Keywords of Systemic Vision is meant to be an encyclopedia of Systemic and Complex science. The word “encyclopedia” refers to definitely acquired information and deep knowledge in a given domain, so that also people who do not belong to the related scientific community can rely on accurate representations of that object. However, Complexity science refers to phenomena, for which it is impossible to find objective information, for reasons such as chaotic evolution, high number of variables, observers’ bias etc. Consequently, the expectations of an encyclopedia of Complexity science should be different from those of a traditional one: this work highlights the incertitude that has always affected complex phenomena, as well as the ways of dealing with this incertitude in very different scientific domains.

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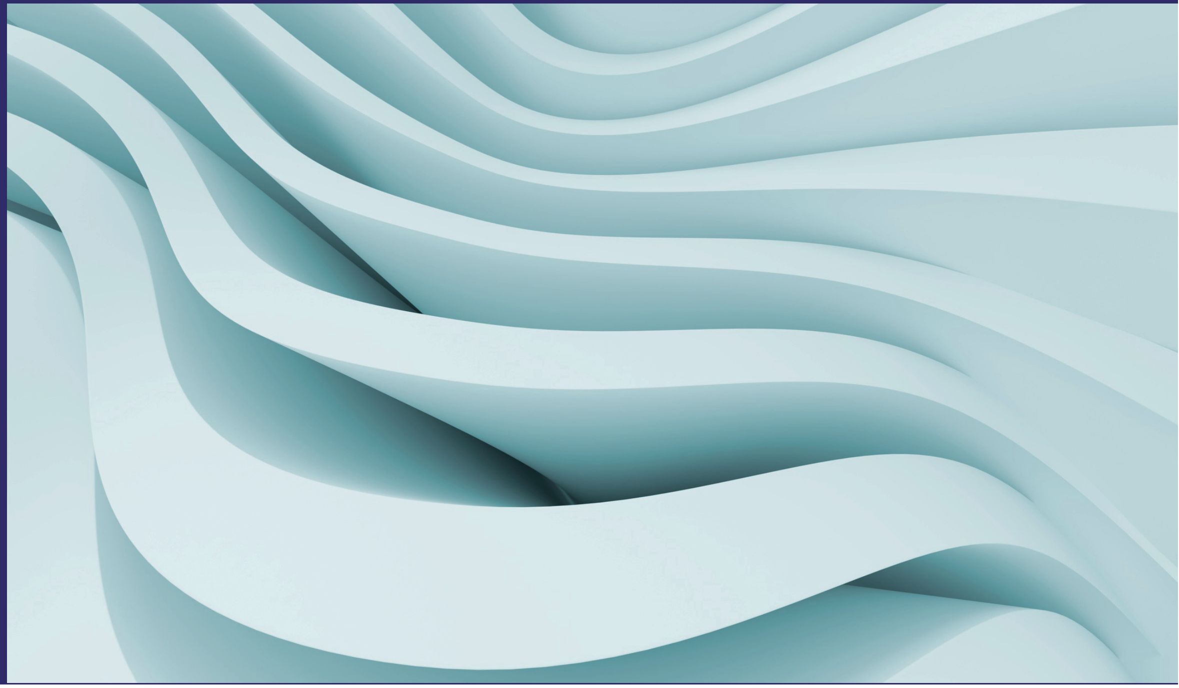

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CHAOS (A. Trobia)

The term *chaos* refers to a particular type of behaviour that characterizes nonlinear dynamic systems with specific features. «In its essence, chaos is an irregular oscillatory process» (Brown, 1995, 8).

A system is said *nonlinear* when its outputs are not proportional to its inputs; in mathematical terms, when the equations that describe the system have at least one term raised to the second power. Nonlinearity, however, does not guarantee alone a chaotic behaviour. Other conditions must hold. We should distinguish, in this case, between *continuous* and *discrete* models, the former kind of models, that employ *differential* equations to describe the system, must have at least three independent variables in order to display a chaotic behaviour (Baker and Gollub, 1996; 2); while the latter, that employ *difference* equations, must contain at least an *iterative* term (that is, the dependent variable at time t+1 must be a function of the dependent variable at time t, then mimicking a feedback loop).

Dynamic systems, on the other hand, are systems whose states change over time, evolving and adapting to the environment. They are studied by *System Dynamics*: «a target system, with its properties and dynamics, is described using a system of equations which derive the future state of the target system from its actual state» (Gilbert e Troitzsch, 2005; 28). Dynamism strongly characterizes living systems and society, and it often takes the form of a *periodic* (i.e. *oscillatory*) behaviour. Many behaviours that are repeated over time, such as going to work, eating, buying the newspaper, or going on holiday, can be interpreted as a form of oscillatory behaviour. This latter is one of the factors that may favour chaos; in particular, irregular oscillatory behaviour.

Chaos has three fundamental characteristics, (1) sensitivity to initial conditions; (2) irregular periodicity; (3) lack of predictability.

Sensitivity to initial conditions means that even very small differences in the initial condition of a system may produce large variations in its long term behaviour. Sensitivity to initial conditions, then, makes the system *dissipative*; that is, irreversible. Once the system has begun to follow a certain trajectory, it is almost impossible to return back, because its initial conditions are likely to be changed. «This point has obvious implications for social scientists as we explore how virtually identical systems generate unique histories» (Kiel and Elliott, 1996; 25). Sensitivity to initial conditions is also known as the *butterfly effect*. A butterfly flapping its wings in Rio, as they say, can cause a typhoon in Texas. If this is true, even smallest *noises* must be taken into account when modelling the system. Measurement errors or noise, besides, can -and does- sometimes lead to the erroneous conclusion that a dynamic system is exhibiting chaos (Sugihara and May, 1990). Since noise is omnipresent, discovering *real* chaotic behaviours in physical and social systems is often quite difficult.

In spite of what appears, chaos is not *randomness*. The term *deterministic* chaos explains this concept. Chaos is, in fact, a particular type of *irregular periodicity*; the sum of several frequencies (harmonics) that yield an apparently irregular behaviour. This can be formalized in the following formula (see Brown, 1995, 28),

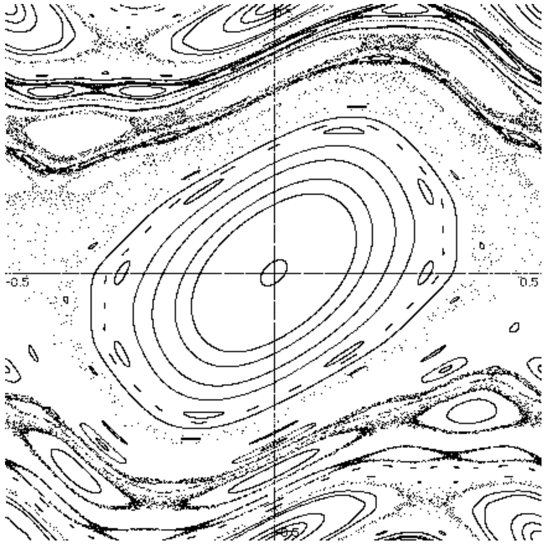
$$f(t) = a_0 + \sum_{n=1}^{\infty}[a_n \cos(\omega nt) + b_n \sin(\omega nt)]$$

Fourier (or *spectral*) *analysis* is used to detect the different frequencies that summed together may yield a particular irregular periodicity. An irregular time series, in fact, can simply be the outcome of a very small set of harmonics. All of these frequencies can be plotted in a *periodogram*, showing the amplitude and the values of the frequencies that fit a given time series, the so-called *spectrum* (see also McBurnett, 1996a).

Thirdly, as said, chaos means lack of predictability. Actually, chaos exhibits a*bounded unpredictability*, which is proved by the presence of attractors in the system.

In order to detect an attractor, a *phase space portrait* of the system should be constructed (see Fig. 1). This is an essential tool for the so-called *qualitative analysis* of a dynamic system. The phase space portrait is a «mathematical space with orthogonal coordinate directions representing each of the variables needed to specify the instantaneous state of the system» (Baker e Gollub, 1996; 7). It shows the behaviour of the system when time tends to infinity. The analysis of the phase space portrait makes it possible to reveal hidden periodicities or patterns, in the form of attractors, within a behaviour that appears unpredictable.

Figure 1 – A phase state portrait with many attractors



An attractor is a particular concentration of points in a phase state portrait. This concentration of points represents a provisional area of stability in the motion of the system. Attractors may show various shapes: points, circles, bows, fractals, etc. Some of them are called *strange attractors*, because of their shape. Moreover, certain systems may reveal *multiple* strange attractors (see Fig. 1).

Collecting and describing the attractors of different dynamical systems is one of the main goals of chaos theory. A goal that recalls the Simmelian idea of a formal sociology (Trobia, 2001). Harvey and Reed (1996; 309) have used the expression “pictorial method” to describe this perspective; a method based on visual correspondences rather than deductive reasoning. «While predictive and statistical models are well established in the social sciences, a third modelling strategy, iconological modelling, is only now coming into its own. It represents a radical epistemological break in the type of knowledge it provides to researchers (...) originating in the iterative mapping of complex systems equations - such as the nonlinear differential equations that generate the quadratic iterator, or the so-called strange attractors» (ibid., 309-310).

The discovery of chaos was made possible only by the advent of computer, in the mid-1970s. Most equations (or systems of equations) that describe chaotic systems, in fact, have no analytical solutions. The only way to study such equations is to input the parameters values and calculate step-by-step the subsequent values of the dependent variables, in an iterative process, displaying system changes graphically (some scholars use, in this case, the expression "geometry of behaviour"). Thanks to the huge power of modern computers, then, it became possible to draw and study the trajectories of chaos, along millions of iterations.

The presence of chaos in a system is determined by various factors; *positive feedbacks* are, however, the main responsible for chaos, as in the logistic *map* (the term map, instead of function, is used in discrete models). One of the most well-studied models of chaos is a general form of logistic map, whose chaotic properties were first investigated by May (1976). Logistic maps are particularly interesting, because they allow to model inversely interactive systems such as predator vs. prey, birth vs. death, or message vs. noise. The general form of the logistic map formalizes a simple feedback process,

$$Y_{t+1} = aY_t(1 - Y_t)$$

where a is a constant multiplier, the rate of growth of a resource in a system (e.g. food, space, information, people, etc.) or, more generally, the influence of the environment upon it; Y_t is the state of the system at time t, ranging from 0 to 1 (e.g. the *carrying capacity* of the system); Y_{t-1} is the state of the system at time $t+1$; and $(1 - Y_t)$ is a simple, limiting, homeostatic factor. May discovered that, when the value of a is more than 3.57, the resulting behaviour is chaotic. A chaotic, unpredictable behaviour, then, may be yielded by a simple *deterministic* process.

The study of chaos can be carried out following two basic perspectives (Brown, 1995; 22): (1) analyzing actual time series, within which one suspects a chaotic deterministic process may exist; or (2) specifying a set of equations that describe the behaviour of a particular system. The first approach is mainly used in the social sciences. *Phase-state portraits*, *Spectral analysis*, *Lyapunov exponents*, *nearest neighbour techniques*, and *correlation dimension* are commonly used, in order to identify chaotic processes within actual time series.

As we have seen, the phase state portrait is the first, simple tool used in order to detect chaos. Spectral analysis, on the other hand, can be useful if we suspect that a certain behaviour is determined by a particular sum of periodic trends (frequencies).

Lyapunov exponents, instead, are used to measure the extent to which small changes in the initial conditions of the system generate large scale divergence over time. They are interpreted as a loss in predictive power, measured in bits per iteration. For example, a Lyapunov exponent equal to 0.2, measured on a monthly time series, indicates a loss in predictive power of 0.2 bits each month. All the information is lost in 1/0.2 = 5 months. There are as many Lyapunov exponents as there are dimensions, which correspond to the number of equations, in the model of the system (Brown, 1995; 22). They can be positive, negative, or zero. «Positive Lyapunov exponents indicate divergence from initial conditions (the chaotic requirement). Negative values for the exponents indicate convergence, and zero indicates neither divergence or convergence, that is, constancy» (ibid., 22). Chaos requires at least one positive Lyapunov exponent. The largest one determines the severity of the local divergences from the attractor (ibid., 25).

Nearest neighbour techniques use the idea of attractors. If there are chaotic attractors, the next state of a system may be predicted by examining the history of its near neighbours, because they are all drawn towards the same attractor(s) (Jadiz, 1996).

Finally, the correlation dimension is an experimental measure that determines the dimension of the attractor numerically. When the correlation dimension value is non integer (or greater than about five (Sprott and Rowlands, 1995; 25)) the dynamics of the system is governed by a nonlinear process and the attractor is a strange attractor (McBurnett, 1996; 182). Moreover, the next-largest integer value greater than the dimension of the attractor tells us the maximum number of variables needed to model the behaviour of the system (ibid.). For example, if the correlation dimension is equal to 2.37, we need three variables (and three equations) in order to specify a model of the system.

All of these techniques, though, require the availability of very large runs of time specified measurements of a kind which are generally not available for social time series (Byrne, 1997). This has strongly delayed the application of chaos theory in sociology until now, though it seems the situation might soon change, thanks to a different attitude of social researchers towards the collection and analysis of longitudinal and big data.

But how frequent is chaos in society? Living systems and societies lie all in a transition space, between chaos and predictable stability, called the *edge of chaos* (i.e. *complexity*) (Langton, 1990). The attractor of a system provides enough stability to store information, and at the same time is a source of uncertainty. «Complex systems outcomes typically cannot be predetermined, yet there is a sense of the predictable about them; their dynamics don't necessarily favour efficiency; and once a stability is established, the system tends to lock in to that steady state and to exclude other possible steady states. The emergence of educational movements, culture, organization, organizational climate, roles, and technologies can all be described by complexity» (Marion, 1999; 27).

Chaos and complexity has been popularized by a number of books, articles and even movies (e.g. Gleick, 1987; Waldrop, 1992). Methodologies and research in the field of deterministic chaos, however, is still under scrutiny, though some applications of chaos theory in the social sciences are quite promising (see Brown, 1995; Kiel and Elliott, 1996; Eve, Horsfall and Lee, 1997; Marion, 1999; Trobia, 2001). McBurnett (1996b), for instance, has used Lyapunov exponents in order to estimate the American public opinion volatility during the 1984 presidential primary season, criticizing electoral poll reliability, whose results may show even radical opinion shifts in a very short distance of time from each poll. Trobia (2001) used chaos theory in order to analyse the production of laws regarding culture in Sicily, discovering a hidden attractor. Other authors tried to find analogies between chaos theory and classical sociological thought (see, for instance, Staubmann, 1997, in the case of Simmel's "Philosophy of Money", and Bainbridge, 1997, for Homansian sociology). Other applications concern public policies, war, children's friendships, domestic division of labour, the biological foundation of social interaction, collective behaviour following disasters (for all these applications, see the volume edited by Eve, Horsfall and Lee, 1997), organizations (e.g. Marion, 1999), cooperation, competition and evolution (e.g. Beltrami, 1987; Dendrinos, 1992), and many other domains.

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