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Interview with Ramin Golestanian: Living Matter, or What Is Life?

MF: Active matter is basically a relatively new area of research. I would like to begin with a question about the history of this research, since you have made an important contribution to this field yourself in your own research, and you have also reflected on it as the editor of a special issue on active matter [Golestanian and Ramaswamy 2013]. Against the background of your own discipline, physics, what questions and research objects do you associate with the beginning of active matter research? And what were the questions and objects that you started out with yourself in this area?

RG: The starting point, as I know it, was the application of statistical physics to the field of animal behavior [Vicsek et al. 1995; Toner and Tu 1995]. Animal behavior is a very active field in which scientists study the collective behavior of animals when responding to environmental changes, shortages of food, threats of predators, as well as other phenomena such as migration. While it is not surprising that animals, which have brains and the ability to process environmental signals, are capable of such behavior, it is remarkable, if you think about it, that even bacteria can exhibit such collective behavior [Wong et al. 2021]. Thus, very simple organisms or life forms can ‘decide’ or ‘decide together’ what to do as a whole in response to an external cue. This affects their mode of existence, and as a consequence, you can also observe changes on the large-scale level of behavior. Statistical physicists are very well equipped to deal with this kind of phenomena because the modeling of minimal many-body systems is pivotal in statistical physics. It provides us with descriptions on the microscopic scale of a system, and from there we can go through the different levels of coarse-graining and predict a large-scale behavior that is related to the interaction of microscopic elements. Historically statistical physics can be traced back to the work of James Clerk Maxwell, Ludwig Boltzmann, and others in the second half of the nineteenth century and at the turn of the twentieth century. They were already trying to understand how one could bridge the different scales and hence make one’s way from the statistical description of individual atoms and molecules at the microscale to thermodynamic behaviors on the macroscale. When studying a gas, we measure various macroscopic properties (such as pressure, volume, and temperature), which we can relate to the microscopic elements that we know make up the system. For example, the temperature in this room is related to the average kinetic energy of individual molecules – this is a fascinating insight. Because statistical physics is such a powerful tool it has made its way into many different

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fields over the years: into chemistry and chemical physics in the study of colloids, polymers, polymer solutions, and various forms of complex liquids and fluids [Jones 2002]; into biology with the study of DNA, proteins, and of the membranes of various biological components;¹ into the study of epidemic spreading [Bittihn et al. 2021]; and into economics (in a field called econophysics) to understand fluctuations in the market as well as economic changes at a global scale.²

Because statistical physics has ventured into so many different fields, it is natural that it has also found its way into the field of animal behavior. The first model that was proposed by a number of physicists was based on the flocking of birds [Vicsek et al. 1995; Toner and Tu 1995].³ These physicists basically studied flocking by assuming some sort of local interaction and developed a simple and appealing understanding of the seemingly complicated behavior of birds. In statistical physics, we tend to focus on simple models and try to develop a deep understanding of the phenomena that they entail. Thus, for some years, the focus was on pushing the models on animal flocking behavior further. The next turning point was the idea of synthetically or artificially making microscopic self-motile systems, hence self-propelled elements. Motility is one of the very visible aspects of life, which is why physicists have studied biological molecular motors in order to design synthetic molecular motors.

This was something I was very much excited about (and involved with) from the very beginning. We started with what I call ‘swimming’ because it is a free movement in a liquid environment. By looking at these self-propelled systems in water or solution, we were able to propose several models.⁴ These microswimmers essentially had to be nonequilibrium systems. Because of the small sizes of the elements in this model system, one has to worry about the laws of statistical physics and fluid dynamics, which in that environment is predominantly viscous. An important aspect is providing a source of energy. We know that biological molecular motors convert chemical energy directly into mechanical work – there are proteins that undergo conformational changes when they are catalyzed and break up the very energetic molecule called adenosine triphosphate into lower-energy components. It is the combination of enzymatic activity and mechanical work that gives rise to the very interesting behavior of these molecular motors. My fascination with molecular motors entered a new level during a workshop on this topic at the Isaac Newton Institute in Cambridge in March 2004. I remember that I bought a copy of the most authoritative book on the topic at the time by Jonathan Howard from a local bookstore in

¹ For the biophysics of the cell, see: [Boal 2002].

² The term ‘econophysics’ was coined by the statistical physicist H. Eugene Stanley from Boston University, who also wrote the first textbook on the new interdisciplinary field of econophysics [Mantegna and Stanley 1999].

³ For a report on recent approaches, see: [Cavagna, Giardina, and Grigera 2018].

⁴ On the first model systems, cf. [Najafi and Golestanian 2004; Golestanian and Ajdari 2008; Golestanian 2010]; for a review, see: [Elgeti, Winkler, and Gompper 2015].

Cambridge and read the introduction that included a very interesting statement: “[...] motor proteins are unusual machines that do what no man-made machines do – they convert chemical energy to mechanical energy directly, rather than via an intermediate such as heat or electrical energy” [Howard 2001, p. 1]. This immediately sparked an interest in me: can we take on this challenge and design a model system – the microswimmer – that could convert chemical energy directly to mechanical work [Golestanian, Liverpool, and Ajdari 2005]? There have been experimental realizations of our prototypical microswimmers which have proved that it is possible to build small-scale systems that behave like living systems [Leoni et al. 2009; Tierno et al. 2008; Grosjean et al. 2016]. Naturally, the nonequilibrium activity of the system physically changes the environment, and a mechanistic knowledge of this change will be important for understanding nonequilibrium interactions between different components. For example, if the system consumes a certain chemical fuel for its activity, it will act as a sink for this chemical, and that would have the long-range effect of depleting the chemical concerned. The local concentration of the fuel would be ‘sensed’ by the other chemicals involved, and this could provide a mechanism for the molecular model systems to communicate and then exhibit emergent traits [Soto and Golestanian 2014].

MF: Some of the model systems operate with sensors and signals, which they use to organize themselves, or which they use to develop collective behavior [Bäuerle et al. 2018] – was that the idea?

RG: It is very fascinating to study the collective effects in these systems, which are similar to what we could attribute to collective effects in microorganisms such as bacteria or in higher organisms such as birds. Microswimmers operate under the condition of consuming a certain chemical energy, which provides them with a flux for maintaining their nonequilibrium activity. They could then naturally communicate with others by means of the laws of the physical medium – for example, momentum conservation in the fluid will basically lead to hydrodynamic interactions,⁵ and the chemicals being depleted will create fluxes that will naturally be felt by everyone [Saha, Golestanian, and Ramaswamy 2014]. Coming back to your question, at the basis of my research is the question of what identifies living systems as *living* systems. What distinguishes them from synthetic systems, even if we can model a few attributes of life – mainly motility, operating in nonequilibrium conditions, sensing, and signaling – or construct these on the nano- or microscale? This can be compared with some developments in science in the nineteenth century. The botanist Robert Brown took an interest in minute moving particles suspended in water that he could observe under a microscope. With his careful experiments Brown

⁵ See the review on studies in synchronization driven by hydrodynamic interactions in: [Golestanian, Yeomans, and Uchida 2011].

could show that an inorganic form of matter such as dust particles would perform this kind of jittery motion in a fluid medium [Brown 1827]. Thus, being ‘alive’ is not a necessary requirement to exhibit some of the behaviors associated with living systems. Interestingly, understanding the Brownian motion was the starting point for molecular theories of matter, since it is the movement of the molecules that form the fluid which enables the motion of the inorganic particles.⁶ Even at thermal equilibrium, when there is basically no consumption of energy, matter is constantly moving due to fluctuations.

The study of active Brownian particles is part of the research on active matter [Gompper et al. 2020]. Our models provide a nonequilibrium analogue to Brownian motion, which was initially observed at equilibrium conditions. We use simple models to show that synthetic systems can behave similarly to living systems. Naturally, this does not mean that there is nothing special about living systems. In our approach, we would like to make living systems from the bottom up in order to find out more about the specificity of what constitutes life and where the boundaries of synthetic systems are – this is the goal of my new Department of Living Matter Physics at the Max Planck Institute for Dynamics and Self-Organization in Göttingen⁷ (see Figs. 1 and 2 for examples of recent research at the Department of Living Matter Physics).

KK: Motility, gradient sensing, signaling, and replication are traditionally seen as properties of living systems. If science is able to reproduce some of these life-related agencies in a synthetic system the result – at least at the moment – will still be a technical thing. Nevertheless, the concept of ‘living matter’ and the physical understanding of matter and material that comes with it is influencing our idea of life and subtly blurring the boundary between living and dead matter. I assume not all biologists approve of the physical description of life?

RG: Biologists have a very specific view on living systems, which regards all the details as important. Physicists tend to use abstraction and simplification, and subtract all the elements that are nonessential. It is natural for a biologist to look for differences because in biology the diversity of species is the fundamental law of life. The fact that species vary in space and time and that a small difference can often lead to a new species inspired Charles Darwin to his principle of natural selection, that is, the significance of variation for the survival of the species. Darwin noticed that the beak

⁶ These molecular movements could only be modeled with the help of statistical physics. At the beginning of the twentieth century, Albert Einstein was able to quantitatively predict Brownian motion, and Jean Perrin was able to experimentally prove these theoretical deductions [Einstein 1905].

⁷ At the time of the interview, Ramin Golestanian was on the point of leaving his post as professor of theoretical condensed matter physics at the University of Oxford to direct the Department of Living Matter Physics at the MPIDS in Göttingen. He subsequently built up the department in Göttingen and organized the research on living matter into the areas mechanical activity, information flow, and dense active matter (<https://www.ds.mpg.de/lmp>, accessed February 4, 2021).

Fig. 1: Particles of two types (red and green) interact with each other. Whereas particles of the same type necessarily experience reciprocal attraction or repulsion, particles of different types can interact nonreciprocally. Here the green particles chase after the red particles. At large scales, high-density bands of green particles chase after bands of red particles, leading to the emergence of global order and net motion in the system. From: [Golestanian 2020]. Image and description: © MPIDS / V. Novak, Saha, J. Agudo-Canalejo, R. Golestanian.

Fig. 2: Like pieces of a puzzle, the proteins (yellow) can fit together to form a complex. Only then are they functional and able to bind to the target molecules (red). The proteins diffuse faster as singlets and form complexes when they need to perform their function. Image and description: © MPIDS / V. Novak, J. Agudo-Canalejo & R. Golestanian.

of the Galapagos finches differed from island to island, and the ornithologist John Gould confirmed that these variations did not belong to one species but indicated that different species lived on adjacent islands.⁸

Biologists build their knowledge on observed differences and details. By contrast, physicists look for similarities in order to find some of the fundamental rules constraining all forms of life. These two approaches are complementary and can help each other immensely, provided there is adequate communication between the two communities. We can understand this better from a simple argument: if our quest to understand living systems can be regarded as a search in a very high-dimensional space of possibilities, then we can narrow down the possibilities – and make the task easier – if physics can tell us which constraints to include. For example, any creature living in the physical world should satisfy the physical conservation laws. Thus, when we are confronted with many different possibilities, we need to look for the subset of the configuration space that satisfies these physical constraints, and it is only physics that will provide that information.

KK: In the twentieth century, molecular biology wanted to decode DNA in order to understand the ‘program of life.’ This research and its attendant ideas have changed what we understand by ‘life.’ To put it simply, the genetic code stood for an abstract structure that informs and predetermines all concrete manifestations of life.⁹ Despite the necessary reduction that accompanies modeling in statistical physics, can one say that the environmental conditions of a living system, the constant exchange between this nonequilibrium system and its environment, and finally also the history of this system play a greater role in active matter research than in genetic biology?

RG: The genetic code needs to interact with the physical world in order to realize its information, and that interaction involves all kinds of things. Firstly, it involves the physical constraints that I talked about, namely the conservation laws. Secondly, there are differences in the environments that influence the system – this you can call the history. For example, a bacterium that lives on the surface of our tooth will develop differently than the same bacterium swimming happily in isolation in its planktonic state. In both cases, the bacterium is using its genetic information, but it is expressing different genes. And sometimes, the same genes change because they are influenced by the environment. What biologists would call the possible impact of the environment on the genetic code, I would call physics, because the creature

⁸ Charles Darwin noticed the differences, but it was only some years after his return to England and John Gould’s examination of the collected specimens that Darwin would understand the significance of variation for the survival of species. In the end, the collected Galapagos finches indeed led Darwin to his principle of divergence and to his famous *On the Origin of Species by Means of Natural Selection* (1859) [Sulloway 1982].

⁹ On the history and wide impact of this idea in the twentieth century (from the 1940s to the 1960s), see: [Kay 2000]; for a more recent gene-centric view of life, see: [Dawkins 1982].

that is made of this information is interacting with its physical world, and that interaction in turn will inevitably have consequences that are different in different circumstances. One also has to take into account the intrinsic stochasticity: if one repeats the same action over and over, one will encounter slightly different initial conditions and slightly different thermal fluctuations or local viscosity. The influence of these changes can escalate because the physical world includes turbulences, chaos, and the tendency to be sensitive to the environmental conditions and how they can unfold over time. It is not difficult to imagine that the genetic code of a living being can unfold in different ways and lead to different results. I would say that physics is able to explain this, whereas the traditional view of biology is not. However, the two fields will become complementary and will have to work hand in hand in order to predict what is basically the state of living matter. Active matter is a starting point for this very challenging task.

MF: In Gautam I. Menon's paper on active matter, the term 'code' does not appear [Menon 2010]. Therefore, I would like to ask, firstly, is that term even relevant? And, secondly, is what active matter actually proposes not in fact changing the definition of life? Instead of reducing life to some sort of genetic code, we might say that life is exactly this list of traits: motility, replication, gradient sensing, and signaling. Hence, can one argue that the choice to distinguish between inanimate and animate becomes dubious?

RG: The research on active matter reminds us in the first instance that we should be a bit more refined in our attempt to define life, because we now know that it will be possible to design synthetic systems that will do what living beings also do. The aim is to shed light on the question of how much of a certain behavior of a living being is simply physics. This could enable a clearer understanding of the specific features that are needed in order to have life, as well as of the features that, simply speaking, can be fabricated.

One can see similarities between active matter research and the history of flight. Humans have always wanted to fly; we have always watched birds with admiration, and there are many accounts of people who have attached artificial wings and jumped from towers – some even managed to fly. However, when we eventually succeeded in building flying machines, it was not by simply mimicking what a bird does, which involves very sophisticated flapping movements of the wings. In the end, all of that was irrelevant. What we really needed was to understand the laws of fluid dynamics, the Navier–Stokes equations (which were found in the nineteenth century), then the development of the science of buoyancy, lift force, and the implementation of this scientific knowledge through engineering. What really did it for us was coming to a fundamental understanding of fluid dynamics, and hence of the science that was behind the movements of the bird. And the field of active matter is trying to extend this scientific knowledge to the microscopic scale, from the scale of individual molecules to the level of organisms and colonies.

In addition to the question of the specific features that constitute life, there is another major question in biology that is yet to be answered and where active matter research could be really helpful, namely the question of the multiscale, hierarchical nature of organisms. We know that changing a small molecular feature can lead to systemic changes at the level of the whole organism, say from a healthy state to a metastatic cancerous state for example. This can be viewed as a question in statistical physics because it relates to a many-body system at the microscale with elements that communicate. We have to understand the phase diagram and the boundaries that correspond to phase transitions between different possible emergent states. Such a problem is not very different from superconductivity or magnetism or superfluidity. Take for example iron. Iron conducts electricity already at normal temperature, but when you cool it down to near absolute zero it becomes a superconductor, which is a state in which the electric current flows without resistance. How do you explain the changing properties of such a material? The interaction of elements – atoms and electrons – leads to phase transitions and to emergent properties. You can see similar effects in living systems, which can be understood using similar conceptual approaches.

KK: What part does nonequilibrium thermodynamics play in active matter research?

RG: The language of thermodynamics is only used for the macroscopic description of a system. Statistical physics is not a separate entity; it provides the formalism that bridges the different scales and takes us from individual molecules and atoms that are fluctuating to the macroscale and predicts their collective behavior in terms of some simple quantities that can be measured. Pressure, for example, is the average of all the kinetic kicks of the molecules bouncing off the wall. With statistical physics you learn how to average those random forces and calculate the pressure that the gas is exerting on the wall of its container. Thermodynamics describes the macroscale – it tells us that when we compress the system, the pressure rises, and when we expand the system the pressure falls. Statistical physics gives us the microscopic picture and explains why a certain behavior is observed at the macroscale, because with statistical physics we can directly trace the specific activity of the molecules that leads to the resulting macroscale behavior of interest.

Now at a fundamental level we can apply statistical physics for the description of systems under nonequilibrium conditions. We only need to define the specific conditions – for example, by defining a temperature gradient or other forms of nonequilibrium drive. While it may be the case that a complete description of all nonequilibrium systems in statistical physics is still not available, I believe the available knowledge has not been used to its full potential. For example turbulence is a part of nonequilibrium statistical physics about which a significant amount is known. If we want to understand the turbulent airflows around airplanes, or predict the weather, we have to apply nonequilibrium statistical physics, since we are predicting a stochastic process that involves the motion of a fluid, in this case the atmosphere. To understand living

systems, we also need to apply those tools, and that constitutes a program of research that has not reached its full potential.

In his 1944 (lectures and) book *What Is Life?*, Erwin Schrödinger asked how to explain the living cell with physics – and he admitted that the physical tools needed for this task were not yet sufficient [Schrödinger 1944]. This was before physicists had fully developed what we now call condensed matter physics, which is the application of statistical physics to understanding dense phases of matter. In these phases, the molecules are so close to one another that the interactions between them dominate their behavior. These interactions create complex emergent properties such as superconductivity, magnetism, and much else. Condensed matter physics predominantly flourished in the 1940s, 1950s, and 1960s, and it has continued to prosper until today [Kohn 1999]. It ventured into soft condensed matter and polymers already in the 1960s and 1970s in the work of Pierre-Gilles de Gennes and many others.¹⁰ Now we have a very strong toolbox, because we know that life is made of soft condensed matter, of polymers, lipids, proteins, and so on, and operates far away from equilibrium. Thus, I am very optimistic about what our field can now contribute to Schrödinger's question: what is life?

MF: You mentioned two turning points in the research on active matter. The first is about applying the tools of statistical physics to flocks of birds for example, or to schools of fish, in order to describe their behavior. This is what Tamás Vicsek and others are concerned with. The second turning point would be the self-propelled materials that we ourselves can produce. Can one say that the third turning point is instability considered from a mathematical point of view? What I mean by that is a consideration of the topological structures, defects, and singularities which emerge while dealing with active matter. As you note in one of your papers, in some of the systems of active matter, “because of the continuous input of energy, defects in [...] [these] systems can be formed in pairs and subsequently move apart giving rise to a steady state where topological defects are continually being created and destroyed” [Thampi, Golestanian, and Yeomans 2014, p. 1].

RG: This is a very interesting aspect of active matter. Structures such as singularities and topological defects have in fact been quite an important part of the studies of condensed matter physics in the twentieth century. Take for example the studies on phase transitions by David Thouless, Duncan Haldane, and Michael Kosterlitz. They received the Nobel Prize in 2016 for their description of topological phases of matter, hence when matter can assume strange states such as those found in superfluids or thin magnetic fields. They developed the idea that a very specific two-dimensional model of magnetism shows phase transition via the creation of pairs of defects [Kosterlitz and Thouless 1972; Kosterlitz and Thouless 1973; Haldane 1983a; Haldane

¹⁰ Pierre-Gilles de Gennes received the Nobel Prize in Physics in 1991 [De Gennes 1991].

1983b; Thouless et al. 1982]. These transitions happen because of thermal fluctuations – at some point the thermal energy provided to the system will be such that it can afford to create a pair of defects that would otherwise come together and be annihilated. If you maintain the system at that temperature, these defects will be constantly created and annihilated in an average equilibrium description. This was a very significant turning point, because the whole field of topological insulators was built on it.

In living systems, understood as active matter systems, it is not the thermal fluctuations that create these vortices and defects but the elements that feed energy at the small scale. A solution of bacteria will look like a turbulent system, and this is not because energy is injected from the larger scale and cascades down to the small scale, which is the traditional description of turbulence, but because the bacteria individually pump in energy and this energy cascades upward to the larger scale to create the collective effect. This is an important point, because you can inject energy via the element itself. Thus, there are subtle differences, but the description of living matter essentially follows a formulation that was already developed for liquid crystals, for elasticity, turbulence, and superfluidity. It is very appealing to be able to build a mathematical formulation to describe the key properties of matter effectively in terms of defects and topological singularities [Thampi, Golestanian, and Yeomans 2015].¹¹

I would say that the important turning point for active matter research was to see that nonequilibrium activity in the form of individual agents bringing in energy could basically excite modes in the system which would otherwise be excited from the outside by injecting energy or having a heat bath to provide the energy. That was the new insight, and it continues to be fruitful in the field of active matter.

KK: Going beyond the topological description of instability, what significance has the aspect of instability for the research on active matter?

RG: For me instabilities have always been very fascinating, because the physical account of the microscopic world, for example the interior of a living cell, describes a very thick, very viscous, very slow environment. There is this quantity called the Reynolds number that tells you in relation to your scale how viscous the environment is felt to be. If the objects are small, they move around in the fluid and they feel the environment as if they were larger objects moving in a much more viscous environment. For us the experience of moving in honey would essentially be the equivalent of how a bacterium feels when it moves in water: it is constantly battling with the environment and the viscous, thick, and sticky nature of it, which slows it down all the time. If we need to move quickly in this kind of environment, how

¹¹ For a more recent modeling of living system properties by means of topology, see: [Tang, Agudo-Canalejo, and Golestanian 2021].

would we do it? On our length scale, we are used to Isaac Newton's first law of motion and force, which is primarily about a system with a certain momentum that will keep going at the same velocity. But a small influence can modify its course, and in a stickier environment, we would have to inject energy to keep the system going. To change the course of motion, we would need to inject even more energy. This is not a very efficient way to instigate change in a system. Living systems have found efficient solutions to this problem that are mostly built around instabilities that are bound to happen but are kept under control, that is, within a small margin of parameters that prevent the instabilities from becoming pervasive. In such a situation, we would only need a small trigger to push a controlled instability across a threshold, at which point it can get completely out of control. Hence, this mechanism can instigate a large change by bringing a small perturbation into the system. Living systems exploit this mechanism widely, since they operate near these instability thresholds. I have studied the properties of living systems many times and used these properties as an inspiration for synthetic systems because they are an incredibly efficient way to enable switches between different traits and behaviors. Instabilities are going to be extremely important in active matter research, since we see them everywhere in the living environment.

MF: I would like to focus on the changes which active matter research is introducing into the natural sciences. It seems that there is an incredible emphasis on modeling with numerical simulations.

RG: The field of active matter is essentially a subfield of condensed matter physics. It arose in the 1990s out of a theoretical impetus, and for some time the theory has been a little more advanced than the experiments. Over the last few years, however, a lot more work has been done on the latter, and these are catching up [Sanchez et al. 2012; Bricard et al. 2013]. The introduction of experiments on synthetic systems has been an important step because it has become possible to compare the results and the theories. Ultimately any field of condensed matter physics – electronic properties, semiconductors, magnetism, insulators, topological insulators – will predict something theoretically and try to realize it experimentally by taking experimental measurements. Only when both parts coincide can the scientific object be said to be clear and understood.

MF: How would you describe your evolution over the last 10 to 15 years in the field of active matter? I suppose it is hard to compare your views 15 years ago with your views today, but how do you consider the changes in the field itself? And how has the field changed with respect to both the academic institutions and the funding institutions?

RG: The biggest change for me personally has been the transition from the scattered activity of seemingly independent fields with a very low profile to this new situation. Fifteen years ago, when I was working in the field of active matter, I was interested in

very simple and very limited questions. I was not thinking about life and how it could be explained with respect to active matter. This kind of ambition comes only after one dares to take one step and then, depending on the outcome, perhaps another step. When there is a consistency in what you see, you develop more courage. The first time I talked about living matter was in 2013 when I was asked to give a public lecture to the alumni of the University of Oxford.¹² I described the physical view on living systems, my understanding of the historical developments, and how we might be able to explain more in the future. In the last 4 or 5 years, I have followed the perspective that I proposed in this lecture. Unfortunately, the resources I had in the UK were limited, and several of my proposals for funding were not successful. The situation has changed – now I can see scraps of those initial ideas coming out in different places. On the whole, I would say that things went in the right direction.

From an institutional perspective, I would say that active matter research has always been an interdisciplinary field. It grows out of physics but also aims to address other disciplines, and as such, it has some intrinsic difficulties. Any interdisciplinary field will have an identity problem – are you a physicist, or a biologist? And there is also the question of approval or acceptance – are the science departments hiring people in this field? I think physics as a community views active matter research in a particular way, since physicists can see that this field has been growing and now plays a major role in the American Physical Society. There are now many conferences and sessions on active matter, and clearly there is a large influence.

Biologists certainly view the research on active matter or living matter with skepticism, since they do not think it is biology. And they are right – the aim of this field is not to explain or replace biology but to provide new information. Active matter research could answer some of their questions which are related to physical principles. It could spare them energy and resources. Eventually, in 10 years, this will feed into biology, but at the moment it may not be viewed that way.

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¹² The podcast is still available [Golestanian 2013].

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