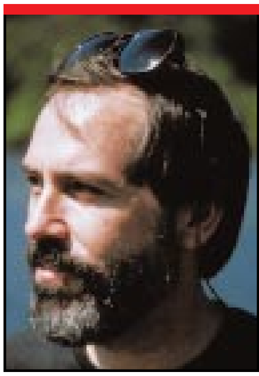

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Agents and Emergence

AGENTS CAN WORK AS noninteractive individuals or as a collective. When agents work as individuals with little or no interaction, what you get is just that: agents simply doing what they are asked to do. As a collective, however, something new and different can result—something that is more than the sum of the individual participants. The stock market, immune systems, and ant colonies are all examples of agents acting individually, yet from the interactions of these agents a new phenomenon arises. With the stock market, thousands of agents act independently to buy and sell shares of particular stocks and bonds. Yet from this independent behavior, an organism-like product called the stock market emerges. In other words, the rise and fall of the market is not controlled by a central process: it results from agents interacting. The stock market crash of '29 was a result of individual human agents—not a central controller. The crash of October '87 partly resulted from individual software agents that buy and sell securities according to programmed rules. The stock market, its crashes, temporary bubbles, dead-cat bounces, and all are more than the sum of the parts; it is an entity in its own right. Such entities are called emergent structures. Ant colonies are emergent structures that arise from individual ants acting interactively. The immune system emerges from the collective behavior of agents such as antigens, T cells, B cells, NK cells, immunoglobulins, lymph nodes, and the spleen. Other examples of emergent structures include families, organizations, societies, markets, flocks of birds, and traffic jams.

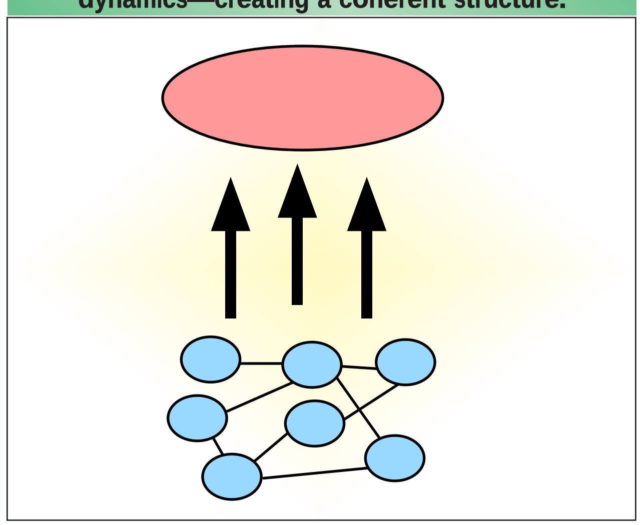
Emergence

> **Emergence is the existence of a coherent pattern that arises out of interactions among simpler objects.**

The diagram in Fig. 1 illustrates this definition. Emergence embodies several properties.

- In emergent structures, agents organize into a whole that is greater than the sum of its parts. In other words, the parts alone do not result in emergent structures—their interaction is required.
- Rules that are almost absurdly simple can generate coherent, emergent phenomena. For example, a neuron by itself has some very simple rules, yet consciousness can emerge from neuron interaction.
- Instead of being designed from top down, most emergent systems emerge from the bottom up. A human engineer would tend to develop top down. This approach can be useful under some circumstances. However, in the world of living systems, most emerge from a population of simpler systems.
- Persistent emergent structures can serve as components of more complex emergent structures. In other words, aggregation hierarchies of emergent structures can be formed.
- Agents and their emergent structure can form a two-way link. Agents can give rise to an emergent structure; the emergent structure can influence its component agents.
- Emergent phenomena are typically persistent patterns with changing components. The birds in a flock or the cars in a traffic jam can change, yet the flock and traffic jam phenomena can remain.
- Collections of agents can be homogeneous or heterogeneous. Emergence can occur due to the interaction of similar agents. More often, though, it occurs as a result of different kinds of agents that function in a society or ecosystem.

Figure 1. Local interaction can give rise to global dynamics—creating a coherent structure.



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In the sections that follow, these properties will be explored in more detail.

Greater than the sum of its parts

Simple-minded reductionism maintains that the whole is simply the sum of its parts. Furthermore, each part can be studied in isolation. However, the parts alone can not produce emergence. Emergent structures also require the collective behavior and interaction of its components. Emergent structures, then, are a process—and the essence of the process is its form, not its parts. Families, organizations, societies, financial markets, schools of fish, and traffic jams are all examples of this phenomenon. A horde of noninteracting web spiders will not produce an emergent structure. However, when an ecosystem of supply-chain software agents can buy and sell goods and services over the web, a "supply web" can emerge.[1] The supply web, then, behaves like a financial market—which does give rise to an emergent structure. Agent-based modeling and bidding systems make this possible.

Simple agent rules can produce emergent structures

A common example of simple rules leading to emergence is that of a flock of birds. Here, each movement of a flock is so beautiful that it appears choreographed. Furthermore, the movements of the flock seem smoother than those of any one bird in the flock. Yet, the flock has no high-level controller or even a lead bird. Each bird follows a simple set of rules that it uses to react to birds nearby. In the flocking simulation of StarLogo (www.media.mit.edu/~starlogo), the birds obey only three rules:

1) If you are far away from other birds, head towards the nearest bird.
2) If you are about to crash into another bird, turn around.
3) Otherwise, fly in the same direction as the bird next to you.

Using these three simple rules, no one bird has a sense of an overall flock. The "bird in front" is merely a position of a given bird. It just happens to be there—and will be replaced by others in a matter of minutes. Flocks of birds are not the only things that work like this. Bee hives, ant colonies, freeway traffic, the Web, and the phenomenon of Silicon Valley are all examples of patterns that are determined by local component interaction, instead of a centralized authority. Complex behavior need not have complex roots.

Top-down versus bottom-up approaches

If you have ever heard classical music or watched a ballet, you will have no doubt that the performances have been orchestrated or choreographed. The centralized, or top-down, development of these kinds of performances is both obvious and necessary. Many of the products we use in everyday life require top-down engineering to be effective. However, most of the emergent phenomena we experience do not occur as a result of top-down efforts; instead, they are the result of decentralized, or bottom-up, processes. For example, the flock of birds mentioned above emerges without an organizer and behaves without a coordinator. So, too, does the applause that follows a classical concert or ballet.

Today, many resource providers and manufacturers are exploring the possibilities of employing a decentralized approach. Many of these organizations are already adopting solutions that will replace their central, globally optimized operations with a distributed, self-organizing, local one. John Holland is fond of pointing out that New York City maintains a two-week supply of food with only locally made decisions. Companies, such as Boeing, John Deere & Company, and Detroit Edison, are beginning to do this.

Both centralized and decentralized approaches are useful techniques. Using one technique and not the other limits the possibilities of a system. Often, our human bias toward centralization precludes the consideration of decentralized solutions. For example, three-year old Rachel developed the theory that clouds rain when the thunder commands them.[2] At four, she developed a new theory: "The clouds get together at night and decide whether or not it should rain the next day." People resist decentralization. When people see a pattern, they often assume a centralized control. This does not mean that centralized theories are wrong, it is just that they are not always appropriate:

- A central agent is a single point of failure that makes the system vulnerable to accident.
- Under normal operating conditions, a central agent can easily become a performance bottleneck.
- Even if it is adequately scaled for current operations, a central agent provides a boundary beyond which the system cannot be expanded.
- For software agents, it tends to attract functionality and code as the system develops, pulling the design away from the benefits of agents and in time becoming a large software artifact that is difficult to understand and maintain.

Emergent structures can themselves be components

One of the most difficult challenges for automated systems is scalability. Living systems provide some excellent examples of scaling up. In the physical systems leading up to life, for example, subatomic particles form atoms, and atoms cluster to become molecules in solid, liquid, and gaseous form. Continuing up this hierarchy, molecules can be organized to form organelles, organelles can group to form cells, cells can aggregate to form organisms, and so on. In other words, living systems and their components emerge in a hierarchy of interlocking mechanisms. In the domain of human organization, similar hierarchies occur as illustrated in

Figure 2. Parallels between business and biology.

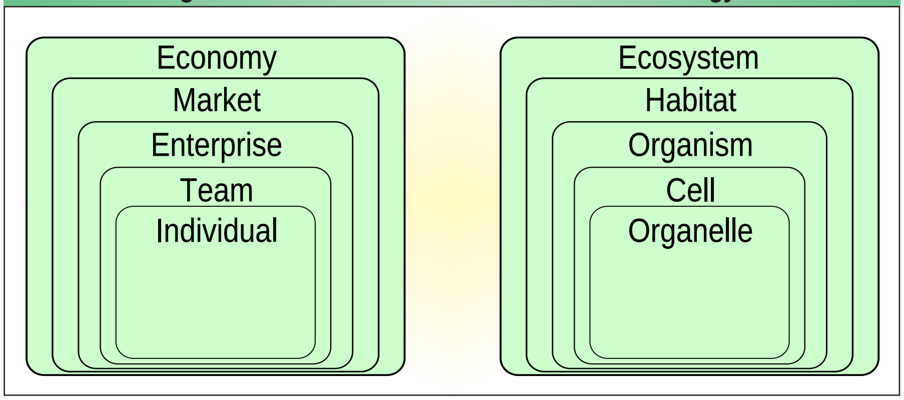


Fig. 2. Here, economies emerge from markets, which emerge from enterprises, and so on.[3]

In a very general sense, complex adaptive systems are large and intricate systems involving active, autonomous agents. Such a hierarchy is a necessary—and some say, a natural—occurrence for complex adaptive systems. Emergence provides the mortar between the bricks to construct viable structures. Furthermore, the new structures can become building blocks for even larger structures—where each level of the hierarchy is very different from the one before and the one after it. Such a hierarchy of interlocking mechanisms is also an appropriate technique for automated agents.

Agents and their emergent structure can form a two-way link

Applause occurs when spectators join in what appears to be spontaneous synchronized clapping. There is no conductor that coordinates this. When everyone starts, the clapping is totally unorganized. Each person's tempo is wildly out of phase with the next person. Eventually groups of people begin clapping at the same tempo. People in the audience sense the emerging rhythms and adjust their clapping to join it. The emerging applause rhythm grows even stronger and more people conform to it. Eventually, the entire audience is clapping in a synchronized pattern. This entire process can take place in a matter of seconds with even thousands of individuals.

We have been exploring how the local interaction and behavior of agents can produce global dynamics of emergent structures. In the example of spectator applause, the interaction of humans in the audience produced the dynamics of applause. However, there was another phenomenon occurring in this example: individually, the spectators adjusted their applause rhythm based on the applause that they heard. In other words, local interaction can give rise to global dynamics; and the global dynamics, in turn, can influence the local interaction. As illustrated in Fig. 3, emergent structures can be linked to their local agent interaction:

- This link influences the boundary conditions of the local agents.
- Local agents can then adjust to the presence of the global dynamics.
- Consequently, the conditions under which the agent behaves might change.

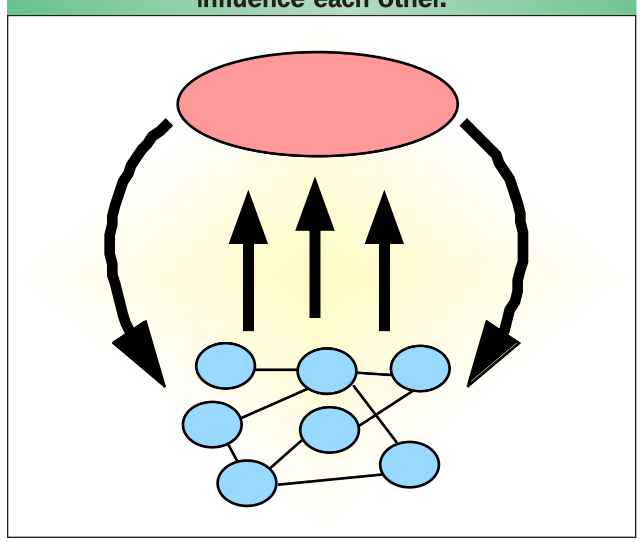
Emergent structures can have components that change

The birds in a flock or the cars in a traffic jam can change, yet the flock and traffic jam phenomena can remain. The same applies to the stock market and supply-chain webs. Just because an emergent structure exists and is stable does not mean that its components cannot change over time. Each of us replaces all the atoms in our body every three years, yet we are still considered to be the same being. Many companies have more turnover than this, while still being recognized as the same organization. Change in the underlying agent population is not required for emergence, but it is a common phenomenon.

Homogeneous and heterogeneous collections of agents

Some emergent structures consist of single kind of agent. For example, a flock of birds consists only of birds. Here, each agent plays the same role. Homogeneous agent collections can still have a single kind of agent, yet its agents can play different roles. For instance, an ant colony can have ants that play different roles. An ant can be a patrolling ant that guards the nest, a nest-maintenance worker, forager, brood-care worker, and so on. Furthermore, an ant can change its role depending on the requirements of the colony. For instance, a nest-maintenance

Figure 3. Local interaction and global dynamics can influence each other.



worker can become a forager or a patrolling ant when the need for food or security becomes more important.

Heterogeneous collections of agents also play different roles because they contain different kinds of agents. The major difference is that in a heterogeneous collection, agents are different in both structure and behavior. For example, the immune system emerges from the collective behavior of various kinds of agents such as antigens, T cells, B cells, NK cells, immunoglobulins, lymph nodes, and the spleen. T cells and B cells not only play different roles, their structure and behavior is also different enough to be considered heterogeneous.

When we construct complex business systems, we need to think of agents as functioning as a society or ecosystem. In designing such systems, we need to consider how we can effectively employ homogeneous and heterogeneous agents.

Conclusion

When constructing agent systems, you should regard emergence as an important concept. Typically, emergence happens unpredictably. However, you can try to "design in" the emergence that you want. Simply define the desired end-product (top down) and then try to design the agents that will yield the desired result (bottom up). In other words, try to design the agents so that the desired structure emerges. Common techniques include neural networks and genetic algorithms, where you can literally guide the learning or evolution of an agent towards the goal. For example, you may want to create a society of agents to buy and sell electrical power in a way that ensures a reliable and economic source of electricity to the end-customer. Agents may be "trained" or "bred" to accomplish this.

In summary:

- You control the action of the parts, not the whole.
- Self-organizing patterns are created without a central designer.
- You must have enough agents acting in parallel to get a "critical mass." A colony of ten ants will not suffice.
- The parts must be interacting—parallelism is not enough. Without interactions, interesting colony-level behaviors will never arise.
- Remember: a flock is not a big bird and a traffic jam is not just a collection of cars.

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