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Source

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On the Agency and Activities of Materials in the 21st Century

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Abstract

Starting the last decades of the 20th century a shift has occurred in how materials are being considered. Materials were no more considered as being passive, inert and shaped by an active human agent, as plastic or iron were usually considered during the end of the 19th century. The rising discipline of materials sciences during the second half of the 20th century, especially with the recent research on 'active', 'smart', 'autonomous' and 'bio-inspired' materials, has started to view materials as having their own agency. In our contribution we aim to review few examples of this shift, examining also the works of James Gibson, Tim Ingold and Bernadette Bensaude-Vincent. We aim to show that in its contemporary uses, 'agency' is the point where the dualisms action/passion and agent/patient are erased and also where the subject/agent is defined in a new way. The question arises, not only whether situating agency also at the side of the materials decenters the notion of action itself, but also whether agency has to be understood as being distributed in an ecology that influences and motivates both the material and the human subject?

Key Words

Levels of organization; biological agency; individuality; development; life cycle

Introduction

In the last decades of the 20th century, a shift occurred in the understanding of materials, whereby materials were no longer considered as passive, inert, and shaped by an active human agent, as had generally been the case at the end of the 19th century with iron, and later also with plastic. Beginning in the second half of the 20th century, and especially in recent research on 'active,' 'smart,' 'autonomous,' and 'bioinspired' materials, the rising discipline of materials science has increasingly viewed materials as having an activity of their own. Nevertheless, this shift in the understanding of materials is remarkable, since the new understanding breaks with a centuries-old tradition – between the early modern period in Europe and the last decades of the 20th century – that naturally assumed the passivity of materials and saw their usefulness precisely in that. To put it summarily, what is at stake in materials science and advanced technologies is whether materials are autonomous or not, whether they have their own kind of 'agency,' and how this agency relates to humans. As Jane Bennett points out, "it is easy to acknowledge that humans are composed of various material parts (the minerality of our bones, or the metal of our blood, or the electricity of our neurons). But it is more challenging to conceive of these materials as lively and self-organizing, rather than as passive or mechanical means under the direction of something nonmaterial, that is, an active soul or mind," (Bennett, 2010, p. 10).

In this paper we ask where this new challenge comes from and whether the latest developments in materials science do not in fact force us to rethink the notion of agency. Moreover, we argue that the scientific allocation of activity also or entirely to materials – as this is done in research on active matter and bioinspired materials – decenters the very notion of agency. This is complemented by an examination of studies in the fields of ecological psychology and social anthropology that show how agency is distributed and redistributed between materials and humans, a redistribution that is constantly adjusted according to the changing relations between humans and materials. It is through these complementary arguments drawn from the sciences and the humanities as well as from the social sciences that the radical change in the understanding of agency becomes apparent.

From Affordance to Agency

If one follows the account developed in Étienne Balibar and Sandra Laugier's article "Agency" in Barbara Cassin's *Dictionary of Untranslatables*, then it becomes clear where the challenge and the difficulty we face in recognizing the historical shift in the understanding of agency comes from. Balibar and Laugier claim that the notion was introduced to philosophy in the 18th century, where its definition still rested on the opposition between 'agent' and 'patient'; in its various usages, 'agency' referred to a physical action, what modifies the action, or the agent – as opposed to the object of action, or patient. Beginning in the 19th century, however, and more prominently in the 20th century, it came to designate "what makes it possible to act, no longer as a category opposed to passion, but as a 'disposition' to action, a disposition that upsets the active/passive opposition." Eventually, 'agency' would come to denote "the point where the dualisms action/passion and agent/patient are erased and also where the subject/agent is defined in a new way," (Balibar & Laugier, 2014, p. 17). In this way, a new understanding is introduced wherein agency is no longer linked to intentionality or consciousness but to a 'disposition' that transcends consciousness and undermines the traditional dichotomy between active agent and passive object. Moreover, the cause of agency lies no longer in the agents themselves but in a constellation, that is, in relation to other agents: "In agency, the agents themselves are no longer only the actors/authors of action; instead, they are also caught up in a system of relations that shifts the place and authority of action and modifies […] the definition of action." We want to expand on Balibar and Laugier's diagnosis for our question about the changed meaning of agency: inasmuch as the trigger and the 'author' of an action is no longer the acting subject but a situation made up of reciprocal dependencies, the understanding of agency changes such that it is more accurate to speak of a shared or distributed agency, since agency can no longer be linked to one party alone.

Balibar and Laugier's examples for their new definition of agency are taken from philosophy, particularly the work of John L. Austin and Donald Davidson.[1] In this respect, their analysis is limited to investigations of the human world: agency "is inseparable from an anthropologization […]: [it] is supposed to be what characterizes, among the events of the world, what belongs to the order of human action," (Balibar & Laugier, 2010, p. 19). The natural sciences are not considered in their article and remain a blind spot.[2] Beginning in the 1980s, however, a revaluation of materials has taken place in materials science (building on the classical sciences, especially physics and chemistry), whereby materials are no longer understood as passive, all-purpose resources, but are attributed an activity of their own – an activity that is even viewed as advantageous to their performance. But in order to take this new understanding of materials as an example of shared or distributed agency, and thus to extend the concept of agency beyond the order of human action, it is necessary – so we claim – to include the concept of affordances developed in 1979 by James Gibson in *The Ecological Approach to Visual Perception*. Gibson's ecological psychology provides a way to apply the concept of agency also to nonhuman and nonliving entities. This becomes clearer when one draws also on Tim Ingold's anthropological considerations on the relationship between humans and materials, since Ingold bases these considerations on the concept of affordances and in this way focuses the potential of Gibson's argument.

Gibson's ecological psychology ontologizes human (and animal) perception by detaching it from mind/body and subjective/objective dichotomies. As he argues and in part experimentally demonstrates, human perception of the world is irreducible to a mental interpretation and representation of sensory data. Rather than a merely subjective image of the world, perception, due to the organism's movement, is always occurring in the world. In addition, perception, for Gibson, is not passive but is itself action, since perception implies a purposeful attentiveness and response to one's environment, and must be understood as a 'direct perception.' The organism reacts to the affordances of its environment, and thus to the positive and negative possibilities that constitute the relationship between organism and environment: "The *affordances* of the environment are what it *offers* the animal, what it *provides* or *furnishes*, either for good or ill. [...] [This term] something that refers to both the environment and the animal in a way that no existing term does. It implies the complementarity of the animal and the environment," (Gibson, 2015, p. 119).[3] As this quotation makes clear, Gibson assumes an interaction between organism and environment, and therefore does not conceive of affordances as mere passive preconditions. Rather, environment and organism together form a niche in the world, and every activity of the organism is based more or less on the affordances of the environment relative to it (such as gravity, the atmosphere, resistant and partially persistent substances such as solids and liquids, as well as phenomena perceived by the senses such as sound, odor, and light). In Gibson's concept of affordances, then, the environment is transformed from a passive fact into an active factor. Hence, the activity that leads to the construction of a niche (and sustains it) can be traced both to the perceiving organism and to the perceived substances, media, and surfaces in the environment. This activity is essentially relational, since it cannot be anchored either in the subject or in the environment alone.[4] Gibson's ecological psychology should therefore be classified as an important step in the historical development toward the idea of a shared or distributed agency, even if Gibson never uses the term 'agency' itself.

Since the 2000s, the usefulness of Gibson's concept of affordances for the interpretation of the relationship between humans and *materials* has been clearly demonstrated by the social anthropologist Tim Ingold, whose thought on materials encompasses the extraction of 'natural' resources, the craft- and technology-based processing of materials, and the resultant cultures. For Ingold, humans should be described in relation to the ways in which they create environments for themselves (e.g., through the processing of materials), both in the 'societal' sphere (human cohabitation) and in relation to every other kind of organism. The social and the ecological development of the environment are always interwoven, and environments are never given as such nor ever finalized: "environments are never complete but are continually under construction," (Ingold, 2000, p. 172; see also p. 13-26). Yet this 'construction' of the environment cannot be reduced to the intentional act of a subject, which is to say that it is not synonymous with the hylomorphic shaping of matter; rather, it should be understood as involving the interaction of humans and materials. When Ingold reflects on designing, making, and doing, he often has recourse to the crafts of carpentry and weaving, both of which can be etymologically related to *techne* (in the sense of practical skills). Nevertheless, his approach divorces the artisanal act from the idea of a clear subject/object opposition, since he rejects the idea of rational control over the material. Instead, with his examples (weaving and carpentry), he focuses on the work process, describing this as an 'itinerant' improvisation with and in the grain of the materials. According to this view, weaving is not merely a learnable artisanal procedure; it also affects the weaver's being, precisely because materials are not passive entities awaiting form, but must be treated as, in his words, "active materials," (Ingold, 2010, p. 93). Materials can be said to have a momentum that has an impact on the humans that come into contact with them and, consequently, on the design of their environments. Such affordances offered by materials can be experienced particularly strongly by people who work directly with materials: "For makers have to work in a world that does not stand still until the job is completed, and with materials that have properties of their own and are not necessarily predisposed to fall into the shapes required of them, let alone to stay in them indefinitely," (Ingold, 2010, p. 93).

While, in his reflections on the interdependence of humans and materials, Ingold has recourse to Gibson's ecological-psychological concept of affordances, his argument refers principally to classical craft techniques and does not address contemporary approaches to materials in highly industrialized societies, or even developments in the materials sciences. Nevertheless, his and Gibson's considerations are well suited to bridging the gap between, on the one hand, the understanding of agency as a distributed activity between humans and, on the other, a transhuman understanding, and thus prepare the way for a conception of agency as a distributed activity between living and nonliving entities. Both Ingold and Gibson relativize the autonomy and sovereignty of humans in relation to their environments, and, in Ingold's case, this occurs explicitly via the relationship between humans and materials. Hence, the revaluation in the understanding of materials carried out in materials science beginning in the 1980s, and especially since the turn of the century, can be seen as a development that confirms and strengthens Ingold's and Gibson's diagnosis: materials science discovers the activity of materials, but an activity that is explained mathematically and scientifically, and thus independently of concepts developed in social anthropology and ecological psychology.

To present our main claim already here, a claim that will be developed further in the following sections, the above conception of the activity of materials as a plural distribution between living and nonliving entities (and thus as an example for shared or distributed agency) is highly significant; this is because, over the last few decades, research carried out in materials science has transformed the category 'material' into a generic category that claims and occupies the status that natural philosophy once accorded to 'matter.' As a result, the plurality of singular materials has acquired a general ontological character, and, in the growing research field on active matter and bioinspired materials, these singular materials are conceived precisely as active materials, which is to say, not as passive materials but as materials with agency.[5] On the one hand, the activity of materials is defined according to the model of living entities (e.g., self-propelled materials), that is, of entities with the ability to move by themselves. On the other hand, however, the mathematical calculation and modeling carried out prior to the production of such materials is achieved by equating living organisms with particles of matter (as with flocks of birds, etc.). One may claim that our description draws too close a link between the study of active matter systems and the broader field of active materials, where 'active materials,' as this research field is termed in materials science, are not considered explicitly as materials with 'shared or distributed agency.' While we will expand on the research of active matter below, we claim that the broader research on active materials also contributes to the new conception of agency, and in this sense we propose considering the study of active matter systems as a subdiscipline of the much broader field of active materials research.

Indeed, the ideological justification for the activity of materials in materials science is in general oriented to the potential of living organisms (and here one can point to an interlacing with conceptions arising in active matter systems); as we will see in the examples presented below, the orientation of this ideological justification can be observed in the development of bioinspired materials (e.g., Bensaude-Vincent, 2019, p. 551-71; Dicks, 2023). The dead/living or artificial/natural opposition is thus referred back from one category to the other in a kind of feedback loop. But this opposition seems to be cancelled altogether when scientific analysis and modeling treats the living in the same way as the dead and the natural in the same way as the artificial. It seems, then, that, by extending the notion of activity from living organisms to 'active' materials, the distinction between dead and living matter starts to collapse. We will elaborate on this in the following, but let us first continue with a brief historical overview on the passivity and activity of materials.[6]

What Materials Can Do

When one looks at the names used to designate the three time periods of human prehistory, namely the Stone Age, the Bronze Age, and the Iron Age, it becomes clear that the emphasis placed on materials in this naming might also be applied to Western cultural development as a whole. What is reflected here is a conception of nature as an (infinite) repository of materials (or of just one privileged material at a time: stone, bronze, or iron) waiting to be used and shaped, whereby human constructions and interventions are thought of as taking place not within but outside of nature. Such a conception of materials as a resource for technological and cultural development finds a parallel in the classical division between matter and form, as is clearly shown by the conceptualization of wood in antiquity.

The ancient Greek word *hyle*, which we know as a term for matter and material, initially referred primarily to a *forest* or to *wood*. Only in the context of ancient philosophy did it become the generic term for matter and material; in Aristotle's writings *hyle* stands for matter in the sense of an abstract possibility (*dynamis*) that is only actualized and, in a sense, realized through form (*morphe*). With their incorporation into philosophy (which in antiquity included natural philosophy, which later gave rise to natural science), 'materials' were increasingly generalized as 'matter,' whereby *hyle* no longer referred solely to wood or to materials, but primarily to an abstract principle: 'matter.' With the gradual differentiation of the natural sciences in the course of the 17th century, the distinction between matter and material, understood as one between an abstract general principle (matter) and individually determined entities (materials), would intensify and would characterize the Western understanding of materials at least until the late 20th century.

The natural sciences draw their authority from the discovery of universally valid laws – that is why, for a long time, there could be no general science of *materials*, but only one of *matter*. The new materials of the 19th century as well as the reconsideration of known materials, such as iron (as an element) and steel (as an alloy), still fit into this schema, since they could be used for any application and could assume any form. As Bernadette Bensaude-Vincent notes, iron became a "single-class" material because it could be treated mathematically as "pure deformable continua," (Bensaude-Vincent, 2011, p. 114). She describes iron as a "model material" for the scientific (and engineering-based) treatment of material in the 19th and early 20th centuries. Iron can be considered as a passive material (insofar as it "does not work by itself; it is put to work"), and it can also be subjected to mathematical treatment, since it is homogenous and isotropic (Guillerme, 1994, p. 233; this source is quoted in Bensaude-Vincent, 2011). In the second half of the 20th century, however, two shifts occurred with respect to the latter conception of matter: First, the dream of finding a single material suited to all purposes and needs, epitomized by the conceptualization of iron as a model material, gave way to extensive research on a range of different materials, as witnessed by the formation of the multidisciplinary materials science in the 1960s. Since the 1980s, this new science has shown a particular interest in the aspect of performance, and thus in an activity attributed to the material itself, which is to say, inherent to the material's structures and properties. In the understanding of materials scientists, a certain kind of 'material' thus implies an autonomous activity, and this activity of materials in relation to an environment and/or living organisms leads to what we call shared or distributed agency. This conception of agency, it should be stressed, duplicates the earlier conception of agency mentioned above, which only referred to the interaction between human agents (Balibar & Laugier), the only difference being that agency is now attributed to a nonhuman agent: a material.[7] Materials science explicitly addresses the autonomous activity of materials, which it sets out to analyze and, as far as possible, to generalize using the methods of natural science (theories, models, and tools from physics, chemistry, and mathematics), which would then ideally lead to new basic knowledge as well as, of course, to new materials and to innovative design.

Second, research on matter has expanded the physical understanding of matter to include nonequilibrium systems, and thus also living systems (being the prime example of nonequilibrium systems). Hence, in an emerging research field that, beginning in the 1990s, started to investigate active matter alongside solid matter and soft matter (or the overarching condensed matter), there has been a growing interest in living matter, whereby the physical theories of statistical physics and hydrodynamics, as well as the accompanying mathematical tools, have established points of intersection between the different fields of matter research. As the theoretical physicists Gerhard Gompper and Roland G. Winkler point out in an exemplary way regarding the research object living matter, "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" (Gompper & Winkler, 2020, p. 2). Whereby 'active' here does not mean an activity imposed from outside, for instance a movement induced by an impact; rather, the movement is understood as a "self-ordered motion," and a driven system in this understanding becomes 'a system of self-driven particles'; that is, the activity is attributed to the material itself.[8]

In the field of *active matter* research, activity is understood as a basic property of matter, but one that requires certain conditions in order to appear. As Gautam I. Menon puts it, "*Active matter is a* *term which describes a material (either in the continuum or naturally decomposable into discrete units), which is driven out of equilibrium through the transduction of energy derived from an internal energy depot or ambient medium into work performed on the environment*" (Menon, 2010, p.194).[9] Research in this field aims explicitly at the universal category of matter and, to this end, works intensively with mathematical modeling and simulations. Here, the research object is frequently related to self-propelled or self-driven entities classified as living matter, examples of which range from the nano- and the micro- to the macroscale (e.g., cell tissue, bacteria, bird flocks, and human dance behavior).[10] 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 living/dead opposition. Thus, bird flocks, for instance, are modeled in a way analogous to ferromagnetic interaction, in which the spins align in the same direction – with the difference, however, that in active matter the cause of movement is inherent to the (nonequilibrium) system, and the aligning refers to the direction of motion.[11]

In active matter research, living matter is the privileged object in the acquisition not only of new knowledge but also of better applications of this knowledge in the invention of new materials – that is, of materials that are artificial and hence dead. In the diverse research directions being undertaken in materials science (i.e., in research on autonomous, smart, self-propelled, self-assembling, or adaptive materials), it is thus biological materials (from living entities, e.g., plants) that are investigated the most. Among the many new active materials being developed, one could mention programmable cellular microstructures, densified delignified wood, and artificial robotic plant tendrils (see Friedman et al., 2022, p. 129-44; Eder et al., 2021, p. 3-36; Correll et al., 2022, p. 173-90). These materials are considered as entities that are able to 'sense' and to respond to their environment, a conception that aligns with an almost parallel conception that assigns activity to dead matter.

One example of research on biological materials concerns the mechanism of the unfolding seed capsules of the ice plant *Delosperma nakurense*. The materials scientists investigating these plants note that "their fruit undergoes a reversible origami-like unfolding upon sufficient hydration […]. The engine of the investigated movement was found to be the water adsorption and swelling of the cellulosic inner layer of the cell wall of the hygroscopic keel cells." They conclude that the unfolding is an example of "passive actuation systems such as these that do not depend on the active role of living cells [and] are particularly good candidates for biomimetic transfer and further development of such autonomous 'smart' systems," (Guiducci et al., 2016, p. 1-2). We claim that such a 'passive actuation system' undermines the active/passive distinction and may be considered as similar to the opening and closing of pine cone scales upon wetting and drying (i.e., due to changes in the environmental conditions). In the latter example the cells of the pine cone are already dead, and therefore considered passive; it is the structure itself that becomes active, due to triggers from the environment. (Reyssat & Mahadevan, 2009, 951-57). While these observations undermine the dead/alive or passive/active distinction, activity, autonomy, and hence agency are attributed to the material itself, and thus material can be seen as having an autonomous agency. But it is an agency triggered by the environment, and thus a shared agency.

The aim of other actors in this field is to arrive at the construction of artificial active materials that are suited to complex tasks, and these too are often based on the complex examples of nature, but as a technical invention. This can be seen, for example, in the statement of the Cluster of Excellence 'Living, Adaptive, and Energy-autonomous Materials Systems' (livMatS) at the University of Freiburg: "The vision of […] livMatS is to combine the best of two worlds – nature and technology […] [– by] develop[ing] life-like materials systems inspired by nature. The systems will adapt autonomously to their environment, harvest clean energy from it, and be insensitive to damage or recover from it," (https://www.livmats.uni-freiburg.de/en [accessed 25.11.2022]). One example of such research is the development of "printed autonomous scale and flap structures […] inspired by the reversible shape-changes of Bhutan pine […] cone seed scale," (Correa et al., 2020, p. 1). Hence, the orientation of materials science is described by the protagonists themselves as bioinspired (or biomimetic), and encompasses two different approaches: in the first, one has direct recourse to biological materials (e.g., pine cones, even fossilized pine cones, i.e., dead materials), but in order to alter them for specific applications; in the second, one draws inspiration from those materials while leaving them 'untouched.' What this research brings about unnoticed, however, is the reframing of living entities (cells, plants, and animals, including humans) as constellations of active materials.

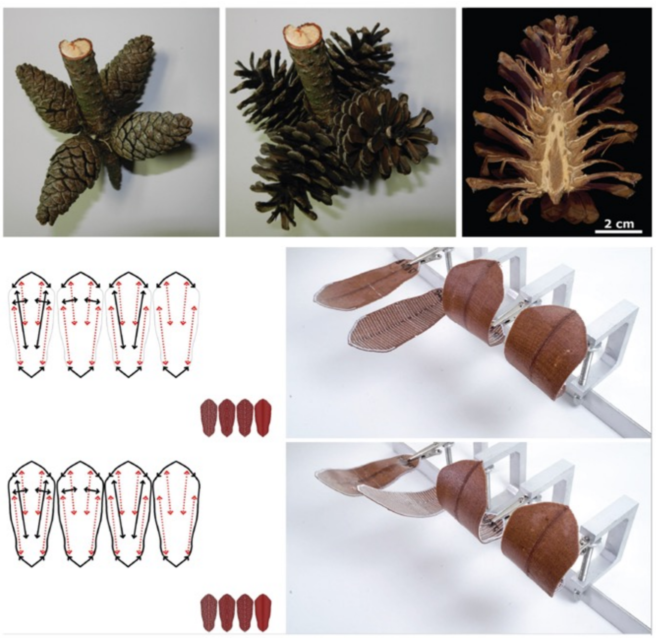

Fig. 1: Above: pine cones in an open and closed state. Below: four-dimensional printed biomimetic scales showing hygroscopically driven motion. Adapted from Correa et al., 2020. © Philosophical Transactions of the Royal Society A, Taylor & Francis.

Agency of 'Autonomous' Materials

As can be seen in the various research projects presented above, one of the main aims of the various researchers in these fields is not only to view nature as a source of and inspiration for inventions and innovations, but also to obtain sustainable, efficient, renewable, and high-performance materials for a variety of applications. As the authors of the abovementioned paper on the seed capsules of the ice plant underline, "Plant hydro-actuated systems provide a rich source of inspiration for designing autonomously morphing devices," (Guiducci et al., 2016, p. 11). Whereby 'inspiration' designates a complex range of scientific procedures that decontextualize the biological materials while simultaneously enabling the construction of active materials, to which the authors also ascribe 'sensing' – an act that echoes Gibson's and Ingold's insights with respect to the shared agency of materials and humans and their shared environment.

If we return to the question with which we started, but now against the background of the contemporary concept of agency, one may ask the following questions: How autonomous are these new active materials? What kind of agency do they possess? Can active materials still be described as autonomous if they are designed to perform specific actions? When materials scientists choose the most convenient properties and ignore others, do "materials by design" (Bensaude-Vincent, 2011, p. 119) not perpetuate the earlier understanding of materials, whereby iron was conceived as the most passive material? What this set of questions underlines is that, in the discourse of materials science, the dead/alive or artificial/biological distinction has become increasingly irrelevant. This is because the actors in this field attempt to examine biological materials as untouched, but at the same time analyze and model them mathematically only in order to produce and construct artificial and singular materials inspired by these highly analyzed biological materials. Once one has understood that the opposition pairs dead/alive and artificial/biological have started to collapse, it becomes clear that the attribution of activity to materials (or their consideration as autonomous systems) does not contradict the practical production of these materials, which consists in choosing specific functions to analyze and model. That is to say, while iron was never attributed such an activity, activity is assigned to materials by design, as well as to smart and active materials.

We claim that, with these active materials, agency is considered as shared or distributed, but this distribution occurs neither solely between the materials nor solely between the designers or 'operators.' To recall, Gibson's conception implies that the environment and the organism interact; the activity of the organism is based on the affordances of the environment relative to it; hence the attributed agency is relational.[12] In Gibson's view, and with the concept of affordances, the environment becomes an active factor, but the interaction eliminates the idea that the activity results solely from the perceiving organism or the perceived substances, media, or materials. The activity itself becomes relational, and, as Ingold stresses, cannot be anchored in the human subject or the environment or the material alone, and all of these actors are ultimately changed by the interaction. In this regard, Gibson's ecological psychology and Ingold's emphasis on manual practices and crafts contribute to the development of the concept of shared or distributed agency. Hence, they both call for a reconsideration of the activity attributed to bioinspired materials, since if these are based, for example, on the seed capsules of the ice plant or on pine cones, then, as our analysis shows, these kinds of active materials, by undermining the active/passive distinction, give rise to another conception of agency: a distributed, shared one.

The ideological orientation of materials science to the potential of the living leads to a consideration of the underlying assumptions of materials science as a kind of ontology of materials and of their activity. With this ontology, not only is the artificial considered as biological (since, even when it does not mimic the biological, it is at least inspired by it), but agency is also redistributed, and this in three ways: first, agency is no longer limited to the human domain; second, it does not belong merely to the domain of the biological or to that of the (re) source material; third, agency, one may claim, has to be understood as being distributed in an ecology that influences and motivates both: the material and the human subject. Only when agency is thought in this way does it become clear not only why 'active,' 'smart,' and 'autonomous' materials are termed as such in materials science, but also why such artificial materials have their own affordances, their own (shared) agency. And while for Balibar and Laugier agency "is inseparable from an anthropologization," materials science offers an account of the agency of materials in which agency is separated from all forms of implicit anthropologization.

Notes

1. See Donald Davidson, "Agency" (first published in 1971), in Essays on Actions and Events (Oxford: Clarendon Press, 1980), 43–62; see also John L. Austin, "A Plea for Excuses," in Philosophical Papers, ed. J. O. Urmson and G. J. Warnock (Oxford: Clarendon Press, 1962), 175–204.

2. Moreover, as a side note, the excellent book by Alvaro Moreno and Matteo Mossio, Biological Autonomy: A Philosophical and Theoretical Enquiry (Heidelberg et al.: Springer, 2015), which discusses questions of autonomy, but also deals with agency (89–110), concentrates mainly on biological systems. For example, Moreno and Mossio note that "autonomy involves […] an interactive dimension, enabling biological systems to maintain themselves in an environment. We will refer to this interactive dimension as agency." (Ibid., 89.) While it is beyond the scope of this article to examine Moreno and Mossio's claims in detail, this paper proposes an extension and distribution of the notion of agency beyond its focus on humans, but also beyond its focus on biological systems.

3. See also Gibson, 2015, p. 120: "The different substances of the environment have different affordances for nutrition and for manufacture. The different objects of the environment have different affordances for manipulation. The other animals afford, above all, a rich and complex set of interactions […]."

4. Gibson refers, among other things, to the niche construction theory of his time. In his further development of niche construction theory, J. Scott Turner focuses on the mutual influence of organ-ism and environment. For Turner, environments should not be understood as something given, and nor should organisms be seen as autonomous entities; rather, both (environments and organisms) emerge and exist in mutual dependency and stimulation. For example, he understands animal-built structures such as anthills as an extension of physiology and at the same time as part of the con-struction of the environment, that is, of the niche construction – in these structures, animal body and environment merge. See J. Scott Turner, The Extended Organism: The Physiology of Animal-Built Structures (Cambridge, MA, and London: Harvard University Press, 2000); J. Scott Turner, "Homeostasis and the Physiological Dimension of Niche Construction Theory in Ecology and Evolution," Evolutionary Ecology 30, no.2 (2016): 203–19.

5. This point about the agency of matter has also been made by Bennett, whose work, however, does not deal with the materials sciences.

6. The following discussion takes up arguments and accounts from our conceptual introduction to the volume Active Materials. See Michael Friedman and Karin Krauthausen, "Materials Matter: Introduction," in Active Materials, ed. Peter Fratzl et al. (Berlin and Boston: De Gruyter, 2022), 3–36.

7. To emphasize, our argument, as was hinted above with Ingold and Gibson, and as will be unfolded below, is to think agency as relational and shared, that is, as occurring between materials and humans.

8. See the famous article by Tamás Vicsek, András Czirók, Eshel Ben-Jacob, Inon Cohen, Ofer Shochet, "Novel Type of Phase Transition in a System of Self-Driven Particles," Physical Review Letters 75, no. 6 (1995): 1226–29, here 1226. The article refers to units of moving particles such as a school of fish – the self in this example of a self-driven system is the school and not a singular fish. Although the examples in the Vicsek article stem from the living world, the article includes nonliving examples that are also considered as active. For a variety of examples ranging from the nano- and the micro- to

the macroscale, including nonliving particles (e.g., vibrated rod-like copper particles), see Gautam I. Menon, "Active Matter," in Rheology of Complex Fluids, ed. J. Murali Krishnan et al. (New York: Springer, 2010), 193–218.

9. For his description of active matter as units of particles that can act on the environment, see Menon, 2010, 193: "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."

10. Indeed, Gompper and Winkler understand their research on living matter as a part of active matter research. See Gompper and Winkler, "Introduction"; Sriram Ramaswamy, "The Mechanics and Statistics of Active Matter," Annual Review of Condensed Matter Physics 1 (2010): 323–45, https://doi.org/10.1146/annurev-conmatphys-070909-104101; Menon, "Active Matter," 193–218; Gerhard Gompper et al., The 2020 Motile Active Matter Roadmap, Journal of Physics: Condensed Matter 32, 193001 (2020); Gabriel Popkin, "The Physics of Life," Nature 529 (2016): 16–18, https://doi.org/10.1038/529016a.

11. To the extent that the source and cause of 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. See Vicsek et al., "Novel Type of Phase Transition in a System of Self-Driven Particles," 1226; Evelyn Fox Keller, "Active Matter, Then and Now," History and Philosophy of the Life Sciences 38, no. 3 (2016): 1–11; Sebastian Vehlken, Zootechnologien: Eine Mediengeschichte der Schwarmforschung (Zürich: Diaphanes, 2012); Mathias Grote, Membranes to Molecular Machines: Active Matter and the Remaking of Life (Chi-cago and London: University of Chicago Press, 2019), 56–110, 186–93.

12. As noted above, and to stress this again, Gibson does not use the term 'agency.'

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