The systems' response is primarily influenced by external stimuli such as electric fields \cite{sasaki_large-scale_2016, zhang_computing_2021, zhang_logic_2022} , temperature gradients \cite{aya_reconfigurable_2020}, chemical activity, or boundary conditions which determines the initial director orientation and anchoring conditions. These stimuli alter the free-energy landscape of the system, driving local director realignments and the resulting defect movements. Parameters such as the applied voltage's amplitude, frequency \cite{sasaki_large-scale_2016}, temperature gradients, sample geometry \cite{aya_reconfigurable_2020}, and material constants such as viscosities, elastic forces, chiralities, and dielectric anisotropies strongly influence these material dynamics. The fundamental criteria that characterize this paradigm are the encoding of information in the topology of defects, a lack of discrete digital memory and the use of non-linear or analog behaviours to guide information transfer though elastic or hydrodynamic flows and reconfigurations.

2. **Core Concept:** In the context of Category Theory, the core concept of this material intelligence can be conceptualized as a functor mapping a space of stimuli, such as electric fields or thermal gradients, via material properties, into a space of topological defect configurations. This mapping is achieved through the minimization of a free energy functional that encodes the material's internal constraints and interactions with their external parameters. The shared principle involves using liquid crystals as the underlying physical medium that supports director field propagation and director reconfigurations due to the anisotropy of interactions and topology, rather than the transmission of an electrical signal, or discrete changes in a molecular configuration. The key implementation components (universal features) across these publications include: a liquid crystal material with a pre-defined alignment; external stimuli (electric fields or light profiles or chemical cues); topological defects as the core ‘information carriers’ and also as information processing and memory components; and dynamic relaxation mechanisms based on material properties and internal parameters. The core of the "intelligent" behavior resides in the ability of the system to dynamically reconfigure using local interplays and couplings to change spatial patterns of the director field by means of external cues or self-driven dynamics coupled to a form of hysteresis or a minimal memory. This transformation occurs through material properties and intrinsic local physics by non-linear or analog mechanisms, instead of digital logic. The architecture of these systems is self-organized, relying on the interplay between the material's inherent properties and the external conditions by setting local interactions with the external world combined with elastic couplings. There is an intrinsic tendency for the system to minimize its free energy by exploring different configurations. A minimal design rule can be expressed as: "Information is coded in the system via topological defect configurations that result from free energy minimization due to external stimuli and internal elastic or hydrodynamic interactions". Feedback loops are implicitly created within these systems. For instance, a change in the director configuration due to a past stimulus influences the material’s energy landscape impacting the subsequent response; the same principle is shown in \cite{kos_nematic_2022}, where the interaction of defects creates additional constrains limiting further actions. In the active matter case \cite{zhang_logic_2022}, the presence of a defect changes the local director alignment inducing a type of "memory" or a local change in boundary restrictions. A 'minimal design' example may incorporate a liquid crystal cell with a defined anchoring condition (e.g. homeotropic), a specific chiral dopant to introduce twist, and a means for applying electric fields through electrodes; this allows control on the pattern of the topological defects or reconfigurable geometries. The minimal operational characteristic would be to observe the spatial pattern and topological properties of emergent topological defects upon electrical stimulation as a signal of a form of encoding that can be read by an optical signal, or another form of transduction, and for the same setup to respond differently depending on past states.

3. **Readiness:** The current implementations, as represented by this cluster, demonstrate a significant gap compared to the ideal of "cognizant matter" defined in the background.

While there is evidence of internal parameter modulations via material properties, there's only a minimal degree of self-regulation and a strong reliance on external programming for establishing system parameters. The implementations demonstrate responsivity to stimuli (a single electrical stimulus) through spatial reorganization, but not the autonomous, adaptive responses described in the reference text. Memory is mostly hysteretic or passive, stored in the director field configurations, and not as an active element that modulates future responses without any form of a specific external input. There's a lack of local computing beyond the simple interactions of topological defects and also a limitation for having multiple stimuli interactions that can be coupled together or generate further feedback loops. The work of \cite{adamatzky_computing_2011} encodes information in the presence/absence of LC fingers, showing a form of processing through the interaction of these moving structures, but this method relies on external electrical stimuli for the creation of this pattern. This approach also lacks real "self" interactions where the system acts by using previous encoded parameters to modulate future response, and is mostly limited to the detection of a "state or condition", not to learn from it. Similarly, in systems using electric fields to manipulate topological defects \cite{kos_nematic_2022, zhang_computing_2021}, the external electrical pulse, determines the new director configuration. Here, "memory" is encoded as metastable states and the system has minimal feedback interactions internally which rely mostly in material relaxation mechanisms, without changes in their physics rules. The system relaxes with very limited information from the past, mostly following general free energy minimization rules set via external conditions. These are far from autonomous learning or adaptation as desired by the framework for the design of cognizant matter. The active system based on myosin \cite{zhang_logic_2022} is slightly closer, by implementing a local spatial activity pattern that can also be changed to alter the path of the defect, but it misses the feedback mechanism based on previous history or any internal signal that promotes any kind of decision. The systems demonstrated in these studies, while showing memory and computation through material reconfigurations, respond linearly rather than non-linearly to stimuli without using internal changes of parameters, thus they are "reactive," not "active," in the sense defined in the background. The probabilistic analysis also shows all systems are grouped into one single topic with the highest probability to be the element of the cluster, suggesting the strong thematic coherence but also the limited range of capabilities implemented in all systems reported up to now. The document probabilities show a near-perfect probability score assigning all documents to the same cluster, reinforcing their shared concepts and strong mutual similarity.

4. **Challenges:** A critical hurdle is controlling material properties at the mesoscale. While macroscopic patterns/boundaries can set system dynamics by controlling overall defect positions, precise control over defect positions and interactions, necessary for complex computation, remains a challenge. Fabricating these systems also requires using very precise microfabrication techniques to implement specific anchoring conditions, adding a level of complexity and costs. The temporal dynamics are mostly limited by viscous

relaxation effects of local structure or by an external control that limits the range of "physical feedback". Without changes on that parameter the system acts mostly on "preprogrammed" steps. The stability of the defect configurations in varied environments also presents a challenge, with possible disruption due to mechanical stress, impurities, or other factors, which may lead to unreliable performance. Scaling up and increasing system complexity brings additional challenges when implementing a network like behavior. Specifically, for a higher-order logic and memory to be efficiently created and implemented by these materials. The energy efficiency is low overall since there is an energy requirement for the change in the director field either with direct electrical pulses or using heat-based gradients. In terms of production, the use of complex lithography techniques and liquid crystal materials limit the throughput or mass scaling for real complex devices. The main obstacles derived from the analyzed examples include: (1) the lack of active, local memory capable of modulating future system behaviour by integrating past and current responses. (2) the need for a more robust or scalable methods for fabrication to control system properties or the geometry of the defects and for the alignment materials. (3) the need of a low power physical mechanism by implementing coupled physics to perform a local analogue computation more efficiently by avoiding external controllers. (4) the limited range for having a high number of inter-linked components with non linear feedback to perform higher order behaviours beyond simple operations or responsivities.

5. **Reflective Insights:** These examples provide insights into using soft matter physics as a platform for non-conventional computation and information storage. While some implementations rely on electric fields \cite{sasaki_large-scale_2016, zhang_computing_2021}, others use thermal or chemical cues, thereby highlighting the versatility of material properties, but also common problems, such as the lack of self-sustained local control, and need of external input or external parameter to complete a given action. The memory and computing capabilities in all examples lie not in individual unit or “gate”, but as collective structural changes based on topology. This suggests that materials' self-organization can potentially be used as a computational resource, if a form of an effective "writing/read" mechanism is implemented and coupled with autonomous control through non-linear interactions by implementing an intrinsic control at material level by local feedback. The most promising path for evolution involves exploiting the materials' internal physics for the creation of more integrated feedback loops by using different stimuli simultaneously. For example, a material with both thermo-responsive and photo-responsive elements capable of changing the local phase via light pulse, might allow a form of optical computing at small scale, and use thermo gradients as a mechanical driving force for creating patterns and changes in the director filed for implementing computation by using topology of defects as output. The least promising area seems to be using liquid crystals as simply a medium or a substrate for encoding digital signals or bits, as it may not fully exploit the material's potential for analog or self-organizing behaviors through its local physics based on free energy minimization. A

complete shift is needed to realize the ideal for cognizant matter based in self-organization and not external controls for the material properties. However, for a simple analog operation, the existing implementations show a great potential if the problem is properly defined where a single stimulus is given for a particular action. The limitation for more complex logic is not solved by more complex structures, but by exploiting how physics interacts locally to create emergent behaviours and new material response rather than simply encoding digital signals in the system. The critical shift needed to fully realize intelligent materials will require a move from systems with pre-defined properties that respond predictably to stimuli, towards materials that can self-regulate, learn and adapt using internal feedback loops that modify the way the material parameters will behave in the future to achieve a new type of response based on past events using embedded physics. Existing techniques are more of building blocks for the new implementation rather than fully functional and independent systems with a high level of autonomy.