A great example to begin with is ants.

The ant researcher Nigel Franks wrote that "The solitary army ant is behaviorally one of the least sophisticated animals imaginable…if 100 army ants are placed on a flat surface, they will walk around and around in never decreasing circles until they die of exhaustion.   In extremely high numbers, however, it is a different story."

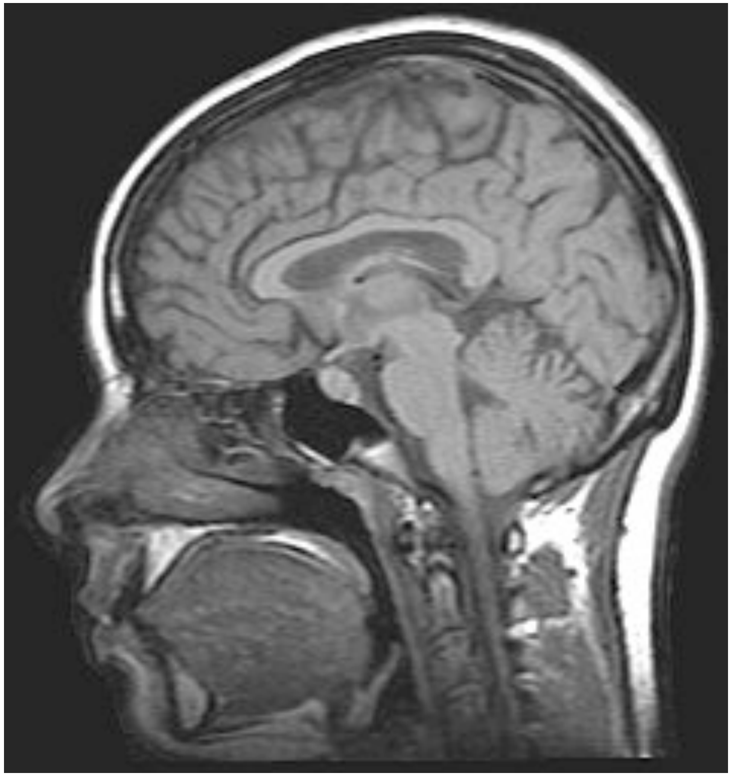
Here, for example, is a colony of army ants, building a tunnel. Each ant on its own is very simple, but the colony as a whole can work together cooperatively to accomplish very complex tasks, without any central control; that is, without any ant or group of ants being in charge.

In other words, ant colonies can organize themselves to produce structures much more complicated than any single ant could produce. Here's an example of ants building a bridge with their bodies so that other members of the colony can cross the gap between two leaves.

Here’s a short video that shows ants assembling this kind of bridge, from a stick all the way down to the ground.   You can see them gradually adding themselves to the structure. Each ant is secreting chemicals to communicate with the other ants, and the whole bridge is built without any central control.   We call this a “decentralized, self-organizing system”.

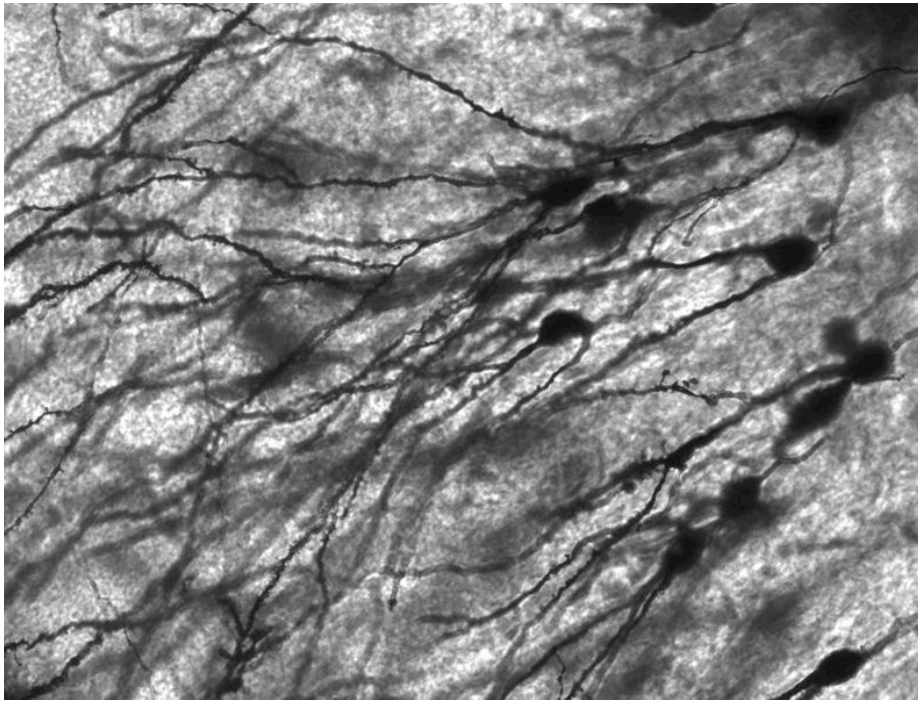
Other social insects produce similar behavior. For example, here is an example of the kind of complex living structure built by termites. Termite mound

A major focus of complex systems is to understand how individually simple agents produce complex behavior without central control? Here the simple agents are insects, but we'll see many other kinds.

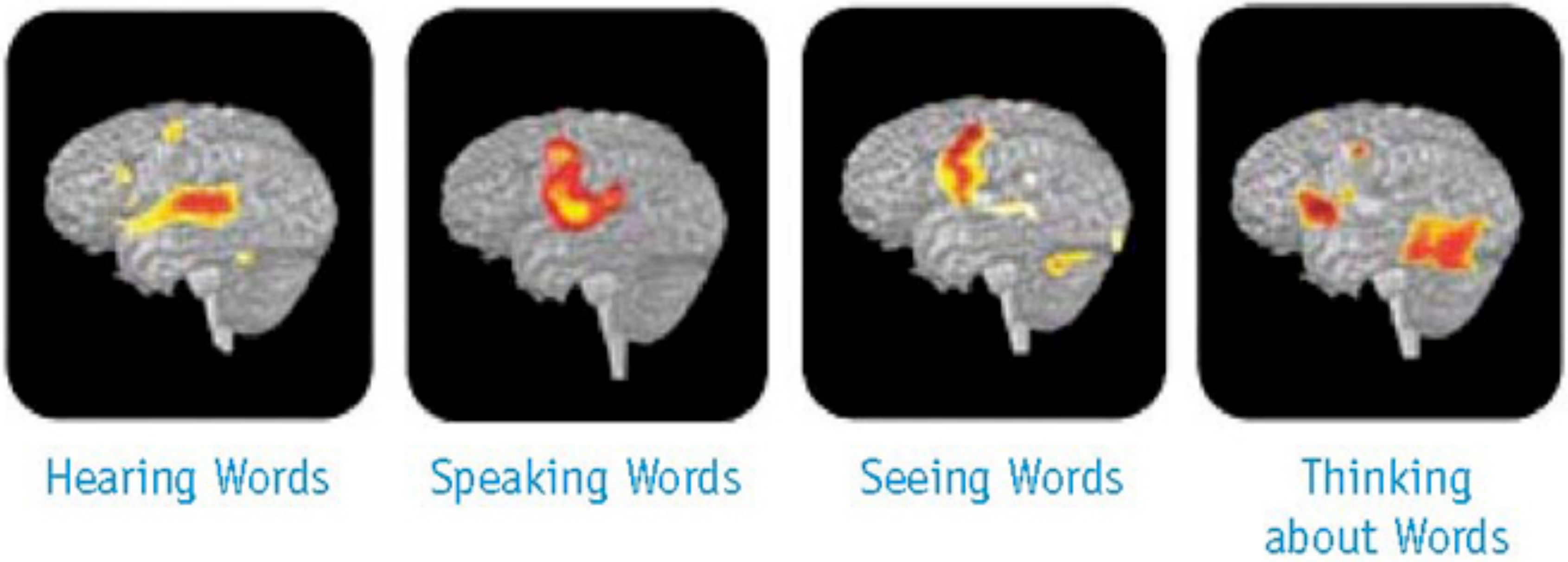


Another classic example of a complex system is the brain.

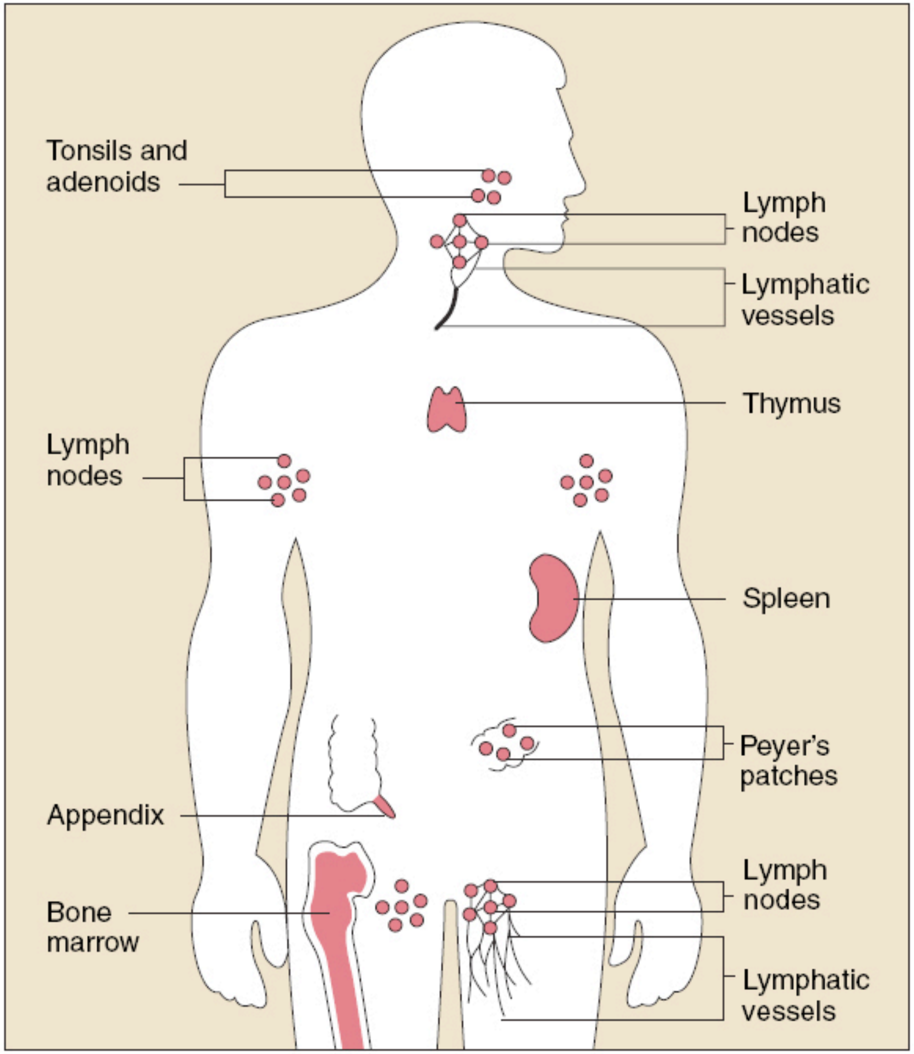
Here the individual simple agents are neurons.



The human brain consists of about 100 billion neurons and 100 trillion connections between those neurons. Each neuron is relatively simple (compared to the whole brain) and, again, there is no central control. Somehow the huge ensemble of neurons and connections gives rise to the complex behaviors we call “cognition” or “intelligence” or even “creativity”.

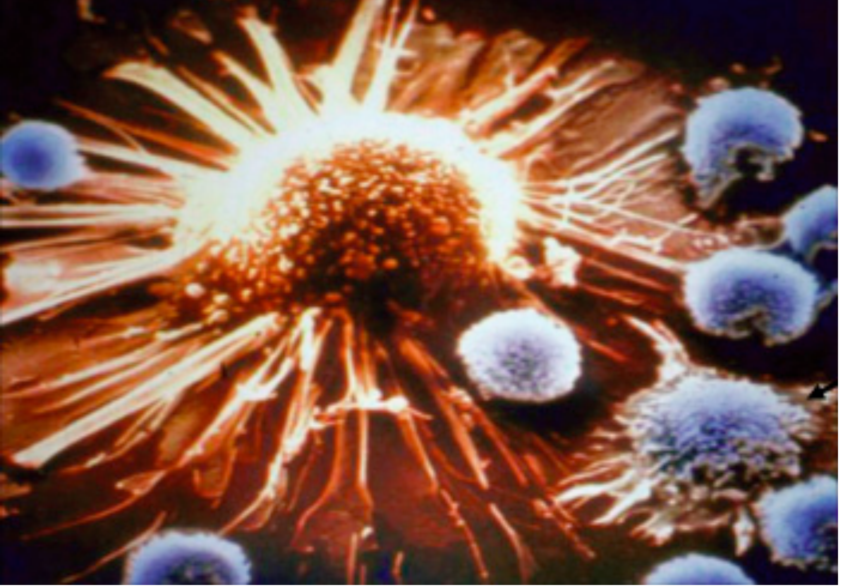


Brain imaging has shown that these neurons have organized themselves into different functional areas. Just like the ants or termites, neurons can self-organize into complex structures that help the species function and survive.



Immune system organs

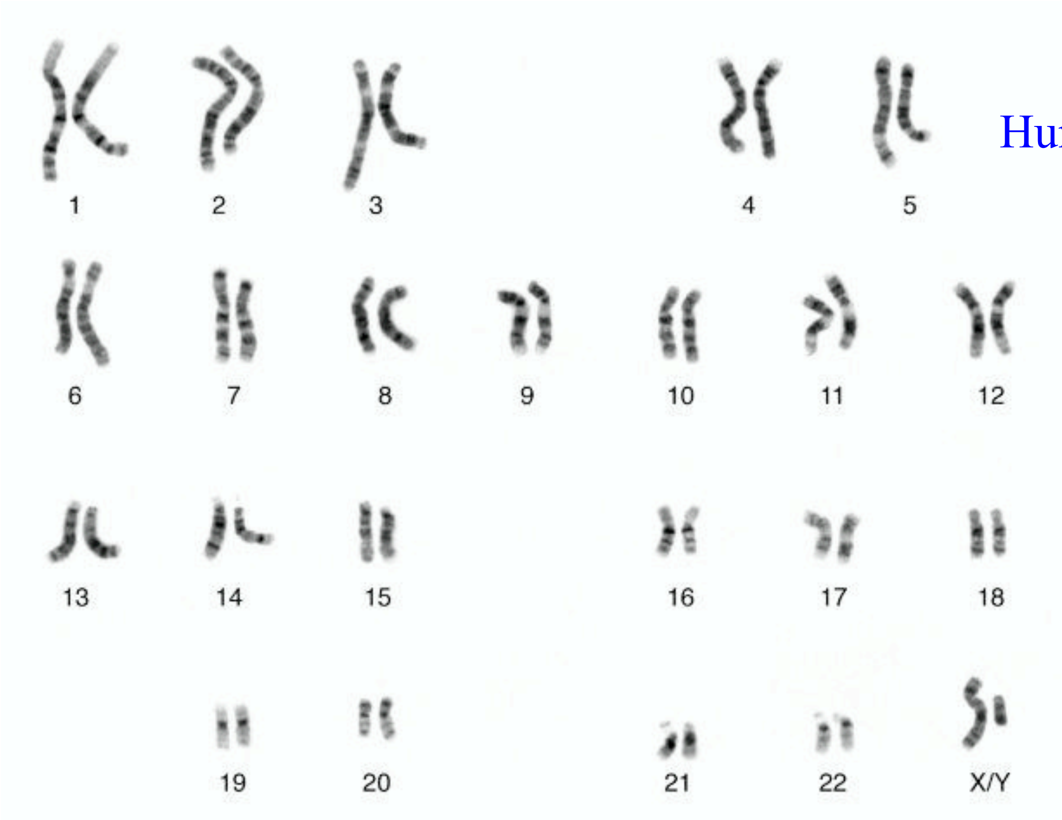
Yet another complex system is the immune system. The immune system is distributed across the body, involving many different organs, as shown in this picture, and trillions of cells moving around in the blood stream or lymph system, protecting and healing the body from damage or disease.



Immune system cells
attacking a cancer cell

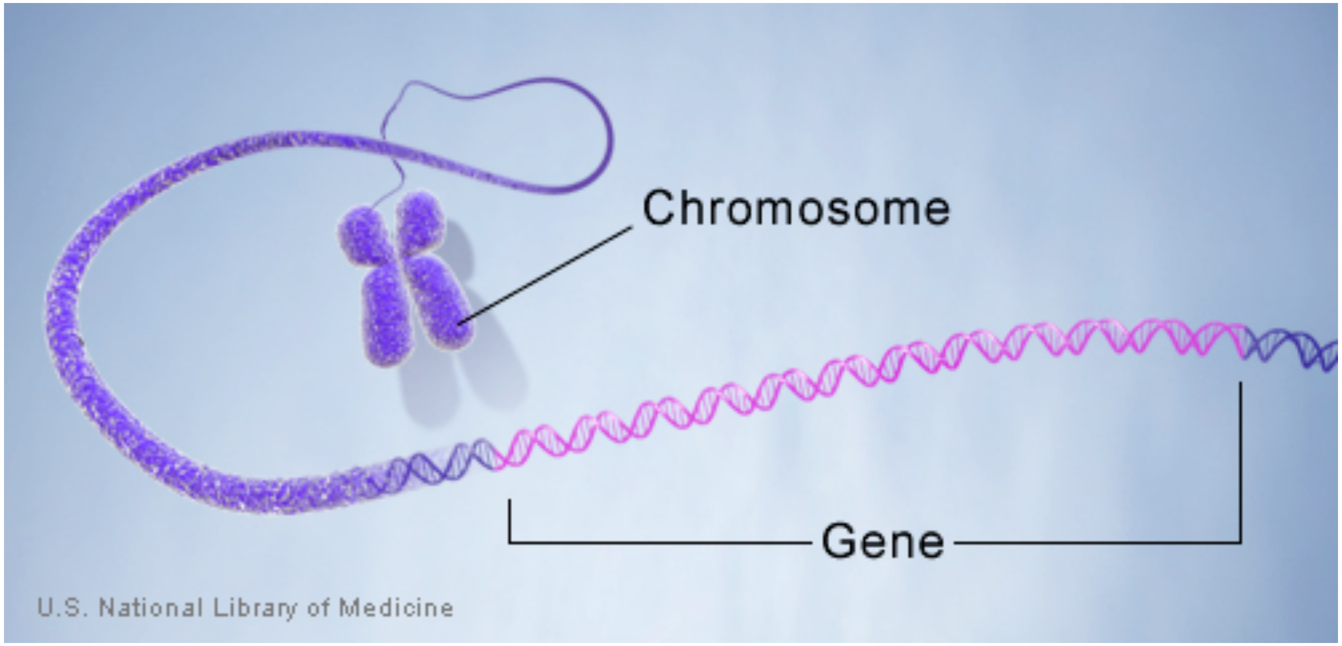
For example, this is a picture of immune system cells attacking a cancer cell. Like the ants we saw before, immune system cells communicate with one another through chemical signals, and work together, without any central control, to launch coordinated attacks on what they perceive as threats to the body.

In addition, the population of immune system cells in the body is able to change, or adapt itself, in response to what that population of cells perceives in its environment. This kind of adaptation is another key characteristic of complex systems.



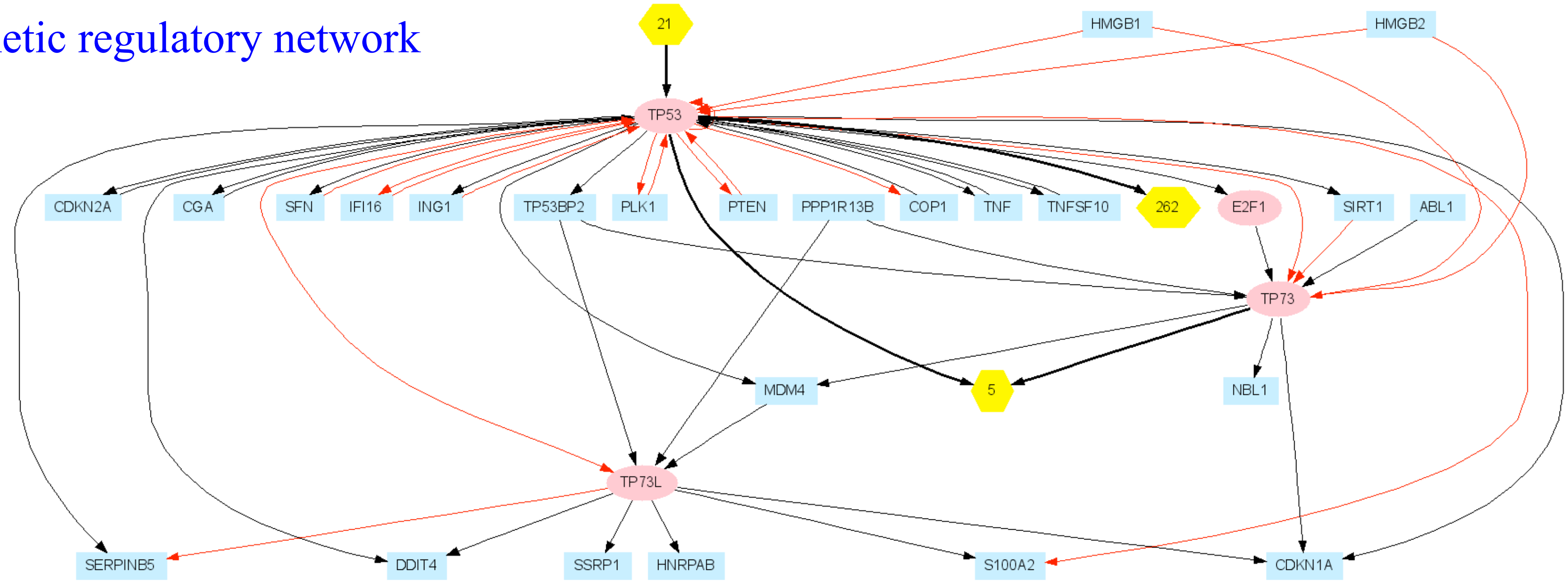
Human genome

Another familiar example of a complex system is the human genome. Here's a image of a human genome. Each of these worm-like structures is a chromosome, and there are 23 pairs of chromosomes, each made up of thousands of genes.

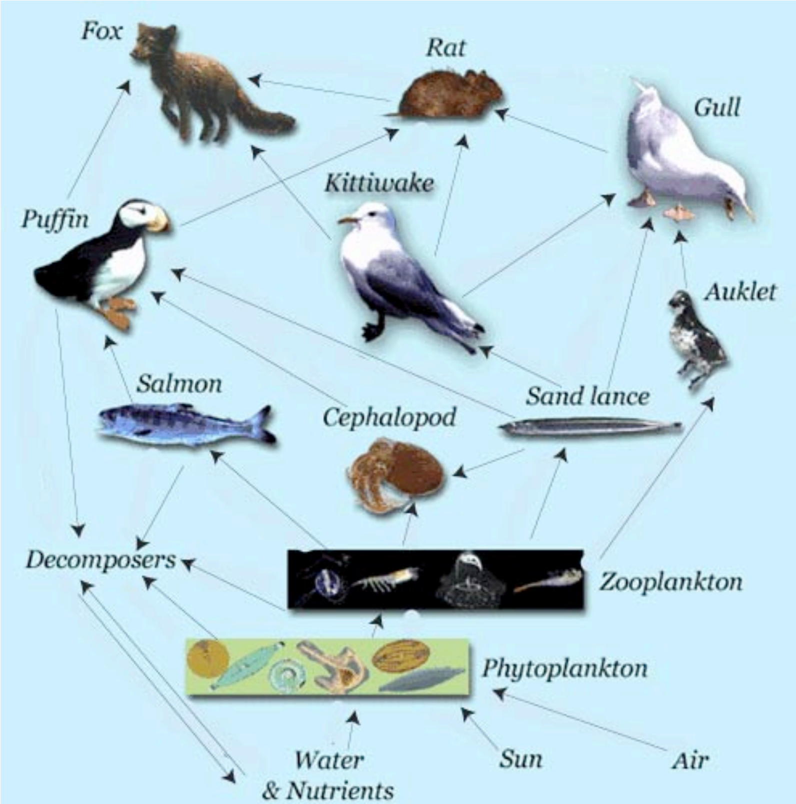


Genes are strings of DNA along the chromosome. It's currently thought that the human genome has about 25,000 genes.   In complex systems terms, you could think of the genes as simple components, that interact with other genes in a decentralized way.

Genetic regulatory network

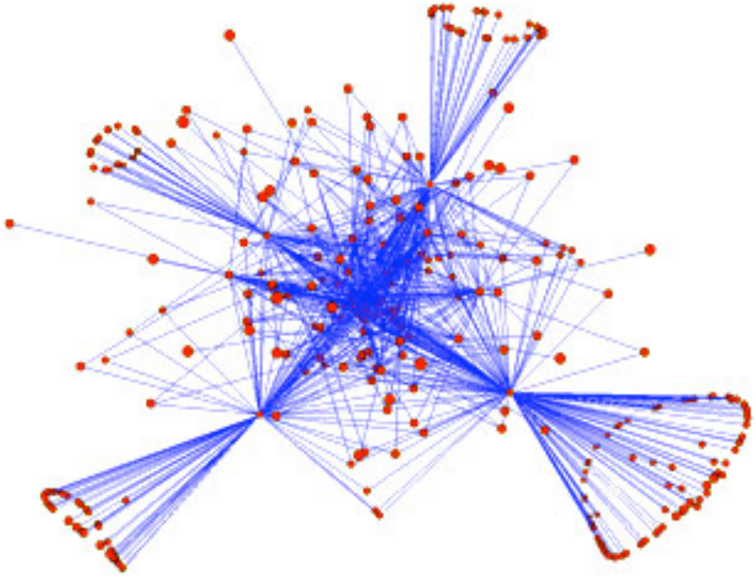


Genes interact by controlling one another's expression – that is, translation into proteins. Here is one small genetic regulatory network that has been mapped out by researchers. Here, each oval or rectangle represents a gene and an arrow from one gene to another means that the first gene controls the expression of the second gene. It turns out that the human genome is made up of thousands of networks like this one, in which genes interact with one another in complicated ways, and it is this interaction that is largely responsible for our own complexity.



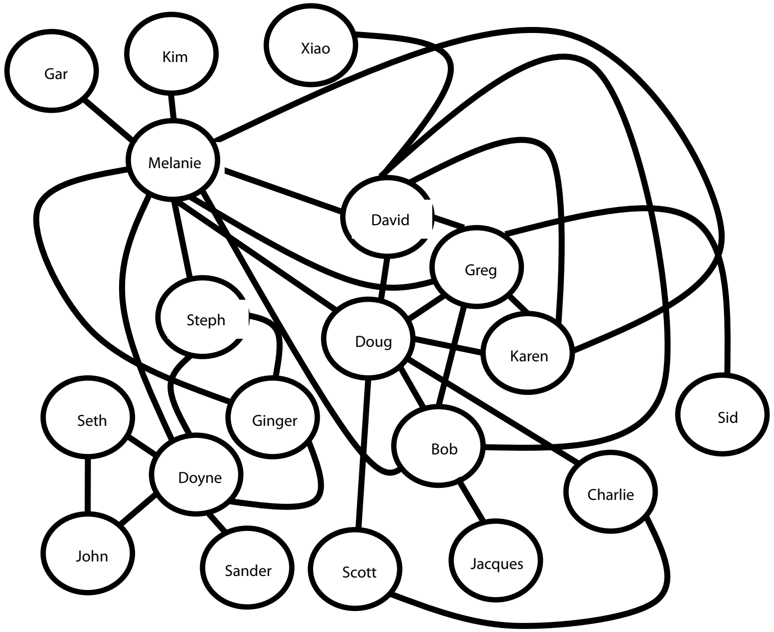
The idea of **networks** is central to the study of complexity in nature. Here is another kind of network, a food web. Here, each node in the network is a particular group of species, and the arrows represent who eats whom. If one species group points to another, that means the first is food for the second. For example you can see that foxes are at the top of this particular Alaskan food web, since they eat several kinds of animals, but nothing eats them, at least on this chart.

Food web



Food web (Gulf of Alaska)

Here is an abstract diagram of an even more complicated food web, from the gulf of Alaska. When we talk about networks later in the course, we'll see some very interesting examples of decentralized self-organizations in food webs and other kinds of networks.



Maybe the kind of network you're most familiar with is a social network. Here's part of my own social network, where the nodes represent people, and the links represent friendship between these people.

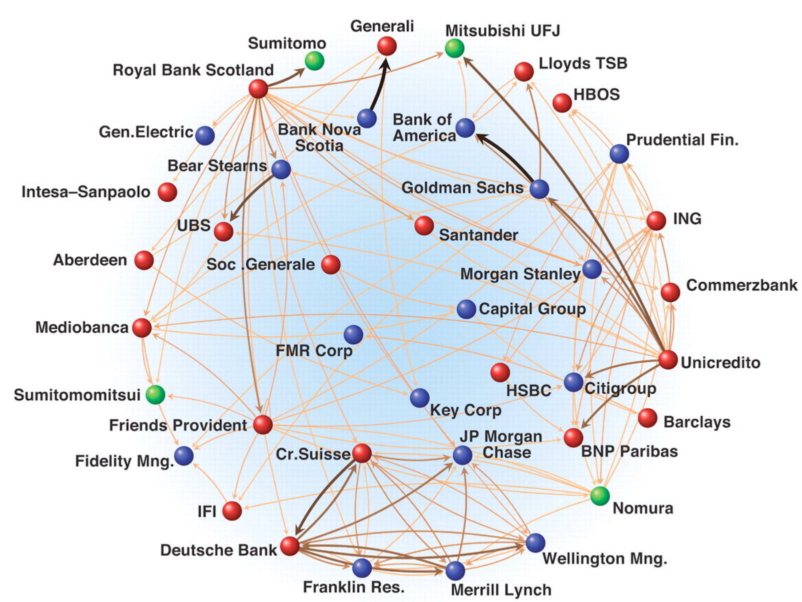
A social network

Facebook "friend" links

Complex systems scientists are very interested in studying large social networks, such as Facebook, to understand their structure, how such networks form, how they change over time, and how information is transmitted in such networks, among many other questions.

Economies are another type of complex system in which networks of interactions are fundamental. Here we see a sample of the international financial network, where nodes represent financial institutions and links represent relations among them – for example, if a bank owns shares of another bank. It turns out that the amount of connectivity in such a network, as well as the kinds of links present, can have a big effect on how stable the network is to changes, such as a bank going out of business. The new interdisciplinary field of network science, which arose from the complex systems research community, studies these kinds of phenomena in networks from many different disciplines.

Financial Institution Network



A final example is the study of cities as complex systems. It has often been said a city is like a living organism in many ways, but to what extent do cities actually resemble living organisms, in the ways they are structured, grow, scale with size, and operate? These and other questions form the basis of a rapidly growing area of complex systems research, which we'll look at in detail later in the course.

Cities as complex systems

Common Principles of Complex Systems

- Simple components or agents (simple relative to whole system)
- Nonlinear interactions among components
- No central control
- Emergent behaviors
  - hierarchical organization
  - information processing
  - dynamics
  - evolution and learning

Definitions of Complexity

- You may have noticed that the previous subunit I gave a list of common properties of complex systems without defining “complexity”.
- That was for a reason: It turns out that Complexity is hard to define! Or, more accurately, it has too many different definitions in different fields.
- So, how do complex systems researchers measure the complexity of a system?
- Seth Lloyd’s paper: “Measures of Complexity: a non-exhaustive list” gives something like 42 different definitions
- Is there a single, useful definition of complexity? Very doubtful!
- These different definitions are useful for measuring different aspects of systems. In this course we’ll talk in detail about Shannon Information and Fractal Dimension. We’ll also discuss the general problems of precisely defining and measuring complexity in the real world
- However, along the way in this course we’ll have a series of “guest spots” – short intertviews in which you’ll have the chance to hear several leading complex systems researchers answer the question “What is complexity?”

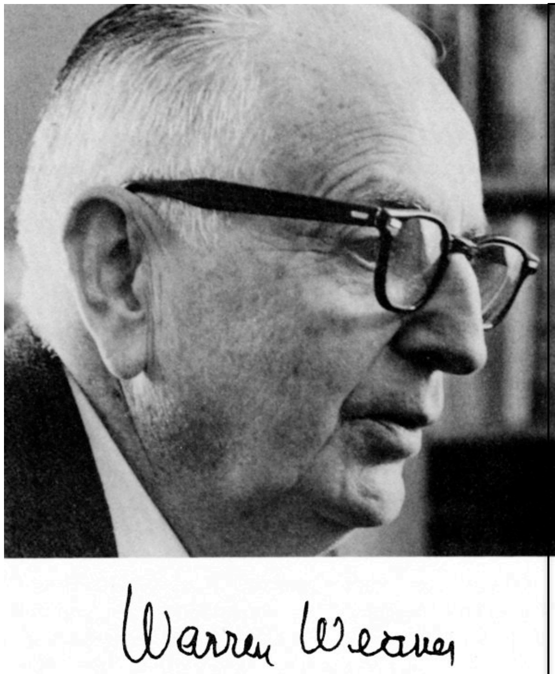
Measures of Complexity: A Nonexhaustive List

By Seth Lloyd

August 2001 IEEE Control Systems Magazine

- Shannon information
- Algorithmic complexity
- Minimum description length
- Fractal dimension
- Logical depth
- Thermodynamic depth
- Effective complexity
- Degree of hierarchy
- Etc...

But before I go on, I want to mention the ideas about complexity in one excellent, classic, and very prescient paper, called “Science and Complexity”, written by the American mathematician Warren Weaver in 1948.



1894–1978

SCIENCE AND COMPLEXITY

By WARREN WEAVER
Rockefeller Foundation, New York City

"Science and Complexity", American Scientist, 36: 536 (1948).
Based upon material presented in Chapter 1' "The Scientists Speak," Boni & Gaer Inc.,1947.

SCIENCE has led to a multitude of results that affect men's lives. Some of these results are embodied in mere conveniences of a relatively trivial sort. Many of them, based on science and developed through technology, are essential to the machinery of modern life. Many other results, especially those associated with the biological and medical sciences, are of unquestioned benefit and comfort. Certain aspects of science have profoundly influenced men's ideas and even their ideals. Still other aspects of science are thoroughly awesome.

How can we get a view of the function that science should have in the developing future of man? How can we appreciate what science really is and, equally important, what science is not? It is, of course, possible to discuss the nature of science in general philosophical terms. For some purposes such a discussion is important and necessary, but for the present a more direct approach is desirable. Let us, as a very realistic politician used to say, let us look at the record. Neglecting the older history of science, we shall go back only three and a half centuries and take a broad view that tries to see the main features, and omits minor details. Let us begin with the physical sciences, rather than the biological,

Problems of Simplicity: a few variables

Examples:

- Pressure and Temperature
- Current, Resistance, and Voltage
- Population vs. Time

Problems of Disorganized Complexity:

Problems of Disorganized Complexity: billions or trillions of variables

Problems of Disorganized Complexity: billions or trillions of variables

Problems of organized complexity:
Moderate numbers of variables

Mostly in the biological and social sciences

Strong, nonlinear interactions among variables.

"Problems which involve dealing simultaneously with a sizable number of factors which are interrelated into an organic whole."

Examples of problems of organized complexity (Weaver, 1948)

- What makes an evening primrose open when it does?
- What is the description of aging in biochemical terms?

- What is a gene, and how does the original genetic constitution of a living organism express itself in the developed characteristics of the adult?

- On what does the price of wheat depend?

- How can currency be wisely and effectively stabilized?

- How can one explain the behavior pattern of an organized group of persons such as a labor union, or a group of manufacturers, or a racial minority?

“These new problems, and the future of the world depends on many of them, requires science to make a third great advance, an advance that must be even greater than the nineteenth-century conquest of problems of simplicity or the twentieth-century victory over problems of disorganized complexity. Science must, over the next 50 years, learn to deal with these problems of organized complexity.“

Core Disciplines

Dynamics: **The study of continually changing structure and behavior of systems**

Information: **The study of representation, symbols, and communication**

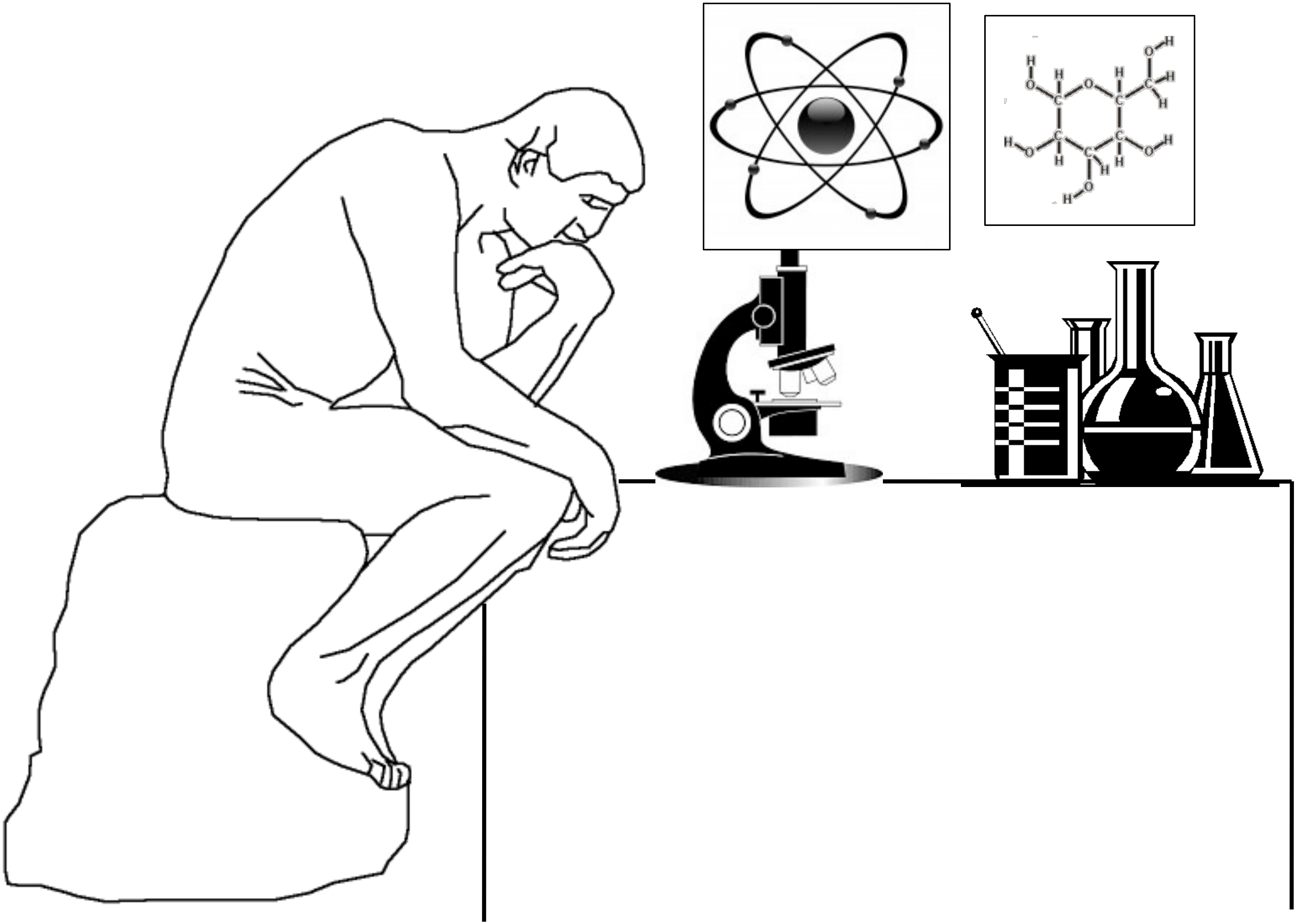
Computation: **The study of how systems process information and act on the results**

Evolution: **The study of how systems adapt to constantly changing environments**

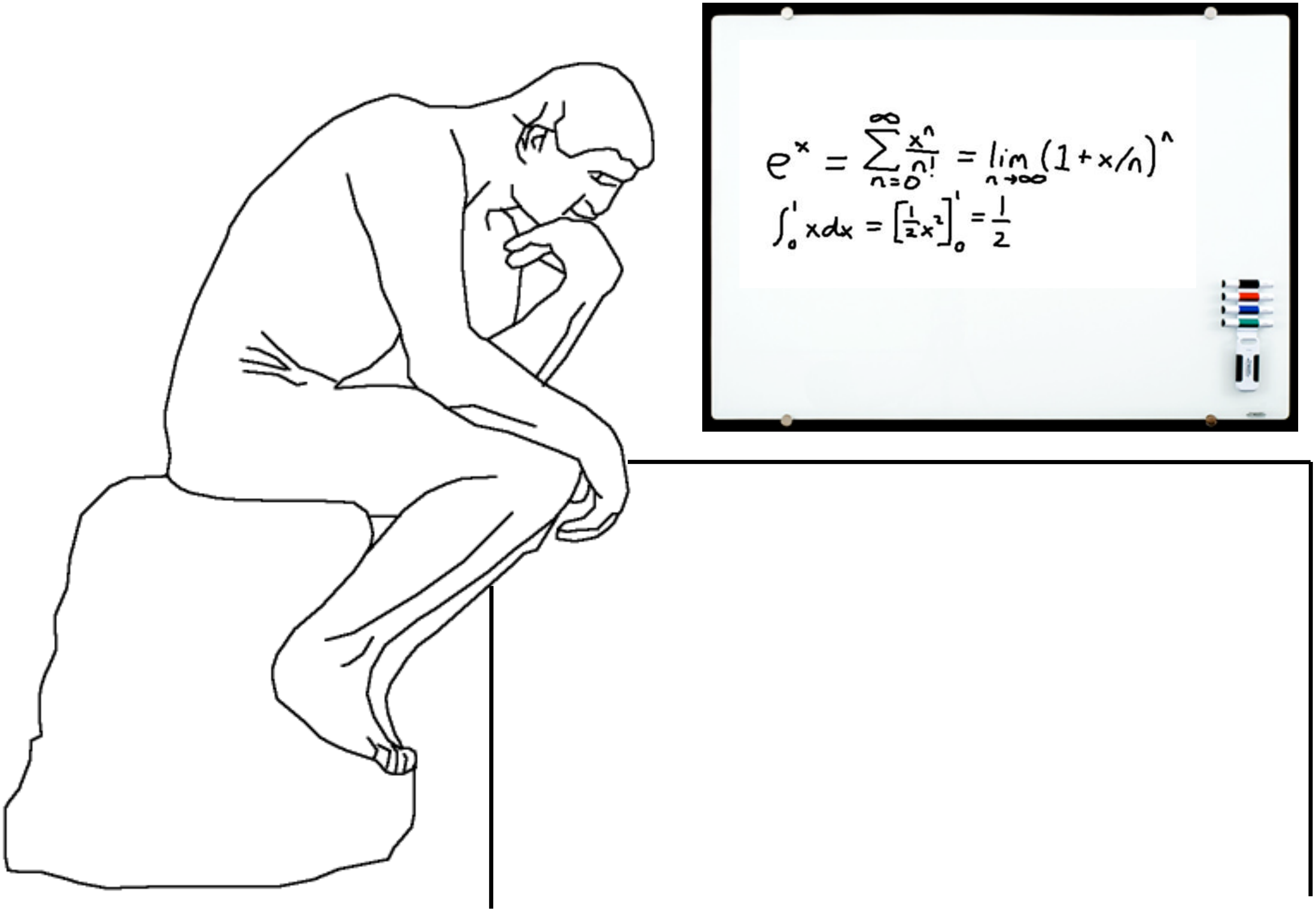
Goals:

- Cross-disciplinary insights into complex systems
- General theory

Methodologies



Methodologies



Methodologies