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Interview with Joanna Aizenberg: On Responsive and Adaptive Materials

MF: The research field of active matter is a very heterogeneous field dealing with several types of materials: active materials, smart materials, and hybrid materials among others. Before entering a discussion on these various distinctions, we would like to begin with your own background in this field. Can you describe how you see the beginnings of this field of research and how your research started and is situated in it?

JA: I entered the field through my PhD research on bioinspired materials, in which I examined the skeletons of marine organisms to try to uncover the interesting material features of these skeletons and of biological structures in general [Aizenberg et al. 1997; Aizenberg et al. 2001; Sundar et al. 2003; Aizenberg et al. 2005]. I became fascinated by the way biological crystalline materials were organized in radically different ways than conventional human-made materials – many combined inorganic and organic components structured in intricate detail from the molecular to the macroscale – and, even more interestingly, I was able to show how the active, bottom-up processes the organisms use to make them can be mimicked in synthetic systems. This research made clear the amazing potential of self-organizing materials. Around the same time, I discovered that the brittle star exerts yet another level of dynamic control over its skeleton: in response to light, it pumps fluid through its porous skeleton to cover and uncover the surface with a protective layer of fluidic ‘sunglasses,’ and the deep-sea sponge evolves a hierarchically structured, fiber-optically illuminated glass ‘house’ inhabited by a pair of shrimp (see Fig. 1). As I studied these and other organisms – like echinoderms that use dynamic spiny surfaces to keep themselves clean – what became obvious to me was that there was one fundamental feature of the biological world which would be absolutely critical to mimic, but which at that time was almost completely absent from nonliving materials. That feature was the ability to respond to the environment, to be active, to reconfigure, to change properties, and adapt to meet changing functional needs. Twenty years ago, our materials were mostly optimized to do one thing and never change, but it has become clear that this would not be enough if we are to design sustainable, energy-efficient buildings, safe and durable infrastructure, or targeted medical interventions. The living world is brewing with an infinite variety of dynamic materials that form and adapt in response to everything from light

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to heat to water to chemical species. My group's research now bridges fields as diverse as optics, mechanics, self-assembly, fluid dynamics, and catalysis, but is united by an underlying passion: to understand and creatively build on the fundamental principles of such living systems to develop not just new materials but entirely new ways of envisioning how we design and interact with materials.

Fig. 1: Left: Marine brittle stars dynamically regulate their light exposure by pumping pigment through tiny pores in their lens-covered skeleton to ‘put upon themselves’ unique fluidic transition ‘sunglasses’ (close-up seen in sunglass lenses). Right: A marine sponge known as the Venus’s flower basket makes a remarkably sturdy house for a pair of shrimp despite being made of glass, thanks to an intricately woven hierarchical architecture. As a bonus, the house also serves as a waveguide for light. © The Aizenberg lab’s.

MF: Your answer brings us to one of the key concepts of active matter research, one which you also often discuss: the concept of architecture, often in the sense of an internally and hierarchically structured 3D shape.¹ Can one say that, with the realization of the potential benefits of dynamic man-made materials, akin to the ones existing in living matter, the concept of architecture changes, that architecture itself becomes dynamic and responsive, in other words reacting, harnessing and transforming energy, and adapting?

JA: Yes, absolutely. Biology uses the concept of a highly hierarchical assembly of features to put together an architecture that can give rise to complex synergies and feedback between components and across scales. In nature, materials are built from the molecular scale to the nanoscale through the microscale and all the way to the macroscopic level, and this hierarchical complexity of the resulting structure

¹ See [Aizenberg et al. 2005, p. 275]: “Structural materials in nature exhibit remarkable designs with building blocks, often hierarchically arranged from the nanometer to the macroscopic length scales.” See also [Noorduyn et al. 2013].

introduces ways to, for example, channel mechanical force into a chemical reaction, or finely control the transport of heat or fluids or light within the material. The new properties that emerge from such architectures and from their precisely controlled combinations of different materials can far exceed the possibilities of any of the components alone.

KK: In your work you often refer to the dynamic between chemistry and the mechanical component,² which characterizes living systems on the micro- to macrolevel. Living systems seem to be continuously transforming or developing, and this development is triggered through the interaction between chemical and mechanical processes, which are also intrinsically linked. Could you describe this dynamic in more detail?

JA: By training I am a physical chemist, but when I started looking into biological structures, whether at their architectural or crystal growth or optical properties, I began to appreciate that it is often not possible to understand how they form and interact with the environment without taking a more interdisciplinary approach that encompasses the coupling of chemistry and mechanics. Even from my earliest work on bioinspired crystal growth, I could see how feedback between chemical reactions and mechanical stresses that develop within the growing material may lead to ‘self-healing’ behavior that corrects structural anomalies during growth – and when manipulated, can be used to precisely control pattern formation. This constant interplay between chemistry and mechanics becomes even more prominent in biological and synthetic materials that actively move and reconfigure. We have developed hybrid materials where a chemical change within a gel drives the up-and-down motion of microscale hairs or fins [Sidorenko et al. 2007], and have even taken these systems further to design homeostatic materials that actively maintain a steady state through chemo-mechano-chemical feedback (see Fig. 2) [He et al. 2012]. In the latter case, when the material is brought out of a steady state, such as a temperature set point, it is capable of bringing itself back: a chemical change in the gel mechanically drives the hairs to stand up, which in turn triggers a chemical reaction that restores the temperature – and ultimately leads to another chemical change in the gel that mechanically drives the hairs back down, to await another cycle.

Some of the most interesting dynamic processes occur, where mechanics and chemistry are further coupled to other energy domains, so that other triggers such as light-induced or magnetic-induced fields can be used to control changes in material

2 See: [Grinthal and Aizenberg 2013, p. 7072]: “A living organism is a bundle of dynamic, integrated adaptive processes: not only does it continuously respond to constant changes in temperature, sunlight, nutrients, and other features of its environment, but it does so by coordinating hierarchies of feedback among cells, tissues, organs, and networks all continuously adapting to each other. At the root of it all is one of the most fundamental adaptive processes: the constant tug of war between chemistry and mechanics that interweaves chemical signals with endless reconfigurations of macromolecules, fibers, meshworks, and membrane.”

Fig. 2: A schematic representation of chemo-mechano-chemical feedback loop, in which mechanical action of temperature-responsive gel is coupled with an exothermic reaction. Material from: [He et al. 2012, fig. 3], Springer Nature.

properties. These feedback processes also extend beyond the solid state to include fluid dynamics and transport, as seen everywhere – from transport of water and gases in trees to secretion and healing processes in fluid membranes.

KK: In your research, you deal with the organism as a hierarchically organized bundle of feedback processes, since all levels of the living system – from cell to tissue to organ – are continuously adapting to each other and to the environment of the whole system. This dynamic is connected to the flows of energy between chemical processes and physical action, as you said. From a thermodynamic point of view, living systems are ‘open’ systems because they are incessantly dependent on the flows of energy and material passing through them. In this understanding, a living system is not in a state of equilibrium. How does research in the field of chemistry describe these systems?

JA: This question gets down to the very basic definitions of chemistry, that is, the fact that chemistry as a science was designed to describe equilibrium.³ Almost everything one does in chemistry, all the equations we know as chemists – for example, concepts of chemical kinetics and thermodynamics and how reactions take place – all these by now are very well-described concepts related to chemical equilibrium. So, often, when we try to dissect a system that is out of equilibrium, we still understand it in

³ One of the important discoveries in chemistry during the 1950s–1960s was the Belousov–Zhabotinsky reaction as an example of a nonequilibrium thermodynamics not dominated by equilibrium thermodynamic behavior.

relation to local states, where there is a local equilibrium. But as the boundaries between chemistry, physics, and biology start to blur, some chemists are moving beyond this view and integrating ideas from reaction-diffusion systems, statistical physics, nonlinear dynamics, chaos, and complexity, with the aim of describing the emergence of life, pattern formation, self-replication, and adaptation in terms of dynamic, out-of-equilibrium processes. I think that, as more researchers are trained in interdisciplinary programs and become intrigued by the beauty of these systems, even basic chemistry will start to encompass such complex behaviors. The move to do so is coming from other fields as well, especially the study of earth systems, atmospheres, and oceans, which also tie chemistry to highly complex, out-of-equilibrium feedback processes and pattern generation.

Chemists are also recognizing the need to rethink the experimental assumptions used to understand living systems. Much of biological chemistry has been based on standard solution chemistry, with kinetics and thermodynamics analyzed as if everything were floating in a dilute solution in a tube. But of course this picture is nothing like the hierarchically organized bundle of feedback processes, where chemical processes may have little chance of ever reaching equilibrium. As with theory, many of the essential experimental techniques are being developed by reaching across disciplinary boundaries – both by focusing on a smaller scale, such as pushing and pulling on individual biomolecules to understand how their enzymatic activity might respond to an environment of mechanical forces, and by looking at the bigger context, such as by developing a variety of probes and sensors to interrogate chemical behavior along with, for example, mechanical changes on larger length- and timescales. Data from such experiments will no doubt further inform the development of out-of-equilibrium theory.

MF: Related to this issue, you have noted also that responsive behavior in synthetic materials is mainly driven by a two-state switch between properties.⁴ You mention that a way to overcome or escape from this deadlock is to think about dynamics or dynamic fluids in a way that transforms our conception of static materials. If we consider fluids as something that points toward an essentially changing geometrical structure of materials, can one think about geometry as something that will prompt such changes? Can a new concept of geometry and its role in how materials are shaped help us bring forward new mathematical tools?

JA: The essential question here is how one might design a material that can undergo a continuum of responses – so that, rather than switching between two stable states, one can rationally program finely graded morphological changes. In traditional solid

⁴ See: [Aizenberg Biomineralization and Biomimetics Lab]: “Materials that adapt dynamically to environmental changes are generally limited to two-state switching of single properties, and only a small number of strategies that may lead to materials with continuously adjustable characteristics have been reported.”

materials, responses generally rely on programmed switches in elastic force balance such as buckling instabilities, but living materials widely integrate liquid, liquid crystalline, and other fluidic components along with solids. These introduce another class of forces – surface tension, capillarity – that can potentially influence morphology in a more graded manner by driving local flows or ‘sculpting’ the liquid’s surface. Although a liquid might seem too dynamic to even be considered a material, an answer is seen everywhere in biology: liquids coat surfaces from our eyes to our stomach lining to ants’ feet, and, in nearly every case, are kept from escaping by an underlying porous solid that holds the liquid in place through capillary forces within the pores [Wong et al. 2011]. In the synthetic liquid-infused materials our group has designed, we have shown how manipulating the pore geometries by stretching or bending the material can lead to a continuum of liquid surface morphologies [Yao et al. 2013]. In other cases, the pore geometry remains fixed but guides local capillary flows of an infused ferrofluid under magnetic force, again leading to highly predictable graded surface morphologies.

Yet, even as we began to demonstrate these possibilities, one of my students was actually challenged at a conference with ‘But a liquid isn’t really a material.’ This reinforced to us how profoundly two components of a hybrid material can influence each other’s behavior. Of course, we would not wear clothes or live in houses made of liquid, but combining it with a structured solid gives us entirely different ways to think about both the solid and the liquid. Together they make the solid’s geometry dynamic and the liquid’s surface both stable and sculptable through selective control over tiny local flows, leading to the emergence of dynamic or adaptive material properties far different from those of either component alone (see Fig. 3).

Fig. 3: Schematics showing the fabrication of a SLIPS (Slippery Liquid-Infused Porous Surface) by infiltrating a functionalized porous/textured solid with a low-surface energy, chemically inert liquid to form a physically smooth and chemically homogeneous lubricating film on the surface of the substrate. Material from: [Wong et al. 2011, p. 444, fig. 1], Springer Nature.

For us an essential part of designing these or any material systems is not just producing a particular structure or properties, but fundamentally understanding the scientific processes underlying how they form and behave under different conditions, so we and others can rationally design and further imagine yet more possibilities. Especially in the hierarchical and multiphase materials we have been discussing, this often means

developing new comprehensive theoretical models to connect previously disparate aspects of physics, mechanics, fluid dynamics, chemistry, and so on, even if we do not always need to reinvent the basic math of these fields.

Probably, the best example of these principles in the biological system is bone [Currey 2002]. This is a material that has structural hierarchy from the molecular scale to the nanolevel to the macrolevel. There are at least 10 levels of structural hierarchy until it arrives at the final bone. It has channels for bodily fluids to pass through, it has collagen (organic material), and it has inorganic material (apatite). Each of these exists in an intimate relationship with the other.

MF: To focus on the plurality of materials or hierarchies in the same ‘material,’ can one also claim that one of the characteristics that enables these pluralities, one might say, is always a change in these hierarchies? These are never stable, in the sense, as you mentioned, that they neither reach nor attain a fixed equilibrium. There is always a change in this hierarchy – the hierarchies themselves or this plurality are never fixed.

JA: Not necessarily always, but certainly in many areas of biology, this is exactly the case. Especially given the integration of solids, liquids, liquid crystals, gels, and glasses, the different components constantly synthesize, dissolve, or metabolize each other, nucleate and trigger phase changes and phase separations, redefine boundaries and flip inside/outside topologies, so that not only the organization but even the existence of hybrids can change on different length- and timescales. All of these activities have been harnessed in the service of making the system inducible and adaptive, by providing access to a range of geometries and hybrid combinations that allow constant transformations and a response to environmental pressures necessary for survival.

KK: How would you then define active materials? According to their responsiveness? Or to their adaptiveness?

JA: My colleagues and I have had a long discussion on what are responsive, what are adaptive, and what are homeostatic materials.⁵ All these types of dynamics certainly overlap, but to me they differ in the complexity of what goes on inside the material and, consequently, of how it interacts with stimuli.

‘Responsive’ is the most basic term and means something changes in the material when it is exposed to a stimulus. Although people like to point out that shattering when smashed with a hammer is a response, we take ‘responsive’ to mean that a specific stimulus, such as light, pH, or a magnetic field, evokes a specific, defined change in a material property or behavior, such as color or adhesiveness –

⁵ On the recent discussion on homeostasis, see: [Lerch, Grinthal, and Aizenberg 2020]. See also all the papers in Volume 32 (20) of *Advanced Materials* (2020) called “From Responsive Materials to Interactive Materials.”

straightforward input–output. Although most often this implies that the change is reversible, that the material will return to its original state once the stimulus is removed, this is not always true, as in food packaging designed to report tampering by permanently changing the color.

Adaptive materials add a level of complexity – rather than just a simple direct input–output, the stimulus-induced change is met with a competing force (e.g., a chemical change competes with larger scale elastic resistance), and the output results from balancing the two via mutual feedback. In this sense, the response is ‘adaptive’ even at the level of its core mechanism. The internal feedback then enables more complex and more diverse stimulus–response behavior that can potentially produce better adapted materials, as small changes in the stimulus can alter the balance in a variety of non-straightforward/nonlinear/more nuanced ways.

Homeostatic or self-regulating material behavior incorporates internal feedback cycles into a larger ‘meta-feedback’ with the stimulus. We have recently discussed how the concept of homeostasis can operate within the material at the most basic mechanistic level, by incorporating what we call ‘mini-homeostatic modules’ – paired processes in which the stimulus-triggered response is opposed by a second process that drives it back toward the original state. The result is not simply a new static compromise, but a dynamic system that continuously evolves as, for example, it gets another kick from the stimulus on its way back to the initial state. While the material will eventually return to the original state once the stimulus is removed and the show is over, in the meantime it can produce an infinite variety of response trajectories depending on how and when in the cycle the stimulus is presented.

This latter case can also be considered the most active, since – as the ‘self’ in ‘self-regulated’ implies – its own internal dynamics enable it to actively interact with the stimulus rather than passively obeying it.

KK: The biological and the physical description of living beings has often influenced the philosophical answer to the question: what is life? On the other hand, research in physics and in biology has always also been inspired by what at a certain time and in a more general sense was understood under the notion of life. In light of your research and your experience, how do you consider the relation between natural biological materials and artificial synthetic materials, even if the latter are inspired by nature?

JA: First, inspiring as life is, I do not put it on a pedestal or over-romanticize its ‘perfection’ compared to nonliving materials. There are many examples where the structures nature produces or the materials it uses are absolutely not optimal. Nature has a very limited range of materials to utilize – it just evolves a certain structure in a way that works at the time for survival and reproduction purposes, using the available material components.

What nature does do in a mind-bogglingly effective way is couple – reactions, forces, materials, timescales and length scales, instabilities, defects, mistakes – whatever it finds or whatever arises can be plugged into the churning gears via the highly structured, hierarchical architecture. In the process, it creates highly complex multilevel physical and chemical networks that not only drive all sorts of otherwise energy-demanding reactions and movements but also provide redundancy to preserve robust, non-failing function – not only compensating for mistakes but turning them into opportunities.

In our own work, we do not aim to mimic life, but nature helps us look at our own synthetic materials from often vastly different and counterintuitive perspectives to see possibilities we did not see before. For all of life's wild and crazy complexity, it is often the more fundamental principles that lead us to new ideas – much of our work stems from discovering how complex coupling, feedback, hierarchy, and redundancy can emerge even in simple, boring materials.

MF: As you said, not only are there a lot of redundancies, but nature also selects for example from a very limited variety of materials,⁶ whereas in the domain of synthetic materials there is a larger variety of materials that one can produce in the laboratory. To focus on redundancy, can you describe how synthetic materials stand in relation to biological ones?

JA: When we design a material, we do not have to worry about a whole range of things that nature has to optimize for. Let us say I want to make the strongest material possible. There are some interesting inspirational examples in biology, but living creatures also have to reproduce. In that respect, I have a somewhat easier task than biology because we can ignore functions that are not critical *and* use a range of extremely strong synthetic materials, such as steel or metals, for example, that might be out of the question for biology. If I want to make synthetic materials that have structural color similar to that used by butterflies or beetles – which rely on organic materials – we have access to a whole range of potentially superior inorganic materials. Thus, to design a synthetic optical system inspired by nature, I can choose to follow nature's structural design principles but reformulate them in completely different materials such as metal oxides, for example, which can give us additional optical properties that might augment the structure in unique ways. This may create a novel bioinspired material with optical properties optimized for the application in mind.

At the same time, we may want to think twice before dismissing certain features of the biological materials as irrelevant to our needs. Even if we are not interested in designing buildings that can lay eggs that hatch and grow into new buildings, we may well want a sustainable building that can perform multiple, often dynamic

⁶ On this selection with regard to optical phenomena see, for example: [England and Aizenberg 2018].

functions, such as changing its critical functional characteristics to adapt to the environment, for example, absorbing or repelling moisture depending on the weather, harvesting energy, collecting light, using dynamic windows that adapt their transparency or reflectance in response to outside temperature, and even self-healing damage. At this point, most building components are designed to optimize one function at a time, but in the future we need to think about multifunctional materials capable of performing a range of functions. Biology gives us numerous examples of how what initially looks like a trade-off may provide built-in redundancy, adaptiveness, or other desired properties that could enhance our needs in unexpected ways, whether or not the organism had the same use for them.

KK: I would like to come back to this antagonistic principle between chemistry and mechanics and to the ‘complex’ systems that can be built out of the relation between chemical processes and mechanical properties. In one of your articles you once called this dynamic relation a “dense, interconnected jungle”.⁷ That is to say that in living systems we are not dealing with a totally controlled or determined architecture but with one that is perpetually in a process of becoming because it deals with instabilities. What is the significance of instability and complexity for the research on active materials?

JA: As I discussed earlier with respect to complexity, feedback – within a material and with a stimulus – is at the core of sophisticated adaptive and self-regulated behavior. But, despite what we might think from looking at biology, complexity can emerge from very simple systems. Dynamic feedback between even two simple elements can lead to the emergence of properties that are not trivial and not easily explainable by either of these components. A beautiful example of complexity from simplicity that does not even rely on mechanics is the gardens of intricate micro-scale flowers we have grown by combining two simple competing chemical precipitation reactions in a beaker (see Fig. 4) [Noorduyn et al. 2013]. We can sculpt vases, grow the flowers in them, even grow snails on the leaves, just by modulating air flow into the beaker or adjusting the temperature to shift the balance between the two reactions – highly interactive meta-feedback behavior that we have been able to theoretically model and rationally control based on the simple starting components. Local instabilities arise all the time. By watching the structure’s evolution in real time and using our model, we can study how instabilities may be suppressed by the feedback, leaving characteristic local signatures in the structure, or be

⁷ See: [Grinthal and Aizenberg 2013, p. 7072]: “By sequestering chemical species in confined micro-architectures, living materials set the stage for energetically coupled reaction cascades that would likely be unfavorable anywhere else. But the reaction components do far more than simply mingle inside a passive architecture. Rather, they are the architecture: reactants and catalysts are strung together in long chains, twisted into filaments, woven into networks, and packed into bilayers, with all of them wrapped around each other in a dense, interconnected jungle.”

Fig. 4: Gardens of microflowers, complete with leaves, blossoms, and even a few snails, can be sculpted simply by combining two competing chemical precipitation reactions in a beaker and taking advantage of unique reaction-diffusion pathways that result. The size of each microstructure is ~ 100 times smaller than the width of a human hair. © The Aizenberg lab's.

amplified and radically alter the global pattern evolution. Guided by our model we can even predict what conditions may drive the system into the 'Valley of Death,' a regime where feedback stops entirely.

MF: To continue the discussion on instability, should these instabilities be resolved? As you note in your work, these instabilities may also be harnessed [Hu, Kim, and Aizenberg 2017]. This employment of instabilities does not set out to resolve them but to reach some sort of static, stable state.

JA: Much of our work would not even exist without instabilities – the patterns, motions, and adaptive behaviors in many of the systems we study rely on tiny instabilities as triggers. For example, in one of these systems, surface arrays of nanoscale hairs, the hairs are designed to stand straight up, but in an evaporating solvent they tend to flop over due to local imperfections that break the symmetry of a hair's response to capillary forces [Pokroy et al. 2009]. This was understandably dismissed as failure by many people, since the hairs then stick to each other and get tangled up. But we discovered that by fully understanding and modeling the competing forces in the system – capillary, elastic, and adhesion – we could harness this symmetry-breaking to make the hairs spiral around each other into hierarchical swirls, and even program hierarchical stages of unspiraling (see Fig. 5). The chiralities are random, but, if we directly program an instability into each hair by introducing just a slight tilt, we can control which way the symmetry breaks so the hairs spiral with either all left- or all right-handed chirality.

We also harness instabilities to entirely transform the topology of microscale cellular surfaces – lattices of interconnected triangles, circles, or other shapes (see Fig. 6)

Fig. 5: Initially, vertical nanoscale hairs spiral around each other in an evaporating liquid, drawn together by meniscus forces, held by surface adhesion, and kissing with uniform chirality if given a slight initial tilt. © The Aizenberg lab's.

[Li et al. 2021]. In this case, we temporarily swell the structure with liquid to soften it and then use capillary forces to zip the walls together, switching, for example, a triangular topology to a hexagonal, with half as many compartments and double the nodes. Due to the symmetry of the initial system none of this would happen without tiny local instabilities that cause the swelled walls to buckle in one direction or another. Again, guided by a theoretical model, we are able to program the buckling direction by introducing tiny angular imperfections at each node. The programmed instabilities can even be used for encryption, since the imperfections are invisible and the encrypted patterns appear only upon transformation.

MF: Alongside this classification of instabilities, you also introduce a differentiation between structural instability and material instability. Could you explain what do you mean by this? Can one really sharply distinguish between the two types? How do you consider the relation between material and structure?

JA: Although there is certainly some ambiguity and overlap depending on what field you are in, we usually use structure to refer to geometry or configuration, generally at the nanoscale or above, and material to mean the composition or phase of the substance it is made of. For example, in the work by Hu et al. you mentioned earlier (and all our hybrid systems based on it), where a micropillar is embedded in a gel, we have both types of instability working together. The structural instability consists of the pillar abruptly buckling under mechanical force; the material instability refers to a discontinuous phase change due to the gel's polymer strands mixing with water in response to temperature. Differentiating matters most in cases like this, where the two types of instability operate in the same system but on different time-scales and length scales, which must be explicitly taken into account in a theoretical

Fig. 6: The generalized lattice consists of nodes with different angles. The edges forming the smallest angle will undergo zipping for angle-guided capillary-driven transformations from circular to square (i), rhombitrihexagonal to hybrid hexagonal (ii), kagome to hexagonal (iii), and rhombic to hexagonal (iv). We note that, compared to the triangular-transformed and kagome-transformed hexagonal lattices, which are comprised of nodes connecting three equal double walls, nodes in the hexagonal lattice assembled from the diamond structure comprise two single walls and one double wall, resulting in additional anisotropy along the horizontal direction. Material from: [Li et al. 2021, p. 389, fig. 3], Springer Nature.

model to predict the system's response behavior and – importantly – can be controlled modularly by distinct handles to influence the response.

KK: I would like to return to the theme with which we started the discussion on instabilities, which concerns the relation between natural biological materials and synthetic ones. In the research on smart or active materials, one finds a variety of objects and research approaches. These include soft robotics and the implementation of computing in soft robotics. I wonder what your relation is to robotics, as I know that some of your objects were intended for and also find applications in the soft robotics context [Kumar et al. 2017].

JA: I approach this topic from a materials point of view, since I am not coming from pure robotics. The majority of things that I have seen so far are robots that are externally controlled, such as, for example, pneumatically or electrically controlled systems. Increasingly these are made of soft materials and are easier to manipulate because you can inflate them, you can swell them, you can bend them, but you still have to use a pneumatic or electric cord to send a signal to, say, move the arm. The direction soft robotics is starting to head in now is one in which the components are smart materials, so that the robot is not externally controlled, but the material itself can transduce signals from the environment into specific responses that enable the robot to navigate in the right direction or catch, release,

secrete, or sort as appropriate.⁸ Many lines of research in our group – such as those we have been discussing – investigate the fundamental principles required to design, control, and predict such materials, and it is becoming possible to envision not only robots but buildings, medical therapies, and more being constructed from autonomous, programmable matter – where it is the material itself that operates, responds to environment, harvests energy from the environment, and operates accordingly.

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⁸ See the recent discussion on interactive materials: [Advanced Materials 2020], as well as the abstract to the volume: “Interactive materials mimicking the embodied intelligence of biological systems lead to a paradigm shift from materials that merely respond to external signals to materials that sense their environment, process the information received, and respond or adapt autonomously.”

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The Aizenberg lab's research is aimed at understanding some of the basic principles of biological architecture and the economy with which nature solves complex problems in the design of multifunctional, adaptive materials. These biological principles are then used as guidance in developing new, bioinspired synthetic routes and nanofabrication strategies that lead to advanced materials and devices with broad implications in fields ranging from architecture to energy efficiency to medicine. Research topics of interest include biomimetics, smart materials, wetting phenomena, bio-nano interfaces, self-assembly, crystal engineering, surface chemistry, structural color, and biomineralization.