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Introduction

The aim of this paper is to introduce the non-specialised reader to the field of non-linear dynamics and its relation to environmental problems. For this purpose we will consider historical aspects and use a very simple logistic model, which can be easily simulated even on hand-calculators or spreadsheet-like software's. This in order to illustrate some basic concepts and to allow personal and self-convincing explorations. Non-linear dynamics and its more popularly known aspect "deterministic chaos" is and has been studied in very different areas of human knowledge, both at theoretical and experimental levels. The interested reader is directed to this literature for more detailed discussions (Table 1).

The way we perceive the natural world / universe has a determinant influence on the way we could imagine to operate or to interact with it. It is a relatively modern opinion that the natural world could be pragmatically (rationally?) analysed by the physical sciences. This originates from the fact that physical sciences have successfully predicted and explained in efficient and comprehensive term's very important environmental phenomena as the movement of planets for instance. This scientific success-story has started as early as 1540 with two fundamental technological discoveries both made by Galileo. First, with his telescope and second with the pendulum which settled the basis for human activities synchronisation by dramatically increasing the precision of time measurement [25] and later allowed a novel (and precise) description / division of the geographical world [2,46]. The division of time in small (infinitesimal: *dt*) fragments together with the formulation of the fundamental physical law of forces elaborated by Newton in 1687 [35] allowed the dynamical prediction of planet movements. It is crucial to mention here that the principle is very simple, once the dynamical mathematical equations have been set in this very short time duration (*dt*), and knowing some important parameters (e.g. mass) and the related initial bodies positions, the mathematical tools available allowed to formulate and solve (integrate) the differential equations which could then be used to describe the movement (displacement) of the object in the future (and past...). In brief, dynamics could appear as being the art of predicting the future of a system by the present

† This paper is dedicated *in memoriam* of A. Molinari (1908-1999).

Table 1. Some examples of fields (theoretical and experimental) where non-linear dynamics and deterministic chaos have been studied or evidenced.

Domain	References
Exhaustive bibliography- 1990.	[50]
General books and reviews (multidisciplinary)	[1, 6, 8, 12, 16, 20, 31, 34, 36, 44]
Mathematics & Theroretical Physics	[12, 13, 22, 32, 37, 38]
Quantum physics	[23, 26]
Physics	[13, 27, 36, 44]
Chemistry	[1, 48, 49]
Biology & human Physiology	[9, 15, 18, 21, 43]
Metabolism & cellular activities	[9, 19]
Epidemiology & Ecology	[5, 14, 42]
Environment (climate)	[3, 17, 30, 31, 40, 47]
Astronomy	[29]
Economics	[4, 33]

instantaneous knowledge of some of its parameters once we can formulate the law of the forces acting upon it. With its "predicting power", it is retrospectively clear that the impact of this scientific success-story has diffused to other apparently unrelated fields including human sciences. This even if it was already known for "informed" people that numerous exceptions were existing even in the "exact" sciences (e.g. hydrodynamics). This diffusion in other fields can be summarised by a typical opinion written by Laplace in 1814 [28] (the English translated text is from Holton and May [24]):

The present state of nature is evidently a consequence of what it was in the preceding moment, and if we conceive of an intelligence which at a given instant comprehends of all the relations of the entities of this universe, it could state the respected positions, motions, and general effects of all these entities at any time in the past or future.

An earlier statement with the same content was already presented by Laplace in 1776 (see Dalmedico [7]). With such a (linear) vision, our knowledge should be unlimited, the observed reality that some systems escape our understanding is only attributable to the difficulty of correctly knowing the very fine (and all) details of the system. More precisely, the future outcome is limited by our ignorance. Moreover, to take account for the obvious and commonly observed "erratic" behaviour of systems, a very important and valid method was elaborated and used efficiently still nowadays: probability theory. However, as we shall see it later, in some instances "noise" is not only generated by the complexity of the system but by the inherent properties of the system itself (even very simple) so to appear unpredictable at a given time horizon. An underlying organisation exists (attractor), but the outcome is somewhat uncertain and appears as noisy [41]. Such behaviour is possible even with very simple non-linear fully deterministic systems.

What is a non-linear system?

There is no general agreement for a definitive definition of what precisely is a non-linear system, but we shall introduce the concept with a broad definition first and then also with a simple mathematical example. As stated by Nicolis [36]: we learn traditionally that "*a natural system in well defined conditions will follow a unique course, slight changes in these conditions will likewise induce a slight change in the system's response*". This is interesting because reproducibility is guaranteed, the predictability (determinism) is unlimited and the solutions are simple. This corresponds to a strong causality principle (see also Gasmann [16]). It is a linear view of the world: "*the observed effects are linked to the underlying causes by a set of laws reducing for all practical purposes to a simple proportionality [...], this idea is now challenged [...] simple observation shows radical, qualitative deviations from the regime of proportionality*".

Why was the linear view so successful? Besides historical reasons already presented, there are also practical ones. The methods used at these times (18-19th centuries) were mathematics, which were the only way to integrate differential equations. However literal integration was not always obviously possible (e.g. the 3 bodies problem). In some cases a good solution consisted to linearise the equations (e.g. by a Taylor's development [27]) or to simply ignore the problem. In Figure 1 we present how we can solve the mathematical pendulum dynamical equation by linearisation.

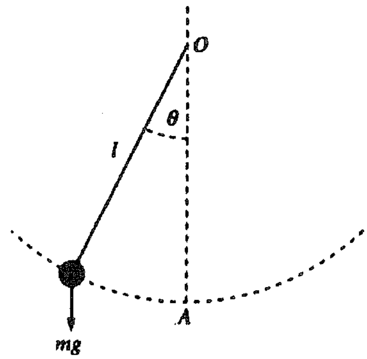
Among some other historical consequences of the linear approach, there was the fact that the solar system was presented as definitively stable. Everyone did not consider this conclusion as something proved. Indeed, it was known as early as from the Newton era that in some circumstances if 3 astronomical bodies were in gravitational interactions, there was no ways for describing the dynamics of the system (i.e. one could not know what will happen in the future). The equations could not be literally solved because of their non-linear nature. This problem was crucial, since it concerned the stability of the solar system in which we live. In order to find an answer to this question a prize was offered by the King Oscar of Sweden at about the turn of this century, the subject being to prove rigorously (mathematically) that the solar system was stable. The prize was won by Poincarré, who invented new methods to inspect "solutions" of dynamical differential equations which could not be solved literally and the conclusion was completely different from the Laplace (linear)view. Indeed Poincarré wrote in 1903 [38]:

Object: describe θ as function of time
m: mass, l: length, θ: angle
g: gravity constant
Newton law:

$$F = mg = ml\ddot{\theta} = -mg\sin\theta$$

$\ddot{\theta}$: angular acceleration

$$\frac{d^2\theta}{dt^2} = -\frac{g}{l}\sin\theta$$



The dynamical differential equation is <u>non-linear</u> with respect to θ (sin θ).
<u>Linearisation</u>:
for small θ, then:

$\sin\theta \cong \theta$, so that $\frac{d^2\theta}{dt^2} = -\frac{g}{l}\theta$

The dynamical differential equation is <u>linear</u> with respect to θ (constant term $\times\ \theta$).
The solution is:

$\theta(t) = \theta_0 \cos(\omega_0 t + \phi)$ where $\omega_0 = \sqrt{\frac{g}{l}}$ is the angular frequency from initial condition θ_0 ,and ϕ is the phase.

Figure 1. Linearisation of the dynamical differential equation of movement of the mathematical pendulum.

A very small cause which escapes our notice determines a considerable effect that we cannot fail to see ... even if the case that the natural laws had no longer secret for us, we could only know the initial situation approximately .... It may happen that small differences in initial conditions produce very great ones in the final phenomena.

This is a notable change from Laplace view in the way that "noise" or unpredictability can be generated even by totally exhaustively known (deterministic) systems. This view was not accepted widely. Even Einstein sentence "God doesn't play with dices" is significant in this respect. Nevertheless, it is clear that this vision was different from the classical one. To be more precise, it was not different but more exhaustive since the non-linear view includes the linear view, whereas the linear one excludes the precedent. Meanwhile, it is important to say that in the mathematical field important progresses were done, particularly at the beginning of this century by the Russian school [10], but the diffusion of knowledge in other scientific fields was very poor. It is only with the advent of computers that things have changed. The reason is very simple: computers can solve almost any dynamical sets of equations by the method of numerical integration. Thus, simulation of very complex or simple non-linear dynamics became progressively possible. In this respect one of the most important papers was written in 1963 by Lorenz [30]. It was shown that in a very simple mathematical model, the solutions were dramatically different depending on very small initial different conditions. The behaviour of the system was soon becoming unpredictable even if the equations were deterministic (deterministic chaos). Other simple and historical examples have been provided by May in 1976 [32] using iterative discrete ecological equations models for growth as, for example, the logistic equation.

The logistic equation:

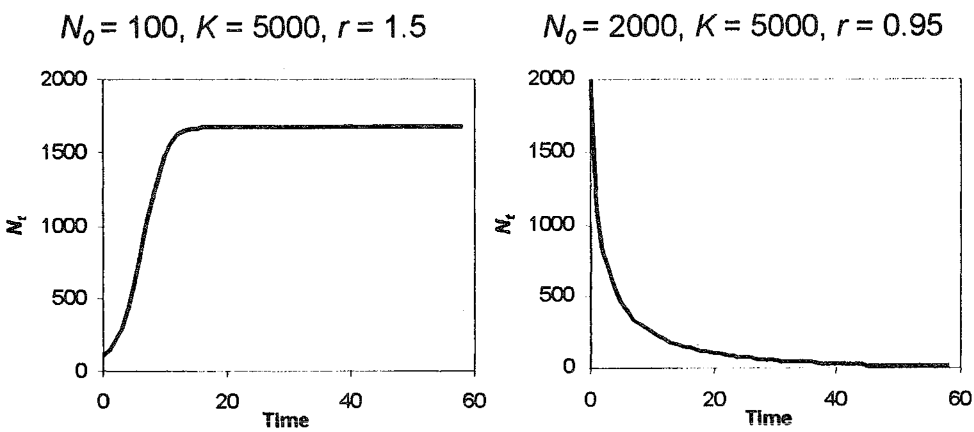


Figure 2. The logistic equation (see text, equation (1)) with different parameters. On the left a growing population and on the right side a decaying one.

The growth of a population of organisms with reproduction at a unique and common epoch has been modelled by the logistic equation (discrete time formulation):

$$N_t = rN_{t-1}(1 - \frac{N_{t-1}}{K}) \tag{1}$$

where N_t is the population at time t, r is the growth rate and K is the carrying capacity of the medium. In Figure 2 we present some examples of this equation with different values of the r, N_0 and K parameters. We will use this equation to illustrate some basic properties of non-linear systems. It is possible to transform the logistic discrete equation into a normalised form. Indeed, if we transform N_t as follows:

$$X_t = \frac{N_t}{K} \tag{2}$$

then we obtain:

$$X_t = rX_{t-1}(1 - X_{t-1}) = rX_{t-1} - rX_{t-1}^{\;2} \tag{3}$$

It is a non-linear dynamical equation since there is a X_t^2 term in it. The numerical calculation of this function is elementary. For example: if $X_0 = 0.01$ and $r = 2.5$, then $X_1 = 2.5\times0.01\times(1\text{-}0.01) = 0.02475$, then $X_2 = 2.5\times0.02475\times(1\text{-}0.02475) = 0.060343\ldots$ and so on. The Figure 3 shows the transition from order to deterministic chaos when the r parameter is changed (bifurcation's can be observed). At a critical value, the system becomes chaotic. In the chaotic regime of there are "isles" of stability and also of particular behaviour (see Ekelund; May [12,32]). An example is shown in Figure 4 at a value of r = 3.8284, a so-called intermittent dynamics is observed.

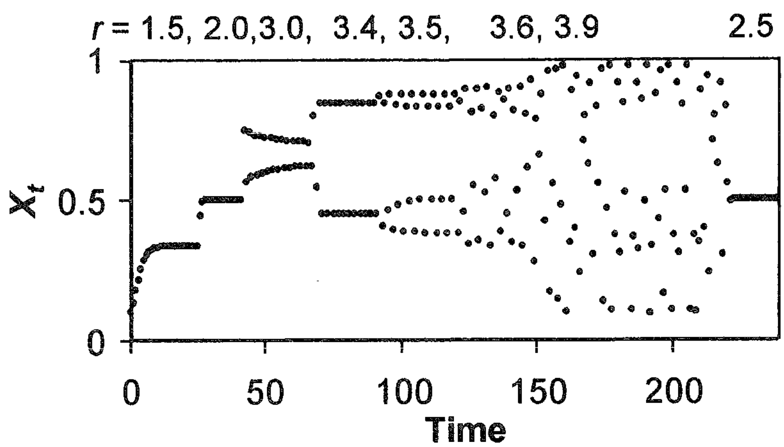


Figure 3. From "order" to chaos in the deterministic logistic equation (3).

A very important concept is the sensitivity to initial conditions, this can also be considered as the sensitivity to external / environmental conditions. As already stated, a small change will lead to completely different solutions. The change can be as small as possible, since in practice it would never be possible to control or to measure a system's initial conditions with an infinite precision (see also Prigogine [39] for a more detailed discussion of this aspect and its implications). An exponential law whose power is called the Liapounov exponent and gives a measure on how fast the solutions will diverge governs the divergence. Figure 5 illustrates this aspect.

An interesting consequence from the sensitivity to external conditions just discussed is the property of chaos control. If small changes have strong effects, then it could be possible by *appropriately* inserting perturbations to control the chaotic regime and to stabilise it. Indeed, this has been shown to be both theoretically and experimentally possible in very different systems [5,11,15,21,43,45]. We will provide here the interested reader with the theory and algorithm to achieve control of the logistic equation. The object is to stabilise the dynamics on periodic (p) trajectories (e.g. if p =

2, then $X_{t+2} = X_t$), once it is in a chaotic regime by changing the control parameter r. For this purpose, consider the function:

$$f^{(p)}(X_t) = \underbrace{f(f(f(...(X_{t-p})))}_{p} \tag{4}$$

where $f(X_t)$ is the logistic function according to (3). It is necessary to find the value X^* that satisfies:

$$g^{(p)}(X^*) \equiv f^{(p)}(X^*) - X^* = 0 \tag{5}$$

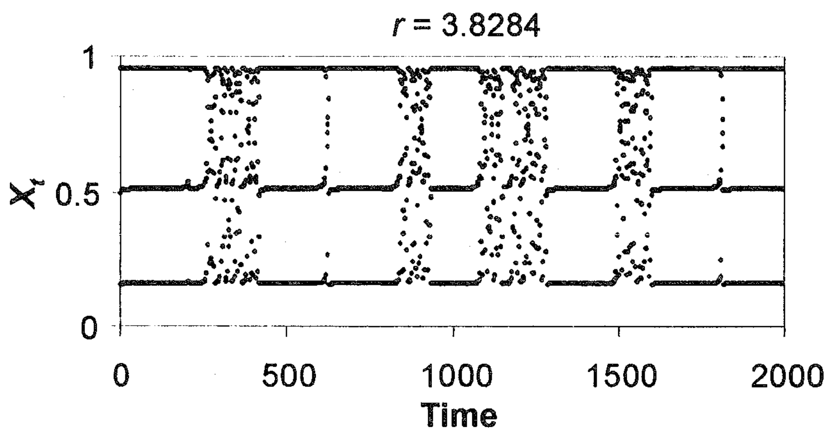


Figure 4. Diversity of dynamics in the chaotic regime of the logistic equation (3). Strange "behaviour" with $r = 3.8284$ (intermittence).

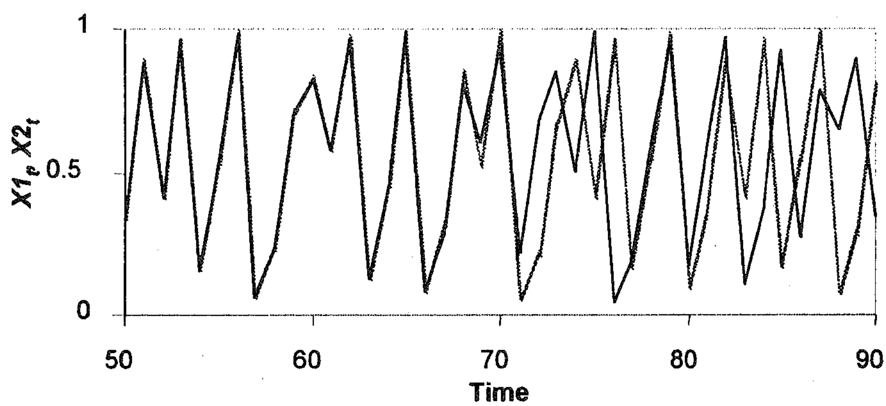


Figure 5. Sensitivity to initial conditions, or sensitivity to environmental changes. Two logistic equation ($X1_t$ and $X2_t$) are represented both with r = 3.95. At time 50, a small change has been introduced in one of them (10^{-6}). At time 70 the divergence appears and the 2 dynamics will definitively differ.

within a limiting error factor ε. To obtain the numerical value of X^* it is possible to use the bisectrix algorithm:

1. Choose xg and xd so that $g(xg)\times g(xd) < 0$
2. Compute $xm = (xd+xg)/2$ as a first approximation of X^*
3. If $g(xm)$ has the same sign as $g(xg)$, then replace xg by xm, else replace xd by xm
4. Repeat step 2 and 3 until ε.

The method to apply control to the logistic function is:

1. Obtain for a wanted stable periodicity p, the corresponding X^* as described before, with a r_0 value
2. Iterate the logistic function until its X_t value is near X^*, by a factor ε (i.e. $|X_t - X^*| \leq \varepsilon$
3. Start the control by adjusting the r_0 value with dr:

$$dr = r_0 \frac{(X^*)(1-X^*)}{((X_t(1-X_t))}$$

   This means, iterate X_{t+1} with $r_0 + dr$. Then wait X_{t+p} and continue with step 3
4. To stop the control reset r to r_0.

In Figure 6 we present the result of chaos control of the logistic equation. It has generally been observed that control can be achieved with a very small quantity of energy [5,11,15,21,43,45]. This might be an advantage, however to correctly achieve this control it is on the other way necessary to obtain information (measurements) on the system and to reinject at appropriate time point with appropriate intensity specific signals. The gain in energy need is counterbalanced by the need of a higher intelligent information – action regulation loop!

Conclusion

It is often said that living organisms and environment are non-linear systems (see e.g. Gasmann, [17]). This is typically because these systems work with regulation. Once a regulation is operating (e.g. feedback) there is little escape from non-linearity. This does not mean that the systems will not work in a linear-like way. Indeed, if we compare to the logistic equation presented as an example, much of its dynamics regime is governed in a "linear-like way" with respect to change in the r controlling factor (0 to ~3.6). However, in some circumstances (r>3.6) a chaotic behaviour typically characteristic of non-linear systems appears. In this regime, there is the possibility of a very great diversity and original behaviours. However, stability and the predictability horizon is very poor, whereas as a counterbalancing factor, control is necessitating

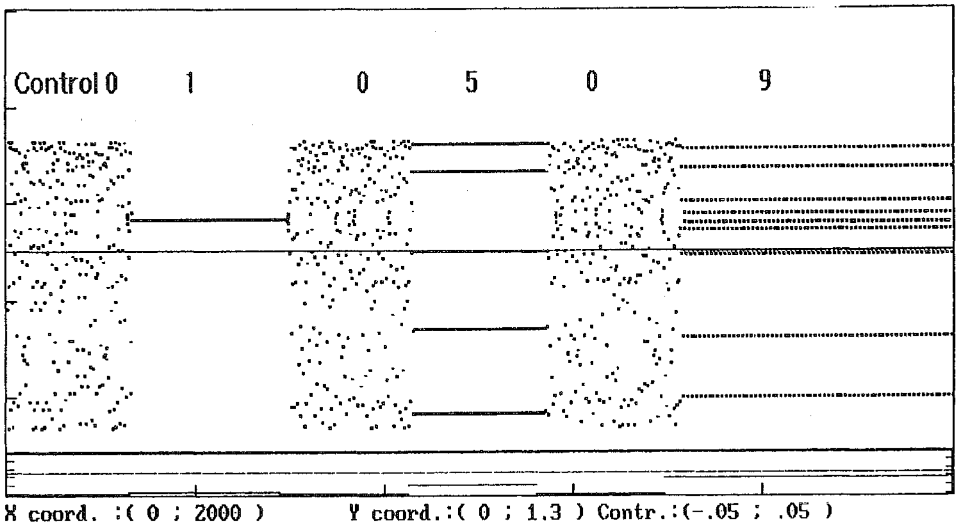


Figure 6. Controlling the dynamics of the logistic equation (3) in a chaotic regime. The controlling factor *r* is set to 3.8. The number 0 represents the dynamics without control. The numbers 1, 5 and 9 represent the starts of an automatic algorithm (described in the text) to very slightly change *r* continuously (regulation) to fix the chaotic dynamics on stable periodic trajectories of period 1, 5 and 9 respectively.

lower energy inputs (but higher information level). This points to the necessity for understanding the physical nature of environment with an as exhaustive as possible measuring / monitoring approach. Indeed, non-linear systems need more measurements in order to be characterised. This has to be coupled to both exhaustive and minimal modelling approaches.

As stated by Prigogine [39] the non-linear nature of systems seems to be the rule rather than the exception, considering this aspect as a kind of fundamental nature of matter and forces governing the world / universe. The reader could be also convinced by the few examples provided in Table 1, which spans theoretical and experimental fields over mathematics and from atomic to astronomical levels (including environmental issues). There is little doubt that this aspect should somehow be correctly integrated to understand environmental problems.

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The Co-Action between Living Systems and the Planet. (H. Greppin, R. Degli Agosti, Cl. Penel, editors)

This volume presents and reflects the development of lectures and discussions that were hold at the University of Geneva for advanced students and researchers (Third cycle of studies in biology between the following Western Switzerland universities: Bern, Fribourg, Lausanne, Neuchâtel and Genève, and with the University and International Center of Human Ecology at Geneva).

The goal of this meeting was to stimulate inter-and transdisciplinary approaches on the interface between Man, Society and Environment by the application of different usely separated scientific information (exact and natural sciences, human sciences, etc). Progressively a new methodology and corpus of knowledges and concepts will emerge as what fundamental researches to do, in the perspective to a better valuation of the risks and to help the final decision in the society, concerning a general sustainable activity.

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