# A Prelude to Complexity

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**Abstract**

An exploration of the major themes of complexity theory is presented. Working definitions of complexity and complex systems are proposed, along with an illustrative example of a complex system in the form of a description of ant colony behavior. An overview of the major themes of complexity theory is presented, going into detail on several key points the author finds interesting. Some closing words provide a leaping-off point for further research.

## 1 What is complexity?

It seems appropriate to discuss what complexity is, before diving into an overview of the various constituent ideas in the field. However, complexity and complexity theory (also known as dynamical systems theory) are very ephemerally focused, loosely defined things. Many researchers in the field cannot definitively agree on one definition of complexity, though most definitions have a few aspects in common. A good, although vague, middle ground definition is “The study of complex systems.” But, without a definition of a complex system, this is useless.

### 1.1 Complex systems

A complex system is just as loosely defined as complexity theory. Mitchell attempts to provide a few definitions in order to ground her study of the field. She first states that a complex system is “a system in which large networks of components with no central control and simple rules of operation give rise to complex collective behavior, sophisticated information processing, and adaptation via learning or evolution” [2].

Reworded, she provides a more succinct "a system that exhibits nontrivial emergent and self-organizing behaviors" [2]. With this, we have a nice platform on which to build examples of complex systems and start to analyze the forces at play in such systems, which Mitchell anoints the "central question of the sciences of complexity" [2].

### 1.2 Ants: nature's prime example

Before moving on to an exploration of the major themes of complexity theory and complex systems, I feel that an illustrative example of a complex system is in order. The behavior of ant colonies is the perfect example of a complex system, and one that I am most enamored with.

Ant colonies manage to accomplish some pretty incredible things, despite having no recognizable leadership or management hierarchy. In an ant colony, each individual worker is an independent unit, capable of doing whatever is required of it at any given time. The colony as a whole goes through an evolutionary, self-organizing process in which ants communicate to other ants what they are currently doing, and each ant evaluates what the colony as a whole needs most, choosing which role they would help the colony the most in and taking the responsibilities of that role to bear. With no designated leader, this process of communication and individual self-evaluation allows complex behavior to occur, providing highly intricate and social communities and societies. Ant colonies rival large human metropolises in the amount of variation they provide, and put human forms of organization to shame with the efficiency that they allow.

In short, ants are awesome in scope and ability, and provide a perfect cookie-cutter example of what a complex system is.

## 2 Themes in complexity

In this section, which forms the body of the treatment at hand, we will examine a few key themes that permeate the field of complexity theory. Readers familiar with artificial intelligence and computability theory will notice a lot of overlap between these fields and complexity. You may be a complex systems analyst and not even be aware of it!

### 2.1 Emergence

A first major theme in complexity is emergence, which is at the very core of complex systems theory. Jeffery Goldstein, editor of the journal *Emergence*, explains that emergence refers to "the arising of novel and coherent structures, patterns, and properties during the process of self-organization in complex systems" [1]. I like this definition, but I find it lacking in an important aspect: emergent systems are composed of small, relatively simple particles or agents, which act with trivial, easily described behavior. To clarify Goldstein's definition, I'll go out on a limb here and state that emergence is the self-organizing behavior of a complex system composed of simple agents embodied in some sort of tangible, analyzable way.

Emergence is so tightly coupled with complex systems that there is a widely considered one-to-one correlation between the two: if you have a complex system, it has emergent properties, and vice-versa. Emergence leads to some other very interesting properties of complex systems by virtue of being a uniting force.

## 2.2 Information and Communication

Information is extremely important in complex systems. By sharing information, the agents in a complex system are able to self-organize and cooperate, allowing some emergent behavior to arise. The information shared can take many forms, such as pheromone trails in the case of ants, a cell's state in the case of a cellular automaton or a random boolean network, or even complex compilations of various pieces of data in the case of a genetic algorithm or even in human communication.

### 2.2.1 Shannon's Information Theory

A brief overview of Information Theory here seems appropriate, given that in many cases these complex systems are computationally modeled. Though this theory does not cover every real-world case of information, it provides a useful abstraction for thinking about and analyzing the information used by a complex system.

Claude E. Shannon's work in 1948 formalized communication and information in a mathematical context [3]. Shannon defined information a series of *bits*, which could be encoded as a string of ones and zeros. Theoretically any information could be encoded in such a way, given a proper set of meta-data, which would essentially act as a decoder.

Though it might not make sense to encode the information provided by a pheromone trail, for example, as a bit series, with a little abstraction this becomes a very handy tool for analysis.

## 2.3 Cooperation

Cooperation in the context of complex systems is the aspect of dynamical systems that provides emergence. Cooperation in such a system may take one of several modes, each of which determine various parameters of a system.

### 2.3.1 Modes of cooperation in complex systems

I present the following modes of cooperation in complex systems, each of which provides a different “attitude” to the system at large.

**Altruistic (or pure) cooperation** This mode of cooperation is one in which agents/particles receive no benefits from cooperating with the other agents/particles in the system, but rather the system as a whole is the only benefactor.

**Symbiotic cooperation** This mode of cooperation is one in which agents/particles form helpful partnerships in which every agent/particle involved in the partnership receives a beneficial side-effect, along with the system as a whole.

**Competitive cooperation** This mode of cooperation describes systems where symbiotic partnerships are formed and these partnerships directly compete with other partnerships to better themselves, while not necessarily harming others, with a net effect of helping the system overall.

**Antagonistic cooperation** This mode of cooperation describes systems where each agent/particle is acting independently (much like in pure cooperative systems), however, each particle is also competing with the other particles to better themselves. Such an antagonistic cooperative system often produces highly competitive agents which are extremely well suited to their intended purposes. Genetic algorithms and many search strategies are the most obvious example of antagonistic cooperative systems.

**Pure antagonism** This mode of cooperation is the only mode in which particles/agents aren’t out to improve their own helpfulness, but rather to directly harm the other agents’ ratings. Pure antagonistic systems often produce chaotic results, providing interesting mathematical properties but often unstable systems.

## 2.4 Algorithms and Searching

Many complex systems can be seen as manifestations of algorithms or search processes. Going back to the ant colony example for a minute, let’s imagine the ant’s foraging algorithm. Mitchell describes it as follows:

> In many ant species, foraging for food works roughly as follows. Foraging ants in a colony set out moving randomly in different directions. When an ant encounters a food source, it returns to the nest, leaving a trail made

> up of a type of signaling chemicals called *pheromones*. When other ants encounter a pheromone trail, they are likely to follow it. The greater the concentration of pheromone, the more likely an ant will be to follow the trail. If an ant encounters the food source, it returns to the nest, reinforcing the trail. In the absence of reinforcement, a pheromone trail will evaporate. In this way, ants collectively build up and communicate information about the locations and quality of different food sources, and this information adapts to changes in these environmental conditions. At any given time, the existing trails and their strengths form a good model of the food environment discovered collectively by the foragers... [2]

This single example concretizes and unifies both swarm algorithmic thinking and search strategies. And yet, the system described follows all of the principles of a complex system: simple autonomous agents/particles with simple, trivial behavior; self-organization; and emergent behavior.

## 2.5 Computability

Computability is an important theme in the field of complexity sciences because it provides a framework for analyzing the results of a complex system's run. Computability analyses often provide a measure of how complex a system truly is, by separating systems into various levels of completeness. For example, it has been shown that Conway's Game of Life is Turing Complete, meaning that any computation that may be solved in Turing Machine may be solved in a large enough world following the rules of Game of Life.

By measuring the effective capability of a system to compute, we are provided a potential glimpse into how complex the system truly is, by some subjective measure.

## 2.6 Evolution

Evolution, the process through which species become adapted to their environments over time, is a driving force which underlies many complex systems. In fact, the computability of many systems relies upon their evolutionary processes. By being able to adapt and change over time, such systems are capable of performing calculations by virtue of holding some sort of state.

Evolution in complexity studies takes two similar, but differing forms: natural evolution in biological systems, and artificial evolution in computational systems.

### 2.6.1 Natural, biological evolution

Natural evolution in biological systems is an interesting field of study, first made famous by Charles Darwin (though Alfred Russel Wallace first proposed the idea to

Darwin in correspondence) [4]. Biological evolution, through the iterative process of natural selection of mutations fit for survival, allows for emergence of new traits in the long run of a system. One could say that the evolution of human beings is the most complex system that we could study, as we are all independent agents, adapted to suit our environments, who are capable of computation and exhibit emergent behavior every day of our lives. And indeed, the social sciences are a branch of the complex sciences.

### 2.6.2 Artificial, algorithmic evolution

Artificial evolution in a computational context provides neat ways of stimulating and simulating the very things that biological evolution provides, at a much faster rate than nature would ever allow. By iteratively simulating new generations of a problem-solving population, the ability to find solutions to a problem becomes simple in many aspects.

# 3 Final words

Complexity is an interesting field that intersects with computer science, artificial intelligence, mathematics, social science, biology, genetics, botany, philosophy, and psychology. In any given context, you could easily find several examples of complex systems, whose constituent parts may have no idea of the overall system. At any rate, complexity is incredibly engrossing when you look at it, and the further down the rabbit hole you dive, the less you ever want to climb back out.

# References


[1] Jeffery Goldstein, *Emergence as a Construct: History and Issues*, Emergence: Complexity and Organization 1(1): 49–72.

[2] Mitchell, Melanie, *Complexity: A Guided Tour*, Oxford University Press, New York, 2009.

[3] Claude E. Shannon, *A Mathematical Theory of Communication*, Bell System Technical Journal, vol 27: 379–423, 623–656.

[4] Alfred Russel Wallace, *On the Tendency of Varieties to Depart Indefinitely From the Original Type*, 1858, `http://people.wku.edu/charles.smith/wallace/S043.htm`.