https://doi.org/10.53656/phil2026-02-05

Philosophy and Modernity
Философия и съвременност

EPISTEMIC STIGMERGY: NATURAL VS. ARTIFICIAL INTELLIGENCE

Rosen Lutskanov
Sofia University "St. Kliment Ohridski"

Abstract. The article[1] defends the thesis that intelligent behavior might require not internal complexity but complex interaction. This is demonstrated by the various forms of stigmergy that can be observed both in social insects and in humans. The exposition is structured as follows: (§0) explains how the term "intelligence" is interpreted in the following text; (§1) clarifies the relation between intelligence and complexity; (§2) shows that intelligent behavior does not require internal complexity; (§3) introduces the concept of stigmergy; (§4) presents the mechanisms that give rise to this phenomenon; (§5) distinguishes several types of stigmergic interaction; (§6) briefly discusses the evolutionary mechanisms that could have produced them; (§7) sketches the possible ways in which the concept of stigmergy is used outside biology; (§8) examines collaborative stigmergy in humans; (§9) points to its epistemic projections; (§10) outlines some conclusions concerning the role of artificial intelligence systems and their place in human society.

Keywords: stigmergy; artificial intelligence; multiagent systems

§0. The field of artificial intelligence (AI) suffers from a typical case of embarrassment of riches: no unambiguous understanding of intelligence can be located in the various publications treating this subject. On the one hand, the way this term was defined originally (in the famous proposal for "a summer research project on artificial intelligence", submitted in 1955 by John McCarthy to the Rockefeller Foundation) is revered to this day: "the artificial intelligence problem is taken to be that of making a machine behave in ways that would be called intelligent if a human were so behaving" (Nilsson, 2010, p. 53). Obviously the "definition" is incomplete, so it is appended later in the same text: "An attempt will be made to find how to make machines use language, form abstractions and concepts, solve kinds of problems now reserved for humans, and improve themselves" (ibid). In the above definition intelligence in general is clearly identified with human intelligence, taken to be exemplified in the accomplishment of a more or less clearly delineated range of tasks, involving some form of understanding. On the other hand, the scope of the field was extended significantly in the following years. For this reason the working definition that I intend to use in this paper runs is much more general: “Intelligence measures an agent’s ability to achieve goals in a wide range of environments” (Legg & Hutter, 2007). Obviously, the key difference between the classical definition and the newer one is the disappearance of the human, taken as setting the paradigm of intelligence. I think that this is a virtue. But this also raises a problem that needs to be addressed.

§1. The problem is that the definition is too general. It is not the case that the achievement of any goal in any possible way is a symptom of intelligence. The more complex is the problem to be solved and the less extensive are the resources that are employed in order to solve it, the more intelligent is the procedure. In other words, less is more. Take a famous example: the eight queen problem (the goal is to place eight queens on a chessboard so that no two of them attack each other). Here the problem is complex, as anyone shall find out soon after trying it. Moreover, there are less intelligent ways to solve it (the brute force search that goes through each possible arrangement until it finds the solution), and more intelligent ways to solve it (by using heuristics that eliminate significant number of possible candidates). Realizing this we encounter a puzzling fact: the systems that are presently considered as the pinnacle of human technology are obviously not intelligent in the sense discussed above. Take for example the most popular large language model GPT-5. It performs lots of complex tasks, but the price to be paid for this is significant: the model is mindbogglingly complex (hence, not really intelligent in the sense discussed above). It is impossible to say how complex (because its number of parameters is a well kept trade secret). Still, taking into account its mixture of experts (MoE) architecture we can make an educated guess – its number of parameters might be about 50 trillion (thirty times more than the previous version). If we also take into account its training (comprising hundreds of billions of words and more – the model is multi-modal), and the number of graphic processors used (probably about 25 000 in a period of several months), we can see that “large language model” is actually a gross understatement.

§2. The previous paragraph displays the development of AI systems as an arms race where brute force is of paramount importance. We are either going to follow the same strategy, or we should step back and reconsider our approach. I think that important insights can be gathered if we take into account the obvious fact that intelligent behavior (effective achievement of goals in diverse environments) is observed not only in humans, but also in other biological entities, much simpler than us (and definitely simpler than GPT-5). I will mention only three examples (in chronological order): (1) In 2004, the book *Ant Colony Optimization* was published, showing that ant colonies can be regarded as computational devices that solve various mathematical problems, in particular the famous traveling salesman problem. What is crucial here is that this is achieved not thanks to the capabilities of individual ants, but because of the way in which they interact with one another

(Dorigo & Stützle, 2004, pp. 33 – 41). More specifically, each ant explores the area in search of food, but which path it takes depends on the pheromone trails left by other ants. The more salient the trail, the more ants have passed recently along that path (hence the more "interesting" the corresponding destination seems). As a result, it turns out that the closer a food source is, the more ants take that path (because it takes them less time to go there and back, hence the trail does not fade). Initially, the movements of the ants are chaotic, but gradually they become increasingly goal-directed; (2) A team from Hokkaido University managed to construct an optimal plan of the railway network covering the Tokyo metropolitan area using … slime mold. To this end, a scaled model was built in which piles of oat flakes corresponding to the individual destinations were placed, after which the environment was "inoculated" with slime mold. In order to survive, it has to discover the shortest possible path that connects the food sources, and it does so quite successfully (Tero et al., 2010); (3) Analogous successes have been achieved with the help of amoebae, which must find an efficient way to traverse spatially distant food sources. Clearly, as in the previous two cases, they are faced with a typical optimization problem whose difficulty stems from the fact that as *N* (the number of nodes in the relevant graph representing possible destinations) increases, the number of possible paths grows exponentially, and there exists no algorithm capable of solving it quickly for large values of *N*. It turns out that amoebae are in no way inferior to ants and slime molds in solving complex problems like these (Zhu et al., 2018). In my opinion, these examples show that intelligent behavior can be achieved at the cost of minimal internal complexity: neither slime molds nor amoebae have a brain (and the nervous system of an individual ant is not particularly complex), yet this does not prevent them from performing remarkable feats. In view of this, I shall defend the following thesis: internal complexity can be traded for social complexity. A great number of interacting agents are able to solve complex tasks in intelligent ways, if they evolve and adapt in a natural setting, hence learn to use the environment as an information processing medium. We train our models, but no one has trained the ants, the slime mold, or the amoebas.

§3. The following pages shall discuss an important term, introduced within biology around the middle of the last century, because it captures a crucial insight. The term "sigmergy" (from *stigma* – mark, and *ergon* – work) encapsulates a whole theory about the origins of intelligence in the natural world. It was coined by the French zoologist Pierre-Paul Grassé, who investigated a puzzling question related to the behavior of social insects – ants, termites, bees, and wasps. It is easy to formulate the problem very briefly: how do such large numbers of so simple creatures manage to accomplish such mindbogglingly complex things? More specifically, how do termites construct intricate structures with remarkable structural properties, given that an individual termite is not particularly intelligent, nor does it possess any knowledge of architecture or engineering? (The number of neurons in termites varies across species and also according to the role performed by the individual, but it appears not to exceed 100,000.) Regarding this Grassé notes that "the coordination and regulation of building activities do not depend on the workers themselves but are mainly achieved by the nest structure: A stimulating configuration triggers a building action of a termite worker, transforming the configuration into another configuration that may trigger in turn another (possibly different) action performed by the same termite or any other worker in the colony" (Theraulaz & Bonabeau, 1999, p. 102). Here is an example: The construction of the colony proceeds through the erection of individual "pillars". In the course of this process the pheromones left by a previous termite stimulate the next one to deposit building material at the same location. When the pillars become sufficiently tall, the pheromones deposited on one pillar can already be detected from a neighboring one; this causes the termites to bend the pillars toward one another, ultimately leading to the formation of an arch. By this utterly simple mechanism, which does not presuppose planning or computational processing enormous colonies are built and expanded.

§4. The earliest theories explaining the feats of social insects assume that what is at play here is some form of emergence: just as a biological organism is something more than a mere aggregate of cells (because it can do things that individual cells cannot), so too a social organism (a human society or an ant colony) can do things that are beyond the reach of its individual members. In his typical manner, Hofstadter presents (and perhaps ridicules) this way of thinking in the legendary book *Gödel, Escher, Bach*, using the story of the anteater and the thinking ant colony Aunt Hillary (Hofstadter, 1979; see the section "… Ant Fugue" in Chapter X). Within entomology, the organismic approach was codified by William Morton Wheeler, according to whom "An organism is a complex, definitely coordinated and therefore individualized system of activities, which are primarily directed to obtaining and assimilating substances from an environment, to producing other systems, known as offspring, and to protecting the system itself and usually also its offspring from dangers emanating from the environment"; accordingly, "we can only regard the organismal character of a colony as a whole, as an expression of the fact that it is not equivalent to the sum of its individuals but that it represents a different and at present inexplicable emergent level" (Theraulaz & Bonabeau, 1999, p. 98). What the current theoretical status of this conception is within present-day biology is difficult to say. According to the reconstruction I adopt here, one may claim that by the mid-1950s the idea of the ant colony as a "supraorganism" was being treated as an extremely loose analogy, one that might be motivated by the fact that it directs our attention to certain questions (for example, what is the unit of evolutionary selection to which we ascribe some degree of adaptation: the individual ant or the colony as a whole), although it is of course not taken literally. Etienne Rabaud, for example, approaches "holistic explanations" with suspicion, treating them as barren metaphysical speculations (Theraulaz & Bonabeau, 1999, p. 99).

In order to show that we can do without them, he introduces two key terms: (1) *interaction*, which refers to the fact that the actions of one individual influence the behavior of the others; and (2) *interattraction*, by which is meant that "any animal that belongs to a social species is attracted in a specific way by any other animal that belongs to the same species" (Theraulaz & Bonabeau, 1999, p. 100). The idea of stigmergy is based on the combination of these two principles and rests on the understanding that "[s]ocial groups are above all characterized by the fact that any individual taken separately produces a specific stimulus upon its fellows, while the group produces in turn a specific stimulus that will influence the behavior of that animal" (Theraulaz & Bonabeau, 1999, p. 100). Indeed, when we speak of *swarm intelligence*, of the intelligent behavior of social insects treated as a paradigm in some sub-fields of artificial intelligence theory, we primarily have in mind effects due to some stigmergic mechanism that generates coordinated action (Bonabeau et al., 1999, p. 205).

§5. The initial definition of the concept of stigmergy was later developed in many ways and with a view to quite different applications. I personally prefer the following modification, which captures all the significant nuances of the concept under discussion: "stigmergy is an indirect, mediated mechanism of coordination between actions, in which the trace of an action left on a medium stimulates the performance of a subsequent action" (Heylighen, 2016a, p. 6). The key point here is that by "medium" we do not mean simply that portion of the material world with which an organism interacts, because different organisms are influenced by different features of the world. Thus, "When we consider stigmergic coordination between different agents, we need to define the medium as that part of the world that is controllable and perceivable by all of them" (Heylighen, 2016a, p. 7). Moreover, when we speak of a "trace" rather than a "mark," we draw attention to the fact that in this case it may be an "an unplanned or even undesired side effect of the action" (Heylighen, 2016a, p. 8). In any case, what is crucial is not so much what the definition includes as what it excludes, declaring it superfluous from the standpoint of explaining the relevant outcome: when we speak of stigmergy, we do not presuppose the presence of "planning or anticipation, memory, communication, mutual awareness, simultaneous presence, imposed sequence, imposed division of labor, commitment, centralized control or supervision" (Heylighen, 2016a, p. 10). It is precisely this fact that makes stigmergy interesting: it suggests that probably the secret of intelligence is that there is no secret, no computationally intensive trick that gets the work done (of course, Marvin Minsky has already claimed this, cf. Minsky, 1986, p. 308). Moreover, the specific mechanisms through which interactions between individual organisms regulate collective activities may differ: "there is no trick" means "there is no *single* trick". We can, for example, distinguish *qualitative stigmergy* (in which organisms are influenced by qualitatively different stimuli – such as the dances of bees) and *quantitative stigmergy* (in which organisms are influenced by quantitatively different stimuli – such as the gradient in the concentration of pheromone trails in termites) (Theraulaz & Bonabeau, 1999, p. 104). Correspondingly, stigmergy itself manifests in different ways, already described by Grassé: by impact on (1) the choice of action ("qualitative effect") and (2) on the location, intensity, frequency, and duration of the action ("quantitative effect"). What is essential is that in both cases the external environment participates in an irreducible way in the coordination of individual activities, which in turn modify it: "The colony records its activity in part in the physical environment and uses this record to organize collective behavior" (Theraulaz & Bonabeau, 1999, p. 111). Another distinction worth introducing is based on whether the traces that function as instruments of stigmergic coordination are persistent or transient (bearing in mind that these are relative rather than absolute determinations). Persistent traces create conditions for *asynchronous stigmergy*, where the agents whose behavior is being coordinated need not be present at the same place at the same time, whereas transient traces give rise to *synchronous stigmergy*, whose possibility presupposes the simultaneous presence of the agents (Heylighen, 2016b, p. 53).

§6. An interesting question, to which I am unable here to devote the necessary attention, concerns how this type of coordination evolved in the first place. Grassé proposed a hypothesis: according to him, in insects there are two ways of generating complex actions composed of several steps. The first is observed in solitary species, in which "the execution of the first movement in a sequence sets some internal state that then, often in conjunction with some appropriate external cue, initiates the second movement, and so on" In the second case, which is observed both in solitary and in social species, "there is no such internal state; the external cue alone is sufficient" (Holland & Melhuish, 1999, p. 176). A primitive form of stigmergy, in which an individual coordinates its actions through the traces it leaves in the material environment, has been observed, for example, in some solitary species of wasps (of the genus *Paralastor*). They build their nests in this way, which suggests that "collaborative stigmergy evolved from the simpler case of individual stigmergy" (Heylighen, 2016b, p. 51). This process is interesting insofar as it implies that the exteriorization of some form of cognitive labor (such as that required for the execution of composite actions) is an effective adaptive mechanism – one that insects, just like us, have managed to stumble upon in the course of their evolutionary history. As we shall see, a significant number of authors claim that we have done (and continue to do) the same: we delegate part of our cognitive labor to the external environment, which allows us to share it among ourselves. In this sense, swarm intelligence manifests itself in humans as well: from web-based encyclopedias to automated recommendation systems and tagging practices, we make use of the traces we leave in real and online environments to realize large-scale forms of cooperation (or division of cognitive labor) that otherwise would be impossible.

§7. Up to this point we have spoken exclusively about social insects, mostly ants and termites. It is obvious that if the concept of stigmergy had remained confined to the field of entomology, this article would not have been written. As the reader may surmise, it gradually moved into a broader context, which made it philosophically relevant. This happened around 1990, when some representatives of the Brussels School, founded by Ilya Prigogine (in particular Jean-Louis Deneubourg), realized that "stigmergy was a prime example of spontaneous ordering or self-organization and as such potentially applicable to complex systems other than insect societies" (Heylighen, 2016a, p. 5). Presently, the idea of stigmergy already resonates in a metaphysical register, as it is extended to virtually every aspect of the human world: "stock markets, economies, traffic patterns, supply logistics and resource allocation", even "urban sprawl and cultural memes" (Marsh & Onof, 2008, p. 147). It is easy to see why stigmergy looms large in this context. One of the earliest texts to take this path makes the point quite unequivocally: since agents interact with the environment locally, and only a limited set of its aspects influences their behavior, an increase in the size of the group, and hence in its complexity, does not require individual members to increase their information-processing capacity (Van Dyke Parunak, 2006, p. 163). The expansion of the domain where stigmergy was searched and found led to the development of computer applications that testify to its heuristic power. The first algorithm of this type is the legendary "ant colony" system mentioned above – it performs quite well in comparison with other standard algorithms, such as simulated annealing, evolutionary computation, and tabu search (Dorigo et al., 2000, pp. 855 – 856). One might object that something is lost when we replace the material world and the traces left within it with a virtual environment of far lower complexity (an objection I personally fully accept). Bearing this in mind, I would point out that the possibilities for creating robots that operate stigmergically in real environments have already been explored (Korb, 2014, p. 742). In addition, presently we have models that suggest that the human visual system may be based on some form of stigmergic mechanism (Correia et al., 2017, pp. 82, 85). Although this seems quite speculative, individual neurons and the ions they release (upon reaching an action potential) can be viewed by analogy with ants and termites and the pheromones they emit (or with piles of oat flakes and the molds spreading among them): here the map is the neural network itself (Xu et al., 2019, p. 54414).

§8. We began with termites and ants, then moved on to robots and algorithms, now we finally arrive to humans and their thinking. In the contemporary history of philosophy there are already authors who claim that "our mental capabilities can be seen as an interiorization of what were initially stigmergic interactions with the environment" (Heylighen, 2016b, p. 54). In particular, it is extremely easy to relate the idea of stigmergy to Andy Clark's approach, which emphasizes the distributed nature of knowledge and cognition; and the environmental appropriation whereby cognitive processes extend into the world" (Marsh & Onof, 2008, p. 142). The examples on which Clark relies are borrowed from other authors associated with the paradigm of situated/distributed cognition. Edwin Hutchins, for example, describes the activity of yacht crews, who function effectively precisely because the actions of each member affect the behavior of the whole crew in ways determined by structural constraints (Clark, 1997, pp. 76 – 77). Of course, a certain effort is required to reduce this example to the ones discussed above: we need to recognize that the living environment of ants and termites is not a pre-given world they find already in place – it evolves along with them. Yachts, as artifacts, illustrate this cyclic dynamics in an especially vivid way: what is done on a yacht and what the yacht is are questions whose answers presuppose one another. In any case, the significance of stigmergy for social regulation has long been established (Theraulaz & Bonabeau, 1999, p. 101). More recently, attempts have been made to show that this mechanism can help us overcome certain well-known and seemingly intractable puzzles concerning the relationship between the actions of an individual – driven by personal interests and by his limited understanding of the overall picture – and the common good: examples include the tragedy of the commons and prisoner's dilemma (see Bovens, p. 2015, where their connection is discussed). When a single ant participates in building, it is hardly motivated by altruistic concerns about what is beneficial for the collective, due to the obvious fact that its cognitive system does not allow for such a feat of abstraction. Still it acts, relying on the information available to it. Similarly, an individual can participate in collective action by relying on the traces that others leave in their shared environment. Whether it can be claimed that "[m]ost forms of human cooperation have this stigmergic dimension, where actions are triggered by the observable results of other people's actions rather than by direct requests or commands" (Heylighen, 2016b, pp. 56 – 57) is a wholly separate question.

§9. Before concluding, I will note one more aspect which, in my view, highlights precisely the epistemic import of stigmergy: the fact that it can serve not only to coordinate certain types of action in the material world, but also to distribute cognitive labor within science. Its importance has already been discussed in other texts (Dogramaci & Horowitz, 2016, p. 136) and stems from the obvious fact that no single scientist, taken in isolation from others, can master all theories, conduct all experiments, learn all measurement techniques, and gather all the data required to resolve a complex problem (Dellsén, 2025, p. 290). At one time this may have been possible, but today typically it is not. As is well known, the paper reporting the experimental confirmation of the existence of the Higgs boson has more than 5,000 authors, and the number of participants in the research is at least twice as large. Here we have a genuine ant colony, albeit spread across several continents. Within it, each participant carries out a narrowly specialized and probably to some extent "craft-like" activity, while it is the group as a whole that achieved one of the most significant discoveries of our time. In this process, the role of the environment in which these scientists communicate and leave behind digital and material "traces" is easy to discern: it is no coincidence that the World Wide Web was created precisely for the needs of CERN.

§10. In light of what has been said, we can take a step back and return to the point made at the outset. Thinking is an instrument that serves collective action (Mercier & Sperber, 2011). Accordingly, we should not expect its paradigmatic manifestations to be observable in isolation (just think about the things a single human can achieve, if he is completely deprived of the cultural scaffolding and the material infrastructure of present-day human societies). The analogy with ant colonies can help us realize this basic fact. It is not ants that think, but ant colonies. In this sense, Putnam was both right and wrong. He is right that a single ant wandering across the sand cannot draw a caricature of Winston Churchill. What it does makes no sense, because it does not mean anything (Putnam, 1981, pp. 1 – 2). The ant colony, however, is capable of heroic deeds – for example, to solve optimization problems (even though caricatures still do not appear to be a typical component of ant culture). Accordingly, the visible differences between humans and ants should not be overestimated. A large part of our actions and the beliefs associated with them are pre-reflective and realized by low-level mechanisms, just like those of our biological "relatives" (Angelova-Elchinova, 2024, p. 126). We have spent a lot of time discussing one of them: stigmergy, which is operative in each case when an ant colony builds, or a group of scientists performs an experiment. From this an obvious conclusion seems to follow: artificial intelligence is possible, but not in the way we were trying to create it (building complex models and feeding them with ready-made products of human intelligence in a digital environment). If we expect algorithms to manifest human-like intelligence we should let them act and interact in our world. Distributed architectures like the MoE are steps in the right direction since they reduce internal complexity by means of encapsulation and modularity. They won't be enough though, because the environment they live in is virtual. Instead of interfaces that let the virtual world mirror processes in the actual world, we need stygmergically interacting robots that extend their processing capacity by transferring it to the environment. Algorithms increasingly participate in social interactions among humans, especially in online environments (Bassanetti, 2023). If they bridge the gap and move on to the actual world they shall become a part of the human colony. We shall think and act in cooperation. Intelligence is a shared feature that resides among us in the natural world. It was never meant to be artificial.

NOTES

1. The author would like to express his gratitude to the anonymous reviewers. Some of their critical comments led to substantial additions and revisions in different parts of the text.

Acknowledgements and Funding

The financial support from of the National Science Fund under the project "Virtual Reality Research Centre at Faculty of Philosophy, South-West University "Neofit Rilski", КП-06-Н80/3 is gratefully acknowledged.

REFERENCES

Angelova-Elchinova, M. (2024). Norms of belief and non-propositional primal beliefs. *Balkan Journal of Philosophy, 16*(2), 117 – 130.

Bassanetti, Th. et al. (2023). Cooperation and deception through stigmergic interactions in human groups. *Proceedings of the National Academy of Sciences, 120*(42), e2307880120.

Bonabeau, E. et al. (1999). *Swarm Intelligence: From Natural to Artificial Systems*. Oxford University Press.

Bovens, L. (2015). The tragedy of the commons as a voting game. In: M. Peterson (Ed.) *The Prisoner's Dilemma* (pp. 156 – 176). Cambridge University Press.

Clark, A. (1997). *Being There: Putting Brain, Body, and World Together Again*. MIT Press.

Correia, L. et al. (2017). On the role of stigmergy in cognition. *Progress in Artificial Intelligence, 6*, 79 – 86.

Dellsén, F. (2025). Disagreement and consensus in science. In: M. Baghramian et al. (Eds.) *The Routledge Handbook of Philosophy of Disagreement* (pp. 286 – 296). Routledge.

Dogramaci, S., & Horowitz, S. (2016). An argument for uniqueness about evidential support, *Philosophical Issues, 25*, 130 – 147.

Dorigo, M., & Stützle, T. (2004). *Ant Colony Optimization*. MIT Press.

Dorigo, M. et al. (2000). Ant algorithms and stigmergy. *Future Generation Computer Systems, 16*, 851 – 871.

Heylighen, R. (2016a). Stigmergy as a universal coordination mechanism I: definition and components. *Cognitive systems research*, *38*, 4 – 13.

Heylighen, F. (2016b). Stigmergy as a universal coordination mechanism II: varieties and evolution. *Cognitive Systems Research, 38*, 50 – 59.

Hofstadter, D. (1979). *Gödel, Escher, Bach: an Eternal Golden Braid*. Basic Books.

Holland, O., & Melhuish, C. (1999). Stigmergy, self-organization, and sorting in collective robotics. *Artificial Life, 5*(2), 173 – 202.

Korb, J. (2014). Robots acting locally and building globally. *Science, 343*, 742.

Legg, S. & Hutter, M. (2007). A collection of definitions of intelligence. *Advances in Artificial General Intelligence: Concepts, Architectures, and Algorithms*, 17 – 24.

Liping, Zh. et al. (2018). Remarkable problem-solving ability of unicellular amoeboid organism and its mechanism. *Royal Society Open Science, 5*(12), 180396.

Marsh, L., & Onof, C. (2008). Stigmergic epistemology, stigmergic cognition. *Cognitive Systems Research, 9*(1 – 2), 136 – 149.

Mercier, H. & Sperber, D. (2011). Why do humans reason? Arguments for an argumentative theory. *Behavioral and Brain Sciences, 34*, 57 – 111.

Minsky, M. (1986). *The Society of Mind*. Simon and Schuster.

Nilsson, N. (2010). *The Quest of Artificial Intelligence. A history of ideas and achievements*. Cambridge University Press.

Putnam, H. (1981). Brains in a vat. In: *Reason, Truth and History* (pp. 1 – 21). Cambridge University Press.

Tero, S. et al. (2010). Rules for Biologically Inspired Adaptive Network Design. *Science, 327*, 439.

Theraulaz, G., & Bonabeau, E. (1999). A brief history of stigmergy. *Artificial Life, 5*(2), 97 – 116.

Van Dyke Parunak, H. (2006). A survey of environments and mechanisms for human-human stigmergy. In: Weyns, D. et al (Eds.) *Environments for Multi-agent systems II* (pp. 163 – 186). Springer.

Xu, X. et al. (2019). Brain-inspired stigmergy learning. *IEEE Access, 7*, 54410 – 54424.

✉ **Dr. Rosen Lutskanov, Assoc. Prof.**
ORCID iD: 0000-0003-4874-2698
Sofia University "St. Kliment Ohridski"
1000 Sofia, Bulgaria
E-mail: R.Lutskanov@phls.uni-sofia.bg