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On the Activity of Materials

The idea of physical reality usually refers to the rigidity and resistance of materials that are regarded as the fundamental stuff out of which our world is built or the ground on which it rests. Above all, solid materials relate to a more general notion of matter. This classical idea is based on the fundamental dichotomies of matter and form, and matter and activity, whereby form appears to be imposed from the outside on amorphic matter, transforming it into objects, and matter, as a fundamentally passive substance, seems to be externally activated, and in this way to undergo a transformation from rest to process.[1] Following these principles – above all, since industrialization – our technology, instruments, objects, and devices have been designed based on materials with controllable behaviors that can be standardized as properties. Hence, solid and rigid materials such as iron, steel, or concrete were considered suitable as stable and reliable components for machinery, bridges, or buildings, whereas elastic materials such as rubber, fiber tissues, or plastics permitted the design of flexible structures. In all these cases, form, activity, or special functions are externally implemented and define materials as their passive carrier.

But materials are also omnipresent in natural systems, from rocks and minerals to wood and wool or silk. Even we ourselves are built from a variety of materials such as bones, muscles (flesh), or hair. Seen in this way, it is obvious that all these natural objects have a function or exhibit some activity. The processes and activities related to these objects are quite complex occurrences. But are the materials these objects are formed of in the same way passive carriers of activities, or do they show a different mode of activity and form-building? Do biological materials perform by themselves what human activity and design implement from outside in the case of artifacts?

These questions challenge the classical paradigm of separating passive matter – which seems to be the essence of a material – from the form, activity, or function the object might have. This separation also echoes the basic dichotomy of matter and mind,

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[1] The dichotomy of matter and form in the sense of hylomorphism focuses on matter as a passive carrier of form. This is evident in the usage of materials. In the nineteenth century, iron is seen as the most formless material that can be brought into any form [Meyer 1907]. Clearly, this tradition did not begin in the nineteenth century (see the introduction to this volume). In his *Kritik der Urteilskraft* (Critique of Judgment), the philosopher Immanuel Kant, for example, noted in 1790: “But the possibility of a living matter is quite inconceivable. The very conception of it involves self contradiction, since lifelessness, inertia, constitutes the essential characteristic of matter” [Kant 2007, p. 222]. On the difference between passive and active matter, cf. [Keller 2016].

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which can be regarded as one of the founding principles of occidental culture.[2] Reframing the relationship between matter and activity in terms of active materials forces us to look closely at basic assumptions connected with the idea of materials and their properties, with the dynamics of energy, information, and activity in a broader sense.

1 Action, Reaction, and Interaction

A very basic physical principle is that there is no action without reaction. The activity of an object (or a material or body) must necessarily be defined with respect to some reference. The existence of an outside reference implies the existence of a boundary of the object and the object's activity corresponds to an interaction with its outside world.

The word 'interaction,' commonly referring to all the forces that govern matter in the most general physical theory, already encapsulates the fact that action is mutual, from the object to its environment and vice versa. Considering gravitation, for example, a small mass falling toward the Earth experiences the same gravitational force from the Earth as the Earth experiences from the small mass (Fig. 1, left). We are just deceived by the fact that the Earth moves much less under the influence of these forces than the so much lighter mass m_2. When this mass touches the Earth's surface, the impenetrability of the Earth creates a solid reaction force that exactly compensates the gravitational force. Hence, the equilibrium of a seemingly inactive

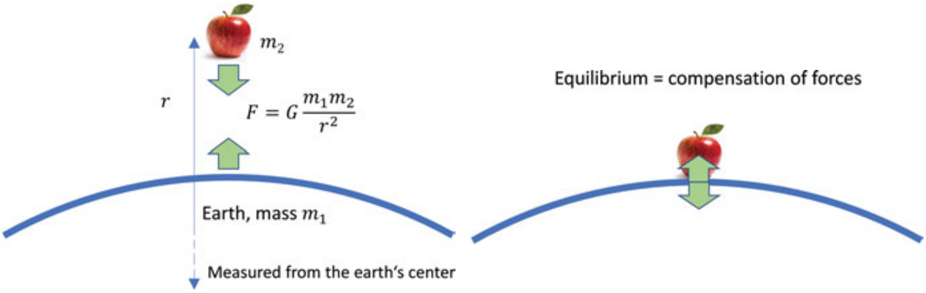

Fig. 1: Gravitational forces between the Earth and a small mass m_2. (Left) The Earth and the small mass exert exactly the same force on each other, just in the opposite direction (with G being the gravitational constant). (Right) When the small mass touches the Earth's surface, the gravitational force is compensated by the solid reaction of the surface, which has exactly the same magnitude. © Graphic by the authors (P.F./W.S.).

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[2] The most famous version of this dichotomy is Cartesian dualism; see: [Descartes 1641]. One of the most evident modern versions of this dichotomy is classical robotics with its separation of CPU-based information and externally controlled material periphery. Soft robotics challenges this separation by emphasizing the intrinsically coded material, referred to as physical intelligence [Sitti 2021].

object lying on the Earth's surface is not the absence of activity but the exact compensation of interactive forces between the object and its environment (i.e., the Earth's surface in this case). Therefore, the perceived inactivity of any object is just an equilibrium of forces between the object and its environment.

2 Disequilibrium

On Earth, any kind of object is exposed to gravity, and is therefore part of an activity field that affects everything, everywhere, and at any time: a falling body, a suspended body, an erected building, or even the solid ground. There is no difference between their status in motion or at rest insofar as both states result from activities depending on their mass and their environment. When the environment exerts an equivalent compensation force, the body is at rest; in all other cases, a downward-oriented force produces motion, since the Earth itself is the bigger mass compared to all the bodies on the Earth. A building collapses when the static forces lose their equilibrium. If a body is sufficiently small, other forces such as wind can easily lift it in the opposite direction.

The interaction between two bodies or between a body and its environment is due to a disequilibrium; it acts only as a relationship between them. The lever as a classical tool of mechanics puts this disequilibrium into action (see Fig. 2).

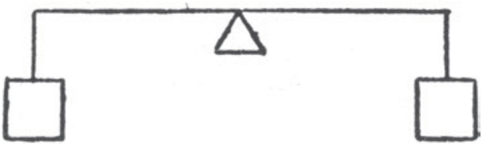

Fig. 2: The lever as a classical tool of mechanics from: [Mach 1897, p. 12, Fig. 2].

The lever beam represents the relational character of activity; it is the connection and the boundary between two objects. It can be considered as a tool where the two bodies are literal 'objects' – directed against each other – so that one is always the environment of the other and vice versa. The downward gravitational force of each body is inverted by the lever into a lifting force upon the other body. When they have the same mass, they are in equilibrium and their mutual activity appears as rest; their different mass, on the other hand, will result in motion. In the latter case, by varying the geometric proportion of the lever beam, equilibrium can be reestablished. The static equilibrium is the result of opposing activities, not the absence of activities.

Architecture also exemplifies this activity of a seemingly static state. Composition and building (Lat.: *struere*) using stones, logs, or steel beams make this permanent activity obvious. To achieve stability, the gravitational forces of the building materials have to be calculated. The classical example is the keystone of an arch that brings all the stones of the arch into a relationship and thus generates their static equilibrium as rest. Architectural statics does not mean the absence of activity but the equilibrium of all activity involved. The building structure describes the diagram of forces in a state of equilibrium. Any fundamental change transforms the inherent activity into an instability that makes the building collapse, thus generating a new equilibrium of the involved elements.

What is important here is that the activity of two objects, or – what is the same – a body and its environment can only be defined in a relational manner. This kind of original difference makes evident that any object and its activity have to be regarded together, as an elementary pair.

3 Material Property: Predictability

Very often, when the environment of an object (a material) is not considered explicitly but described only with respect to the challenge to the material, the symmetry of physical interactions is broken. Taking the example of Fig. 1, it is easy to combine all the effects of the environment into a single challenge to the object that we call ‘input’ (in this example, the gravitational field strength *g*), which will result in the gravitational force (see Fig. 3), which we might call ‘output’ in this case.

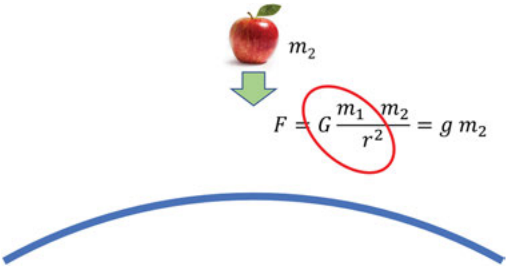

Fig. 3: The influence of the Earth on the small mass (see Fig. 1) is grouped into a single ‘input’ to the little mass m_2 and the gravitational field strength g. In this formulation, the symmetry of the interaction between the object (the small mass) and its environment (the Earth) is no longer obvious, although it of course still exists. This ‘input’ multiplied by the mass of the small object yields the ‘output,’ that is, the force moving this small object. © Graphic of the authors (P.F./W.S.).

In this way, the input from the environment is converted through a property of the object alone (its mass) into an output, the gravitational force. Usually, the intrinsic properties of a material would be expressed per unit of volume so that the relevant material parameter for this interaction is the mass density. For any given input (here, the gravitational field strength at a given position on Earth) would lead to different outputs in terms of gravitational force depending on the mass density of the material (e.g., in grams per centimeter cubed, mass density would be 0.95 for an apple, 1.3 for typical plastic films, 2.8 for granite rock, 8 for steel, and 11.3 for lead).

Material properties are therefore operational quantities that define how an input from the environment is transformed into an output that acts back on the environment. Of course, materials may possess a large number of material properties that transform all kinds of input. To give a few examples: resistivity is a property that transforms electric voltage into current, the elastic Young's modulus transforms uniaxial pressure into deformation, thermal conductivity transforms a temperature difference into a heat flux, and color is the result of the way by which a white light spectrum is reflected. Some material properties also define the limits within which materials operate in the way described. Material strength, for example, describes the limiting force that can be applied to an object before it fractures.

Materials should therefore be considered as operators transforming various inputs from the environment into well-defined outputs. Material property charts have been developed to help designers choose the right material for each type of application [Ashby 1999]. Figure 4, for example, shows areas of the diagram where Young's modulus and density are defined for whole material classes. It is relatively easy to find stiff materials (that resist deformation) with high density (metal alloys and ceramics), but there are very few stiff materials with low density, a well-known challenge for lightweight construction.

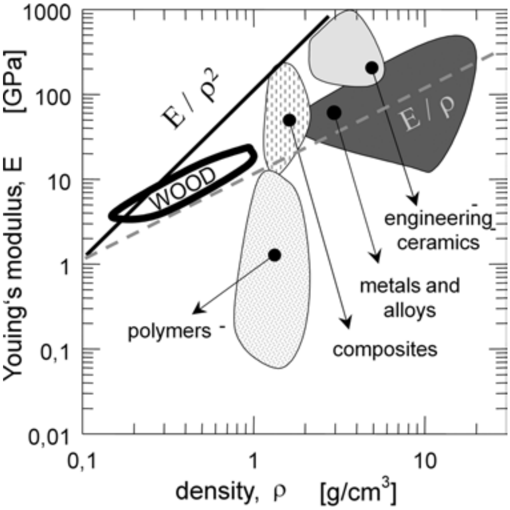

Fig. 4: Ashby map for whole material classes showing Young's modulus (i.e., resistance against deformation) against the mass density. Such charts imply that material properties (and thus the operability of the material) are fully predictable. The two lines in the graph show positions with equal values of either E/ρ or E/ρ^2, parameters essential for mechanical design purposes [Ashby 1999]. Reproduced from: [Fratzl and Weinkamer 2007, p. 1282, Fig. 17]. License: CC BY-NC 4.0 (https://creativecommons.org/licenses/by-nc/4.0/).

In principle, if one knows all the relevant material parameters, one can predict how a material will behave based on various inputs from the environment. The more precisely the material parameters are known, the better the predictability and the better the materials will fulfill the technical requirements.

4 Material, Environment, Machine

The perspective changes fundamentally if one considers materials not as passive elements but as operators. In general, a property is a stable characteristic of a material, a state of being that can be standardized and used as a reliable building block. If one considers a material as a device that acts with respect to its environment, all its properties are transformed into the operational elements of a processing unit. The material processes according to its inherent structure, thus transforming an input into a different output.

This involves a decisive shift in which materials are no longer conceived as bodies exposed to forces but are understood as modes of processing, transmitting, and storing activities. It is a shift from physics to machinery. The classical model of machinery, as it was developed by Jean-Victor Poncelet in the nineteenth century, is composed of three parts: (1) a motor or receiver (*receveur*), (2) a communicator or modificator, and (3) a tool (*outil*), where the special output of work is done [Poncelet 1845, p. 15]. Between receiver and working tool, the machine processes the energy of the motor into a special type of movement (rotation, step movements, etc.). Thus, the special types of material property, such as resistivity, elasticity, stiffness, thermal conductivity, or hydro-reactivity, describe inherent ‘gear’ mechanisms that transform temperature or humidity into color change or mechanical work in a predictable way.

In this context, the fundamental relationship between the material and its environment can be regarded as an input into a chain of internal transmission and processing, and as its corresponding output. Therefore, both elements – material and environment – are extrinsically as well as intrinsically related to each other as a pair of elements. Black-boxing all these activities dates back to the times of thinking matter as solid and taking materials as passive substances defined by their specific properties. Looking more closely into these black boxes allows us to focus on the material’s inner structure and its operational character.

5 Predictability and Entropy

Let us now consider all the possible states in which a material can exist for a given set of conditions imposed by the environment (such as temperature, pressure, electric field, and mechanical load). These states can be shape, color, smell, texture, and so on, including all material properties. If the material is perfectly predictable, then there will be only one state for a given set of conditions. However, if several states are possible, then we define these as degrees of freedom. Traditionally, the number W of degrees of freedom is measured through the Boltzmann entropy S that is directly related to the logarithm of W, through a famous formula engraved on Boltzmann's gravestone in the Vienna Central Cemetery (see Fig. 5). A situation where there is only one state $(W = 1)$, therefore, has an entropy of zero.

A robotic arm, or an even more complex device, has many possible states based on the number of articulations. In this case, external control is needed to reduce the number of degrees of freedom (and thus reduce the entropy) in order to generate a predictable behavior of the robotic arm, for example. Many degrees of freedom reduce the predictability or require extreme outside control. This is why stiff elements connected by few articulations are easier to control than a soft body that can deform in many ways. This need for control has led very naturally to the selection of materials that are as predictable as possible, stiff, and without any degrees of freedom. This separation between, on the one hand, passive and fully predictable materials and, on the other, active (usually digital) control systems is a hallmark of our digital age. Mechanical systems that were the state of the art in the nineteenth-century technology use mechanical information transmission, and so do many natural systems (see Fig. 6).

Fig. 5: Gravestone of Ludwig Boltzmann with his formula for entropy. Wiener Zentralfriedhof, Austria. From: https://de.wikipedia.org/wiki/Datei:Zentralfriedhof_Vienna_-_Boltzmann.JPG. License: CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0/).

What is striking about the movement of the awn of a plant seed (Fig. 6B) is the fact that the material is by no means rigid. Nevertheless, its internal structure is such that the geometric shape is predictable based on the outside air humidity. In this sense, the internal structure of the cellulose fibers confers to this material a property that relates air humidity (input) to shape (output) in a way that is totally analogous to mass in the case of gravitational forces (Figs. 1 and 3). The gear in Fig. 6A would normally be considered a system and not a material, while the awn is composed of woody cells and is thus very similar to wood, which would normally be considered a material. The complexity of the awn's movement is, however, more reminiscent of a system. What if we coated the gear in Fig. 6A with a skin, not revealing the inside? Could it then be a material in the same right as the awn in Fig. 6B? Does the distinction between material and system even make sense? In fact, both are only defined by their interactions with the environment, and setting the boundary is what defines them. Hence, each material is a system, and each system can be a material for the construction of larger entities. This hierarchical principle is a hallmark of natural materials [Fratzl and Weinkamer 2007] and can be directly generalized to all materials and systems.

Fig. 6: Degrees of freedom and energy supply in mechanical systems. (A) The right wheel in the system governed by a belt or a gear has no degree of freedom. It has to turn either in the same direction or in the opposite direction to the left wheel. The energy for the movement is transferred directly from the movement of the left wheel. Adapted from: [Reuleaux 1876, p. 262, figs. 182, 183]. (B) The various states of the *Erodium* awn depend on its water content, which in turn depends on air humidity. © Rivka Elbaum (Hebrew University of Jerusalem) and Peter Fratzl (MPI-CI). As with any material property, the geometric appearance (output) is a direct function of air humidity (input). Hence, the geometric state is completely predictable from the input, in the same way as the rotation direction of the right wheel in (A) is completely predicted by the movement of the left wheel. The corresponding material property has been programmed by the plant during the growth of the awn by a complex arrangement of cellulose fibrils [Abraham et al. 2020]. The energy for the shape change is directly taken from the environment (via water absorption or evaporation). (C) In contrast to (A) and (B), the robotic arm in (C) has several degrees of freedom materialized by its articulations (the photo was edited by Peter Fratzl). The control is delegated to an outside processor and the information needs to be imported through a cable (blue arrow), as does the energy for the movement (second blue arrow).

6 Symbolic Dimension: Constraints and Information

The operational character transforms the material from a static solid body into a series of possible states. Thus, the material as a realm of possibilities also acquires a symbolic character. The degrees of freedom define a space of possibilities that can in principle be realized.[3] Under certain conditions, therefore, every state has a certain degree of possibility. If the material has a high degree of freedom (due to elasticity, for example), it is less predictable, since every circumstance can result in a large number of possible states. The higher the degree of freedom, the lower the inherent information. And vice versa: material constraints embody information.[4] Only by reducing the degree of freedom does a predictable action of the material become possible. This is – according to Franz Reuleaux – the fundamental principle of mechanical machines as chains of constrained elements [Reuleaux 1876, p. 46]. The gears made of stiff metal transform the energy input at the receiver into a specific work as the output. The mechanical constraints select predictable operations from the possible states. Thus, the constraints can be considered the programming and implemented information within the internal structure of the machine. The transfer or the input and its transformation into a constrained process reduce the possible states to the very precise mode of action prescribed by the machine.

In the case of a steam engine, this chain of constraints transforms steam energy into the intermittent movement of the piston, which is transformed in turn into the rotation of a wheel, which – in the case of a railroad – is constrained by the tracks to a linear movement, whereas, in the case of a car, an external coding by the steering wheel is required. Here, two modes of information processing become evident. First, the material 'programs' its activity through its intrinsic structure, comparable to mechanical gears in machines; second, the material is defined by a lot of possible states as less constrained and has to be controlled by means of outside information in order to generate predictable actions. Whereas the first mode integrates physical action and information processing in one and the same structure, the second mode separates the control operations from the mechanical device. This last version is the cybernetic and finally digital mode of separating information and physical work by isolating the control unit and its information processing from the material. Information then has to be supplied to the material from outside in order to be executed in the form of predictable work.

In the integrated version of an intrinsically programmed material, where mechanical work is simultaneously information processing, Boltzmann entropy and Shannon entropy can coincide, in the sense that the structural constraints decrease entropy

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[3] For Terrence Deacon, absence is a fundamental element of the informational dimension of matter [Deacon 2012].

[4] See Chapter 12 "Information" and Chapter 13 "Significance" in: [Deacon 2012, pp. 371–420].

and increase information.[5] In this case, the small internal structures of the active material permit the fusion of information and work processes. Shannon's information theory, however, is modeled according to the second mode of separating information and working machine, since it is all about the transmission of information between sender and receiver. In the integrated mode, the receiver (in terms of Shannon's information theory and of Poncelet's machine theory) is not an empty black box – with a high degree of freedom – that has to be fed with information from outside, but a material that contains its intrinsic coded structure.

In nature (compared to artificial mechanical gears), much softer and more elastic materials are used for this integrative mode of information processing. Natural materials are based on ever-repeating constituents, such as proteins, polysaccharides, and minerals, with a hierarchical structure [Fratzl and Weinkamer 2007]. Due to this hierarchy of structures, materials can be adapted to a variety of sometimes conflicting functions [Weinkamer and Fratzl 2016], such as, simultaneously, optical, mechanical, and thermal functions, leading to multifunctional materials [Eder, Amini, and Fratzl 2018].

7 Information and Energy

The concept of a passive material is a convenient engineering concept. In such a picture, materials would react according to their set of material properties. Hence, the activity (of a robotic arm, for example) depends on an external input in the form of information (e.g., from digital processors) and in the form of energy (generated remotely) (see Fig. 7). Any intrinsic activity of the material is then considered a defect, an error, or a failure. Examples are beams bending under too much load, disrupting electrical cables, or plastic embrittlement under UV light – irrespective of the fact that in some systems these properties can become functional (in fuses, safety valves, etc.). The important conceptual difference is that an active material gains system properties, with information being processed directly in the material. An example of this is the complex curling movement that the *Erodium* awn performs when the air humidity changes (Fig. 6B). Active materials may also extract energy directly from the environment or even convert energy directly (e.g., the internal stresses that are released when certain seed pods explode).

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[5] See: [Deacon 2012, pp. 378–379]: "According to Shannon's analysis, the quantity of information conveyed at any point is the improbability of receiving a given transmitted signal, determined with respect to the probabilities of all possible signals that could have been sent. Because this measure of signal options is mathematically analogous to the measure of physical options in thermodynamic entropy, Shannon also called this measure the 'entropy' of the signal source. I will refer to this as Shannon entropy to distinguish it from thermodynamic entropy."

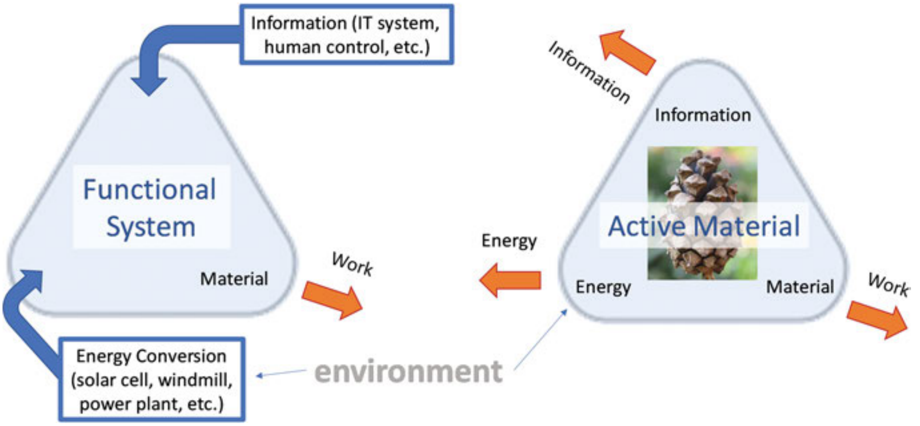

Fig. 7: Removing the dichotomy between information/energy and material in an active material. A functional system (left), such as a robotic arm, is based on a passive material (e.g., steel or aluminum) that is activated through the import of information from an IT system (e.g., a digital processor) and through the import of energy (previously converted from environmental or fossil sources). An active material (right) is a functional system in its own right. It is not just a passive material but carries information for the function (such as the cellulose fiber arrangement that encodes the opening movement of the pine cone) and takes the required energy directly from the environment (e.g., humidity changes to actuate the pine cone scales). Orange arrows symbolize potential outputs (e.g., work). Active materials may also convert environmental gradients into information (and thus work as sensors) or even into (electrical) energy, for example, by coupling to a piezo element. Reproduced from: [Eder et al. 2020, fig. 1]. © 2020 The Authors of [Eder et al. 2020]. Published by Wiley-VCH GmbH.

This difference between technical devices and biomaterials understood as machines is remarkable and corresponds to the two modes of operation mentioned above: of separating work and information processing and of integrating both. Furthermore, the way in which energy is supplied is different; whereas the technical arrangement of machines depends on an artificial environment that has to be established by larger amounts of external energy and information, biological material, in contrast, only uses the naturally existing environment, where sunlight, humidity, and gravitational forces are the basic requirements for its activity. The inner structure of a material – containing special functions – is the operator structure that becomes active through the extrinsic activity of, for example, water and temperature. In biological materials, this interaction with the environment combines information and energy for the mechanical work in one and the same process and structure. In this case, the material as an operator integrates several informational and mechanical activities, namely, acting as a sensor for the external conditions that trigger the coded action of the material, the processing and execution of information within the material structure, and finally the transformation of the activity into mechanical work as its output. For example, the internal structure of wood as an active material [Eder et al. 2020] contains an assemblage of different hydrophilic elements, whose geometry determines a certain material code and transforms the humidity gradient into mechanical movements. This integrated operator of sensor, structure, and mechanical execution can be seen as an analog code that, in contrast to digital coding, not only symbolically represents but also physically performs the action. In this sense, the geometric elements take on the role of an analog code that is the operative basis for the programmed material thus executing its intrinsic information.

The operator material has limited degrees of freedom and thus contains the necessary information that can be processed within the geometric structure, whereas the energy supply depends on the external environmental conditions. Nevertheless, storage and amplification of energy is also made possible by special structures such as spring mechanisms that can release stored energy in an explosive manner.

In terms of machinery, one can therefore distinguish three different types: (1) a cybernetic or digital machine, where the mechanical operation is fed by external artificial sources of energy and information; (2) an analog – or gear-controlled – machine, where the information is integrated or programmed as mechanical constraints within the gearbox, whereas the energy has to be added by an external artificial source; and (3) material as an operator that contains its information in its intrinsic geometric structures that are activated by the energy gradients of its natural environment.

8 Programmable and Self-Learning Materials

Recent developments in materials science have started to shatter the concept of immutable material properties as a paradigm for technical design. The concept of programmable materials seeks to modify the material property (that is, its operationality transforming an input into an output) depending on needs.[6] Programming steps can be of rather diverse types: the growth of the seed awn (Fig. 6B), for example, would involve a step in which microtubules in the living plant cell would control the orientation of the cellulose fibrils [Cosgrove 2016] that then provides the desired functionality after the death of this cell (so that only the woody cell wall remains). The internal structure would then be the code that defines the relationship between air humidity and the shape of the awn (Fig. 6B). Another possible type of programming is 3D fabrication used to generate internal structures that confer mechanical or optical properties to a material that it would not otherwise have. Properties could be programmed into a textile by different knitting or weaving procedures. Even thermomechanical processing is often used to adjust (program) the material properties of engineering alloys.

Perhaps, the simplest example of a programmable material is an electrical resistor that transforms voltage into current, the relevant material property P being its

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[6] See https://cpm.fraunhofer.de/en.html (accessed June 20, 2021); https://selfassemblylab.mit.edu/programmable-materials (accessed June 20, 2021).

resistivity. Since resistivities depend on temperature, a control of the environmental temperature would control the resistivity and thus allow the programming of the voltage–current relation. A more compelling example would be a material that changes its shape depending on a particular input, such as humidity or temperature. Going back to the awn of a plant seed (Fig. 6B), this material changes from a straight needle-like shape to a helix as a function of the air humidity in its environment. With the diagram in Fig. 8, the input is humidity and the output is shape. The corresponding material property *P* is complex and cannot be found in typical material property charts, but it fulfils the definition of relating the input (humidity) to the output (shape). *P* is complex because it depends on the internal fiber structure of this cellulosic material. With another fiber structure, the shape change would be different. By laying down a specific arrangement of cellulose fibrils, the plant programs the material for a specific behavior, relating humidity to desired shapes. Shape-changing objects have also been a strong focus in current research on programmable materials (see footnote 6). While it is easy to reprogram resistivity by changing the temperature, it is more difficult to reprogram the cellulosic seed awn, which was generated by the plant in a complex synthesis process. The cellulose fibril arrangement in the seed awn is therefore an analog code inscribed in the cell wall by a programming step, while the cell was still living and growing its cell wall. It then allows predictable shape changes even after the plant tissue is dead (in the sense that plant cells have lost their metabolic activity, leaving only the cellulosic cell walls behind).

Self-learning or adaptive materials possess even more exciting behaviors. As sketched in Fig. 8, the signal for the modification of the property *P* is derived directly from the output signal. In this way, the output signal has an influence on the material property *P*, which in turn influences how the input is converted into the output. Such

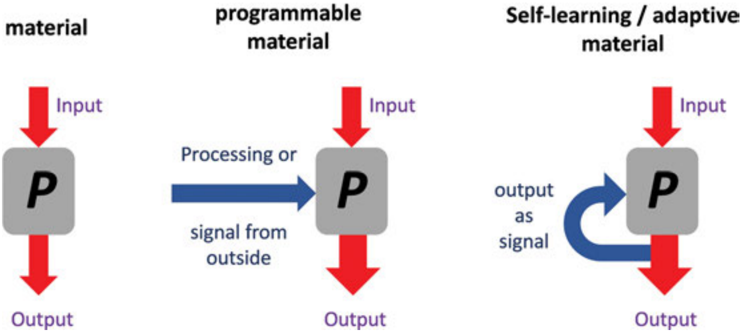


Fig. 8: Any material with property *P* is an operator that transforms the input from the environment into an output. Creating or modifying this property *P* by processing the material or through some outside signal changes the relation between input and output, allowing a programming of the material. Such materials are often also referred to as responsive. If the modification of the property *P* occurs in response to the level of output, a feedback loop is generated. Such a material would be adaptive or self-learning. © Graphic by the authors (P.F./W.S.).

feedback loops are a hallmark of living systems, and the combination of many such loops is known to lead to emergent lifelike behavior and is studied in the discipline of systems biology [Klipp, Liebermeister, and Wierling 2016; Alon 2019]. The muscles and even the bones in our bodies can be trained to become thicker and thus to respond better to challenges. If we train a muscle, the input is a mechanical load (generated by the weight to be lifted), and the output is the lift height. The mechanical contraction force of the muscle (relating input to output) depends on the muscle cross-section, which increases with training. Similarly, sustained loads on our bones increase the latter's thickness. Such materials are adaptive or self-learning. For an adaptive material, as sketched on the right in Fig. 8, the output might modify the material property in two principal ways. If an increase in the output leads to a modification of *P* so that the output for a given input is reduced, the system is stable and often called homeostatic. Many processes in living bodies are homeostatic, preserving the amount of material despite varying challenges from outside. If, on the contrary, an increase in the output leads to such a modification of *P* that the output for a given input increases further, then the situation is unstable. Instability may be problematic and lead to failure, but it may also be productive and lead to a new homeostatic equilibrium or induce growth, for example. The transfer of the concept of adaptive materials from biology to engineering is still in its infancy. It is not yet clear how adaptive materials can be fabricated based on nonliving components, and their behavior is complex and difficult to predict. The properties of adaptive (self-learning) materials depend on their history, and their combination may lead to emergent behaviors that cannot be inferred from the material properties of the individual components. In many ways, the challenges resemble those of artificial intelligence, except that the learning does not occur in formal networks but in analog and tangible materials.

9 Conclusion and Outlook: Logic, Code, and Material

Active materials change our classical understanding of material. The active structures of the material act as an operator that consists of an integrative system of material, energy, and code, which can be understood as a new type of hardware. This material hardware will no longer combine code and material by externally implementing symbolic algorithms in a passive material carrier but will embody their radical fusion. The understanding of materials as operators that are simultaneously their own material code is not limited to the study of biological materials; it provides a conceptual framework that fundamentally changes the way we conceive the relationship between material, information, and activity. This reconceptualization brings to light a downright revolutionary mode of material activity, one that incorporates an integrated version of code, working process, and building structure within its inner structure.

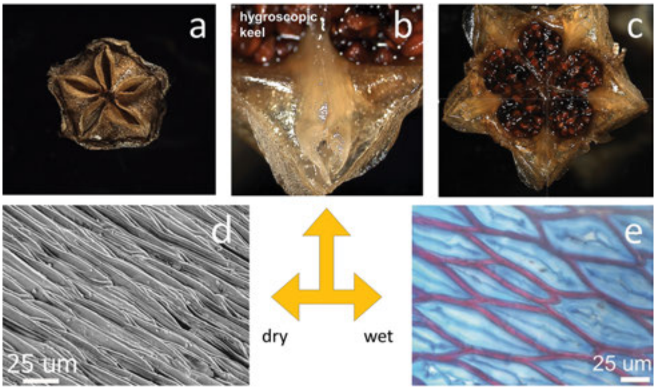


Fig. 9: The mechanical movement of the seed capsule of an ice plant (shown closed in (a) and open in (c)) is based on the intrinsic honey comb structure of the actuating keel shown in (b). The change from dry (d) to wet (e) makes the honeycomb structure swell and thus opens the closed capsule Adapted by permission from Springer Nature: [Harrington et al. 2011, figs. 1, 3].

The active material of the ice plant (see Fig. 9) is a switching structure that transforms the input into an output depending on a coded procedure. But it is simultaneously the unit that transforms the energy of the signal into the mechanical operation coded within the switching structure. The switching energy, however, is not electricity but water.

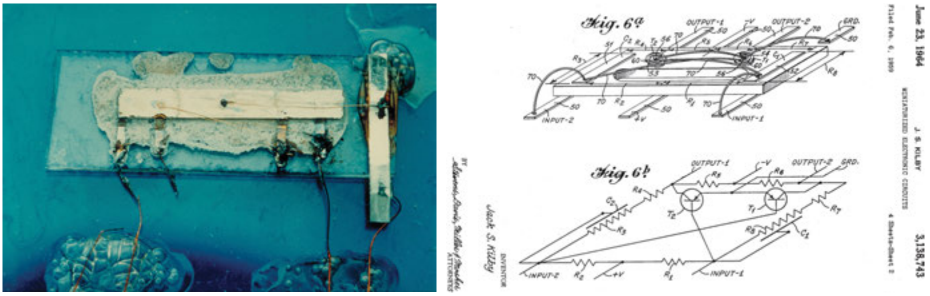
If we compare this water-fueled active structure with electronic switching elements, it is interesting to look back to the invention of the integrated circuit, which combined electronic elements such as transistors in a single wafer.

Digital hardware consists of an external activation of materials that obey the specific functions they represent within the preconceived operation activated by the externally added electricity. Figure 10A shows the elementary hands-on way the digital revolution started as integrated hardware 60 years ago. Instead of trying to minimize the single elements of switching circuits, integration here means incorporating all the elements into one and the same component.

Compared to this crude activation of material as a digital switching device, the active structures of the biomaterials we can identify today in nature exhibit a quite different level of sophistication. Therefore, it is clear that in the development of analog coding, biomaterials can be seen as highly promising active materials.

Our analysis of materials as operators and of their intrinsic material code shows that we have to reestablish the relationship between logic, code, and material. This includes – as its most important feature – the inversion of the classical idea of logic and code understood as an artificial intelligence implemented in our physical world, which is still essential for the digital world.

The emergence of the computer as a logical machine was due to the coupling of electrical engineering and logical operations. In analog electric circuits, the electrical



(A) (B)

Fig. 10: The first integrated circuit, developed by Jack Kilby at Texas Instruments in 1958 as a crude assemblage of wired materials. (A) A complete circuit of a phase-shift oscillator on a single crystal bar of germanium. (B) Kilby's patent drawing from 1964 showing the single body of the semiconductor material, which integrated all electronic components of the switching circuit [both from Jack Kilby, US Patent 3,138,743 Miniaturized Electronic Circuits. Patented June 23, 1964]. © Courtesy Texas Instruments.

flow is controlled by switches that open or close the circuit and thus make a machine run or a light burn. More complicated switching circuits – above all, in telephone networks or control units – require a large number of switching elements to produce the desired performance. This was Claude Shannon's starting point for optimizing switching circuits through a symbolic analysis [Shannon 1937]. Based on a binary logical calculus, Shannon could describe a mode in which logical operations could be 'interpreted' as switching circuits and thus transform a complex switching circuit into an algebraic expression (see Fig. 11).

This means inversely that logical operations such as addition and multiplication could also be performed by parallel and serial connections of switches. The electrical flow and its discrete sequential switching implement information transmission and processing as a sequential flow of signals that goes through matter but does not take into account matter's inner structure. Matter as digital hardware is some sort of material flowchart where the bistable switching elements perform logical operations. The very property of the material is reduced to its reliable and immediate reaction to the input commands. Thus, logical operations could be implemented in switching circuits that are fundamentally separated from the mechanical periphery they control.

This relation of logic, code, and material, however, has to be rethought within the context of adaptive materials. The coupling of logical operations and matter, which includes the fundamental separation between symbolic operations and mechanical work, has to be overcome. Instead of implementing logical operations within matter, it is necessary to conceive the 'logic' of the material structure itself. Instead of taking binary logical operations and looking for ways to find materialized modes of performance, one has to invert the procedure: the analysis of biological materials has to reveal their inner operational logic in terms of a basic code of the analogue.

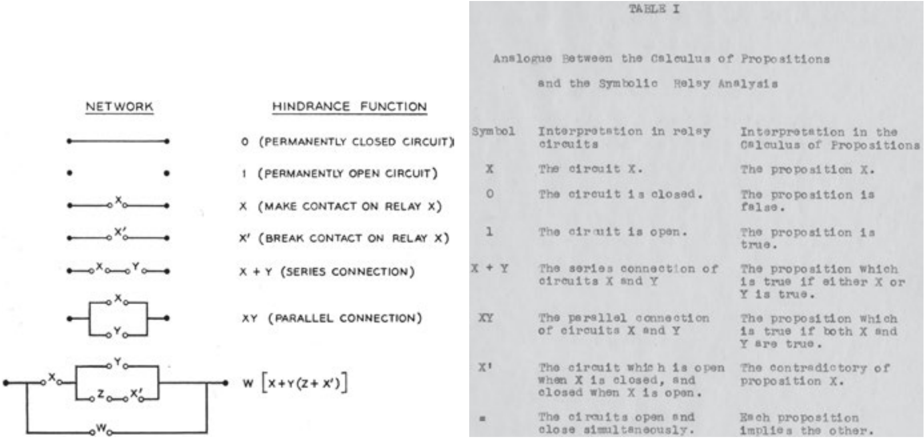


TABLE I

Analogue Between the Calculus of Propositions
and the Symbolic Relay Analysis

Symbol	Interpretation in relay circuits	Interpretation in the Calculus of Propositions
X	The circuit X.	The proposition X.
0	The circuit is closed.	The proposition is false.
1	The circuit is open.	The proposition is true.
X + Y	The series connection of circuits X and Y	The proposition which is true if either X or Y is true.
XY	The parallel connection of circuits X and Y	The proposition which is true if both X and Y are true.
X'	The circuit which is open when X is closed, and closed when X is open.	The contradictory of proposition X.
=	The circuits open and close simultaneously.	Each proposition implies the other.

Fig. 11: A symbolic analysis of relay and switching circuits. Left: [Shannon 1949, p. 60, Fig. 1]. Reused with permission of Nokia Corporation and AT&T Archives. Right: [Shannon 1937, p. 11, tab. 1]. © Massachusetts Institute of Technology.

A symbolic system that is not based on alphanumerically discrete elements such as letters or numbers, but on discrete and continous, symbolic, extended – and thus analogue – operations is the very classical realm of geometry. Conceiving in this sense geometric objects as operators, therefore, appears to be a basis for analyzing the operational character of materials. The materials science makes evident that a material's intrinsic operations are based on geometry, on interconnected hierarchical dynamic structures that perform mechanically. The operational character of this analog code is different from the sequential alphanumeric digital code, since it is a material code that performs the coded physical process at the same time. Thus, the approach of taking materials as operators raises the question of the intrinsic logic of the materials' geometry, which can be analyzed as a symbolic and material operation.

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