Dancing with Swarms: Utilizing Swarm Intelligence to Build, Investigate, and Control Complex Systems

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We are surrounded by a natural world of massively parallel, decentralized biological “information processing” systems, a world that exhibits fascinat-
ing emergent properties in many ways. In fact, our very own bodies are the result of emergent patterns, as the development of any multi-cellular organ-
ism is determined by localized interactions among an enormous number of cells, carefully orchestrated by enzymes, signalling proteins and other molec-
ular “agents”. What is particularly striking about these highly distributed developmental processes is that a centralized control agency is completely ab-
sent. This is also the case for many other biological systems, such as termites which build their nests – without an architect that draws a plan, or brain cells evolving into a complex ‘mind machine’ – without an explicit blueprint of a network layout.

Obviously, being able to understand, build and harness the emergent prop-
erties of such systems would be highly beneficial. Designers of complex sys-
tems could utilize their adaptability and robustness. Such systems would con-
struct themselves through self-organization. However, system designers and programmers are facing an enormous challenge. How can we actually build highly distributed systems of which we have only limited understanding? Would we have to invent new ways of building, maintaining, and controlling such systems? It seems to be necessary to explore a completely new mindset for programming and system control:

“It is no longer possible to use traditional, centralized, hierarchical command and control techniques to deal with systems that have thou-
sands or even millions of dynamically changing, communicating, hetero-
geneous entities. [...] the type of solution swarm intelligence offers is the only way of moving forward, [we] have to rethink the way [we] control complex distributed systems.”

Eric Bonabeau, 2003, co-author of Swarm Intelligence [7]
4.1 The Emergence of Complexity

Despite the fact that we have become so used to living with machines and devices, which seem to be relatively easy to handle from a user perspective, these mostly represent extremely complex systems, built by carefully engineered top-down design processes. Cybernetics and systems sciences are experiencing a revival, mostly in combination with the sciences of complexity. Studying designs from an integrated systems perspective has become increasingly important as we recognize that the understanding of emergent properties of complex systems that are built and designed from a bottom-up perspective prove to be more and more advantageous [3, 42, 68]. Artificial neural networks and artificial immune systems as adaptive units that learn from training data and do not rely on large-scale programming are just one aspect of the success story of the integrative systems paradigm [13, 39, 45, 55, 72]. Advances in small-scale technologies and manufacturing enable us to build systems in a self-organizing manner – with a large number of interacting entities [12, 54]. Engineers, physicists, computer scientists, biologists, and life scientists are also getting a better understanding of complex systems as a whole, and how observations and behaviors on higher levels are effects of system-specific, underlying emergent properties with bottom-up and top-down feedback loops [8, 23, 40, 51, 63, 65].

We also want to know increasingly more details about vastly complex systems that we can either currently build on our own – such as nano-devices for medication and minimally invasive diagnostics – or natural systems that we do have to understand – such as regulatory processes inside our human bodies, or complex inter-relationships within eco-, economic or social systems [27, 38, 50]. Medicine has made major advances. However, too many of all the intricate details to make our human bodies work are still mysteries to us. Will we ever get definite answers to questions such as: How does the immune system work? How does the human brain work? How can we re-program cells that had a ‘program crash’ and have become cancerous? What do we understand about gene expression and the complex regulatory mechanisms involved? And from an educational point of view: Do we adequately prepare our next generations of medical doctors, biologists, software developers, and engineers to equip them with these new mindsets necessary to cope with the challenges that come with the complexities of natural systems? How do we make them reveal their secrets and utilize these for our engineered systems, which we want to build, understand, and control?

4.2 Emergent and Agent-Based Computing

Agent-based computing and simulation approaches to study emergent phenomena are starting to become more and more prominent within computational and mathematical modeling [1, 20, 22, 73]. It seems necessary to explore