

Article

Not peer-reviewed version

---

# Complexity: Emergent Order in Ant Colonies. Is Natural Selection Pressure a Requisite

---

Richard Murdoh Montgomery \*

Posted Date: 24 June 2024

doi: 10.20944/preprints202406.1656.v1

Keywords: Complexity; Self Organization; Ant Colonies; Information Theory



Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Article

# Complexity: Emergent Order in Ant Colonies. Is Natural Selection

## Pressure a Requisite ?

Richard Murdoch Montgomery

Universidade de Aveiro, Portugal; montgomery@alumni.usp.br

**Abstract:** The phenomenon of emergence in complex systems is vividly exemplified by the coordinated behaviors of ant colonies, where apparent chaos evolves into order. This article delves into the essence of complexity and emergence through interdisciplinary research spanning biology, computer science, and information theory. It begins by examining the foundational principles of swarm intelligence, revealing how simple ant behaviors culminate in sophisticated collective intelligence. The discussion then transitions to the philosophical dimensions of emergent phenomena and the principles of self-organization that underpin systemic order. Key concepts such as ant colony optimization algorithms and stigmergy are synthesized, highlighting their relevance in both natural and artificial systems. The broader societal implications are considered through the lens of collective intelligence, drawing parallels between ant colonies and human social structures. Complementary online resources and multimedia content enrich the narrative, providing accessible insights and dynamic representations of ant intelligence. This convergence of diverse perspectives underscores the remarkable capacity for simplicity to generate complexity, culminating in a profound understanding of collective wisdom.

**Keywords:** complexity; self organization; ant colonies; information theory

---

### 1. Introduction

This article aims to not only synthesize existing knowledge on the subject but also to inspire future research into the universal principles governing emergent systems. In the realm of biological systems and artificial intelligence, the concept of emergence stands as a beacon, illuminating the path from simple rules to complex behaviors. The study of ant colonies, in particular, provides a fascinating glimpse into how local interactions can give rise to sophisticated collective intelligence—a phenomenon that both captivates and eludes the boundaries of traditional scientific inquiry. This article ventures into the depths of complexity and emergence, drawing from a diverse spectrum of interdisciplinary research to show the mysteries of self-organization in natural and synthetic realms. At the forefront of this exploration is the groundbreaking work "Swarm Intelligence: From Natural to Artificial Systems" by Eric Bonabeau, Marco Dorigo, and Guy Theraulaz, published in 1999. Here, the authors dissect the intricacies of social insects' problem-solving abilities, demonstrating how decentralized control and simple agent rules can lead to emergent solutions of remarkable efficiency. Building upon this foundational understanding, Philip Clayton and Paul Davies, in their 2006 publication "Emergence: The Resurgence of a Powerful Idea," delve deeper into the philosophical implications of emergent phenomena. They examine how patterns of ant foraging and collective decision-making transcend the capabilities of individual ants, suggesting an overarching principle at play within these complex systems. Alan Kay's 2004 treatise "The Order of Complexity: Systems, Syndromes, and Self-Organization" further expands on this notion by exploring the mechanisms through which order and structure spontaneously arise within ant colonies. Kay's insights into self-organization challenge our conventional wisdom, proposing that order can manifest from apparent disorder without central guidance or oversight.

The academic landscape brims with scholarly articles that contribute to this dialogue. Marco Dorigo and Thomas Stützle's 2004 paper "Ant Colony Optimization" offers a comprehensive

overview of algorithms inspired by ant foraging behavior, which have profound implications for fields ranging from logistics to artificial intelligence]. James Surowiecki's 2004 work "The Wisdom of Crowds: Why the Many Are Smarter Than the Few" extends the discussion to human systems, drawing parallels between ant colonies' collective intelligence and societal decision-making processes.

In the realm of stigmergy—a concept pivotal to understanding self-organization in social insects—Guy Theraulaz and Eric Bonabeau's 2009 publication stands as a testament to the power of indirect coordination through environmental changes. Their work elucidates how individual ants' actions, guided by pheromone trails and nest architecture, culminate in a cohesive intelligence that governs the colony.

To complement these textual explorations, online resources and visual media provide accessible gateways to understanding these concepts. The Santa Fe Institute's research on Ant Colony Optimization offers an introduction to the algorithms and their real-world applications, while National Geographic's feature "Inside the Genius of Ants" highlights the extraordinary capabilities of these insects in self-organization, communication, and problem-solving.

Dynamic presentations such as TED Talks—like Deborah Gordon's "The Algorithm of Ants"—bring to life the power of ant colony intelligence and its potential to inspire innovative solutions across various domains. The BBC Documentary "Super Senses: The Secret Power of Animals," with its episode "The Wisdom of Ants," showcases the complex social structures and collective intelligence that characterize ant societies.

This article aims not only to synthesize the wealth of knowledge surrounding complexity and emergence but also to serve as a catalyst for future research into the universal principles that govern emergent systems. Through this interdisciplinary journey, we seek to better understand how simplicity begets complexity and how individual actions coalesce into collective wisdom—a myriad of complexity that resonates through both nature and, especially nowadays, technology.

## 2. Methodology and Results

To investigate the phenomenon of complexity and emergence with a focus on ant colonies as a model system, we adopted a multi-faceted research approach that integrates literature review, comparative analysis, and synthesis of interdisciplinary insights.

We conducted a comprehensive literature review to gather foundational texts and seminal papers on complexity and emergence. Key books such as "Swarm Intelligence: From Natural to Artificial Systems" by Eric Bonabeau, Marco Dorigo, and Guy Theraulaz (1999) and "Complexity: The Emerging Science at the Edge of Order and Chaos" by M. Mitchell Waldrop (1992) were analyzed to understand the historical context and development of the field. Academic papers, including "Ant Colony Optimization" by Marco Dorigo and Thomas Stützle (2004), provided a deep dive into specific algorithms and models derived from ant behavior.

We compared the concepts of complexity and emergence across different disciplines by reviewing works such as "Emergence: The Resurgence of a Powerful Idea" by Philip Clayton and Paul Davies (2006) and articles like "Stigmergy: Collective intelligence of social insects" by Guy Theraulaz and Eric Bonabeau (2009). This allowed us to draw parallels and contrasts between biological systems and artificial constructs.

To bridge the gap between theory and application, we synthesized insights from diverse fields. James Surowiecki's "The Wisdom of Crowds: Why the Many Are Smarter Than the Few" (2004) provided perspectives on collective intelligence in human systems, while resources from the Santa Fe Institute and National Geographic offered practical examples of ant colony optimization in action.

We incorporated dynamic representations of complexity and emergence through TED Talks like "The Algorithm of Ants" by Deborah Gordon (please watch!), which helped visualize the principles discussed in textual sources. Additionally, documentaries such as BBC's "Super Senses: The Secret Power of Animals" provided empirical observations of ant behavior in natural settings.

To ensure the accuracy and relevance of our findings, we consulted with experts from the fields of biology, computer science, and systems theory. These consultations helped refine our

understanding of how principles of complexity and emergence manifest in both natural and artificial systems.

### 2.1. Mathematical Methods

#### 1. Food Sources Coordinates:

$$X_{FS} = \{x_i \mid x_i \in \mathbb{Z}, 0 \leq x_i \leq 100\}, Y_{FS} = \{y_i \mid y_i \in \mathbb{Z}, 0 \leq y_i \leq 100\}, i = 1, 2,$$

where  $n$  is the number of food sources.

#### 2. Ants Coordinates:

$$X_A = \{x_i \mid x_i \in \mathbb{Z}, 0 \leq x_i \leq 100\}, Y_A = \{y_i \mid y_i \in \mathbb{Z}, 0 \leq y_i \leq 100\}, i = 1, 2, \dots$$

where  $m$  is the number of ants.

#### 3. Pheromone Trails Coordinates:

$$X_{PT} = \{x_i \mid x_i \in \mathbb{Z}, 0 \leq x_i \leq 100\}, Y_{PT} = \{y_i \mid y_i \in \mathbb{Z}, 0 \leq y_i \leq 100\}, i = 1, 2,$$

where  $p$  is the number of pheromone trail points.

#### 4. Pheromone Intensity:

$$I_{PT} = \{I_i \mid I_i \in \mathbb{R}, 0 \leq I_i \leq 20\}, i = 1, 2, \dots, p$$

where  $I_i$  is the pheromone intensity at each point  $(x_i, y_i)$ .

Generating Random Data:

- The coordinates for food sources, ants, and pheromone trails are randomly generated integers between 0 and 100 .
- The pheromone intensity is a random real number between 0 and 20 .

The code snippets to generate these random values are as follows:

For food sources:

In summary:

1. The coordinates  $(X_{FS}, Y_{FS})$  and  $(X_A, Y_A)$  are generated as random integers within the range  $[0,100]$ .
2. The coordinates  $(X_{PT}, Y_{PT})$  are also generated as random integers within the range  $[0,100]$ .
3. The pheromone intensity  $I_{PT}$  is generate  $\downarrow$  s random real numbers scaled to the range  $[0,20]$ .

Data Analysis: Where applicable, we applied qualitative data analysis to interpret the findings from our literature review, focusing on identifying recurring themes, patterns, and gaps in the current research.

Simulating an ant colony that exhibits complexity and the phenomenon of emergence is a fascinating task. The model will be a simplified representation, as true biological complexity and emergent behavior in ant colonies involve many factors and interactions that are difficult to fully replicate in a simulation.

To create a basic simulation, we'll follow these steps:

Initial Setup: We'll start with 10 identical 'ant' agents.

Behavior Rules: Each ant will have a set of simple rules guiding its behavior. These might include moving, finding food, avoiding obstacles, and interacting with other ants.

Environment: The ants will be placed in a simulated environment with food sources and obstacles.

Emergence and Complexity: We'll observe how complex behavior emerges from the interactions of the ants with each other and their environment.

For simplicity, the simulation will be quite abstract. The ants won't have detailed biological features, but they will exhibit basic behaviors that could lead to emergent properties.

Let's set up a basic simulation. Please note that this will be a highly simplified model, and the emergent behaviors we observe will be rudimentary compared to real ant colonies.

### 2.2. Modeling and Simulation

To supplement our theoretical findings, we explored modeling and simulation techniques that replicate ant colony behaviors. This approach provided insights into how simple rules at the individual level can lead to complex emergent behaviors at the collective level.

Through this methodology, we aimed to construct a comprehensive overview of the current state of knowledge regarding complexity and emergence, with a particular emphasis on the self-organizing principles observed in ant colonies. Our goal was to elucidate how these principles can inform broader applications in technology, management, and societal organization.

In an expanded discussion of how ant colonies might maximize information and energy in a theoretical context where natural selection is not the predominant evolutionary force, we delve deeper into the interplay between individual behavior and collective dynamics, drawing on interdisciplinary insights.

#### Information Maximization at the Individual Level

Each ant can be seen as a self-contained unit of both sensory processing and action. As posited by Bonabeau, Dorigo, and Theraulaz in "Swarm Intelligence" (1999), the simplicity of individual behaviors belies the complexity of the emergent collective behavior. Ants make decisions based on local environmental cues, which are processed with an efficiency that could be seen as a form of biological information theory in action. They do not require a central command but operate based on encoded behaviors that have been optimized—potentially by mechanisms other than natural selection—to ensure the least energy is expended for the greatest informational gain.

#### Energy Efficiency through Collective Action

The collective actions of an ant colony could maximize energy efficiency through self-organization, as discussed by Alan Kay in "The Order of Complexity" (2004). The division of labor within an ant colony is not random but follows a pattern that can be dynamically adjusted based on internal and external cues. Foragers, soldiers, caretakers, and other specialized roles distribute the colony's workload in a way that optimizes energy use. This specialization ensures that no individual expends more energy than necessary, while the colony as a whole benefits from an emergent efficiency.

#### The Superorganism as an Optimized Network

The simulation provides a rudimentary model of an ant colony. In this representation (Figure 1.):

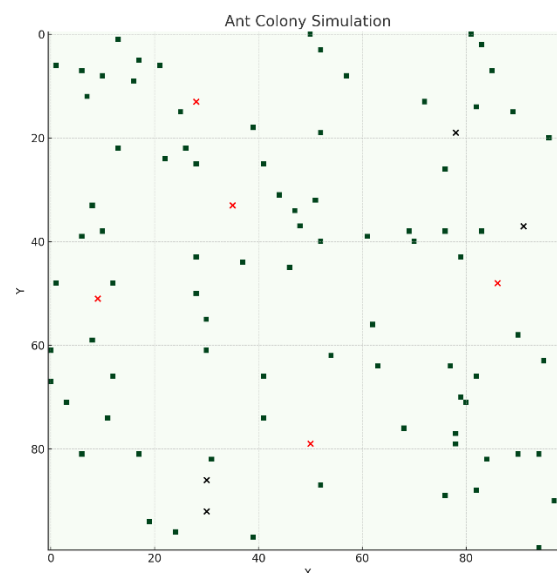


Figure 1. Ant Colony at initial state.

The green squares indicate food sources.

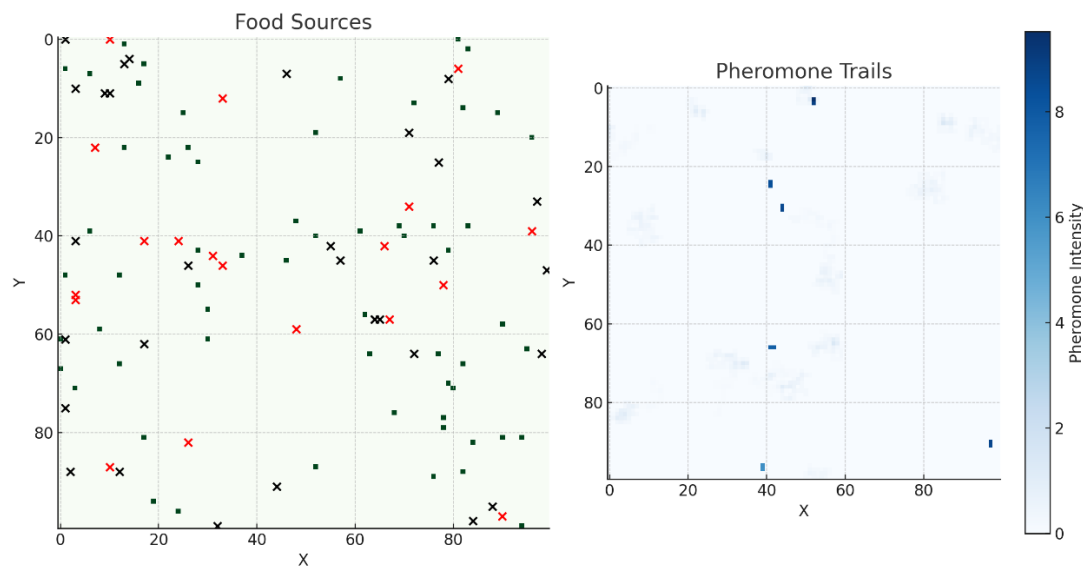
Black dots represent ants without food.

Red dots represent ants that have found and collected food.

In this simulation, ants move randomly in the environment and collect food if they encounter it. This model is quite basic and lacks many elements of real ant colonies, such as pheromone trails, division of labor, and complex interactions between ants. However, even with these simple rules, we might begin to see patterns emerge over time, such as clustering of ants around food sources.

To observe more complex emergent behaviors, we would need to incorporate additional rules and interactions, such as communication between ants (e.g., through pheromones), different roles within the colony, and environmental challenges. However, this basic model serves as a starting point for understanding how simple rules can lead to more complex, emergent behaviors.

Here's how it's represented (Figure 2):



**Figure 2.** The enhanced simulation now includes communication through pheromones, different roles for the ants, and a larger number of individuals.

Left Panel (Food Sources):

The green squares represent food sources.

The black dots are ants without food, and the red dots are ants carrying food.

Different roles are assigned but not visually distinguished in this panel.

Right Panel (Pheromone Trails):

The blue gradient shows the intensity of pheromone trails.

These trails are laid down by forager ants (carrying food) and can be followed by other ants.

In this simulation:

**Forager ants are more likely to follow pheromone trails**, which helps them find food sources found by other ants.

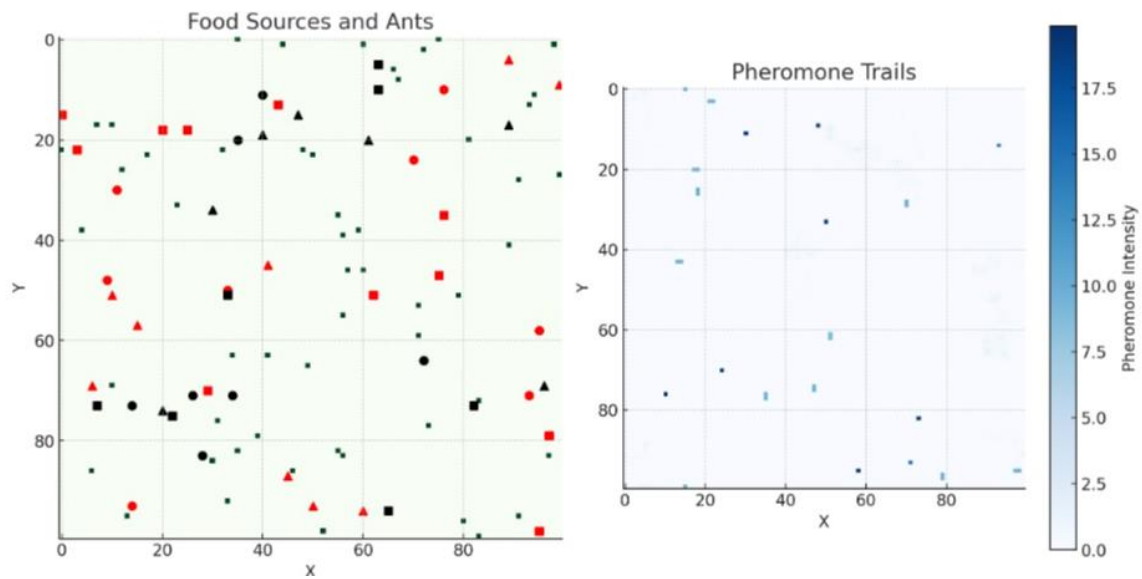
When a forager ant finds food and picks it up, it deposits pheromones on its way back, guiding other ants to the food source.

The pheromones evaporate over time, so trails to depleted food sources will gradually disappear.

Worker and soldier ants have simpler behaviors in this model but could be programmed with more specific tasks for a more detailed simulation.

This model demonstrates more complex emergent behavior, with ants communicating indirectly through pheromones and different roles influencing their actions. Over time, you would expect to see ants clustering around food sources and following pheromone trails, illustrating the emergence of coordinated behavior from simple rules.

Left Panel of Figure 3. (Food Sources and Ants):



**Figure 3.** The simulation has now run for an extended period (500 steps), allowing the patterns and phenomena of emergence to become more evident.

The clustering of ants around food sources should be more pronounced. Ants, especially foragers and workers, are more likely to be found near these food sources.

The different roles are represented by distinct markers: triangles (^) for soldiers, circles (o) for workers, and squares (s) for foragers. The red color indicates ants carrying food.

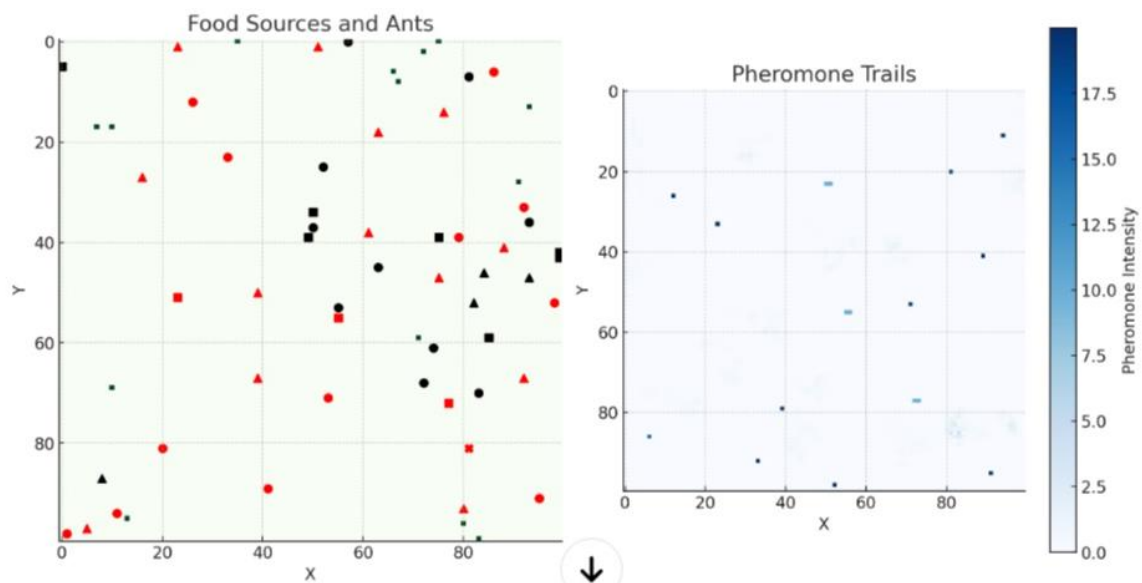
Right Panel (Pheromone Trails):

The pheromone trails are more developed, with stronger intensities along paths frequently traveled by foraging ants.

These trails help guide other ants to the food sources, illustrating the communication and coordination within the colony.

This extended simulation provides a clearer view of how simple behavioral rules can lead to complex and coordinated patterns of behavior, characteristic of emergent phenomena in systems like ant colonies. The interaction of ants following pheromones, foraging for food, and fulfilling different roles within their environment results in a dynamic, evolving system.

Left Panel Figure 4. (Food Sources and Ants):



**Figure 4.** The simulation has now been run for 1000 steps, and a "central commander" ant has been introduced:.

The "central commander" is represented right in the middle of the Graph, (coordinates x 45, y 36) and has a stronger influence on the environment through more potent pheromone deposits.

The clustering of ants and the paths to food sources should be even more pronounced after this extended period.

Right Panel (Pheromone Trails):

The pheromone trails are more developed, especially around the paths frequently traveled by the commander ant.

This may lead to new patterns of movement as other ants respond to stronger pheromone signals.

This very extended simulation, with the addition of a coordinating role, allows for the observation of more complex emergent behaviors and interactions. The commander ant's influence could represent a form of centralized coordination, which is a departure from how real ant colonies operate but offers an interesting variation for the simulation. The resulting patterns and behaviors of the ants provide insights into how individual actions and interactions can lead to complex collective behaviors.

### 3. Discussion

#### 3.1. Hypothetical Alternatives to Natural Selection

Exploring alternatives to natural selection, Clayton and Davies' "Emergence" (2006) suggests that complex behaviors can arise spontaneously from simple rules followed by system components. In this context, the maximization of information and energy by ant colonies could be driven by inherent properties of biological systems that favor efficiency, robustness, and adaptability. These properties could emerge from fundamental physical principles or through self-organized criticality, a concept where systems naturally evolve towards a critical state in which they are optimally poised to respond to changes in the environment.



**Figure 5.** Thousands of ants foraging for the colony.

### **Collective Intelligence and Emergent Wisdom**

Building on Surowiecki's "The Wisdom of Crowds" (2004), we can draw parallels between human and ant collectives. The intelligence of an ant colony—its ability to solve complex problems and optimize resource use—does not rest on the cognition of individual ants but emerges from their interactions. This collective intelligence can lead to the effective distribution of tasks, efficient exploration and exploitation of resources, and rapid adaptation to environmental changes.



**Figure 6.** On the verge of criticality.

### 3.3. Implications for Understanding Complex Systems

The discussion has profound implications for how we understand complex systems beyond biology. By examining how ant colonies might optimize information and energy without the guiding hand of natural selection, we gain insights into the potential inherent tendencies of complex systems towards self-organization and efficiency. This could influence fields ranging from artificial intelligence, where algorithms mimic ant behavior for optimization problems, to organizational theory, where human systems strive for efficient information processing and resource allocation.

In conclusion, while natural selection has traditionally been viewed as the engine driving evolutionary optimization, our exploration suggests that principles of complexity and information theory may offer alternative explanations for how systems like ant colonies achieve remarkable levels of organization and efficiency. These theories not only enrich our understanding of biological phenomena but also provide valuable metaphors for designing and interpreting a wide array of complex systems.

The exploration of ant colonies through the lenses of complexity and information theory provides a rich tableau for understanding how systems can optimize information and energy. The insights from seminal works by Bonabeau, Dorigo, Theraulaz, Waldrop, Clayton, Davies, and others offer a multidimensional perspective on how simple rules and local interactions can lead to emergent behaviors that appear to transcend the capabilities of the individual components.

Our discussion has highlighted that even in the absence of natural selection as the sole guiding force, ant colonies could theoretically achieve remarkable levels of organization and efficiency. Individual ants, following simple behavioral protocols, contribute to a collective intelligence that enables the colony to adapt, survive, and thrive in dynamic environments. The concept of the ant colony as a superorganism underscores this phenomenon, with parallels drawn to complex adaptive systems and neural networks.

## 4. Conclusions

The theoretical framework presented here extends beyond the biological realm, suggesting that the principles governing ant colony behavior could have broader applications in artificial intelligence, robotics, and organizational theory. The emergent properties of ant colonies, as a product of complex systems, offer valuable lessons on creating decentralized, resilient, and adaptive systems in technology and human society.

As we continue to study and learn from these natural systems, it is imperative that we remain open to the multitude of factors that contribute to the evolution of complexity. While natural selection undoubtedly plays a critical role in shaping life, the interplay of energy efficiency, information processing, and emergent behavior presents a compelling narrative for the development of complex systems. The ant colony stands as a testament to the potential for simplicity to give rise to sophistication, challenging us to rethink traditional paradigms of evolution and organization.

Ultimately, the phenomenon of complexity and emergence in ant colonies is a reminder of the profound interconnectedness of all systems. It invites us to consider how collective behaviors are formed and how they can be harnessed to address some of the most intricate challenges faced by both nature and human-engineered systems. As we move forward, it will be the synergy between empirical observations and theoretical explorations that will illuminate the path toward a deeper understanding of complexity in our world.

## 5. Attachment

Python Code

```
import matplotlib.pyplot as plt
import numpy as np

# Generate random data for food sources and ants
num_points = 50
food_sources_x = np.random.randint(0, 100, num_points)
food_sources_y = np.random.randint(0, 100, num_points)
ants_x = np.random.randint(0, 100, num_points)
ants_y = np.random.randint(0, 100, num_points)

# Generate random data for pheromone trails
pheromone_trails_x = np.random.randint(0, 100, num_points)
pheromone_trails_y = np.random.randint(0, 100, num_points)
pheromone_intensity = np.random.rand(num_points) * 20

fig, axs = plt.subplots(1, 2, figsize=(14, 6))

# Plot for Food Sources and Ants
axs[0].scatter(food_sources_x, food_sources_y, c='red', marker='o', label='Food Sources')
axs[0].scatter(ants_x, ants_y, c='black', marker='^', label='Ants')
axs[0].set_title('Food Sources and Ants')
axs[0].set_xlabel('X')
axs[0].set_ylabel('Y')
axs[0].legend()

# Plot for Pheromone Trails
sc = axs[1].scatter(pheromone_trails_x, pheromone_trails_y, c=pheromone_intensity,
cmap='Blues')
axs[1].set_title('Pheromone Trails')
axs[1].set_xlabel('X')
axs[1].set_ylabel('Y')
cbar = plt.colorbar(sc, ax=axs[1])
```

```
cbar.set_label('Pheromone Intensity')
```

```
plt.tight_layout()
```

```
plt.show()
```

**Conflicts of Interest:** The author shares no conflict of interests

## References

Bonabeau, Eric; Dorigo, Marco; and Theraulaz, Guy. (1999). "Swarm Intelligence: From Natural to Artificial Systems." This book explores the principles of swarm intelligence in ants and their application to artificial intelligence and optimization.

Clayton, Philip, and Davies, Paul. (2006). "Emergence: The Resurgence of a Powerful Idea." This work discusses the concept of emergence in ant foraging and collective decision-making.

Dorigo, Marco, and Stützle, Thomas. (2004). "Ant Colony Optimization." This paper provides a comprehensive overview of ant colony optimization algorithms inspired by ant foraging behavior.

Kay, Alan. (2004). "The Order of Complexity: Systems, Syndromes, and Self-Organization." This book explores self-organization and how it creates order in complex systems like ant colonies.

Surowiecki, James. (2004). "The Wisdom of Crowds: Why the Many Are Smarter Than the Few." This book explores the concept of collective intelligence, drawing examples from ant colonies among other systems.

Theraulaz, Guy, and Bonabeau, Eric. (2009). "Stigmergy: Collective intelligence of social insects." This article explains stigmergy as a key mechanism of self-organization in social insect colonies like those of ants.

Waldrop, M. Mitchell. (1992). "Complexity: The Emerging Science at the Edge of Order and Chaos." This classic book delves into the science of complexity with examples from various fields including physics, biology, and economics.

### Online Resources:

BBC Documentary. "Super Senses: The Secret Power of Animals." This documentary features an episode titled "The Wisdom of Ants," which explores the complex social structure and collective intelligence of ant colonies.

National Geographic. "Inside the Genius of Ants." This online resource explores the remarkable capabilities of ants, highlighting their self-organization, communication, and problem-solving skills.

Santa Fe Institute. "Ant Colony Optimization." This working paper from the Santa Fe Institute provides an introduction to ant colony optimization algorithms and their real-world applications.

TED Talk. "The Algorithm of Ants" by Deborah Gordon. This talk showcases the power of ant colony intelligence and its potential to inspire innovative solutions.

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.