Mobile Networks and Applications (2023) 28:486–489
https://doi.org/10.1007/s11036-022-02066-7

Editorial: Renaissance of Biomimicry Computing

William A. Casey[1] · Yang Cai[2]

Published online: 14 December 2022

Nature is an ultimate inspiring source of imagination and innovation. Mathematical models of biological phenomena can be traced back to the 13th century when Fibonacci described a growing population of rabbits with his famous Fibonacci Series. Disease outbreak was modeled mathematically in the 18th century by D. Bernoulli. In 1836, Pierre Francois Verhulst formulated the logistic growth model that became a building block of modern system dynamics and machine learning algorithms. In the 1950s, the pioneers of modern Computer Science Alan Turing and John von Neumann not only developed their one-dimensional computing machine models but also discovered two-dimensional cellular automata, which explain distributed textural patterns and self-reproduction in nature [1,2,6]. In collaborating with neuroscientists and engineers in the 1960s, Norbert Wiener developed mathematical models for feedback control, nervous oscillation movements, self-reproduction, learning, and even Gestalt phenomena which he called "Cybernetics" [3].

Furthermore, pioneers of Artificial Intelligence Marvin Minsky and others developed neural networks "Perceptrons" to simulate perception and cognition processes, which is the milestone of today's Deep Learning algorithms [4]. Still, other investigators such as David Marr extended theoretical neural models to account for visual processing tasks enabling advances in visual processing algorithms [18]. Throughout history, the challenges of observing biological phenomena and capturing salient dynamics within mathematical models endured as a wellspring of advances. From the same source, biomimicry computing has evolved from mathematical descriptions to systems engineering models, up to executable, large-scale computer algorithms.

As Norbert Wiener discovered: "It is these boundary regions of science which offer the richest opportunities to the qualified investigator." The two-way interactions between biology and computing have led to the scientific revolution. Claude Shannon leveraged a mathematical abstraction for genetic materials where its relation to engineered circuitry can position communication theory within its most profound and unifying frame of view. His thesis "An Algebra for Theoretical Genetics" was published in 1939 [11], which was twenty years before the DNA molecule structures were discovered. The theory and subject of codes, signals, and meaning were entwined with advances in both communication technology as well as computing devices.

For decades, biologically-inspired computing has been a vital branch of the Artificial Intelligence family, for example, Ant Colony Optimization, Swarm Intelligence, and Genetic Algorithms. The biomimicry algorithms have been integrated into broader engineered complex systems such as designing satellite antennas and space mobile robots that walk and climb over rough terrain without a world model, or traditional planning or reasoning. Rodney Brooks referred to this as Behavior-Based Robotics [14], in which there is no standalone cognition *per se*. Instead, there are simply fast, cheap, and out-of-control perception and actuation components. The same design philosophy has been implemented in home cleaning robots. Also, Artificial Immune algorithms have been developed to detect computer viruses and prevent adversary events. The algorithms mimic natural defense systems to screen invaders and manufacture proper tools on the fly to neutralize attacks or vulnerabilities [15].

Emerging theories of computation biomimicry aim to look into the fundamentals of commonsense behind natural phenomena and pave the way for futurist innovations. Instinctive Computing [16], for example, attempts to connect artificial intelligence to primitive intelligence. It explores the idea that a genuinely intelligent computer can interact naturally with humans. To form this bridge, computers need the ability to recognize, understand and even *have* instincts similar to humans, including primitive problem-solving, learning, tool-making, pheromones, and foraging. More than ever, we need systematic thinking for designing cyber-physical systems. We need more innovative theories

✉ Yang Cai
ycai@cmu.edu

1 United States Naval Academy, Annapolis, Maryland, USA

2 Carnegie Mellon University, Pittsburgh, PA, USA

for artificial intelligence, cybernetics, ethology, human-computer interaction, data science, computer science, security and privacy, social media, and autonomous robots.

We are in the era of the Renaissance of Biologically Inspired Computing. Our society has been increasingly digitized and become more and more complex. It needs more effective algorithms. For example, how to incorporate an artificial immune system to improve cyber security? How do we use evolutionary algorithms to solve the scalability problem in a Blockchain system? How to detect Deep Fake media content? On the other hand, modern biological discoveries provide new computational models for problem-solving, for example, CRISPR therapy and RNA vaccine, et al. Furthermore, modern computing technologies enable more powerful means to implement biomimicry algorithms, for example, biomorphic chips such as Akida Spiking Neural Network chip [17].

Yet biology and biological signaling systems in particular offer key insights into signaling modalities and behaviors. A rich area for signaling system science is found within its abstract game-theoretic form, where partially informed agent communicators derive various signal types to form signaling strategies various signal types to form signaling strategies. Many of these behaviors which worry contemporary designers are precluded by empirical observation and theory in biology. Consider for example the subject of mimicry, in the late 19th century the German naturalist Fritz Müller discovered that several distinct species of Butterflies were both toxic to predators and appeared similarly with coloration and markings. He felt the appearances being similar required a theoretical explanation of its own as convergent evolution was so unlikely that other considerations are needed. Reasoning that the butterflies were also toxic to their predators, and those predators could learn avoidance, he theorized that the two traits (phenotypic markers, and toxicity) formed a credible signaling system that could be sustained by its mutual benefits for all organisms. The butterflies who mimic each other benefit by co-teaching their predators not to eat them, while the learned predators benefit from avoidance. This type of mimicry, which acts in beneficial ways for all involved, is now known as Müllerian Mimicry. Also in the late 19th century the English Naturalist Henry Bates observed that not all flies are honest and that when a credible signaling convention for avoidance arose, a species could potentially enjoy a free ride by adapting the signaling without paying the cost to make those signals credible. The cheater enjoys the benefit of not being eaten by the duped predator, and the mistrained predator mistakenly avoids metabolic inputs. This mode of signal mimicry is now called Batesian Mimicry and its parasitic relation bears clear resemblances to various exploits and vulnerabilities of communication systems: Social Engineering, Sybil Attacks, malware, man in the middle, and so forth. In addition to these seemingly antipodal modes, biological mimicry includes many more strategies such as *crypsis* and camouflage where organisms blend into insignificant backgrounds avoiding the detection methods of their predators, *aggressive mimicry* is when a species attempts to confuse a predator by appearing as anything that could dissuade encounters.

Many of the mimicry forms fit well within the survival strategies of species, but even some signaling strategies seem to contradict them. Darwin noted the seeming contradiction between natural selection and the extravagant ornamentation of organisms and suggested a secondary selection distinct from natural selection to account for sexual signaling. The Israeli biologist Amotz Zahavi suggested the handicap principle [19] in the early 1970s to shed light on secondary signals, the basic reasoning, also known as *costly signaling* proposes that high-cost signals are more likely to be provided by honest senders who are more efficient than cheap talkers [20]. This notion fits well within the abstract Signaling game theory conceived by David Lewis' Signaling System [21] to account for emergent meaning and conventions in language. Notions such as cheap talk and costly signaling can be modeled by appropriate signaling game parameters to provide a unifying model of various signaling modes including Mimicry in biology and communication systems. Within biology, the notion of costly signaling sheds insights into signaling, and the same can be accomplished in communication networks. The notion of deceptive, honest, and costly signaling has also been applied to understand human deception [12]. In economics, the subject of cost signaling is wide and deep, including earlier notions of conspicuous consumption, offered by Thorstein Veblen at the close of the 19th century, to Job market signaling [13]. Application of these ideas to communication technology can help designers grapple with the quick pace of evolution and meet system requirements.

This leads us to the present where a confluence of biological theory, economics, engineering, and technologies can potentially enable a deeper understanding of signaling behaviors in an ever more connected world. The connections between systems and biology and economics, signaling theory may herald new approaches and insights to multidisciplinary subjects: signaling systems, signaling game theory, protocol designs, cellular signaling, signaling control, honest signaling, coding and modulation, regulatory signaling, narratives and virology, costly signaling, and so forth. An approach that models signaling to include the vast array of known biological signaling types may be beneficial to anticipate the signaling that could actually be enabled by new and novel communications and computer technologies. In general, the vast array of signaling strategies as it informs novel systems is a timely application of bio-inspired communication technologies that is well suited for current engineering challenges including improving trust and making communication technology more trustworthy.

To illustrate how these subjects are so enmeshed we select one contemporary topic within the biologically inspired community and explore how the present state of various research fields avail a novel and multidisciplinary research need. *Can biological signaling provide predictions for evolving behaviors in communication systems?* Communication technologies have connected humans and machines in novel ways that enable new utilities but also warrant the introspection of risks. These risks are so pressing that several initiatives have been launched among industry practitioners and academic researchers: trustworthy computing and cyber security to name a few. When the first telegraph and radio signals were sent, it would have been hard to anticipate the lineage of development leading us to fake personas distributing fake news on social media or the disruptions posed by various cyber attacks.

This Special Issue is designed to carry forward the vision founded at the Eleventh International Conference on Bio-inspired Information and Communication Technologies (BICT), held on March 13th and 14th 2019 at Carnegie Mellon University in Pittsburgh PA, USA. There a new way forward for Bio-Inspired technologies was envisioned. Breaking from traditional molds, the conference challenged participants to plot a more profound and sustainable course for developing bio-inspired engineering within the context of contemporary human history including the last two centuries of science and engineering progress as well as the desired path for the next. Such an ambitious task requires that the artifacts of bio-inspired design be positioned soundly upon a substrate of scientific reasoning, but also that they self-describe their relation to foundational principles. Too many contemporary research papers lack a clear attachment to their underlying assumptions and their position on scientific or engineering pillars. Our goal is more than a reactionary response, by enhancing these connections we enable bio-inspired engineering communities to reason and achieve greater stability and by consensus select the path of progress for the common architecture in the century to come.

This is a timely and important task, especially now, as our designs and systems are on pace to achieve capabilities displacing human labor, disrupting populations, and enabling or accelerating inequities. Believing that the course of progress should allow everyone to co-determining its path, the organizers of BICT felt that a new type of conference is needed.

The eleventh International attracted researchers and practitioners in diverse disciplines, we expanded the community in an important way by forming a new track to address the game theoretic, evolutionary, philosophical questions, and foundational aspects of bio-inspired engineering. The conference attendees, practitioners, and researchers engaged in the new task with overwhelming enthusiasm indicating that the new direction is not only possible but attainable through our common interest. Those who attended are researchers and practitioners in diverse disciplines. They are unified by seeking a deeper understanding of key principles, processes, and mechanisms in biological systems. The common thread is that insight from biological processes is leveraged into the design, engineering, and technological applications. Past iterations of the conference have attracted significant contributions in Direct Bioinspiration as well as Indirect Bioinspiration. Direct Bioinspiration relates to the physical-biological materials and systems used within technological designs. Indirect Bioinspiration relates to the use of biological principles, processes, and mechanisms within the design and application of technologies. At the Eleventh International, we expanded the scope to include a new thrust Foundational Bioinspiration that engages the game theory, evolution, information theory, and philosophy of science within the design of technologies. Through Foundational Bioinspiration we gain scientific and philosophical perspectives on the role of emergent bioinspired and biomimicry technologies and their wider implications. See the BICT-2019 Program in the appendix.

In this Special Issue, we selected four papers out of many outstanding submissions. In Kevin Pilkiewicz and his co-authors' paper [7] "Predicting supramolecular structure from the statistics of individual molecular events," the authors explore biomolecular communication in a single self-assembly sequence and its branching structural end states. The study shows how the high computational cost of such a fine-grained model can be overcome through approximation when extending it to larger, more complex systems. In Vincent A. Cicirallo's paper [8] "On Fitness landscape analysis of permutation problems: from distance metrics to mutation operator selection," the author tried to solve the permutation problems with a novel fitness measurement. In Alberto Arteta's paper [9] "An encrypted proposal method in membrane computing aggregation (MCA)," the author proposed a biologically inspired encryption method for cyber security and privacy. Finally, in the paper of Yassine Meraihi, et al., [10] "Mesh router modes placement for wireless mesh networks based on an enhanced moth-flame optimization algorithm," the authors proposed a biomimicry positioning algorithm for wireless mesh network optimization. Due to the limited capacity of this Special Issue, we can not cover broader biomimicry theories and applications. We hope this Special Issue as a virtual piazza to gather curious minds and inspire more original explorations.

In his seminal book "Cybernetics: or Control and Communication in the Animal and the Machine," Norbert Wiener said: "We had dreamed for years of an institution of independent scientists, working together in one of these backwoods of science, not as subordinates of some great executive officer, but joined by the desire, indeed by the spiritual necessity, to understand the region as a whole, and to lend one another the strength of that understanding." Biology offers an empirical and profound glimpse of dynamic stability, robustness, control, resilience, and survival. Accordingly, the application of biological research to systems and technology holds immense potential and reveals many technical challenges. This volume represents the continuation of work on this new path of charting the current and future advances in bioinspired technologies.

Guest Editors of the Special Issue: William A. Casey (United States Naval Academy, wcasey@usna.edu) and **Yang Cai** (Carnegie Mellon University, ycai@cmu.edu).

Acknowledgements We would like to thank Bud Mishra, Jun Suzuki, Eric Hatleback, Bilal Khan, Aftab Ahmad, Mohammad Upal Mahfuz, Adriana Compagnoni, Linda Canon, Tadashi Nakano, and Andrea Piekova for organizing the BICT 2019, and many reviewers, including Prof. Mel Siegel, Dr. Jose A. Morales, Eric Hatleback, Paola Hernández-Chávez, and Leigh Metcalf. Thanks to the editors in Springer-Nature for making this special issue possible. We would also like to thank our sponsors EAI, CMU, and Galois.

BICT 2019 Program

Our keynote speakers were Sheri M. Markose (Professor of Economics at the University of Essex), Brian Skyrms (Distinguished Professor of Logic and Philosophy of Science, Economics, and Philosophy at the University of California Irvine, and Professor of Philosophy at Stanford University), Michael Lotze (Department of Surgery, Immunology, and Bio-engineering at the University of Pittsburgh School of Medicine) and William E. Novak (Carnegie Mellon University Software Engineering Institute). The program contained fourteen accepted papers and four special sessions: Human Machine Teaming (chaired by Ryan D. McKendrick from Northrup Grumman), Ethics in AI Applications in Industry (chaired by Thomson Nguyen of Kleiner-Perkins), and Re-Engineering Philosophy of Nature, Multiple Realisation, and Natural Kinds (chaired by Paola Hernández-Chávez at the University of Pittsburgh), and Nature and Games (chaired by Steven Massey at the University of Puerto Rico). Additionally, the banquet featured an interactive music composition by Jakub Polaczyk (New York Conservatory) titled "Around the B-E-ES".

References

1. Turing, AM (1950) Computing machinery and intelligence. Mind, 59, 433–460.
2. Turing, AM (1952) The chemical basis of morphogenesis, Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, pp. 37–72, 1952. View at: Publisher Site, Google Scholar
3. Wiener N (1961) Cybernetics: or control and communication in the animal and the machine, The MIT Press, 1961
4. Dartmouth AI Proposal.
5. von Neumann J (1966) Theory of self-reproducing automata. Edited by A. Burks, Univ. of Illinois Press, Urbana. 1966
6. Conway J (1970) Game of Life. Scientific American 223, Oct. 1970: 120–123
7. Kevin Pilkiewicz, et al, predicting supramolecular structure from the statistics of individual molecular events, MONE, Special Issue on Biomimicry'
8. Alberto Arteta, An encrypted proposal method in membrane computing aggregation (MCA), MONE, Special Issue on Biomimicry, 2022
9. Vincent A. Cicirallo, On Fitness landscape analysis of permutation problems: from distance metrics to mutation operator selection, MONE, Special Issue on Biomimicry, 2022
10. Yassine Meraihi, et al, Mesh router modes placement for wireless mesh networks based on an enhanced moth-flame optimization algorithm, MONE, Special Issue on Biomimicry, 2022
11. Shannon, Claude Elwood. An algebra for theoretical genetics. Diss. Massachusetts Institute of Technology, 1940.
12. Gambetta, Diego. "10 Deceptive Mimicry in Humans." Perspectives on imitation: Imitation, human development, and culture (2005): 221.
13. Signaling for Spence, Michael A. "Job Market Signaling." quarterly Journal of Economics 87 (1973): 355 – 74.
14. Brooks, R. A., Flesh and Machines, Pantheon Books, New York, NY, 2002. (Arabic edition, Obeikan Publishers, 2002.
15. Dipankar Dasgupta, Artificial Immune Systems and Their Applications, Springer, 1999
16. Yang Cai, Instinctive Computing, Springer-London, 2016
17. Brainchip, Akida: https://brainchip.com/akida-neural-processor-ip/, captured on November 10, 2022
18. Marr, David, and Ellen Hildreth. "Theory of edge detection." Proceedings of the Royal Society of London. Series B. Biological Sciences 207.1167 (1980): 187–217.
19. Zahavi, Amotz, and Avishag Zahavi. The handicap principle: A missing piece of Darwin's puzzle. Oxford University Press, 1999.
20. Grafen, Alan. "Biological signals as handicaps." Journal of theoretical biology 144.4 (1990): 517–546.
21. Lewis, David. Convention: A philosophical study. John Wiley & Sons, 2008.