[3]

Physics and Aesthetics: Simulation as Action at a Distance

Christina Vagt

In today's material science, "spooky" *action at a distance* has no place. When an Australian banksia tree suddenly opens the follicles of its cones to release its seeds in the aftermath of a wildfire, cause and effect are evident to the careful observer: The fire gets rid of the competition. But the sheer fact that the cone, which has been technically dead for a decade, can actually perform this kind of specific and goal-oriented motion does appear strange—until experiments in combination with imaging and modeling techniques finally enable scientists to procure a viable model that can not only simulate the opening process of the follicles but also explain its material structure in detail. The role of computer models for this kind of material research is crucial because it mediates not only between theory and data but also (re-)directs the research itself. By discussing two experimental systems from the field of biomaterial research in terms of aesthetic theories, this essay pursues two strategies: to demonstrate how the mediation between experimental and simulated data codetermines whether a viable model of a biomaterial structure can ever be procured, and second, to understand scientific computer models themselves as aesthetic procedures that create their own specific objects of study

[“*Anschauungsobjekte*”], therefore extending the media question underlying natural sciences into the realm of digital technologies. Computer simulations belong to a long history of action at a distance through models but also through concepts, and the question they raise does not concern causality and instantaneity so much as the relation between living processes and their mathematical conceptualization.

Computer Simulations with Blumenberg

Recent decades have produced a growing number of publications on the history and epistemology of computer simulations within the history of science, media studies, and philosophy of science. Peter Galison describes the coming of computer simulations as a new and interdisciplinary way to conduct science beyond the traditional distinction of theory and experiment. Beginning with historic computer simulations that led to the design of the first hydrogen bomb in 1952, computer simulations changed the status of the computer within science and engineering from “computer-as-tool to computer-as-nature” (Galison 2011, 121). Paul Edwards states that, during the Cold War, simulations had “more political significance and more cultural influence than the weapons that could not be used” (Edwards 1997, 14). Claus Pias (2011) demonstrates the rootedness of computer simulations in so-called mode-two sciences that operate in a problem-oriented, contextualized, and multidisciplinary fashion. They produce second-order statistics that can model the behavior of systems within complex environmental interactions, and, as a political technology, they belong to preventive risk-managing strategies of governance. Eric Winsberg (2003) argues that techniques of simulation, like experiments, have a life of their own and carry their own credentials. Meanwhile, Till Grüne-Yanoff and Paul Weirich (2010) refer to the flexible distinction between computer models and simulations, while providing a useful overview of the scientific use of simulations that might function as proof, projection, explanation, or policy formulation. Last but not least, Gabriele Gramelsberger stresses the role that computer simulations play in sciences without "first principles," such as life sciences, neurosciences, and climatology and their role for sociopolitical practices that rely heavily on models (Gramelsberger 2011). She also relates computer simulations to textual narrations in fiction, such as a short story, novella, or detective story. Like literature, computer simulations apply different temporalities, and the temporality of the plot is not identical with the time of the plot (Gramelsberger 2008).

The following essay builds on this historic and epistemological research, while stressing the role that *aesthetic procedures* play for computer models and pursuing the hypothesis that computer simulations are aesthetic procedures in and of themselves, because they create their objects of study—they make things appear that weren't known before. The starting point for this inquiry into the interaction of technology and aesthetics are two experimental systems in the field of biomaterial research, which investigates structural mechanics performed by animals and plants. The role of imaging technologies for computer models in biomaterial research was obvious from the start, yet, through observations and discussions with the involved scientists and engineers over the period of one year, it also became clear that the models redirect the imaging process. This "loop" between scientists and modelers (Gramelsberger 2008) gave rise to my own research on the function of aesthetics for concepts of matter, because it raised questions about the influence of design [*Formgebung*] on the conceptualization of biomaterials and living matter.

To mobilize aesthetic theories in order to understand the role of imaging and modeling technologies in material sciences might seem an awkward approach—to scientists and engineers, at least, who usually think of them as tools. What this aesthetic discussion provides is insight into the reality claims of both the model and the modeled object, something that is rarely discussed in science and engineering but is nevertheless crucial when it comes to discussing the outcomes of scientific research with a broader public, especially when modeling plays a central role in politics and policy making. The experimental setup of these systems, which constantly trade first- and second-order data, allows for a "close reading" of the modeling process itself. Even though no immediate political or ethical questions implied in the research will be discussed here, understanding how imaging and simulation techniques bridge the gap between classic experiments and computer models might also provide insight into how to read more complicated models in which the mediation between object and model cannot be as easily followed, as is the case with climate models (see Oreskes, Stainforth, and Smith 2010).

Within their respective experimental systems, computer simulations define living matter as scientific objects in terms of the "space of possibility," a term borrowed from Michel Serres, who borrowed it from Robert Musil (see Serres 1978). The computer model defines the probabilistic realm that restricts possible data values and behavior—both experimentally and virtually. This highly dynamic space that—unlike the classic spaces associated with Newtonian mechanics or Euclidean geometry—is not fixed once and for all, but rather its actuality depends on its ability to simulate the behavior of the material under specific conditions. And while the model is being used to simulate behavior under variable conditions, it is itself subject to modifications by the modeler. As an epistemological technology, i.e. a knowledge-generating technology, computer simulations are themselves the outcome of a new statistical concept of matter that started with thermodynamics and electrodynamics and was eventually formalized in nuclear and quantum physics during the first half of the twentieth century. According to quantum physics, matter is conceived as being both discrete and continuous but more importantly as dynamic, since it exchanges energy with its environments. It even defines certain properties of time and space rather than being submerged to fixed space coordinates. Not only does matter stop being passive and inert, it also gives rise to new means of manipulation and technology design. When John von Neumann and Stanislav Ulam designed the first computer model, it happened in the attempt to solve the almost unsolvable problem of how to design a hydrogen bomb. How can one build a weapon whose physical properties were not understood in detail and that, furthermore, couldn't be subjected to classic experimentation either, because the forces and temperatures involved were too destructive to be tried out under laboratory conditions? Over the course of the twentieth century, simulating something that cannot be tested under real-world conditions became the new third category added to the former scientific duality of theory and experiment, according to Galison (see Galison 2005). This "third way" of simulation became particularly productive in engineering. Largely overlooked, however, has been that any procedure for making things appear to the senses—making things appear where they are not, or rather before they actually come into being—is an aesthetic procedure.

When computer simulations are part of complex experimental systems involving different kinds of measuring and imaging techniques, they mediate between image and model. This process cannot be entirely reduced to semantic or logical terms. It is in fact an aesthetic procedure in the sense of designed sensual cognition [*gestaltete sinnliche Erkenntnis*], whose outcome depends on the potential and quality of the measuring and imaging techniques that are applied, as well as the design of the model. In this sense, computer simulations themselves can be understood as an aesthetic procedure that requires, like any other aesthetic procedure in literature or art, a certain temporal and spatial distance to real-world phenomena of the living environment and its corporeal and tactile information. In today's scientific cultures, computer simulations are a prominent type of action at a distance, a classic concept of agency that does not exclusively refer to physical phenomena, such as electromagnetism or gravitation, but also to cognition. According to Hans Blumenberg, action at a distance signifies physical as well as cognitive processes, and cognition always implies sensual data and therefore aesthetics (see Blumenberg and Haverkamp 2010). The ability to act from a spatial and temporal distance, to act on something *in absentia,* is not exclusive to humans—after all, the sun acts on the earth from quite a distance—but it does characterize human agency to a large degree. For Blumenberg, human action is characterized by an "ontological distance between an object of knowledge and its knower" (Blumenberg and Hawkins 2015, 156). Conceptuality is grounded in this type of remote agency: A *Begriff,* a notion or concept, is an action that implies the absence of the object. The German notion for "notion"—*Begriff*—implies *greifen,* which can be translated as "to grasp," "to grab," or "to seize," as does the English notion "concept," a calque from Latin "*concipio*" or "*con"* (with) + "capio," where *capio* means "to capture," "to seize," or "to take." Concepts have to be vague enough to encompass the boundaries of a thing and yet leave enough room for any concrete perception still to come along. Concepts act like a mesh for future sensations, they are a form of preemptive action, which Blumenberg imagines to have started in prehistoric times with the throwing of a spear or the setting of a trap. Preemptive behavior exists in all human societies, at work in hunter-gatherer cultures as well as in European philosophies of mind, matter, and life. Concepts as preemptive behavior are not simply based on objects—as a fact, the former constitutes the latter. According to Kant, this is particularly valid for mathematical terms; according to Freud this is true for the notion of the unconscious; and according to Leibniz, it also applies to playing music, a mental power of computation without the awareness that one is generating numbers. Mathematics, the unconscious, music—these are three very diverse realms that nevertheless are driven by objects that are themselves generated by concepts. In a more general sense, Blumenberg implies that they provide a particular insight into the structure of human reason, which is another example of an object generated by concepts. Human reason as the sum of conceptuality relies on action at distance, on the aesthetic intermediation between concepts and objects. Computer simulations therefore belong to the history of action at a distance through notions and reason, they are a type of symbolic labor [*Arbeit am Begriff*] with real-world consequences. And just as concepts and reason evolve through aesthetic processes involving metaphoric, metonymic, and contingent elements, computer simulations—even though mathematical in nature—depend on experimental data, pattern recognition, and design [*Formgebung*].

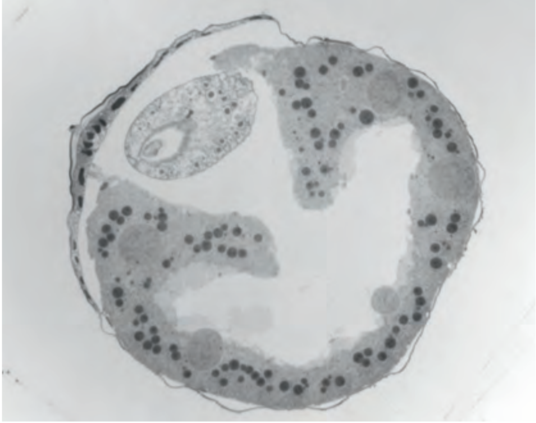
The two experimental biomaterial systems that are discussed here serve as close readings of engineering methods applied within the life sciences. They demonstrate how matter and life are converging within the modeling process, and how imaging and modeling techniques bridge the gap between these formerly distinct orders. Of primary interest here are not the scientific outcomes but the modeling process itself, how it can be better understood within the intertwined histories of aesthetics and matter, and how it can inform media-theoretical discussions on matter and materiality.

Imaging Tunicates

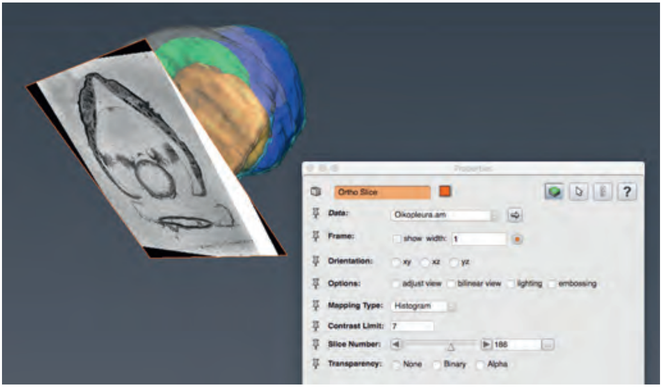
Tunicates, in Latin *oikopleura dioica,* are tiny marine animals almost invisible to the human eye. As part of the zooplankton, they inhabit the upper, warmer layers of the world's oceans, especially coastal waters (Scripps Institute 2019). Their specialty is that they unfold a "house" or "body housing," also described as "filtering mechanism" that enables the animal to filter the sea water for digestible algae and transports it into the mouth of the animal (see Jany und Razghandi, forthcoming). A research group at Humboldt University in Berlin and the Max Planck Institute for Material Science in Potsdam under the leadership of biologist Thomas Stach investigates the anatomical mechanism that unfolds the house. In order to study the filtering and unfolding operations of the house, they are attempting to build a computer model of the organism in order to eventually be able to simulate the unfolding process of the house as a whole and to find answers to the leading question: Is there a specific design, a biomaterial design, that enables the tunicate to unfold its complex cellulose house approximately every four hours during its short lifespan of seven days?

After slicing the material and taking single microscopic images, thousands of slices have to be reassembled both manually and

[Figure 3.1]. Microscopic image of a living tunicate inside its "house." The head of the animal is dyed yellow and orange, parts of the house are already filled with undigestible purple-dyed plant particles. Image courtesy of Khashayar Razghandi.



[Figure 3.2]. As with most biological research, it starts with microscopy. The animal body or biomaterial is cut into ultrathin slices, each only a couple of hundred nanometers thick, and each microscopic image is digitally captured. Image courtesy of Khashayar Razghandi and Thomas Stach; produced in the laboratory of Thomas Stach (Humboldt University, Berlin, Comparative Electronmicroscopy).



[Figure 3.3]. A 3D model is then built from the microscopic images. Image courtesy of Khashayar Razghandi and Thomas Stach; produced in the laboratory of Thomas Stach (Humboldt University, Berlin, Comparative Electronmicroscopy).

through software into a three-dimensional model, which is then able to generate parameters to create a second model that can be used to run computer simulations on the material.

There are also non-invasive imaging methods that try to capture the living animal in water. The high-resolution images and two-minute-long microscopic film sequences that are produced grant insight into the motoric skills of plankton. The animals drift directionless, absorbing algae. Their movements are characterized through the pulsating rhythm of their beating tails, and the different degrees of liquidity and firmness, translucence and opacity, create the ambience of a floating dance. Beautiful without question, it is difficult to capture on microscopic film the exact moment when the animal unfolds a new house. Stach's group has not been able to realize a computer model on the basis of this imagery. There were simply not enough viable data. Among the difficulties of the modeling process lies life itself. Technologies such as Raman spectroscopy and electron microscopy often help to identify the distribution of biochemical components and structural organization within biomaterials, but the biomaterial has to be

[Figure 3.4]. Still image from a microscopic film, with a cloud of orange-dyed algae that the animal will start feeding on soon. After a couple of hours of eating and filtering, the house is completely opaque and congested. The animal leaves its house behind, and after a couple of hours and unfolds a new one. Image courtesy of Khashayar Razghandi.

"prepared" in order to employ such technologies, a highly technical process that is also deadly for the animal. The paradox of these efficient measuring and imaging techniques lies in the fact that they cannot be performed on living organisms, and a dead animal can no longer perform the unfolding mechanism.

Biomaterials with Bergson and Schrödinger

This paradoxical relation between living motion and its visual and conceptual representations lies at the core of science and philosophy—at least in the view of French philosopher Henri Bergson, who calls it the "cinematographic mechanism" of the human intellect. It signifies a fundamental shortcoming of perception, intellect, and language: Humans perceive, recognize, and verbalize motion by looking at it from the outside, as a succession of discrete states or forms. In science and engineering, this leads to the idea of motion as being sprawled out within a Cartesian coordinate system, allowing for its translation into algebraic formula and calculation (see Bergson 1908, 295–375). The cinematographic mechanism is probably the most quoted Bergsonian metaphor, ever since Gilles Deleuze based his cinema theory on it. But beyond its historic epistemology of chrono-photography and cinema and in an even more general sense, Bergson used it as metaphor for human cognition as a mode of simulation.

The mechanism that simulates continuous motion by moving a succession of still images at a rate that escapes the human eye is a technical concretization of the relation between intellect and matter—at work in our everyday perceptions just as in the measuring sciences. Bergson never seems to get weary of pointing out this blind spot in European philosophy, tracing it from ancient Greece to modern physics of the early twentieth century, following the succession of paradoxes on motion and time. The deficiencies of language are not the point of origin for this blind spot, nor does it lie in the mathematical worldview of scientists. Rather, the cinematographic mechanism points to Bergson's anthropological conception within the structure of the universe itself. It is a necessary intellectual and scientific self-deceiving mechanism that results from what one might call the *will to conceptualization or abstraction* from a concrete situation or object that lies at the bottom of both image- and language-creating processes—Nietzsche calls it the "will to metaphor." It is not restricted to a specific media-technological apparatus; the apparatus simply demonstrates or concretizes the general act of human cognition, which can only deal with real processes and their perceptual data in their absence, by simulating them: Every continuous motion, be it that of light or that of one's own arm, is dissected into discrete sections only to be artificially reanimated into a perceivable motion. European thought has been confusing processes of becoming with the successions of forms right from the beginning, from Platonism onward. According to Bergson's judgment, both science and philosophy are based on this self-concealing mechanism. But while science needs to adhere to it as best it can, philosophy needs to reveal it in order to illuminate the mind's constant simulation of motion, which permits—through distance—different, more complex forms of behavior and action. When it comes to simulation, science and philosophy seem to work in opposite directions. This division of labor becomes particularly clear when Bergson elaborates on the history of matter: Most physicists before 1900 and the advent of special relativity theory treated solid matter as if it were identical to geometry, following a concept of passive matter inherited from Descartes and the technique of analytical geometry culminating in Newtonian mechanics. From a historical perspective, the task of physics has been to push representations of matter virtually toward the direction of space, because matter and human intellect (which is itself immersed in a material universe) alike have a natural affinity for space and geometry; matter and intellect share a certain degree of inertia, so to say. As a result, physics before the nineteenth century ignored the temporal aspect of the material universe, the fact that it is immersed in processes of evolution and becoming (see Bergson 1944, 216). Bergson sees the reason for this geometrical bias, this geometrical inclination of science, in the structure of the universe itself: Everything that exists, including matter, is subjected to processes of temporal change and becoming but can only appear to the senses because it is embedded in matter. Science has to overlook the fact that it deals with life only in terms of the cinematographic mechanism, that it has to simulate an object in order to learn anything about it. According to Bergson, concepts of science are but symbolic or visual simulations, mathematical notations, aesthetical procedures, and they could have turned out in many different ways. But even though they are never inevitable or determined, they also did not evolve by pure chance, otherwise science would not have progressed:

> And yet there is an order approximately mathematical immanent in matter, an objective order, which our science approaches in proportion to progress. [. . .] It is true that

> laws of mathematical form will never apply to it completely. For that, it would have to become pure space and step out of duration. (Bergson 1944, 218)

Matter appears to be subjected to change and becoming, and at the same time it has a tendency toward the rigor of geometric relations. It is extended between two poles, one of pure space and one of pure becoming, but it will never entirely coincide or converge with either one of them. The artificial or human aspect of modern science is not the geometrical bias itself but rather the need to measure, which paradoxically generates its success:

> In a general way, measuring is a wholly human operation, which implies that we really or ideally superpose two objects a certain number of times. Nature did not dream of this superposition. It does not measure, nor does it count. Yet physics counts, measures, relates "quantitative" variations to one another to obtain laws, and it succeeds. (218)

Against the background of evolutionary theory, Bergson concludes that mathematical order is in itself not factual or real but simply "the form toward which a certain interruption tends of itself, and that materiality consists precisely of an interruption of this kind" (219). Lacking the modern concept of information, Bergson struggles to explain how mathematics introduces negativity into matter, and how this solely serves a communicative, social function: "Negation, therefore, differs from affirmation properly so called in that it is an affirmation of the second degree: it affirms something of an affirmation which itself affirms something of an object" (288).

If negation is a process that takes place in time, it is primarily a temporal and not a logical operation and immanent in all material processes. With this understanding of mathematics as a symbolic and socially determined type of interaction with material processes of change and becoming, there is no need to assume a prestabilized harmony between mathematics and the world, because their relation—being social and communicative in nature—is not determined but contingent to a certain degree, just like the relation between actuality and formalism in philosophical systems, spoken or formal languages, social organization, and so on.

> And yet it [mathematics, CV] succeeds, just because there is no definite system of mathematical laws, at the base of nature, and because mathematics in general represents simply the side to which matter inclines. [. . .] we can take matter by any end and handle it in any way, it will always fall back into some one of our mathematical formulae, because it is weighed with geometry. (219)

Life and matter are two different motions bound to interrupt each other. In its most extreme forms, matter almost exhibits purely geometrical, mechanistic behavior—that is why Bergson sometimes refers to it as the "automatic" or "inert order"—a pretty adequate description of what physics nowadays calls the stillness that befalls quantum systems near absolute zero. Matter near absolute zero does not allow for life, because the living is weighted with becoming and subject to constant change. Transformation cannot happen without matter, matter would not exist without transformation: "Things and states are only views, taken by our mind, of becoming. There are not things, there are only actions" (248). Over the course of the history of Western sciences and their media technologies that measure motion, matter seems to be on its way toward mathematics. In the late 1930s, at the end of Bergson's lifespan, which saw the coming of relativity theory and quantum mechanics and the settlement of the mathematical *Grundlagenstreit* through Gödel's *Entscheidungstheorem,* matter and mathematics really do seem to converge. But according to Bergson's prognosis, even though the latest matter models come very close to being completely mathematized, they will never completely coincide, not because of faulty science or mathematics but rather because matter is also subjected to becoming and life. Life and matter are inverse and continuous movements that interrupt (or discretize) each other.

> In reality, life is a movement, materiality is the inverse movement, and each of these two movements is simple, the matter which forms a world being an undivided flux, and undivided also the life that runs through it, cutting out in it living beings all along its track. (249)

Together but in opposite directions, life and matter are part of the same real process, while both human cognition and science can only account for the result of their interaction, namely the cut-out forms of living beings. Bergson's image of an "undivided flux of matter" follows the energetic model of late nineteenth-century thermodynamics and its second law, stating that matter, if left alone, has a tendency toward equal distribution. While matter is subject to the time arrow of entropy, living beings seem to be able to hold off this process of thermodynamic equal distribution (or death) during their lifespan. An organism is able, for as long as it stays alive, to withstand the second law of thermodynamics and decrease the amount of entropy by interacting with its environment. Bergson understands this counterforce to entropy as a vital force [*élan vital*] (268). Quantum physicist Erwin Schrödinger states the problem in a very similar manner in his book *What Is Life?,* which resulted from a series of public lectures in 1943. Schrödinger explores, like Bergson, the threshold between physics and biology, but instead of using Bergson's vitalist term *élan vital,* Schrödinger invents the concept of "negative entropy":

> Every process, event, happening—call it what you will; in a word, everything that is going on in Nature means an increase of the entropy of the part of the world where it is going on. Thus a living organism continually increases its entropy—or, as you may say, produces positive entropy—and thus tends to approach the dangerous state of maximum entropy, which is death. It can only keep aloof from it, i.e. alive, by continually drawing from its environment negative entropy—which is something very positive as we shall immediately see. What an organism feeds upon is

> negative entropy. Or, to put it less paradoxically, the essential thing in metabolism is that the organism succeeds in freeing itself from all the entropy it cannot help producing while alive. (Schrödinger 1992, 71)

Living matter is able to keep entropy, aka death, at bay by absorbing negative entropy from its environment. Schrödinger did not receive much praise from the scientific community for his neologism, apparently translating the order of the living organism into the order of computable matter did not help. In a rhetorical move, Schrödinger both introduces and abandons the concept in *What Is Life*, and introduces instead—for the first time in the history of science—the concept of a genetic code. The rhetoric of *What Is Life?* and the emergence of the concept of a genetic code are remarkable, because unlike negative entropy, it has made an almost unprecedented career as a scientific concept within the life sciences over the course of the twentieth and twenty-first centuries. Revisiting Schrödinger's disputed and now outdated concept of negative entropy is nevertheless insightful, because it differentiates between the computability of matter and the organization of life, a distinction that the notion of the genetic code effaces (Weigel 2006). Schrödinger and Bergson were convinced that the two orders of life and matter cannot be converted into one, because they are complementary to each other. If they ever converge, it would mean the end of time and life. Their insight, that life and matter, living matter, is not just governed by a single movement but by two (because their movements are essentially inverse or negative toward each other, a form of difference or interruption) effectively gets lost in the models of cybernetics and information theory that succeeded them. But the practical obstacles in building computer models of living matter again brings the twofold aspect of living matter to the fore: When modeling dynamic or living processes, organized and coded processes, both movements have to be taken into account: the tendency of matter toward geometry and its interference with immanent becoming. And the problems of imaging and data analysis do not stop once and for all, indeed they carry on into the actual building of the model itself.

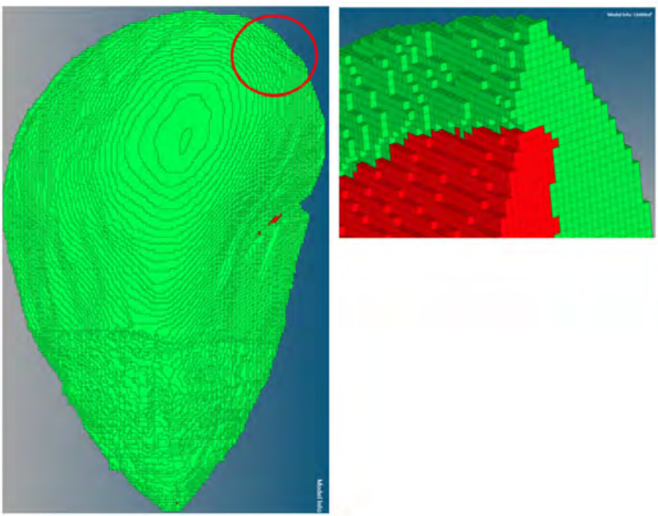
Simulating Banksia

Our second experimental system of biomaterial investigates the opening mechanism of follicles of *Banksia attenuate.* Banksia plants come in diverse sizes and shapes of trees and bushes, and among botanists they are famous for their seed pods. These cones are technically “dead” or “inanimate” because they no longer participate in the active metabolism of the plant, but they nevertheless are able to open after being exposed to the extreme environmental conditions of a wildfire.

Its opening mechanism enables this species, endemic to Australia, to compete with other trees. The research group of Michaela Eder at the Max Planck Institute of Colloids and Interfaces in Potsdam is building a computer model that allows them to run computer simulations of this opening mechanism. The model is an example of the standard computer simulation for structural analysis of solid matter and for the design of such, e.g. for airplane and automobile designs, the so-called Finite Element Method (FEM) (see Clough 2004). FEM is one of the most common types of computer simulations in and outside science today. It has a vast distribution among industrial engineering fields as well as in material science. Many disciplines use it to simulate the behavior of solid-state bodies under fluctuating environmental conditions such as physical impact, air temperature, and so on.

[Figure 3.5]. Banksia pods. After a wildfire, the pods suddenly open their lips and release the seeds. Image by the author.

Every FEM starts with defining the investigated object (and its model) in terms of computer mathematics and the governing physical and chemical laws—including Newtonian laws of motion, the fundamental equilibrium equations of solid mechanics, and the thermodynamic laws for the conversation of energy and increasing entropy—that mark the boundary conditions for every possible motion: its space of possibility. The virtual model has to comply with the same natural laws that govern the properties of the actual body, but, unlike the real banksia pod, the numeric model can only deal with discrete states and a finite set of elements. Therefore, the material continuum of the solid object has to be transformed into groups of finite numbers of discrete elements. One of the first decisions the modeler has to make, then, is what kind of mesh should be applied to describe the body as a network of joint points: If the mesh is too wide, the virtual system will be unstable, and, if it is too fine, the computer will take forever to run the simulations. After defining all mechanical-mathematical conditions and laws



[Figure 3.6]. An important step in building the model is the segmentation of the continuous object into discrete elements. Image courtesy of Huynh Nguyen.

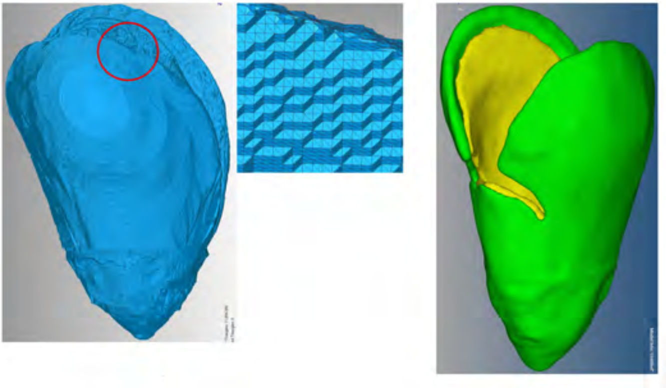
of the model, one needs experimental data from the object under investigation.

Every computer model in biomaterials starts with imaging, and in this case the raw data do not stem from microscopy but from computer tomography scans of the pod in different stages of the opening process. This experimental system has the huge advantage over the tunicate experiment in that the opening process can easily be captured by the imaging technology, e.g. by exposing the pod to wildfire temperatures inside a CT scanner until it opens its lips.

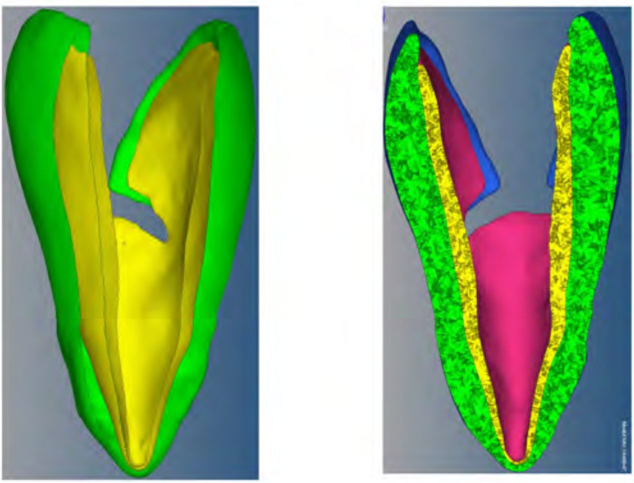
It is also quite convenient that CT and MRI already produce 3D images, therefore they do not have to be aligned like laser sheet microscopies. But they do come in a continuous, analog data form, therefore they have to be segmented before they can be fed into the computer model in the form of discrete mathematics. There would be no computer models in biomaterial research without the countless media technologies of data analysis: from simple microscopic films and photograms to x-rays, CTs, and MRIs, electron microscopies, cryo-electron microscopies, and so forth.

Once a viable computer model has been built, the scientists run simulations on different environmental parameters. The model is constantly revised in the process of simulation and further experimentation on the mechanical and biochemical qualities and properties of the pods. Through this interplay or loop between simulation runs and real-world data analysis, the behavior of the biomaterial and its mathematical model do indeed converge.

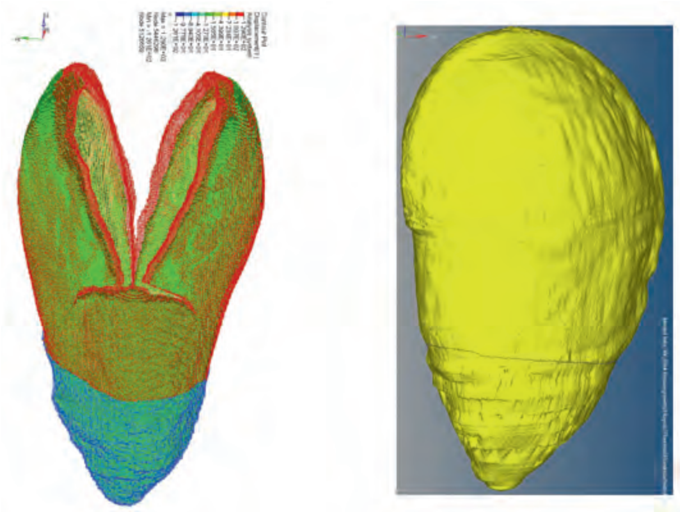
In comparison, the two experimental systems point out the difficulties in building a viable computer model of living matter. We also see that the FEM method much better serves to simulate the structural motion of inanimate matter. The obstacles for analyzing the unfolding of the tunicate already start with imaging—it is quite difficult to gather experimental data when it is impossible to perform electron-microscopy on the material. The movements that would describe the unfolding of the tunicate's house seem



[Figure 3.7]. Meshing of the smooth surface. Image courtesy of Huynh Nguyen.



[Figure 3.8]. A first FEM model of the pod. Image courtesy of Huynh Nguyen.



[Figure 3.9]. Validating the experimental data, the model converges with the experimentally minded data. The term "convergence" refers to the state when the model can finally be used to analyze the actual movement of the cone and predict its behavior according to changing environmental factors like temperature, humidity, etc. Image courtesy of Huynh Nguyen.

to be much more complex than those of the banksia pods. The unfolding of the tunicate house transgresses the borders between one, two, and three dimensions, and the unfolding motion of the fragile cellulose houses probably would have been better described in terms of fluid dynamics, since this takes place in water. By running simulations of the banksia opening mechanism, the model has falsified earlier assumptions about the material structures of the follicles. Searching for experimental evidence, a new set of spectroscopies and 3D images was produced, and eventually the opening mechanism was described in a satisfying way (Huss et al. 2017). These research projects count as basic research [*Grundlagenforschung*], and accordingly the models do not have any design applications. It is obvious, however, that the temperature-sensitive mechanism built or coded into the structure of the Banksia pods could enable further research on how plants deal with wildfires and could very well lead to new bio-inspired designs in industry and architecture.

Computer simulations are able to deal with materials by focusing on patterns and structures instead of substances and qualities—they are entirely ignorant of whether or not they model the behavior of tunicates, banksia, or auto bodies. Their ability to abstract from the immediate impressions of sensual data and their focus on the mathematized functions and possible behaviors of a biomaterial is what makes them so valuable at the interface of science and industry. Their degree of abstraction—their distance—from any concrete body or organism enables them to determine the space of possibility, even for the most extreme or even impossible environmental conditions. The model deals with the immanent process of becoming in negative terms by excluding and falsifying everything that the material could not become or do. Unlike cinematic simulations, computer models do indeed converge matter and mathematics. Because they are based on thorough discretization and mathematization, however, they can only be applied after a satisfying amount of data has been collected through classic experimentation. It is therefore misleading to speak of computer simulation as dematerialization—they just operate from a distance, in absence of the object, like concepts and numbers.

Computer Simulations between Physics and Aesthetics

Since the discretization of the object can only take place in its absence, action at a distance is a cornerstone in biomaterial science—not despite but because it also depends heavily on the data gathered through close-up measuring and imaging technologies such as photography, spectroscopy, and 3D imaging. Both imaging and modeling are inevitable for the simulation of biomaterials, because they intermediate between measurements of the actual material and the virtual design of the computer model that generates second-order data—data gathered through simulations (Pias 2011). Like cinematography, today's simulation techniques discretize continuous movements and then add artificial motion, but the resulting images and films are data visualizations. Instead of representing past or actual motion, they produce negative maps that chart impossible motions. Like concepts, their most important accomplishment lies in their ability to exclude possibilities: The mapping of possibilities is production of negation (see Blumenberg and Haverkamp 2010, 75–76). Simulation allows for the recognition of something that cannot be perceived, measured, or experienced in any other way. It enables one to discern gaps within the perceived, the measured, the experienced.

Simulations belong to a history of algorithmic images, which are generated in a symbolic space (see Montaña and Vagt 2018). But the numerical models they are based on are also derived from experimental data and operate within theories based on natural laws. Therefore, computer simulations assemble two movements in different directions: one that follows the spatial, geometrical, and immanent order of the model and another of impossible states that are interrupting or rather restricting each other, generated by the runs of the simulation. In this sense, computer simulations do indeed take both spatial and temporal motions into account, something that Bergson, at the beginning of the twentieth century, reserved for intellectual beings.

This bridging of life and matter in computer simulations relies equally on physics and aesthetics, the only two inner-worldly processes that can be called "real," according to Max Bense. While physics follows the second law of thermodynamics, according to which the time arrow of increasing entropy describes the world in the direction of disorder or the probability of maximum equal distribution, aesthetics can be comprehended as the inverse movement, segregating instead of blending (Bense 1960, 20). In Bergson's philosophy of the living, this results in two opposed academic cultures of science and philosophy. In Bense's computerinformed aesthetics of physics from the 1960s, aesthetics occupies the place that for Bergson still belonged to vital concepts such as *élan vital* or statistic concepts such as Schrödinger's negative entropy. Both physics and aesthetics have ceased to simply describe the world as given—instead they try to figure out how to change it. Neither imitates nature any longer, rather both create their own objects. The computer with its regime of information and organization does not dissolve the boundaries between physics and aesthetics, or science and art. What it does is relate them closer to each other than they had been for a long time. Since computer simulations do not yield to any defined reality but operate within terms of possibilities and probabilities, attempting to create viable scenarios rather than ontological certainties, and abstaining from determining the actual outcome of single events, they are not mere tools or instruments of science. They are aesthetic instruments that change the perception of reality.

The idea that the texture of reality itself is subject to historic transformations is not new to the humanities, but it seems to be largely absent in scientific discussions. When Blumenberg distinguishes between different types of reality over the course of European history, he points out that, unlike the incontrovertible and instantaneous reality mediated and guaranteed by Christian theology and ontology in medieval and early modern times, modern realities are neither guaranteed nor instantaneous. Instead, they come with "a sort of 'epic' structure, relating to the totality of a world that can never be completed or grasped in its entirety—a world that can be only partially experienced and so can never exclude different contexts of experience which in themselves constitute different worlds" (Blumenberg 1979, 33). Realities do not refer to one nature any longer but require constant actualization and realization. They often take the form of logical paradoxes, something modern physics incorporated like no other scientific discipline. Quantum and relativity physics have been operating with restricted realities for more than one hundred years and they reflect the boundaries of their validity through physical constants. For physics as well as for aesthetics, reality is a context, a surrounding grammatical or mathematical structure:

> Reality can no longer be considered an inherent quality of an object, but is the embodiment of a consistently applied *syntax of elements.* Reality presents itself now as ever before as a sort of text which takes on its particular form by obeying certain rules of internal consistency. Reality is for modern times a context [. . .]. Now, if aesthetic objects can have such a thing as a specific reality, they, too, are not only bound by the criterion of context as proof of their reality but are also constrained, as regards their scope and the wealth of elements they incorporate, to compete with the context of *Nature,* i.e., to become *secondary worlds:* they no longer extract, by imitation, realities from the one reality, but imitate the fact of being real. (Blumenberg 1979, 42)

Secondary worlds, worlds that imitate the fact of being real, are simulated worlds. When media theory speaks of computer simulations as artificial nature or world-making technology, it has to take the interdependence between science and aesthetics into account. It must do so because not only is there an aesthetic context to scientific objects, but science also frames aesthetic objects. What might perhaps be difficult to understand about this relation is the fact that it disables arguments in terms of causality and instantaneity, because the time arrows of aesthetics and physics do not run in the same direction. Furthermore, the efficacy of their interaction, the interdependent calibration, can only be understood through distance. The virtual model has to be reconfigured in accordance with real-world data and curves that describe the actual behavior of the material under certain stress conditions, such as pressure, temperature, and humidity. Since the computer model is able to converge the actual and the virtual, as well as matter and mathematics, it can reach a degree of reality that allows experiments to be conducted within this model. Once a model converges—when it reaches an adequate degree of reality, so to speak—it serves as second world or second nature in which mathematical experimentation beyond the limits of actual matter can be conducted. It will never produce certainty; instead it creates new spaces of possibility, be it for the design of new materials according to user and environmental concerns or policy making in regard to phenomena beyond perception, such as climate change. It is not a medium of certainty but of investigation and speculation.

Notes

The idea for this project emerged from interdisciplinary research on self-moving materials at the Cluster of Excellence “Image Knowledge Gestaltung,” a joint venture of Humboldt University Berlin and the Max Planck Institute for Colloids and Interfaces in Potsdam. This article would not have been possible without the work and help of Susanne Jany, Khashayar Rhazgandi, Nhu Huynh Nguyen, Michaela Eder, John Dunlop, and Thomas Stach. In addition, I would like to thank Matthias Koch, who introduced me to Blumenberg’s concept “actio per distans,” and to Jacob Watson for editing this article.

References

Bense, Max. 1960. *Programmierung des Schönen: Allgemeine Texttheorie und Textästhetik*. Baden-Baden: Agis-Verlag.

Bergson, Henri. 1908. “L’evolution creatrice.” https://archive.org/details/levolution creatr00berguoft.

Bergson, Henri. 1944. *Creative Evolution,* trans. Arthur Mitchell. New York: Modern Library.

Blumenberg, Hans. 1979. “The Concept of Reality and the Possibility of the Novel.” In *New Perspectives in German Literary Criticism*, ed. Richard E. Amacher and Victor Lange, trans. David Henry Wilson. Princeton, N.J.: Princeton University Press.

Blumenberg, Hans., and Anselm Haverkamp. 2010. *Theorie der Unbegrifflichkeit*. Frankfurt am Main: Suhrkamp.

Blumenberg, Hans., and Spencer Hawkins. 2015. *The Laughter of the Thracian Woman: A Protohistory of Theory*. New York: Bloomsbury Academic US.

Clough, R. W. 2004. “Early History of the Finite Element Method from the View Point of a Pioneer.” *International Journal for Numerical Methods in Engineering* 60:283–87.

Edwards, Paul N. 1997. *The Closed World: Computers and the Politics of Discourse in Cold War America*. Cambridge, Mass.: MIT Press.

Galison, Peter Louis. 2005. *Image and Logic: A Material Culture of Microphysics*. Chicago; London: University of Chicago Press.

Galison, Peter Louis. 2011. “Computer Simulations and the Trading Zone.” In *From*

Science to Computational Science, ed. Gabriele Gramelsberger, 118–57. Zürich: Diaphanes.

Gramelsberger, Gabriele. 2008. “The Epistemic Texture of Simulated Worlds.” In *Simulation: Presentation Technique and Cognitive Method,* ed. Andrea Gleiniger and Georg Vrachliotis. Basel-Boston-Berlin: Birkhäuser.

Gramelsberger, Gabriele. 2011. “From Science to Computational Sciences: A Science History and Philosophy Overview.” In *From Science to Computational Sciences,* 19–44. Zürich: Diaphanes.

Grüne-Yanoff, Till, und Paul Weirich. 2010. “The Philosohy and Epistemology of Simulation: A Review.” *Simulation and Gaming* 41, no. 1: 20–50.

Huss, Jessica C., Vanessa Schoeppler, David J. Merritt, Christine Best, Eric Maire, Jérôme Adrien, Oliver Spaeker, et al. 2017. “Climate-Dependent Heat-Triggered Opening Mechanism of Banksia Seed Pods.” *Advanced Science* 5, no. 1: https://doi.org/10.1002/advs.201700572.

Jany, Susanne, and Khashayar Razghandi. Forthcoming. “Filterarchitektur als Modell: Eine interdisziplinäre Auseinandersetzung mit dem Manteltier Oikopleura Dioca.” In *Typologie der Hütte*. Zürich: Diaphanes.

Montaña, Ricardo Cedeño, and Christina Vagt. 2018. “Constructing the Invisible—Computer Graphics and the End of Optical Media.” *Communication Plus 1* 7, no. 1: Article 2. https://doi.org/10.7275/ksgk-8x88.

Oreskes, Naomi, David Stainforth, and Leonard A. Smith. 2010. “Adaptation to Global Warming: Do Climate Models Tell Us What We Need to Know?” *Philosophy of Science* 77, no. 5: 1012–28.

Pias, Claus. 2011. “On the Epistemology of Computer Simulation.” *Zeitschrift für Medien- und Kulturforschung* 1:29–54.

Schrödinger, Erwin. 1992. What Is Life? Cambridge: Cambridge University Press.

Scripps Institute. 2019. “Zooplankton Guide.” June 28, 2019. https://scripps.ucsd.edu/zooplanktonguide/species/oikopleura-dioica.

Serres, Michel. 1978. “Exact and Human.” *SubStance* 6, no. 21: 9–19.

Weigel, Sigrid. 2006. “*Die innere Spannung im alpha-numerischen Code“ (Flusser): Buchstabe und Zahl in grammatologischer und wissenschaftsgeschichtlicher Perspektive*. Köln: W. König.

Winsberg, Eric. 2003. “Simulated Experiments: Methodology for a Virtual World.” *Philosophy of Science* 70:105–25.