Introduction

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Materials Matter: Introduction

“materials are a boundary concept”¹

Why should materials be considered a boundary concept? First, materials are increasingly seen as simultaneously both specific and general; second, they have become historically loaded with a range of metaphysical and empiricist, scientific and artisanal interpretations. Taking this boundary character into consideration, it would not be an understatement to claim that in the second half of the twentieth century our understanding of ‘materials’ has changed decisively. Starting in the middle of the twentieth century, alongside well-established ‘raw’ materials such as iron, wood, or ceramics, one starts to see the appearance of “materials by design” [Bensaude-Vincent 2011b, p. 119]. But what are these ‘materials by design’? In contrast to raw materials, these new materials are designed for complex and specific tasks, and for that reason stand not at the beginning but at the end of the research and design process. This remarkable shift in our understanding and handling of materials should also be seen against the background of the considerable growth in the importance of materials for industry and engineering. At the latest since the establishment of materials science departments (beginning in the 1960s), ‘materials’ have become “characteristic ontological creatures of a new style of reasoning” [ibid., p. 108]. And yet materials science is also a symptom of an even more comprehensive transformation: the emergence of a “materials way of thinking” [ibid., pp. 107–108]. The aim of this volume is to explicate and explore this novel way of thinking.

Of course, the extraction and consumption of materials is fundamental in all societies. The relation of humans to their environment (including what is called ‘nature’) is

¹ Epigraph taken from: [Bensaude-Vincent 2011b, p. 117]. “Boundary concept” is probably a paraphrase of the notion of ‘boundary objects,’ which according to Susan L. Star and James R. Griesemer are “scientific objects which both inhabit several intersecting social worlds [...] and satisfy the informational requirements of each of them” [Star and Griesemer 1989, p. 393]. Their boundary character is shown by the fact that they may be simultaneously specific and general, “abstract or concrete.” See also: [Star 2010].

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structured and secured via materials and the ‘techniques’ of extracting and processing these materials.² This is all the more so in highly industrialized and technologized societies. It is hardly surprising, therefore, that materials in these societies have become an important object of research, as well as, consequently, high-performance products. Linked with this development, however, are two notable changes: On the one hand, with the founding of the materials science, material becomes a worthy epistemic object and simultaneously a generic category – despite the material still being understood until late into the twentieth century as a specific, largely individuated substance. Unlike the traditional physical category *matter* (with its claim to universality), metal, ceramics, wood, and other things constitute a “zoology of materials” [Bensaude-Vincent 2011b, p. 110], and thus a multiplicity of materials is studied by different disciplines and linked with different techniques.³ With this, not only the individual material migrated into the natural sciences but also a practical knowledge: technology became even more tightly linked with epistemology and ontology.

On the other hand, since the 1980s at the latest, the aspect of ‘performance’ came to the fore in materials science, and thus an ‘activity’ that is attributed to the material itself – to the extent that this is inherent to the material’s structures and properties. In this understanding, ‘material’ implies an autonomous agency that should be analyzed and, as far as possible, generalized using the methods of natural science (theories, models, and tools from physics, chemistry, and mathematics) – which ideally should then lead to new basic knowledge as well as, of course, to new materials and innovative design. This attentiveness to ‘active’ materials has grown considerably in importance both in and beyond the natural sciences (in particular, in engineering, architecture, and design). One’s focus in the materials science is the analysis of ‘biological materials’⁴ and ‘biomaterials’ and thus on the one hand of complex configurations of structure and process with outstandingly functional properties, which can be found not only in plants and animals but also at the microscale in cell tissue; and on the other hand of engineered substances, which are developed for among other things medical-therapeutic or -diagnostic interaction with components in living systems. Since the mid-1990s in physics and in particular in condensed matter physics, however, another field called *active matter* has emerged. In this field, activity is understood as a basic property of matter, but one that requires

² That is the approach of André Leroi-Gourhan, a historian of pre- and early history, who describes historical societies via techniques of the extraction and processing of material [Leroi-Gourhan 1971 (1943)].

³ Metallurgical research was linked to physics, the science of wood to biology, and the knowledge of ceramics to chemistry – and all three were frequently boundary fields to the extent that they stimulated the transfer to application, for instance, in engineering.

⁴ For ‘biological materials’ the term ‘nature’s materials’ is also in circulation in the materials sciences. These terms are actors’ terms, that is, technical terms used by the protagonists of this research. For ‘biological materials’ see, for example: [Meyers et al. 2008]. For ‘nature’s materials’ see, for example: [Fratzl and Weinkamer 2007; Fratzl 2007; Fratzl and Barth 2009].

certain conditions in order to appear. The research in this field aims explicitly at the universal category of matter and, in doing so, works intensively with mathematical modeling and simulations. Here too, however, the research object is frequently related to ‘self-propelled’ or ‘self-driven’ entities that are classified as ‘living matter,’ with examples extending from the nano- and the micro- to the macroscale (e.g., cell tissue, bacteria, bird flocks, and human dance behavior) [Ramaswamy 2010; Menon 2010; Gompper et al. 2020; Popkin 2016]. The scientific description of this living matter is oriented to the theories and equations of statistical physics and hydrodynamics that, from a formal perspective, ignore the opposition living/dead. Thus, bird flocks, for instance, are modeled analogue to the ferromagnetic interaction, when the spins are aligning in the same direction – with the difference, however, that the cause of the movement in the case of active matter is inherent to the (non-equilibrium) system, and the aligning refers to the direction of motion [Vicsek et al. 1995, p. 1226; Keller 2016; Vehlken 2012; Grote 2019, pp. 56–110, 186–193].⁵

Since the 1980s, and increasingly in the 2000s, therefore, the question of the activity of materials, and more fundamentally of matter, has gained enormously in significance. This is due not only to the possibilities of mathematical modeling and the new instruments of investigation; the promise of active materials goes beyond epistemological procedures and concerns. The hope is to create ‘better’ – since more sustainable and/or efficient – materials. Drawing on the model of biological materials, artificial materials should be developed that are not only controllable but also capable of similarly complex performances. This performance specification can be read from the characterization of the corresponding research objects: ‘self-propelled’ materials, ‘self-assembling’ materials, ‘self-healing’ materials, ‘responsive’ materials, ‘adaptive’ materials, ‘smart’ materials, ‘intelligent’ materials, and so on.⁶ Those characteristics are given to both biological materials and artificial (i.e., man-made) materials. A few examples are: Andreas Walther describes the “humidity-induced actuation in a pine cone” as a “responsive system,” the “dynamic camouflaging on cephalopods” as a “dynamic adaptation of color and topography,” and the “signal-induced actuation in a venus fly trap” as a “single trajectory adaptation” [Walther 2019, p. 3]; Giovanni Noselli et al. point out that the construction of “[s]mart helical structures” is “inspired by the pellicle of euglenids” [Noselli, Arroyo, and DeSimone 2019, p. 234]; Barbara Mazzolai et al. note that “[p]lants or plant parts, such as roots or leaves, offer countless cues for making innovation in technology” and that one may summarize some “of the main principles studied in the plant roots” as the “capacity of growth and movement,” “sensory

⁵ To the extent that the source and cause of the self-movement lies in the system itself, the need to include an external impetus in the physical consideration is eliminated. In the case of self-propelled particles, the ability to move is among the requirements of the material system.

⁶ We refer to the interviews in this volume, which exemplify these various characterizations. See also the contribution by Peter Fratzl and Wolfgang Schäffner for the difference between programmable, adaptive, and self-learning materials.

capabilities,” and “emergent behavior” [Mazzolai, Beccai, and Mattoli 2014, p. 2]; and last but not least Thomas J. Wallin et al. have developed, using 3D printing, “fluidic elastomer actuators,” a “material system [which] permits rapid autonomic self-healing via sunlight” [Wallin et al. 2017, p. 6253].

In the meantime, however, this search for new kinds of materials is no longer merely a technical but in part also an ecological concern. The enormous consumption of resources by highly industrialized and technologized societies is leading to a destabilization of the ecological balance and the rapid depletion of materials such as wood, coal, oil, and ore – and this fatal spiral should now also be countered by these new materials.

Against this background, the urgency of the field of active matter research becomes apparent, whereby three directions can be discerned: (1) ‘active materials’ is a research field with a strong internal dynamics that has the potential to significantly expand the natural sciences; (2) a promise arises from this research, and from the prospective development of related technologies, of a ‘better’ treatment by humans of the environment; and (3) the research on active matter changes how we understand ‘material’ and ‘matter’ – not only in the natural sciences but also in engineering, architecture, design, and finally within the whole culture. This edited volume responds to this urgency and takes the recent growth in research on active matter as a starting point for disciplinary and interdisciplinary analyses. Thus, the state of natural-scientific research is surveyed through interviews with central protagonists on their representative research objects (see the interviews with Joanna Aizenberg, Nikolaus Correll, John Dunlop, Ramin Golestanian, Jean-François Joanny, Barbara Mazzolai, Rob Shepherd, and Thomas Speck). Parallel to this ongoing research on active materials is also multiply contextualized: the transfer of approaches in the materials science to design practice is carried out and reflected on (see the contribution by Ianis Lallemand); the interdisciplinary negotiation of active materials is opened up on the one hand between physics, materials science, and cultural studies (see the contribution by Mohammad Fardin Gholami, Lorenzo Guiducci, Susanne Jany, and Khashayar Razghandi), and on the other hand between biology and philosophy (see the contribution by Sonja Dheur and Sven J. Saupe); and the topos of the activity of material and matter is complemented by perspectives on significant historical discourses from art history, visual and literary studies, and philosophy (see the contributions by Horst Bredekamp, Stephan Kammer, Sylvie Kleiman-Lafon, and Charles T. Wolfe). In addition, these interviews and contributions are preceded by a programmatic position in which Peter Fratzl and Wolfgang Schäffner jointly consider active materials’ characteristic features from two different but related perspectives: materials science and the cultural history of knowledge.

This introduction in turn will address in a first part three significant *historical* material scenes (from Georgius Agricola in the sixteenth century to eighteenth- and nineteenth-century chemistry to the material sciences of the twentieth and twenty-first centuries) in order to highlight the different ways material has been conceived and

handled in technology and science. The second part focuses on central aspects of *current* research on active materials, thus primarily the field of active matter and the promise of ‘bioinspired’ materials. This is outlined by a quick look at the prehistory of active materials research (which is still partly in force today): the suggestion of a ‘dematerialization,’ which is linked to pliable, high-performance, and essentially passivized materials such as iron, particularly in nineteenth- and twentieth-century architectural theory.

1 Technology and Science

1.1 “Man’s Needs”

From a modern Western historical perspective, the meaning and importance of materials for the development of culture seems to be clear, since the broad historical periods of mankind are demarcated according to the materials that were used and available: the Stone Age, the Bronze Age, or the Iron Age. However, these demarcations are very much influenced by a conception of nature as an (infinite) repository of materials (or just one material: stone, bronze, or iron) waiting to be used and shaped. This conception of the material as a resource for technological-cultural developments has parallels with the classical division between matter and form. The ancient Greek term ὕλη (*hyle*) forms the generic root of all material phenomena – a term which was translated into Latin as *materia* or *materies*, but which originally meant ‘dead wood,’ ‘brushwood,’ or ‘timber.’ The Greek term ὕλη (*hyle*) stood in opposition to the concept of form. For Aristotle, matter is abstract possibility, δύναμις (*dynamis*), which has to be shaped and in a sense ‘realized’ by form. According to this understanding, material too is largely passive or inert and shaped by the active and external imposition of form. Accordingly, hylomorphism postulates an asymmetry between passive matter on which a form is imposed – a view that has had (and still has) a widespread influence. In hylomorphism, form and matter are treated as separate principles, whereby matter is thought of as a receptive substance (and in this sense as a mere ‘possibility’) and form as a causing and fulfilling ‘reality’ [Detel et al. 1980].⁷ As Tim Ingold notes, following Gilbert Simondon’s interpretation of hylomorphism, the problem here is that man (from the early modern period on, as natural philosopher or later, as scientist) is presented as the one who “stands outside the works and sees what goes in and what comes out but nothing of what happens in between, of the actual processes whereby materials of diverse kinds come to take on the forms they do. It is as though, in form and matter, he could grasp only the ends of

7 “Because matter is a precondition of form, the two behave like *possibility* and *reality*.” (“Weil die Materie Vorbedingung der Form ist, so verhalten sich beide wie *Möglichkeit* und *Wirklichkeit*” [Baumker 1890, p. 261 (emphasis spaced out in the original)].)

two half-chains but not what brings them together [...]" [Ingold 2013, p. 25]. Instead of the hylomorphic model, Ingold suggests shifting the point of view toward materials, that is, forgetting what we know from the sciences about the chemical composition of materials and following instead the artisan's "desire to see what the *material* can do, by contrast to the scientist's desire to know what it is" [ibid., p. 28].⁸ Ingold is of course not alone when he stresses this research direction. To give only two examples, Pamela Smith and Pamela O. Long also emphasize the artisan's knowledge with respect to materials and the techniques of their processing [Long 2011; Smith 2004; Smith 2018]. A similar attention to techniques of processing has also been suggested by André Leroi-Gourhan (already in 1943). Material is explained by the historian of pre- and early history via "techniques de fabrication" ("techniques of fabrication") [Leroi-Gourhan 1971 (1943), p. 161], which include the elements fire, water, and air, as well as the use of elementary forces (the "Moyens élémentaires d'action sur la matière" ("elementary means of acting on material/matter") [ibid., p. 43]). But in order to appreciate the significance of *la matière* – used in Leroi-Gourhan in the double sense of 'matter' and 'material' – one also has to take production into account. Material/matter becomes intelligible and understandable only in connection with gestures and techniques that put it in relation to man. Thus, while Leroi-Gourhan speaks in connection with material of solids (*solides*), and thus uses a term that is also used in solid-state physics (a sub-field of condensed matter physics),⁹ when he divides the solids, on the basis of their state, into six categories (stable, fibrous, semi-plastic, plastic, supple, and fluid),¹⁰ the detailed description of the individual materials relates to the way they were extracted and processed, that is, via techniques.¹¹ For Leroi-Gourhan, therefore, material/matter (*la matière*) stands for physical-concrete components of the world (*solides*), which he understands in a broad sense (as *matériaux* (materials)), but in respect to human needs and practices, that is, in their technical-instrumental and to a certain extent 'nurturing' function. Accordingly the individual materials cannot be determined in a solely formal-abstract way, for instance only via the classification of 'bodies' (solids) according to their physical states. The materials exhibit certain properties, which in turn can be linked

⁸ See also [ibid., p. 28]: "What do we mean when we speak of materials? [...] To understand the meaning of materials for those who work with them – be they artisans, craftsmen, painters or practitioners of other trades – I believe we need, as art historian James Elkins recommends, to take a 'short course in *forgetting* chemistry'" (emphasis M.F./K.K.).

⁹ In physics, the term solids is used to describe material in a certain (solid) state. The research on these states contributes to a general theory of matter.

¹⁰ See the titles of the subchapters in Chapter IV, "Les techniques de fabrication": "Solides stables," "Solides fibreux," "Solides semi-plastiques," "Solides plastiques," "Solides souples," "Fluides" [ibid., pp. 162, 174, 191, 206, 234, 296]. Leroi-Gourhan's division of the solids does not represent a physical classification, but is founded in his epistemic perspective: an anthropology of techniques.

¹¹ Thus metal, for example, belongs to the "solides semi-plastiques," hence, bodies that in part can be 'formed,' whose extraction from the earth and stone through mining, smelting, and processing in smithies is described by Leroi-Gourhan [ibid., pp. 191–206].

with certain functions – each material is characterized by its own particular possibilities and limitations (analogue to Ingold’s “what the *material* can *do*” quoted above), which in turn are to be thought in relation to the possibilities and limitations of humans, thus their techniques, their knowledge, and their needs (as it were, what *humans* can *do*).

Simondon’s rejection of the traditional matter/form or material/form opposition goes in a similar direction, but puts a greater emphasis on the logic inherent to the technological aspect [Simondon 1995 (1964), p. 53]. ‘Nature’ ‘offers’ itself to the engineer (but also to the artisan and the artist) not as an abstract substance that can be mastered and controlled but in its structured materiality. As Henning Schmidgen notes, technicians must always deal with “matter-forms” (“Materie-Formen”) to meet human needs – to that extent humans constantly move in a “prefigured region” (“präfigurierten region”) [Schmidgen 2012, p. 128] with which they enter into an exchange mediated by tools and techniques.¹² In short, solely the interaction between man and material can provide information about what is to be understood under ‘material,’ and this approach does not lead to an ontology (the knowledge of what material is), but to a technology, that is to a knowledge of the necessary gestures, procedures, and techniques that determine “the material exchange with nature” (“den Stoffwechsel mit der Natur” [Schmidgen 2012, p. 127]).¹³

1.2 The Sixteenth Century: Action on Materials

If one looks at the history of the changing attitudes to a ‘material,’ then the approach of Leroi-Gourhan (or of Ingold and Simondon) is well founded. If one consults Georgius

¹² On the knowledge of materials through tool use, see Simondon: “Knowing how to use a tool is not only to have acquired the practice of the necessary gestures; it is also to know how to recognize, via signals that come to man through the tool, the implicit emerging form of the matter in the precise place that the tool strikes.” (“Savoir utiliser un outil, ce n’est pas seulement avoir acquis la pratique des gestes nécessaires; c’est aussi savoir reconnaître, à travers les signaux qui viennent à l’homme par l’outil, la forme implicite de la matière qui s’élabore, à l’endroit précis que l’outil attaque” [Simondon 1995 (1964), p. 51].) Unless stated otherwise, all translations from German and French were made by Benjamin Carter.

¹³ Presupposed here is Simondon’s understanding of technology as an unavoidable medium. See the elegant exposition by Schmidgen: “Simondon is much more cautious when speaking of the technical objects as mediators (*médiateurs*) between nature and man. The consideration of technical objects is thereby transferred to a medial register that [...] is oriented to the problem of production. Since Marx, production is described as a material exchange with nature, which through man’s activity is ‘mediated, regulated, and controlled.’” (“Deutlich vorsichtiger spricht Simondon von den technischen Objekten als Vermittlern (*médiateurs*) zwischen Natur und Mensch. Die Betrachtung des technischen Objekts wird damit in ein mediales Register überführt, das [...] sich am Problem der Produktion orientiert. Seit Marx ist Produktion als ein Stoffwechsel mit der Natur bestimmt, der durch die Tätigkeit des Menschen ‘vermittelt, geregelt und kontrolliert’ wird” [Schmidgen 2012, p. 127].) Here Schmidgen is quoting [Marx 1972 (1869), p. 192].

Agricola's *De re metallica libri XII* (1556) – and thus a famous early treatise on the methods and machinery of mining and smelting metal – then it becomes clear that the work on material (the extraction and further processing of material), as well as the resistance that the material offers to this work, essentially belongs to the clarification of what a material at a certain time 'is.' This is particularly true of Agricola's 'metal' to the extent that during his time the term 'metal' is used in the broad sense that the term had in the sixteenth century, namely to designate silver, gold, and iron, but also other useful 'earths.' Agricola's study does not simply recapitulate traditional philosophical and/or alchemical knowledge on metals, but nor does it merely bring together the observed tools and recipes.¹⁴ Rather he systematizes the mining practices and systematizes at the same time the causal relations of smelting procedures (which temperatures and catalyzers for which metals) as well as the geometrical recording of the metal-bearing veins, the passages to be constructed, and the construction of diverse lifting, ventilation, and crushing machines. *De re metallica libri XII* was intended not only as a learned treatise (as evidenced by the choice of Latin and the historical remarks) but also as an empirical study of contemporary machines and techniques, and in sum an encyclopedic work *avant la lettre* (i.e., before the publication of Denis Diderot and Jean Le Rond d'Alembert's famous *Encyclopédie* in the eighteenth century). The novelty of Agricola's work is the combination of theory and practice that aims to optimize the techniques of acquiring resources through the collection and dissemination of explicit and tacit knowledge. Thus, *De re metallica* not only represents the gradual transition from natural philosophy to the natural sciences but can also be understood as a prefiguration of the twentieth century applied sciences. This is seen clearly in the fourth and fifth books of *De re metallica*, which present geometrical considerations and constructions that – at least according to Agricola – are essential for mining.¹⁵ The introduction of practical geometry for the research of artisanal and other practices is one of the characteristics of the early modern period, but as Thomas Morel notes, there is "a gap between the uses of geometry in early modern mines and their presentation in the *De Re Metallica*" [Morel 2020, p. 42].¹⁶

Notwithstanding the imaginary mathematization of mining techniques, the treatise focuses on among other things the extraction of metals. But while this extraction is extremely useful, and thus valuable, the Latin term *materia* – which generally stands for a substance from which something emerges – is rarely used. Agricola speaks rather of *terra* (earth or soil in the most general sense), which, with its components (soil, stones,

¹⁴ On this and the subsequent discussion on Agricola, cf. [Krauthausen 2022]. See [ibid.] also for references to further secondary literature.

¹⁵ Hoover and Hoover's English translation, [Agricola 1912, p. 117]: "[...] the miner who is not ignorant of geometry can calculate from the other mines the depth at which the *canales* of a vein bearing rich metal will wind its way through the rock into his mine."

¹⁶ See also the entire paper for a thorough survey of the cultural background of Agricola's practical geometry and the mathematical practices introduced by him for mining.

and sediments), hides the metals from sight and makes them “unformed” (Latin: *informe*; in the German translation: *ungestalt*). He emphasizes the active extraction of the metal by smelting in book IX, which begins as follows:

Since I have written of the varied work of preparing the ores, I will now write of the various methods of smelting them. Although those who burn, roast and calcine the ore, take from it something which is mixed or combined with the metals; and those who crush it with stamps take away much; and those who wash, screen and sort it, take away still more; yet they cannot remove all which conceals the metal from the eye and renders it crude and unformed [*ac efficit informe*] [...]. Wherefore smelting is necessary, for by this means earths, solidified juices, and stones are separated from the metals so that they obtain their proper colour and become pure [*purum*], and may be of great use to mankind in many ways. When the ore is smelted, those things which were mixed with the metal before it was melted are driven forth, because the metal is perfected by fire in this manner [*metallum igni quodammodo perficitur*].¹⁷ [Agricola 1912, p. 353]

For Agricola, material does not mean an accessible, natural resource, but something obscured, indeterminate, without a form, which has to be ‘completed’ (Latin: *perficitur*) by human intervention in order to be made visible and useable (i.e., present in its utility for further uses). This is to be seen in the glossary of terms in Latin and German that Agricola adds to his treatise. Here, he uses the term *materia* only in combination with various activities: “*Materiam metallicam discenere a terris &c.*” (literally ‘to separate/distinguish the metallic matter/material from earth’) and translates this Latin phrase with a single German word, a verb, “*ertzscheiden*”¹⁸ (in the sense of ‘to separate the ore’). The ‘metallic material’ must be actively separated from the

17 Hoover and Hoover’s English translation. For the Latin original, see [Agricolae 1556, p. 285 (book 9)]: “*Scripsi de diverso venarum praeeparandarum opificio, nunc scribam de varia earundem excoquendarum ratione. Quanquam enim qui venas urunt, & torrent & cremant, aliquid detrahunt de his, quae cum metallis mista vel composita esse solent: multum, qui tundunt pilis: plurimum, qui lavant, cribrant, discernunt, omne tamen id quod metallorum speciem ab oculis removet, ac efficit informe quiddam & rude adimere non possunt: quocirca necessario inventa est excoctio, qua terrae, succi concreti, lapides sic separantur a metallis, ut suus cuique color insideat, ut purum fiat, ut multis in rebus homini magno usui sit. Cum autem excoctio sit eorum, quae, antequam venae excoquerentur, cum metallis erant permista, secretio, quodque metallum igni quodammodo perficitur.*” (The Latin has been slightly conventionalized.)

18 Agricola’s extensive glossary, which records the nomenclature of mining and metallurgy of his time in Latin and German, is present in the Latin first edition from 1556, but is not retained/adapted in either the German or the English translations. That is regrettable since this glossary was important for the contemporary reader from mining practice to the extent that they spoke little Latin. The glossary, like the figures, mediates between the scholarly audience and the practitioners. In addition, the author inserts the list of terms twice: once following their naming in the books (“*Rei metallicae. Nomina latina graeca qve germanice reddita, et ex ordine, quo quodque primo occurrit, collocata.*”) and once in alphabetical order (“*Index secvndvs continens eadem rei Metallica nomina Latina, Graeca Germanice reddita, sed in Lectoris gratiam, secundum Alphabeti ordinem digesta.*”). The terms in the two glossaries do not completely overlap. See [Agricola 1556, index without page numbers]; here all from “*Libro Octavo*” and correspondingly under ‘M’ in the second alphabetic index.

earth (*a terris*) before it can be brought to its proper (distinguished) appearance with the help of the fire of the smelter. And even when a little later in the glossary, Agricola lists “*Materia metallica*” (metallic matter/material) as a substantive, and not as an activity, this is translated to German as ‘das werck’ [Agricola 1556, index],¹⁹ a term meaning “tätigkeit, wirksamkeit, arbeit” (activity, agency, work), or occasionally “anstrengung, mühe” (endeavor, effort).²⁰ If one follows Agricola’s own lexical explanation, then the Latin *materia* (in the context of mining and smelting) denotes a skillful and purposeful as well as laborious activity in which the useful metal is obtained and brought to visibility. The result, the artfully ‘perfected’ metallic resource, can take on a variety of appearances (silver, iron, gold, etc.). But Agricola’s use of the Latin *metallum*, despite this plurality, does not mean a general category, but denotes specific modes of being – or, more precisely, specific modes of *coming into being*.

The early-modern understanding of metals (and in this sense of material) thus remains linked to the procedures of extraction and processing (see Fig. 1). Due to the laborious extraction of metals, their origin, the earth (*terris*), is as meaningful as the human techniques that detect, expose, and complement the material. Agricola’s description of the *materia metallica* suggests an understanding of material that locates this midway between nature and culture – an understanding that, according to Bernadette Bensaude-Vincent, has been forgotten in the current conception of materials in the natural sciences: “material combines *phusis* and *technē*, it is a hybrid notion referring to an alliance between natural beings and man’s needs [...]” [Bensaude-Vincent 2011b, p. 109]²¹

In Agricola’s study on the mining of ‘metal,’ technique is deployed even before establishing a function (tools and weapons from iron, coins from gold, etc.), namely, during the mining of the metal itself. Nevertheless, these techniques still remain linked to the given world, hence, *phusis* and *technē*. Even when the metals in Agricola’s treatise, due to the systematization of the practices and considerations, already grow in abstraction, the understanding of ‘material’ remains tied to the specifics of the respective process of uncovering, and in this way to the concrete process of becoming material. However, the activity that Agricola attributes to the *materia metallica* (metallic material/matter) in his Latin–German glossary with the help of the old German term *werck* (activity, agency, work), and in this way a compound of nature

¹⁹ Shortly afterward in [ibid.] again “*Materia, werck.*”

²⁰ For the meaning of the German ‘werck,’ cf. the article “Werk” in [Grimm and Grimm 1960, Sp. 347, Z. 13] – here the Latin equivalent is given by the terms “opus,” “opificium, operatio,” thus not ‘*materia*.’ The semantic shift that Agricola carries out in his register (by translating ‘*materia*’ by ‘werck,’ and thus with a word that is strongly related to activity) is significant for his understanding of metal, and that means from today’s perspective of material.

²¹ On the extraction of wood from trees, see: [ibid.]: “Trees were extracted from nature, separated from their natural environment and became wood in relation to the design of a specific artefact.” Material thus designates a transformation process: the tree becomes wood because man decontextualizes and functionalizes it.

Fig. 1: The mining and smelting of metals in the sixteenth and seventeenth centuries.
 From: [Löhneysen ca. 1660, plate 6]. Zentralbibliothek Zürich, NG 132 | G, DOI: 10.3931/e-rara-50189. Public Domain Mark.

and human techniques, is, in his view, increasingly located solely on the side of man. Already for Agricola, man's systematic approach, with the help of tools, machines, and knowledge, brings forth the 'pure metal' and in this way the specific material (iron, silver, or gold, etc.). The more, in the following centuries, this epistemic and technical competence is formed into a separate field, the more the activity is attributed solely to the intervention of man – and the material to a merely passive counterpart.

1.3 The Eighteenth and Nineteenth Centuries: A Science of Substances and Its Alphabetization

Agricola posited the miner in the role not only of an experienced practitioner but also of a proto-scientist – that is, as the one who can decipher nature’s composition and work according to a plan, thereby uncovering from the earth the various particular materials and processing them to make them pure. As such, in its ‘purest’ form, processed according to the wishes of the miner, material becomes perfected – and in this way more controllable and docile, but also *passive*. Crucial to this development was on the one hand the improvement of the techniques of extracting material, and on the other the compiling and systematization of analytical knowledge (as opposed to focusing on authorities, as in the scholarly tradition). Added to the extraction and smelting techniques are thus epistemic techniques that along with the emerging natural sciences are developed into a separate field. In his treatise, Agricola dissociated knowledge about which ores could be smelted and broken down (e.g., through the addition of substances, through temperature) from alchemical explanations. Nevertheless, chemistry had not yet been invented, which is why he still has to introduce the knowledgeable handling of various ores as practical knowledge. Only with the introduction of chemistry does one see the beginning of the systematic scientific understanding of the various substances of nature and their composition – which gradually prompts a new understanding of materials. Thus, in the eighteenth and nineteenth centuries, one sees a growing tendency to treat materials ‘alphabetically,’ and that means as more or less equivalent elements in a formal system.²² This is done by deciphering their pure chemical compound, which in turn led, with synthetic chemistry (in the twentieth century), to a specific conception of materials as something that can be duplicated. To explicate, when considering chemistry and the research of materials, during the eighteenth century – and here one should note that chemists at that time tended to use the term ‘substances’ rather than ‘materials’ to denote materials – “there was a comparatively small group of substances that chemists identified and classified according to their chemical composition, and a much larger group that they identified and classified according to their natural origin, mode of extraction, perceptible properties, and practical uses” [Klein and Lefèvre 2007, pp. 299–300]. In short, in the eighteenth century, the systems of classification of substances were heterogeneous – there was neither a single taxonomic system nor a “single conceptual umbrella or paradigm” for their classification [ibid., p. 3]. Moreover, the theories of eighteenth-century chemistry

²² In such a formalization, the materials become abstract values – and the eligibility conditions (the resistance of the materials and the techniques for their extraction, which stand to the fore in Agricola) disappear completely from view. For this symbolic negotiation of materials, Ingold’s “*forgetting* chemistry” can be asserted, thus that procedure with which he wants to return to the practices in the handling of material and thereby also to the activity of the materials [Ingold 2013, p. 28].

“evolved not primarily around ‘atoms’ or ‘corpuscles’ but chemical substances” [ibid., p. 6], which points to the fact that the conception of treating materials ‘alphabetically’ was neither an obvious nor a dominant one during this period, although it certainly announced itself with the rise of the chemical ‘paper tools.’²³ In the nineteenth century, there was a shift regarding the experimental study of structure: “The stabilization of quantitative analysis and the use of chemical formulae by nineteenth-century chemists privileged knowledge of composition and structure over sensible properties, but also extended the chemists’ tools box for identifying and classifying chemical substances” [ibid., p. 304]. In this sense, one can speak of an “ontological shift that reconfigured the range of substances accepted as objects of inquiry in organic and inorganic chemistry” occurring in nineteenth-century chemistry with respect to the investigation of materials [ibid., p. 305]. This shift embedded the research of materials in a new scientific milieu “of experiments, precision measurement, and work on paper with chemical formulae” [ibid., p. 304]. As noted above, with the nineteenth-century chemical ‘paper tools,’ as Ursula Klein notes, there was a shift with respect to the understanding of ‘organic’ materials in terms of their chemical formula:

Organic no longer meant a particular natural origin of chemical materials from the organs of plants and animals. [...] The new concept of the ‘organic’ was defined mainly by the elemental composition of the substances [...]. In the experimental culture of carbon chemistry, an ‘organic’ substance was, first, a pure chemical compound rather than any kind of extracted vegetable and animal material. [Klein 2003, p. 221]

With the insights delivered by crystallography (during the nineteenth century), on the one hand, and stereochemistry (starting in the second half of the nineteenth century) on the other (by, among others, René-Just Haüy and Jacobus Henricus van’t Hoff, respectively), it became clear that not only the chemical formula played a role in determining the properties of the materials but also the three-dimensional structure of the crystal or molecule. The twentieth century saw the advance of chemical synthesis, which reinforced, with the production of various synthetic chemicals, a conception of materials as something that “can always be replaced or substituted” [Bensaude-Vincent 2011b, p. 111], which in turn favors a conception of nature as a “huge library of resources gathered through random processes of combination” [Bensaude-Vincent and Newman 2007, p. 18]. These processes, and especially, one may suggest, chemical synthesis, underline a slow process of ‘passivization’ of materials, which might be understood as a return to the Aristotelian understanding of *hyle* in contrast to form. These passivization processes may therefore be conceived via a ‘textualization’ or ‘alphabetization’ of (chemical) materials, presented as a set of letters and three-dimensional structures, which can later be combined and recombined, produced and reproduced. The shift toward alphabetization and ‘readability’ reached its

²³ We refer here to the title of [Klein 2003]: *Experiments, Models, Paper Tools*. On the history of the metaphor of the readability of nature and the world, see: [Blumenberg 1981].

zenith in biology, one may argue, as Lily Kay does, with the discovery of DNA and the acceptance of its associated discourse as the ‘code’ of life [Kay 2000].

1.4 The Twentieth and Twenty-First Centuries: Materials Science

Bensaude-Vincent has pointed out that, until the middle of the twentieth century, material was always understood as a specific, individuated substance. The different materials – metal, ceramics, wood, and so on – formed a “zoology of materials” (i.e., a variety of material species) researched by different disciplines [Bensaude-Vincent 2011b, p. 110]. Hence, if the natural sciences aim at generality, abstraction, and systematics, as can be seen with the ‘alphabetization’ and ‘code’ paradigms and discourses of the twentieth century, there can be no basic science of *singular* materials, Bensaude-Vincent claims. This is already implicit in the conception of chemical synthesis – as if *any* material can be reduplicated, hence ignoring its singularity, which leads to materials being understood as an abstract ontological and epistemic category similar to that of matter in physics. In the mid-twentieth century, however, a fundamental shift took place regarding the difference between materials (as individual and technological) and matter (as universal and ontological). With the emergence of *materials science* as a discipline, materials have become a scientific category and, moreover, a generic concept. The new discipline is the expression and motor of a ‘science of materials’ (i.e., a systematics of the individuated materials), and thus of a hybrid of the singular and the generic, that is, not a ‘science of matter,’ as seen in the classical disciplines [ibid., p. 112].

Materials science emerged in the USA in the 1960s,²⁴ primarily in metallurgy departments (which were increasingly renamed, e.g., ‘metallurgy and materials science’ departments) before establishing itself as an independent subject a few years later [ibid., p. 114]. What characterizes metallurgy in the twentieth century is the coupling of structure and property, a characterization that is at the root of materials science. With the help of x-ray crystallography during the first decades of the twentieth century, for example, it was possible to analyze the microstructure of crystals and metals.²⁵ Terms such as ‘crystal lattices,’ ‘dislocation,’ or ‘defect’ have been used to describe the micro- and nanostructure of a material and in this way to help to understand its macroscopic properties. The connection of microstructure and mechanical properties is tested and the physicists’ models help to design new materials [Hoddeson et al. 1992]. Indeed during the 1960s, “[t]he focus on structure-sensitive properties in the study of crystals

²⁴ We follow here mainly: [Hentschel 2011; Bensaude-Vincent 2011b].

²⁵ To explicate: “Not only instrumental techniques – from x-ray diffraction to STM and AFM – opened the way to microstructures and nanostructures, but also they helped create a scientific community” [Bensaude-Vincent 2011b, pp. 121–122].

has been identified as the main route leading to materials science” [Bensaude-Vincent 2011b, p. 114].

It is around this time that there was a shift in the conception of materials, which later, in 1989, consisted of four related aspects: properties, structure, processing, and performance (see Fig. 2). This tetrahedron of ‘fundamental aspects’ was and is considered – already before its presentation in 1989 but mainly after it – as a paradigm for materials science [Hentschel 2011, p. 26]. Bensaude-Vincent notes that the novel “notion of material” – as a plural entity (i.e., materials) – was not only thought from the beginning as an interdisciplinary one. It also “requires that structure and properties be coupled with functions or performance. It is only with respect to functionalities that one can gather under the same umbrella such dissimilar stuffs as wood, concrete, paper, polymers, metals, semiconductors, and ceramics. [...] they are all materials *for ...*” [Bensaude-Vincent 2011b, p. 115].

Fig. 2: Tetrahedron of the fundamental aspects of materials science. See [COSMAT 1989, p. 29].

© Graphic redrawn by M.F.

The history of materials science consists, then, starting in the 1960s, of heterogeneous research directions: prompted by research on polymers (a research that began at the end of the nineteenth century and continued to be developed during the first decades of the twentieth century) [Bensaude-Vincent 2013; Bensaude-Vincent 2007, pp. 294–297], there was a shift to the production of “composite materials with desirable properties” [Bensaude-Vincent 2011a, p. 105] – an approach known as ‘materials by design’ – rather than of “conventional materials with standard specification” [Bensaude-Vincent 2013, p. 21], and since the 1990s one has seen a rise in the importance of the nanosciences, followed (starting in the 2000s) by a focus on bioengineering and bioinspired materials. While the first generation of materials science dealt with relations between structure and properties, the second dealt with the tetrahedral relations presented above. Smart materials – as “systems responding to their environment” [Bensaude-Vincent

2011a, p. 108] – are named explicitly as such during the 1980s, whereas the general conception of these newly developed materials – whether bioinspired, smart, or programmable – considers them as end products: “it testifies to the changing status of materials, which used to be a priori constraints for engineering projects and eventually turned into the *end product* of a design process” [Bensaude-Vincent 2011b, p. 117].

With the establishment of materials science departments, a decisive change in the natural-scientific understanding of material occurs, one that (1) strengthens the individuality of the materials (high-end materials or materials by design) and thereby (2) brings clearly into view the techniques of production, and yet (3) explicates materials as a quasi-generic category, and in this way leads them to converge with the category of matter. Linked to this, however, is a further important aspect: to the extent that the ‘performance’ of materials is declared – alongside properties, structure/composition, and synthesis/processing – to be a core concern of scientific analysis, the activity of the materials comes explicitly into view. Whereas in the chemistry of the nineteenth century, materials were understood as formalizable and combinable units, and thus respond to the question of what a material *is*, the materials sciences are concerned with what materials can *do* (if in a slightly different sense to Ingold). Techniques and technology again come to the fore, but this time right at the center of the sciences’ claim to universality.

2 Active Materials

Due to the new focus on materials of the second generation of materials science, the activity of materials is also taken into consideration. But this newly formed focus on active materials was reinforced as well as intertwined with the almost parallel and by now related rise and development of a much more specialized domain in physics: active matter.²⁶

2.1 Matter in Action

In the 2000s, the research on active matter attracted considerable interest in and beyond the natural sciences, with particular attention being given to a new understanding of

²⁶ Here it is essential to emphasize that, while it seems that this domain of research seems to offer a new theory of matter, the theory (or theories) of matter developed within the framework of active matter neither include (or cover) nor aim to include the entirety of the discoveries and the developments of the twentieth and twenty-first centuries with respect to the question of what matter is. To give two prominent examples: neither what may be seen as the derived theory of matter of quantum mechanics (or quantum mechanics itself) is dealt with in the discourse and investigations of *active matter*; nor the fact that, starting in the second half of the twentieth century, a variety of the produced *materials* are in fact ‘electronic,’ that is, composed of semiconductors and transistors.

bird flocks. Following a paper by Tamás Vicsek et al., bird flocks could be modeled as spontaneous formations, whereby this form is precisely not initiated or guided by a lead bird (see Fig. 3) [Vicsek et al. 1995]. Rather the emergence of a flock depends solely on the density of the cluster of birds, while the bird's flight behavior is determined by the interaction between neighboring birds. This physical description of a biological phenomenon was remarkable in a number of ways: Above all, the flock is not understood via consciousness and intention or communication and hierarchy between individuals. While the totality of the birds and the transition from disorder (random cluster of birds) to order (flock) come into view, this agent-based modeling need not refer to the fact that at issue here is living beings. Rather the behavior of the birds is compared to the motion of mere particles and in this sense to a 'lifeless' material entity – insofar as a form of mathematical modeling is employed on the flock that is known from the description of Brownian motion or ferromagnetic formations.²⁷ However, Vicsek's model was not the first successful attempt to model such flocking movement – one should also mention the 1987 model developed by Craig W. Reynolds. In order that a structure of a cohesive flock exists, Reynolds' model, in which “the *simulated* flock is an elaboration of a particle system, with the simulated birds being the particles,” imposes the restriction that each animal should avoid collision with its neighbors, follow

Fig. 3: (a) Auklet flock, Shumagin Islands 1986. Wikimedia Commons, the free media repository, 2020. Available from https://commons.wikimedia.org/wiki/File:Auklet_flock_Shumagins_1986.jpg (accessed June 28, 2021). (b) Vicsek et al.'s model of flock behavior: “In this figure the velocities of the particles are displayed for varying values of the density and the noise” [Vicsek et al. 1995, p. 1227]. Reprinted with permission from: [ibid.]. © 2021 by the American Physical Society.

²⁷ See [Ramaswamy 2010, p. 327]: “Like the continuous-spin magnets that they resemble, the Vicsek family of models display a well-defined phase transition from a disordered phase to a coherent flock as η is decreased or the number density is increased [...]” Although always with the difference that in active matter it is a question of *self*-movement.

its species, and move in the same direction as the rest of the group, where ‘group’ here means the animal’s six or seven immediate neighbors [Reynolds 1987, p. 25, 28].²⁸

Nevertheless, the formalization conceptualized by Vicsek et al. as an ‘analogy’ of ferromagnetism differs in one essential way from what it was modeled on: “In this sense our model is a [...] nonequilibrium analog of the ferromagnetic type of models, with the important difference that it is inherently dynamic” [Vicsek et al. 1995, p. 1226] – thus expanding the focus of their research to include nonequilibrium phenomena. From a scientific point of view, this approach has been extremely productive, since it has allowed further deductions on the emergence of collective behavior and above all a broadening in scope to include phenomena of movement at different scales and in different contexts. This broad claim of active matter research, however, is at odds with the relatively narrow definition formulated, for instance, by the mathematician Gautam I. Menon in 2010:

The term *active matter* describes diverse systems [...] [which] are often idealizable in terms of collections of individual units, referred to as active particles or self-propelled particles, which take energy from an internal replenishable energy depot or ambient medium and transduce it into useful work performed on the environment, in addition to dissipating a fraction of this energy into heat. [...] [The] active particles can exhibit remarkable collective behavior as a consequence of these interactions, including non-equilibrium phase transitions between novel dynamical phases, large fluctuations violating expectations from the central limit theorem.

[Menon 2010, p. 193]

The physics of flocking was extended not only through descriptions such as John Toner and Yuhai Tu’s continuum field-theoretic approach [Toner and Tu 1995] but also through the creation of additional subject areas: through apolar flocks, which in contrast to the directed, ‘polar ordered’ states of bird flocks are understood as “flocks that go nowhere” (e.g., active polar states in granular matter) [Ramaswamy 2010, p. 331]; through the so-called ‘swimmers’ who designate the movements of living entities in a fluid medium (from bacteria and algae to schools of fish – thus through different scales); through ‘active gels’ (e.g., the cytoskeleton), to the extent that these follow the same hydrodynamic equations;²⁹ and finally through the collective movement of living cells during growth and healing (tissue dynamics).

What unites the objects from different scales and milieus (such as flying birds and swimming fish, bacteria and cells, tissues and gels, and real entities and hypothetical model systems) under the umbrella term ‘active matter’ is the use of theories and tools

²⁸ The media history of the swarm during the twentieth century as well as the problem of representation and modeling of it is described extensively in: [Vehlken 2012].

²⁹ The cytoskeleton is understood as a “suspension of filaments endowed with active internal forces” and active matter research aims at the “natural mechanisms that promote the alignment of neighboring filaments, through excluded volume as well as activity” [Ramaswamy 2010, p. 325].

of statistical physics and hydrodynamics or liquid crystal hydrodynamics (thus soft matter physics).³⁰ These include active nematic theory (i.e., the descriptions of symmetry breaking and topological defects), conservation laws, and agent-based standard models, as well as analytical tools such as simulations, field-theoretical methods, and “dynamic density functional theory” [Gompper et al. 2020, p. 3]. The overarching field to which active matter research is explicitly assigned [Ramaswamy 2010; Menon 2010] is condensed matter physics, which brings together the multiplicity of matter’s manifestations (solids, liquids, plasmas, etc.) in their macroscopic and microscopic properties under a collective roof – insofar, for instance, as basic physical principles are applied to the states of matter.

According to Sriram Ramaswamy, the research on active matter takes up the comprehensive approach of condensed matter physics and should therefore develop a “systematic theory” by expanding the principles of statistical physics and hydrodynamics to include living entities and thus the objects of biology [Ramaswamy 2010, p. 323]. “[L]iving, metabolizing, spontaneously moving matter” is a paradigmatic object for activity and should therefore be integrated as ‘active matter’ into condensed matter research [ibid., p. 326]. That is an ambitious claim that in the final analysis might mean that ‘living matter’ will be classified using descriptions and explications that closely relate to those of ‘nonliving’ matter – it remains to be seen, however, whether the claim of the research field active matter can be realized in this way.

Clearly the project of active matter research also recalls nineteenth- and early-twentieth-century biophysics, as it is prominently represented by D’Arcy Wentworth Thompson. The approach of active matter research, however, is not concerned with the forms of living beings (e.g., anatomy and shape) or the evolution of these forms but with a ‘matter in action,’ understood here as a spontaneously emergent collectivization and form construction,³¹ which calls on a different physical regime: nonequilibrium thermodynamics or statistical physics. Living systems are a prime example of this, since they are open systems that operate far from equilibrium and successfully accommodate the related instabilities. Examples are found, however, beyond living systems and at all scales. The aim of developing a comprehensive physics of life based on nonequilibrium thermodynamics has already – that is, before the research

Here it should be borne in mind that these active gels are not considered as a medium but as a “distinct type of material” and thus as a particular manifestation of matter [ibid., p. 339].

30 And not only that, but also as Menon emphasizes the “philosophy” of active matter, one does not begin with distinct units, but with a continuum model: “The philosophy of these approaches is the following: Rather than begin from a microscopic model for a swimmer or individual moving particle and then generalize from the microscopics to realize symmetry-allowed equations of motion for the fluid velocity field and for the local concentration of swimmers, one can start with a coarse-grained continuum model for a physical viscoelastic gel which is driven by internally generated, non-equilibrium sources of energy” [Menon 2010, p. 213].

31 See [Menon 2010, p. 194]: “Such [active matter] systems are generically capable of emergent behavior at large scales.”

on active matter – been formulated by Ilya Prigogine. Nevertheless, he introduced these themes much more broadly in physics and chemistry³² and in addition looked for support in philosophy. Already in 1984, in their book *Order Out of Chaos*, in a chapter titled “Active Matter,” Prigogine and the philosopher Isabelle Stengers note programmatically that “[a]t all levels, be it the level of macroscopic physics, the level of fluctuations, or the microscopic level, nonequilibrium is the source of order. Nonequilibrium brings ‘order out of chaos.’” [Prigogine and Stengers 1984].

What is particularly difficult about nonequilibrium systems is that for their explication one cannot have recourse to classical physical principles such as temporal reversibility but is forced to have recourse to the challenging theories of nematic physics and liquid crystal hydrodynamics. Thus, active matter researchers see their domain as a radical expansion: “a new area of fundamental physics” [Ramaswamy 2010, p. 341]. In 2020, this statement from 2010 has to be supplemented and corrected: active matter research is explicitly no longer the concern of physics alone but can be considered a “truly interdisciplinary endeavor at the interface of biology, chemistry, ecology, engineering, mathematics, and physics” [Gompper and Winkler 2020, p. 2].

In order to summarize the understanding of activity being developed in the context of the research on active matter, one must emphasize three aspects: (1) activity is linked with movement (motility) but cannot be equated with movement, rather it is distinguished from other driven systems to the effect that here (2) internal energy is converted and consumed; and (3) this movement can give rise to phase transitions and to the emergence of order, as for instance in the remarkable collective behavior of the bird flock or the repair work of cells in tissue. This characterization can be formulated for active matter research. However, this by no means covers the full range of current research on active materials.

2.2 Inherent Activity

One can ask oneself why the research on the activity of materials has grown so significantly since the 1990s. That materials – and in particular organic materials – have a life of their own was not unknown. The carpenter or instrument maker has long been aware that wood expands and shrinks and that it continues to change shape long after it has been worked. Nevertheless, especially in the nineteenth and early twentieth centuries, a conception of an ideal material becomes prevalent that associates this material with passivization and plasticity – or that even wants a material to disappear almost completely. Here architecture becomes an exemplary field, since, with iron construction in the nineteenth century, a changed structural deployment of

³² See his focus on self-organization and his concept of dissipative structures in: [Prigogine and Nicolis 1977].

materials begins. The bulkiness of stone construction is exchanged for lightness and modularity, but this leads above all to the impression of a dematerialization and to a claim of overcoming matter. The research on active materials, on the other hand, radically distances itself from this utilization and understanding of materials by investigating, for instance, their internal architecture in its function for movement. This is linked above all with a new interest in ‘nature.’ Now the organisms of nature are interrogated for the potential in their material structure for movement and other activities.

2.2.1 ‘Dreams of Dematerialization’

Agricola describes the *materia metallica* neither as homogeneous nor as passive. While metal is a natural resource, this must be laboriously extracted from the ground through the deployment of people and machines and then be gradually revealed in the smelting works through additional techniques. Only when the desired properties are manifested can the metal be made available for more precise functions and be turned for instance into gold coins, silver jewelry, tools, or weapons. However, the greater the number of new techniques and facilities that were developed in the following centuries (e.g., when the steam engine in the eighteenth century improved the bellows and thus the performance of the furnace), and the more new knowledge was acquired about chemical composition and physical behavior, the more reliably specific materials could be created and accurately processed. As Bensaude-Vincent notes, in the nineteenth century iron became a “single-class” material that could be treated mathematically as “pure deformable continua” and well controlled both formally and in the concrete processing [Bensaude-Vincent 2011b, p. 114]. She therefore describes iron as a “model material” for the scientific (and engineering-based) handling of material in the nineteenth and early twentieth centuries [ibid.]. The material iron can be considered passive (insofar as it “does not work by itself; it is put to work”) and also allows mathematical treatment, since it is homogeneous and isotropic [Guillerme 1994, p. 233].³³ Indeed, in the architecture of the nineteenth century, iron became a highly functional material. It allowed a ‘lighter’ method of construction that is capable of surprisingly tall towers (such as the Eiffel Tower (1889) in Paris), of long bridges (the Brooklyn Bridge (1883) in New York), and of vast buildings (the Crystal Palace (1851) in London). But metal-rod construction also changed the perception of load-bearing structures. The architectural theorist Gottfried Semper speaks of an “almost invisible material” (“gleichsam unsichtbaren Stoffe”), a dematerialization of architecture that he finds regrettable [Semper 1849, p. 521].³⁴ Nevertheless, already in the

³³ Quoted in [Bensaude-Vincent 2011b, p. 113].

³⁴ See the full quotation: “However, this much is clear, that iron, and indeed every hard and tough metal used as slender rods and sometimes as cables as befits its nature, due to the slighter surface which is offered by these forms withdraws all the more from the eye the more perfect the construction

nineteenth century and fully developed in the twentieth century, lightweight construction is the object of a new aesthetic and the motor of a new architecture. The architect and theorist Richard Buckminster Fuller designates the new possibility of “structural lightness” [Fuller 1979, p. 175] in architecture as “ephemeralization” [Fuller 1938, p. 284], which he describes as follows: “Doing the most with the least – segregated compression and tension members, flexible joints, stabilized force triangles – net scientific structure in time annihilating transportation, communication, and power harnessing” [Fuller 1932, p. 36].³⁵ Therefore ephemeral buildings should not only reduce the amount of material used but also develop and present a new type of load-bearing structure. Fuller wants to modularize, network, and dynamize the structures, as for example in his most famous geodesic dome, the American Pavilion at the 1967 International and Universal Exposition in Montreal, Canada (see also the variant in Fig. 4). The dematerialization leads in Fuller’s case to an understanding of architecture as a highly efficient lightweight structure – here too the material seems to recede behind the structure, or to become one with it, but in this particular case it is already a matter of the dynamization of structures.

Fuller’s innovative concept of ephemeralization, however, belongs to the mid-twentieth century. In the nineteenth century, dematerialization was associated with the idea of a plastic and passive material. If one takes into account the discussion on the various materials invented during the nineteenth century – rubber, celluloids, the development of plastics – a discussion accompanied, on the one hand, by a demand to bring justice or “truth to materials” (“Materialgerechtigkeit”), one cannot ignore that this discussion culminated in a demand to develop a single material that would be appropriate to the desires and needs of man. In 1902, Henry van de Velde claimed that “our dream of a supple material that follows our intentions as easily as our speech follows our thoughts will come true.”³⁶ No longer imitation or perfection of nature,³⁷ a

is, and therefore architecture, which accomplishes its effects on the spirit through the organ of vision cannot admit of this as it were invisible material when it is a matter of effects of mass and not merely of light accessory parts.” (“Doch so viel steht fest, daß das Eisen, und überhaupt jedes harte und zähe Metall, als konstruktiver Stoff seiner Natur entsprechend in schwachen Stäben und zum Teil in Drähten angewendet, sich wegen der geringeren Oberfläche, welche es in diesen Formen darbietet, dem Auge umso mehr entzieht, je vollkommener die Konstruktion ist, und daher die Baukunst, welche ihre Wirkungen auf das Gemüt durch das Organ des Gesichts bewerkstelligt, mit diesem gleichsam unsichtbaren Stoffe sich nicht einlassen darf, wenn es sich um Massenwirkungen und nicht bloß um leichtes Beiwerk handelt” [Semper 1849, p. 521].) On dematerialization and ephemeralization as aesthetic experience and technological program in the nineteenth and twentieth centuries, cf. [Krausse 2001]. On ‘dreams of dematerialization,’ cf. [Bensaude-Vincent 2013].

³⁵ Quoted in [Krausse 2001].

³⁶ “Denn unser Traum von einem geschmeidigen Material, das unseren Absichten so leicht folgt, wie die Sprache unseren Gedanken, wird in Erfüllung gehen” [Van de Velde 1902, p. 31].

³⁷ On how this new image of man emerged during the early modern age, who neither imitates nor perfects nature (a conception of the relations between man and nature which is highly influenced by Aristotle), see: [Blumenberg 2000].

Fig. 4: R. Buckminster Fuller's necklace dome (1950) is one of the first geodesic, dome-shaped structures constructed by Fuller. The folded structure emphasizes the modularity and dynamic character of these buildings. © Courtesy, Estate of R. Buckminster Fuller.

wish emerges of a future invention of an almost formless material that will fulfill all of man's needs.³⁸ At the beginning of the twentieth century, a similar development occurred regarding wood. As Cecil Elliott notes, "German companies in 1933 began manufacturing synthetic resin glues," and while, as "linear structural members, timbers performed well [...] at connections the more complex forces were limited by the lateral weakness of the material. By gluing crossed layers of veneer, plywood balanced these capabilities of wood, so long as it was used as a sheet" [Elliott 1992, p. 21]. This shift to the mass production of plywood can be seen as an effort to treat it as a "passive material" [Eder et al. 2020, p. 3]. Such a passivization was clearly formulated, for example, in Alfred Gotthold Meyer's reflections on iron and iron constructions. In his posthumous 1907 book *Eisenbauten: Ihre Geschichte und Ästhetik (Iron Constructions: Their History and Aesthetics)*, Meyer (1864–1904), a professor of the history of decorative arts in Berlin, examined iron as a building material and its effects on the development of style. According to Meyer, iron was celebrated as what does not have any constraint, in contrast to wood or stone. It enables architects and

³⁸ See also: [Wagner 2004, 2015]. In this sense, the call during the twentieth century to a (new) "conversation with materials" can be seen as a continuation of the discussion on *Materialgerechtigkeit* during the nineteenth century. See: [Schon 1992].

engineers to achieve their mutual goal: “they [architects and engineers] [...] have a common goal: the victory over matter [*Materie*].”³⁹ This victory enables one to free oneself from the constraints of the materials and to see iron constructions as an “embodiment of what is abstractly recognized as necessary.”⁴⁰ The reduction to the necessary must be understood here with regard to the seamless mathematical treatment of material and form: “And with the unlimited plasticity of iron it is possible to create the statically most ‘rational’ form [...] artificially.”⁴¹ Emphasizing the role of mathematics and geometry for architecture in general, Meyer notes that iron constructions enable one to “transfer the problems of mechanics from the area of arithmetic operations and algebraic forms into the depictions of graphic formations” [Meyer 1907, p. 29–49].⁴² In this sense of dematerialization and unlimitedness, iron constructions allow much more freedom than stone or wooden ones, since the former are also more easily mathematically calculable.

2.2.2 Dreams of Architecture

Meyer’s “victory over matter” calls for an understanding of matter that grasps this via properties such as mass, strength, rigidity, and indivisibility – as is found prominently in Isaac Newton’s mechanical philosophy, but which remained in force into the nineteenth century.⁴³ This points to an underlying conception of matter as passive and shapeless. But it is worth recalling that, against the mechanical approach

39 “Architekten und Ingenieure haben [...] ein gemeinsames Ziel: den Sieg über die Materie” [Meyer 1907, p. 4].

40 “[...] die Verkörperung des abstrakt als notwendig Erkannten” [ibid., p. 5].

41 “Jeder Teil einer Eisenkonstruktion übertrifft einen gleichgroßen Holzbalken an Festigkeit zehnfach [...]. Und bei der unbeschränkten Bildsamkeit des Eisens wird es möglich, die statisch ‘rationellste’ Form [...] künstlich zu schaffen” [ibid., p. 13].

42 “Ist doch eine Eisenkonstruktion schon an sich eine besonders sinnfällige Verkörperung der im Bau wirksamen statischen Kräfte; sie steht dadurch gewissermaßen nur am Ende jenes synthetischen Weges, der die Probleme der Mechanik aus dem Bereich arithmetischer Operationen und algebraischer Formeln in die Anschauung graphischer Gebilde überträgt” [ibid., p. 43].

43 One may also recall the earlier approach of René Descartes, of a homogenous matter consisting of extension alone. But as Andrew Pyle notes, to view the history of matter theory in the seventeenth century “in terms of the rejection of Scholastic Aristotelianism and its replacement by one version or other of the mechanical philosophy (Cartesian or atomist) would be oversimplified, to say the least. As Leibniz saw, neither the Cartesians nor the atomists had a satisfactory account of material substance” [Pyle 2017, p. 440]. Nevertheless, mechanical philosophy in the natural sciences was progressing during the seventeenth century, accompanied by a growing mathematization of various phenomena. During the eighteenth century, the advancement of the mechanization of matter theory certainly left its mark on how matter theory was reshaped: it became “reductionist rather than essentialist, [and] it embraced quantification where possible [...] and in reaction to its association with mechanism, it emerged very much as an experimental, as opposed to a speculative, discipline” [Gaukroger 2014, p. 689].

of inert matter, the seventeenth- and eighteenth-century vitalists – though far from being a homogenous group – posited matter as active,⁴⁴ objecting to the world being reduced to a heap of dead, passive matter.⁴⁵ As the nineteenth century continued, however, vitalism was gradually abandoned and rejected, to be replaced by chemical and physical explanations as theories of matter. Nevertheless, in the second half of the twentieth century, two shifts occurred with respect to the latter conception of matter: first, as noted above, the dream of finding one single material for all purposes and needs, which is encapsulated in Meyer's claim of a victory over matter, is replaced by an extensive research on materials – as can be seen with the formation of the multi-disciplinary materials science out of metallurgy departments; second, the research on active matter expanded the physical understanding of matter to include nonequilibrium systems – and thus also living systems (the prime example of nonequilibrium systems). Thus, next to solid matter and soft matter (or the overarching condensed matter) comes living matter, whereby the physical theories of statistical physics and hydrodynamics as well as the accompanying challenging mathematical tools produce points of intersections between the different fields of matter.⁴⁶ Here 'active' means not an activity imposed from outside, for instance, a movement induced by an impact – in active matter research, driven systems are always self-driven systems; that is, the activity is attributed to the matter itself.

Within the – in comparison to active matter – broader field of research in the materials science, the activity of materials is explicated less via the theory of nonequilibrium systems than via the internal architecture of living or dead materials. Indeed here too one frequently has recourse to exemplary configurations from living nature. A well-known example is the research on the capacity of bones to adapt to stress, since bones are capable of adapting to concrete environmental and living conditions through growth and remodeling [Weinkamer and Fratzl 2011]. And yet the 'dead' (or, more precisely, nonliving) components of organisms are also considered for the understanding of active materials insofar as these exhibit an ability to move and react based on their internal architecture. A well-known example is the pine cone, which consists largely of cellulose and thus of a dead substance, but still has the ability to open its scales (when dry) or to close them (when wet) in order to release its seeds into the environment only with the appropriate environmental conditions (dry weather;

⁴⁴ For the various approaches to vitalism and their reactions to the mechanical theories of the eighteenth century, see: [Wolfe 2014].

⁴⁵ To give only one example, Charles Wolfe notes that John Toland, in his *Letters to Serena* from 1704, "is explicit that 'Matter neither ever was nor ever can be a sluggish, dead and inactive Lump, or in a state of absolute repose' [...] he also denies that '[...] Matter is or ever was an inactive dead Lump in absolute Repose, a lazy and unwieldy thing'" [Wolfe 2014, p. 99]

⁴⁶ See: [Gompper and Winkler 2020, p. 2]: "Fundamental biological processes, such as morphogenesis and tissue repair, require collective cell motions [...] Tissues are nature's active materials, and are therefore very interesting as blueprints for synthetic active materials."

see Fig. 5) [Reyssat and Mahadevan 2009; Dunlop, Weinkamer, and Fratzl 2011].⁴⁷ This reversible movement is not motivated by internal energy balance but is based on the internal anisotropic structure, that is, the specific arrangement of the cellulose fibers – it is therefore the internal architecture (together with the environmental conditions) that enables the activity, and not an external active force that imposes movement on an actually inert object. Similar functional arrangements of cellulose are found in the trunk and branches of trees. Although here it is not a matter of reversible movements, as in the pine cone, but of a combination of rigid and minimally flexible tissue adapted to stresses and environmental conditions so that, in the appropriate places, either the load-bearing capacity or elasticity is promoted. For Michaela Eder et al., living trees are therefore, also in their dead tissue parts, anything but homogeneous and passive: “woody material [...] does not obey this idea of neutral matter” – rather, “wood shows an intrinsic activity” [Eder et al. 2020, p. 3].

Fig. 5: Three-dimensional rendering of x-ray microtomography images of the same pine cone (*Pinus sylvestris*) in the wet (left) and dry (right) states. Note the two different tissue types, light yellow and orange, that can be seen in the base of the pine cone scales. © MPIKG and Michaela Eder.

The activity of wood and other nonliving materials determined by their internal architecture is not an experience of the naked human eye. Rather, it is made visible in the experimental setups of natural scientists. It is first of all the epistemic procedures that enlighten us about the ‘properties’ of the components of a tree – and via the scientific generalization of these findings, these properties are to a certain extent ontologically established. At the same time, however, something else occurs: the tree (a living organism) becomes in this perspective the carrier of a variety of ‘materials,’ which it

⁴⁷ Compare also the structure of the seed capsule of an ice plant, which is discussed in several of the contributions in this volume (Fratzl and Schöffner; Gholami, Guiducci, Jany, and Razghandi; Dunlop and Krauthausen) and earlier biological research [Haupt 1977]. Wolfgang Haupt even terms this movement, induced by the structure alone, as “structural work” (“Strukturarbeit”) [ibid., 137].

has produced itself, which it exploits, and whose entirety it consists of. The talk of ‘biological materials’ or of ‘nature’s materials’ is not self-evident and should be thought in all its consequences: ‘nature’ is harnessed to a logic of engineering and in this way of technology. It is now indeed the supplier of not only renewable resources but also materials that are complex in themselves. And yet the equation of organic entities with materials understands nature as a ‘manufacturer’ or ‘inventor.’ Only from this perspective advocated by (but not only by) the discipline of the materials science can one consider, for example, that the tree is above all a producer of wood and its goal the highest possible efficiency, thus optimal performance.

2.2.3 Dreams of Bioinspiration

For active matter research, living matter is the privileged object to acquire not only new knowledge but also better applications of this knowledge in the invention of new materials and other technical things. For the diverse materials science research on active materials (in all their shades, whether smart, self-propelled, self-assembling, adaptive, or responsive), it is thus biological materials that are investigated.⁴⁸ The aim is to develop basic knowledge on structure–property–performance–synthesis relations, to arrive at the construction of artificial ‘active’ materials that are suited to complex tasks. This orientation of the materials science is described by the protagonists themselves as ‘bioinspired’ (or ‘biomimetic’), and encompasses two different approaches: in the first approach, one has direct recourse to biological materials, but in order to alter them for specific applications, for instance when the researchers “embed functionality into the wood structure and thereby generat[e] wood *materials* with new property profiles and responsiveness” [Eder et al. 2020, p. 10 (emphasis M.F./K.K.)]; the second approach, on the other hand, attempts for example to draw “inspiration from the activity of wood” [ibid., p. 12], that is, not to add properties to natural materials but rather to be inspired by their given structure, whereby ‘nature’ – in this example the tree – is considered as an object in the untouched realm of reality, which ideally can and should be viewed undisturbed, as if one can indeed only be inspired by it.⁴⁹

The inspiration paradigm is clearly aligned with the “view of nature as an unrivaled engineer, [a view which] underlies the attempts at making artificial materials with characteristics analogous to the variety of properties offered by natural materials [...]” [Bensaude-Vincent and Newman 2007, p. 18]. This view is not new, however. Already in his book *On Growth and Form* published in 1917, Thompson compares the

⁴⁸ On this see also the interviews with the natural scientists in this volume.

⁴⁹ See also the statement by Stanislav Gorb, who notes that one of the recent foci of the latest developments in the field of materials sciences is the one given to bioinspired materials, when one “[is] [d]rawing on living Nature as an endless source of inspiration” [Gorb 2020, p. 57].

structure of the bone and its resulting properties to the work of the engineer.⁵⁰ Bensaude-Vincent plays down the implicit metaphysical implications and aspirations to be found in the contemporary ‘inspiration’ discourse: while the “goal is neither to produce a faithful copy, nor to reproduce the appearance of the biological model [...] [c]ontemporary materials scientists are content with picking up local models as solutions to their current technological problems [...]” [Bensaude-Vincent 2007, p. 304]. Nevertheless, there are crucial distinctions to be made between late-nineteenth-century biophysics (to which Thompson relates) and the current bioinspired research. In a recent volume on materials research published in 2020 by the *Deutsche Akademie der Technikwissenschaften*, the focus is explicitly on nature as “a source of and inspiration for inventions and innovations” [Spath and Schraudner 2020, p. 7]. But the difference to Thompson and others lies in the fact that it “is now possible to make use of our increasing understanding of biological structures and growth processes to develop new materials” [Fratzl et al. 2020, p. 14]. Bioinspiration is thus based on an expanded basic knowledge:

The [c]ore aspects of this application of Nature’s principles to modern materials development are the multicomponent structure across hierarchical levels, which [...] makes it possible to encode new and specific functions in the material structure, [and] the selection of ‘intelligent’ (functional) structures by computer simulation and modelling. [Ibid.]

Here it becomes clear what is meant by the investigation of nature. This is certainly not a romantic return to nature, rather it focuses on very specific (biological) materials⁵¹ with several structural hierarchies with the aim of “encod[ing] specific functions in the material structure,” followed by a selection of various structures via “computer simulation and modelling” [Fratzl et al. 2020, p. 14]. If we concentrate again on wood, only by this “encoding”⁵² – that is, by the investigation of the different materials by various instruments, modeling, and simulations – can one even say that “wood shows an intrinsic activity” [Eder et al. 2020, p. 3], and only then can one lay claim to

⁵⁰ See: [Thompson 1917, pp. 680–683] concerning the comparison between Hermann Meyer’s research of the trabeculae of bone and Karl Culmann’s research on engineering of structures and cranes.

⁵¹ Besides an overview of the current research directions in bioinspired materials, the domains and examples discussed in this volume are, among others, “bio-inspired elastic cement,” “bio-inspired modification of wood,” “cellulose-based optical materials,” or “organic iontronic devices for neuro-morphic computing.” See [Bensaude-Vincent 2013, p. 26]: “Despite their admiration for nature’s achievement, biomimetic chemists are not inclined to revive natural theology and its celebration of ‘the wonders of nature.’ Rather, biomimicry proceeds from a technological perspective on nature.” While Bensaude-Vincent stresses the practical point of view of the work of biomimetic chemists, the statements cited above do point toward such a celebration, which is accompanied with an unclear distinction between the natural and the artificial.

⁵² See also [Eder et al. 2020, p. 3]: “[...] in seed awns one can perceive strong active torsion by drying or elongation through humidity as a reversible operation. This plant device acts according to its inner structure as a sort of *intrinsically coded matter*” (emphasis M.F./K.K.).

“harvesting the activity of wood” [ibid., p. 9], that is, to producing, for example, “wood materials with magnetic properties or transparent wood” [ibid., p. 10].

While ‘nature’ is one umbrella term used occasionally quite vaguely in the discourse of the materials sciences and of bioinspired materials, the term ‘inspiration’ is another such term. ‘Inspiration,’ which since antiquity has been used as a religious and artistic term – it is enough to recall the origin of this word in the Latin *inspirare* (‘to breathe or blow into’), which has given rise to the word ‘spirit’ – becomes a blanket term covering a complex range of scientific procedures.⁵³ In turn, these procedures decontextualize the biological materials – not only by ignoring their genetics, or their evolutionary processes (i.e., how the hierarchical structures found in these biological materials evolved and in which ways), but also by isolating them from their milieu, their surroundings – hence by examining them first as an experimental and ‘epistemic object’ and then – after the internal structure is understood – turning them into a ‘technical object.’⁵⁴ Only then is the material scientist able to select and isolate specific structures in order to “convert[] them into inorganic functional and structural materials” [Fratzl et al. 2020, p. 17].⁵⁵ No longer conceiving nature as such as a “library of resources” [Bensaude-Vincent and William R. Newman 2007, p. 18], it is the biological materials themselves that are now considered one by one as unique libraries of possible structures and solutions. Hence, the term ‘inspiration’ refers to an expansion of the universe of libraries, whereby biological materials now ‘offer’ unique solutions but only after a laborious experimental investigation. The resulting developed materials (i.e., the bioinspired materials) are not natural resources but complex artifacts and belong to the category of ‘materials by design’ that Bensaude-Vincent declares to be archetypical of materials in the late twentieth and early twenty-first centuries [Bensaude-Vincent 2011b, p. 119]. To repeat what was highlighted at the beginning of this introduction, these materials by design are *not* the materials one starts with (as passive materials waiting to be shaped) but the end product; they are high-performance materials that are often made for very specific purposes, that is, truly singular phenomena to be examined at the end of the research

⁵³ For example, see the following citation from 2018, which presents natural materials as a source of inspiration, that is, as a repository of sources to be inspired from: “Although natural materials have long been a prime source of inspiration for engineered ones, with our modern tools from nanoscience that allow inspection and construction at the scale of molecules, research in this direction is rapidly expanding” [Eder, Amini, and Fratzl 2018, p. 543].

⁵⁴ Hans-Jörg Rheinberger distinguishes between the ‘epistemic things’ of the experimental sciences that advocate for an open question and an unknown terrain (what one does not yet know) and ‘technical things,’ into which the epistemic things frequently transform when they are described and understood. These technical things designate instrumental facilities and applications of the erstwhile obscure, since unknown, research object [Rheinberger 1997].

⁵⁵ The authors of the introduction to the volume on materials research published in 2020 refer to the process of biotemplating: “Biotemplating is another possible approach, which takes biopolymer structures and converts them into inorganic functional and structural materials” [Fratzl et al. 2020, p. 17].

and production processes. If the bioinspired materials want to achieve the complexity of their models, then this will depend on how the ‘encoding’ of specific functions and the ‘operativity’ of these new artificial materials are understood.⁵⁶ The question thus arises of what is meant by ‘code.’ Is it in fact another name for a non-static, dynamic structure that interacts with its environment due to its specific and special geometrical and topological properties? Is not what lurks behind this term and its derivatives a return to a discourse of the readability of materials or their alphabetization? In his recent edited volume *Active Matter*, Skylar Tibbits claims that when we “redefine our relationship with matter,” either by embedding “properties of the digital [...] in the physical world like logic, reprogrammability [...],” or by embedding “properties from the natural world [...] in the synthetic world, like growth, repair [...],” then “[t]hese principles are now fundamentally available to read/write within *matter* itself.” [Tibbits 2017, p. 16].⁵⁷ Here one should ask whether there is in fact another form of reading (and writing) of ‘nature.’ Following the developments in materials science, it can be suggested that this ‘encoding’ is no longer an alphabetization of nature or of materials in general, as if one scheme (or one alphabet) would suffice for an understanding of the entire “zoology of materials” [Bensaude-Vincent 2011b, p. 110] or for “read[ing]/writ[ing] within *matter* itself” [Tibbits 2017, p. 16], but rather a much more concentrated effort of making *specific materials*, and hence the activity of certain specific biological materials, ‘readable.’ This can be seen in several current research projects and directions in materials science, which carefully select “local models as solutions” – although, as we note, not necessarily or not only “to their current technological problems” [Bensaude-Vincent 2007, p. 304], but rather as a motor to construct new materials. This is the epistemological landscape in which one can situate the research on active materials, in which materials themselves emerge as a unique category, as a boundary concept.

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⁵⁶ On code and the operativity of materials, cf. the programmatic contribution by Peter Fratzl und Wolfgang Schäffner in this volume.

⁵⁷ Although what is meant here by “reading” or “writing” is not historically reflected in the above-mentioned volume. Moreover, in the same edited volume, the single contribution offering a philosophical reflection on active matter concentrates mainly on *New Materialism*, Manuel DeLanda and Félix Guattari/Gilles Deleuze [Leach 2017]. Though essential to the philosophical understanding of active matter, we claim in this volume that a broader perspective is needed.

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