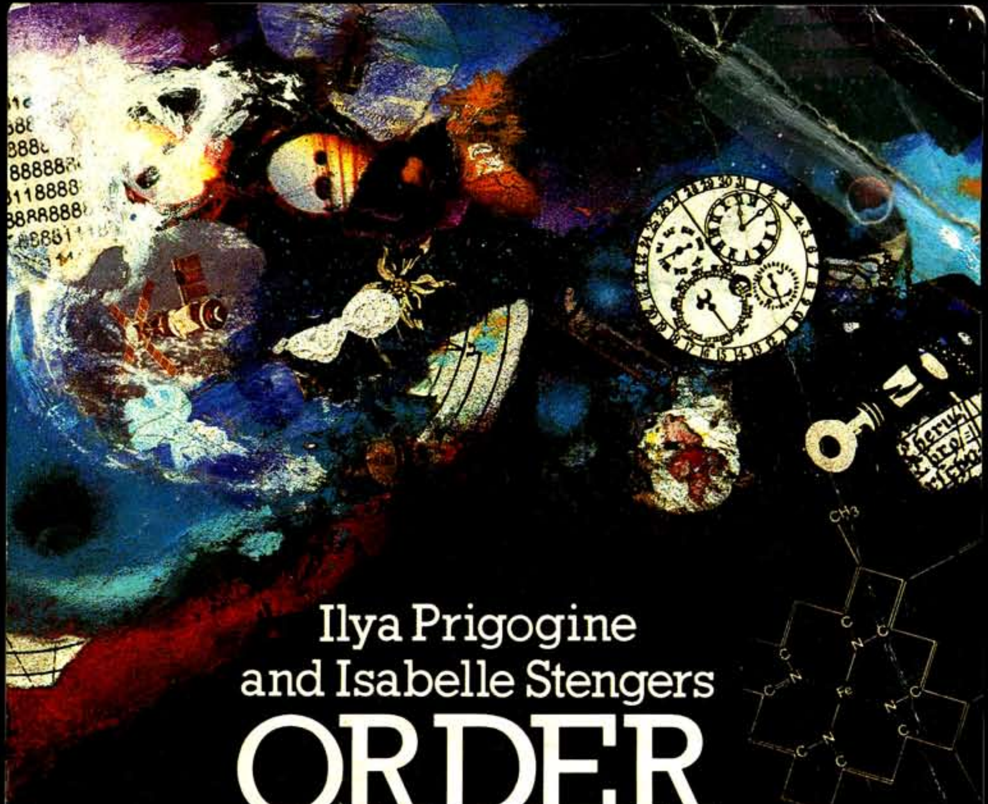

Ilya Prigogine
and Isabelle Stengers

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Logistic Evolution

In social cases, the problem of structural stability has a large number of applications. But it must be emphasized that such applications imply a drastic simplification of a situation defined simply in terms of competition between self-replicating processes in an environment where only a limited amount of the needed resources exists.

In ecology the classic equation for such a problem is called the "logistic equation." This equation describes the evolution of a population containing N individuals, taking into account the birthrate, the deathrate, and the amount of resources available to the population. The logistic equation can be written $dN/dt = rN(K-N) - mN$, where r and m are characteristic birth and death constants and K the "carrying capacity" of the environment. Whatever the initial value of N, as time goes on it will reach the steady-state value $N = K - m/r$ determined by the differences of the carrying capacity and the ratio of death and birth constants. When this value is reached, the environment is saturated, and at each instant as many individuals die as are born.

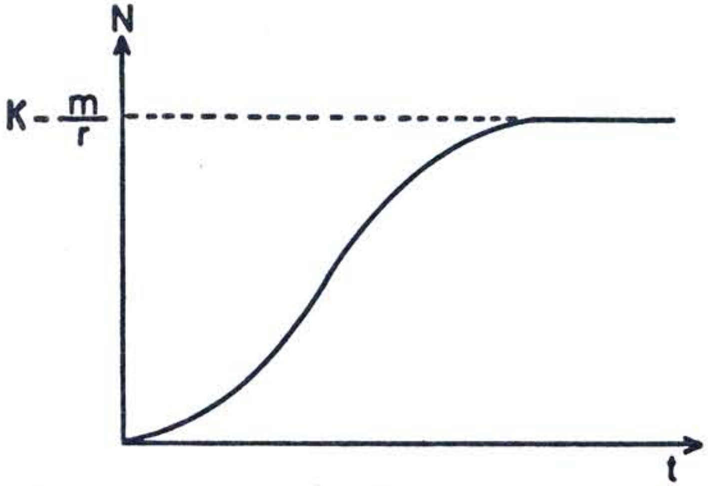


Figure 20. Evolution of a population N as a function of time t according to the logistic curve. The stationary state $N=0$ is unstable while the stationary state $N=K-m/r$ is stable with respect to fluctuations of N.

The apparent simplicity of the logistic equation conceals to some extent the complexity of the mechanisms involved. We have already mentioned the effect of external noise, for example. Here it has an especially simple meaning. Obviously, if only because of climatic fluctuations, the coefficients K, m, and r cannot be taken as constant. We know that such fluctuations can completely upset the ecological equilibrium and even drive the population to extinction. Of course, as a result, new processes, such as the storage of food and the formation of new colonies, will begin and eventually evolve so that some effects of external fluctuation may be avoided.

But there is more. Instead of writing the logistic equation as continuous in time, let us compare the population at fixed time intervals (for example, separated by a year). This "discrete" logistic equation can be written in the form $N_{t+1} = N_t(1 + r[1 - N_t/K])$, where N_t and N_{t+1} are the populations separated by a one-year interval (we neglect here the death term). The remarkable feature, noted by R. May,[8] is that such equations, in spite of their simplicity, admit a bewildering number of solutions. For values of the parameter $0 \leq r \leq 2$, we have, as in the continuous case, a uniform approach to equilibrium. For values of r lower than 2.444, a limit cycle sets in: we now have a periodic behavior with a two-year period. This is followed by four-, eight-, etc., year cycles, until the behavior can only be described as chaotic (if r is larger than 2.57). Here we have a transition to chaos as described in Chapter V. Does this chaos arise in nature? Recent studies[9] seem to indicate that the parameters characterizing natural populations keep them from the chaotic region. Why is this so? Here we have one of the very interesting problems created by the confluence of evolutionary problems with the mathematics produced by computer simulation.

Up to now we have taken a static point of view. Let us now move to mechanisms, whereby the parameters K, r, and m may vary during biological or ecological evolution.

We have to expect that during evolution the values of the ecological parameters K, r, and m will vary (as well as many other parameters and variables, whether they are quantifiable or not). Living societies continually introduce new ways of exploiting existing resources or of discovering new ones (that is, K increases) and continually discover new ways of extending their lives or of multiplying more quickly. Each ecological equilibrium defined by the logistic equation is thus only temporary, and a logistically defined niche will be occupied successively by a series of species, each capable of ousting the preceding one when its "aptitude" for exploiting the niche, as measured by the quantity $K-m/r$, becomes greater. (See Figure 21.) Thus the logistic equation leads to the definition of a very simple situation where we can give a quantitative formulation of the Darwinian idea of the "survival of the fittest." The "fittest" is the species for which at a given time the quantity $K-m/r$ is the largest.

As restricted as the problem described by the logistic equation is, it nonetheless leads to some marvelous examples of nature's inventiveness.

Take the example of caterpillars, who must remain undetected, since the slowness of their movement makes escape impossible.

The evolved strategies of using poisons and irritating hairs and spines, as well as intimidating displays, are highly effective in repelling birds and other potential predators. But none

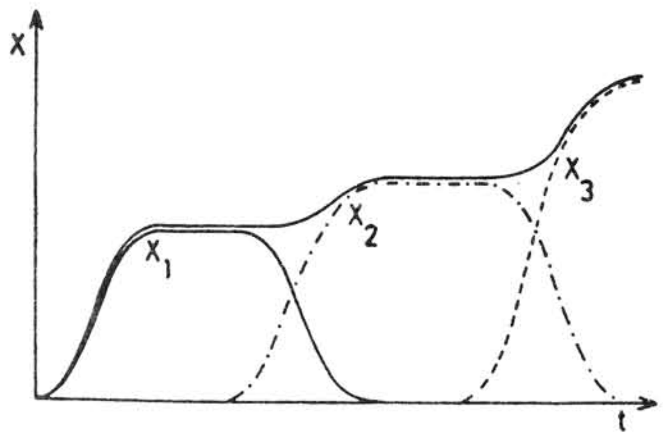


Figure 21. Evolution of total population X as function of time; the population is made up by species X_1, X_2 and X_3, which appear successively and are characterized by increasing values of $K-m/r$ (see text).

of these strategies is effective against all predators at all times, particularly if a predator is hungry enough. The ideal strategy is to remain totally undetected. Some caterpillars approach this ideal, and the variety and sophistication of the strategies used by the hundreds of lepidopteran species to remain undetected bring to mind the words of distinguished nineteenth-century naturalist Louis Agassiz: "The possibilities of existence run so deeply into the extravagant that there is scarcely any conception too extraordinary for Nature to realize."[10]

We cannot resist giving an example reported by Milton Love.[11] The sheep liver trematode has to pass from an ant to a sheep, where it will finally reproduce itself. The chances of sheep swallowing an infected ant are very small, but the ant behaves in a remarkable way: it starts to maximize the probability of its encounter with a sheep. The trematode has truly "body snatched" its host. It has burrowed into the ant's brain, compelling its victim to behave in a suicidal way: the possessed ant, instead of staying on the ground, climbs to the tip of a blade of grass and there, immobile, waits for a sheep. This is indeed an incredibly "clever" solution to the parasites problem. How it was selected remains a puzzle.

Other situations in biological evolution may be investigated using models similar to the logistic equation. For instance, it is possible to calculate the conditions of interspecies competition under which it may be advantageous for a fraction of the population to specialize in warlike and nonproductive activity (for example, the "soldiers" among the social insects). We can also determine the kind of environment in which a species that has become specialized, that has restricted the range of its food resources, will survive more easily than a nonspecialized species that consumes a wider range of resources.[12] But here we are approaching some very different problems, which concern the organization of internally differentiated populations. Clear distinctions are absolutely necessary if we are to avoid confusion. In populations where individuals are not interchangeable and where each, with its own memory, character, and experience, is called upon to play a singular role, the relevance of the logistic equation and, more generally, of any simple Darwinian reasoning becomes quite relative. We shall return to this problem.

It is interesting to note that the type of curve represented in

Figure 21 showing the succession of growths and peaks defined by a given logistic equation's family with increasing $K-m/r$ has also been used to describe the multiplication of certain technical procedures or products. Here too, the discovery or introduction of a new technique or product breaks some kind of social, technological, or economic equilibrium. This equilibrium would correspond to the maximum reached by the growth curve of the techniques or products with which the innovation is going to have to compete and that play a similar role in the situation described by the equation.[13] Thus, to choose but one example, not only did the spread of the steamship lead to the disappearance of most sailing ships, but, by reducing the cost of transportation and increasing its speed, it caused an increase in the demand for sea transport *("K")* and consequently an increase in the population of ships. We are obviously representing here an extremely simple situation, supposedly governed by purely economic logic. Indeed, in this case innovation seems merely to satisfy, albeit in a different way, a preexisting need that remains unchanged. However, in ecology as in human societies, many innovations are successful without such a preexisting "niche." Such innovations transform the environment in which they appear, and as they spread, they create the conditions necessary for their own multiplication, their "niche." In social situations, in particular, the creation of a "demand," and even of a "need" for this demand to fulfill, often appears as correlated with the production of the goods or techniques that satisfy the demand.

Evolutionary Feedback

A first step toward accounting for this dimension of the evolutionary process can be achieved by making the "carrying capacity" of a system a function of the way it is exploited instead of taking it as given.

In this way some supplementary dimensions of economic activities, and more particularly the "multiplying effects," can be represented. Thus we can describe the self-accelerating properties of systems and the spatial differentiation between different levels of activity.

Geographers have already constructed a model correlating these processes, the Christaller model, defining the optimal spatial distribution of centers of economic activity. Important centers would be at the intersection of an hexagonal network, each being surrounded by a ring of towns of the next smallest size, each being, etc. . . . Obviously, in actual cases, such a regular hierarchical distribution is very infrequent: historical, political, and geographical factors abound, disrupting the spatial symmetry. But there is more. Even if all the important sources of asymmetrical development were excluded and we started from a homogeneous economic and geographical space, the modeling of the genesis of a distribution such as defined by Christaller establishes that the kind of static optimalization he describes constitutes a possible but quite unlikely result of the process.

The model in question[14] stages only the minimal set of variables implied by a calculation such as Christaller. A set of equations extending the logistic equations is constructed, starting from the basic supposition that populations tend to migrate as a function of local levels of economic activity, which thus define a kind of local "carrying capacity," here reduced to an "employment" capacity. But the local population is also a potential consumer for locally produced goods. We have, in fact, a double positive feedback, called the "urban multiplier," for a local development: both the local population and the economic infrastructure produced by the already attained level of activity accelerate the increase of this activity. But each local level of activity is also determined by competition with similar centers of activity located elsewhere. The sale of produced goods or services depends on the cost of transporting them to consumers and on the size of the "enterprise." The expansion of each such enterprise depends on a demand that this expansion itself helps to create and for which it competes. Thus the respective growth of population and manufacturing or service activities is linked by strong feedback and nonlinearities.

The model starts with a hypothetical initial condition, where "level 1" activity (rural) exists at the different points; it then permits us to follow successive launchings of activities corresponding to "superior" levels in Christaller's hierarchy—that is, implying exportation on a greater range. Even if the initial

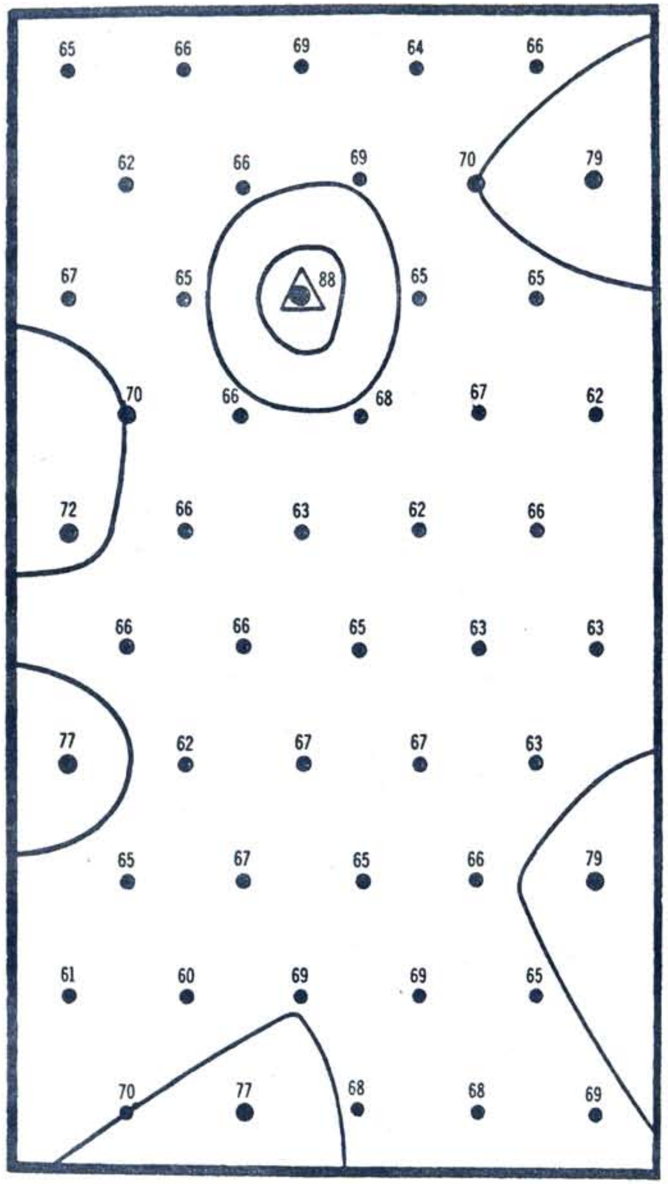
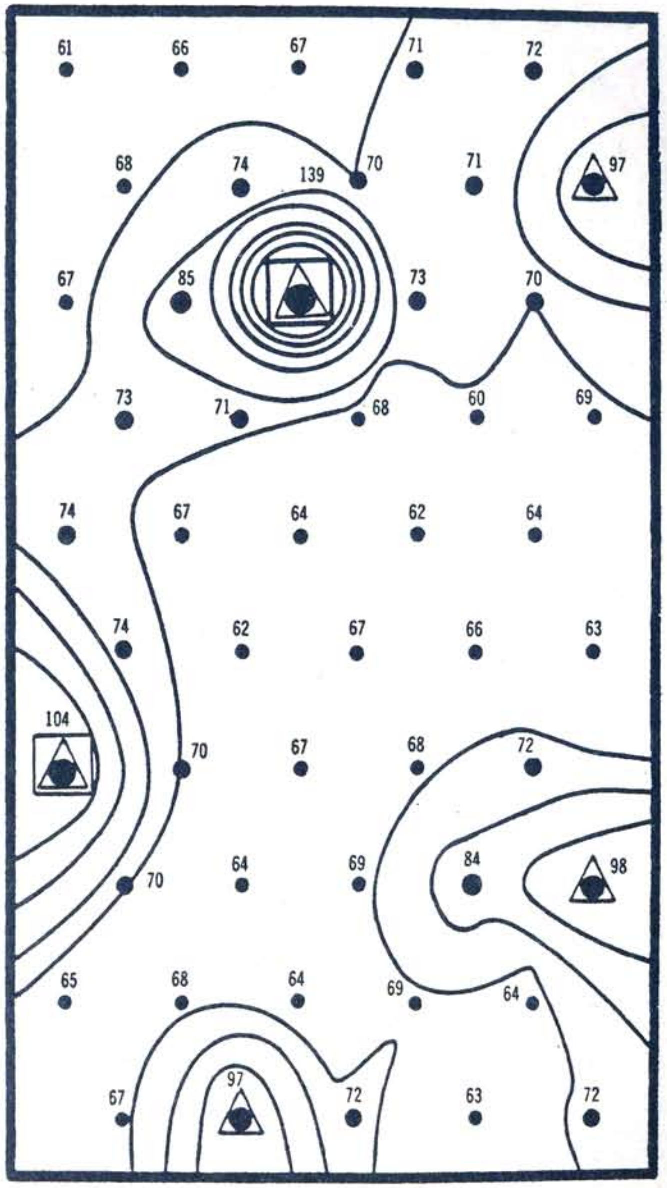
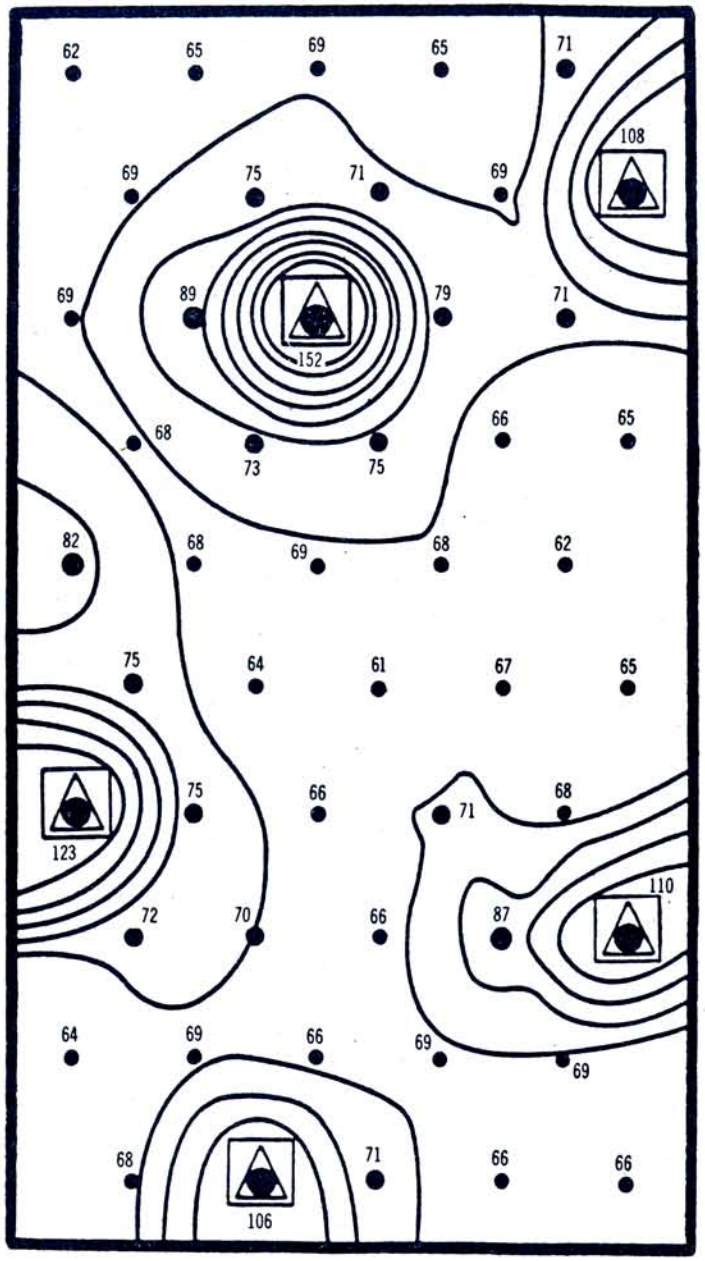


Figure 22. A possible history of "urbanization." ● have only function 1; ● have functions 1 and 2; △ have functions 1, 2 and 3. [△] are the largest centers, with functions 1, 2, 3, and 4. At $t=0$ (not represented), all points



have a "population" of 67 units. At C, the largest center is going through a maximum (152 population units); this is followed by an "urban sprawl," with creation of satellite cities; this also occurs around the second main center.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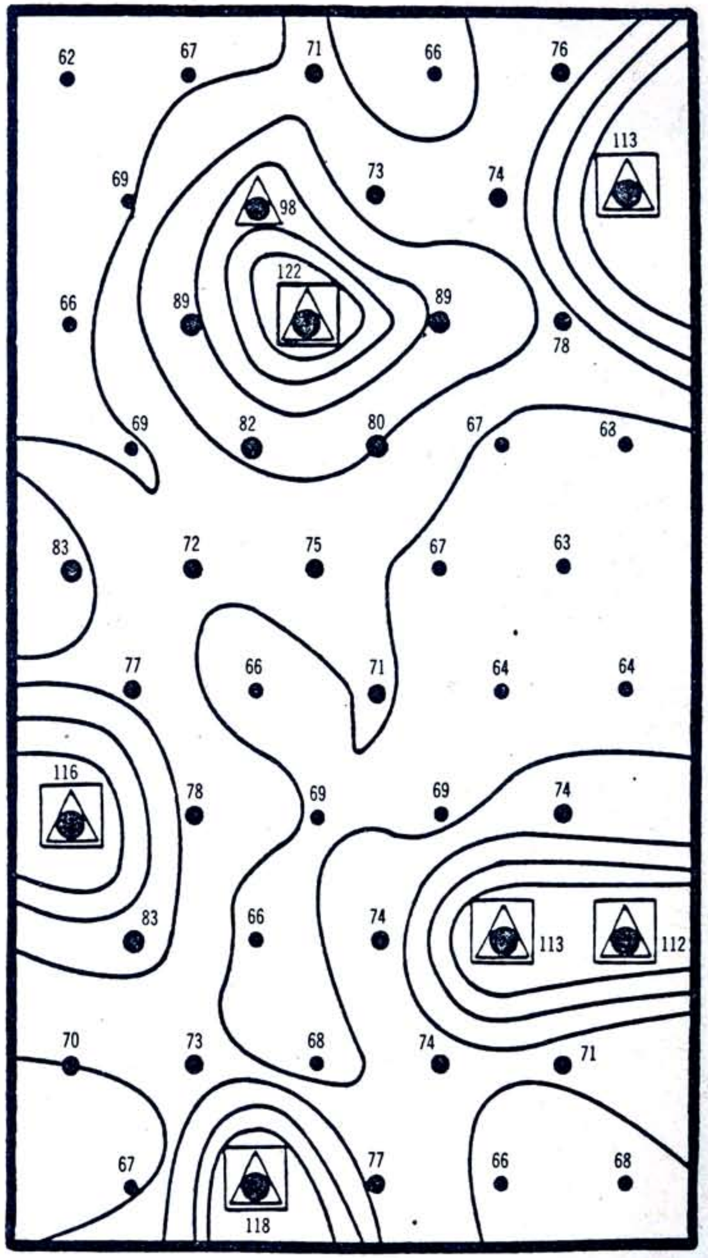
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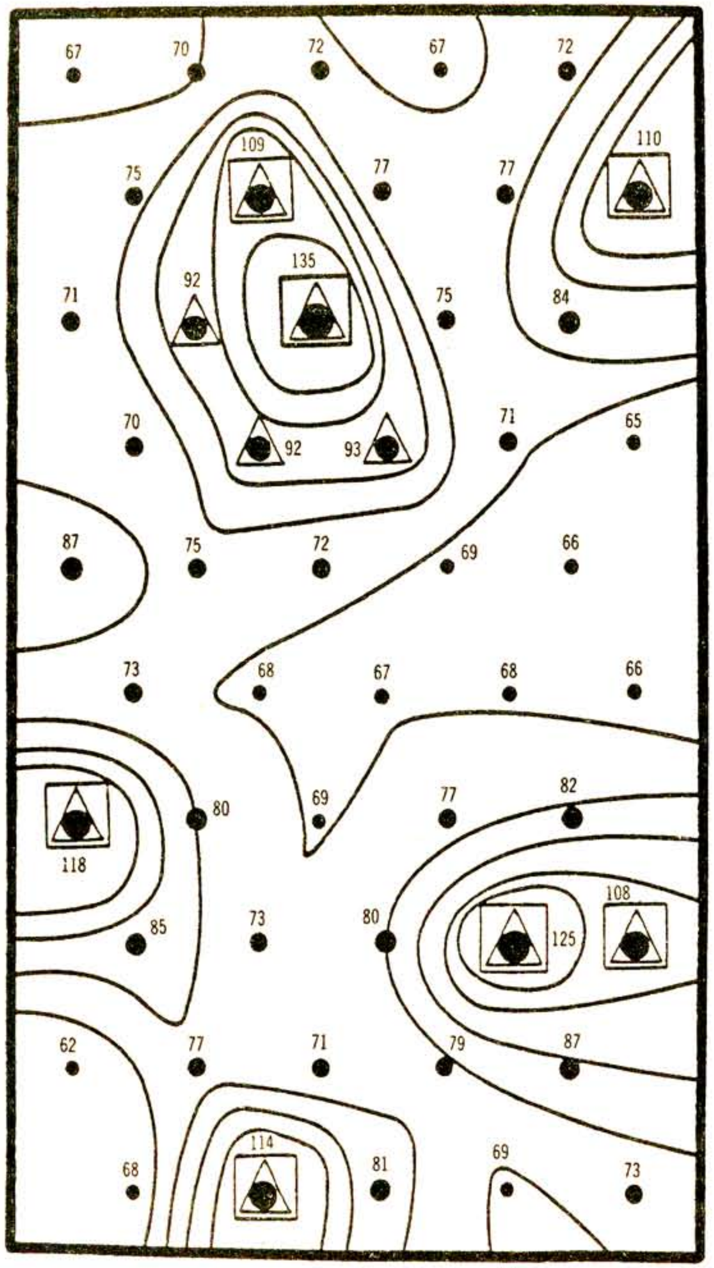

state is quite homogeneous, the model shows that the mere play of chance factors—factors uncontrolled by the model, such as the place and time where the different enterprises start—is sufficient to produce symmetry breakings: the appearance of highly concentrated zones of activity while others suffer a reduction in economic activity and are depopulated. The different computer simulations show growth and decay, capture and domination, periods of opportunity for alternative developments followed by solidification of the existing domination structures.

Whereas Christaller's symmetrical distribution ignores history, this scenario takes it into account, at least in a very minimal sense, as an interplay between "laws," in this case of a purely economic nature, and the "chance" governing the sequence of launchings.

Modelizations of Complexity

In spite of its simplicity, our model succeeds in showing some properties of the evolution of complex systems, and in particular, the difficulty of "governing" a development determined by multiple interacting elements. Each individual action or each local intervention has a collective aspect that can result in quite unanticipated global changes. As Waddington emphasized, at present we have very little understanding of how a complex system is likely to respond to a given change. Often this response runs counter to our intuition. The term "counterintuitive" was introduced at MIT to express our frustration: "The damn thing just does not do what it should do!" To take the classic example cited by Waddington, a program of slum clearance results in a situation worse than before. New buildings attract a larger number of people into the area, but if there are not enough jobs for them, they remain poor, and their dwellings become even more overcrowded.[15] We are trained to think in terms of linear causality, but we need new "tools of thought": one of the greatest benefits of models is precisely to help us discover these tools and learn how to use them.

As we have already emphasized, logistic equations are most relevant when the crucial dimension is the growth of a popula-