Some open problems in chaos theory and dynamics

10000 open problems

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Abstract

Here we propose six open problems in dynamical systems and chaos theory. The first open problem is concern with rigorous proof of a collection of quadratic ODE systems being non-chaotic. The second problem is for a universal definition of non-chaotic solutions. The third problem is about the number of systems that can have chaotic solutions when the right hand sides are polynomials. The fourth problem is: topologically how complicated a 2D invariant manifold has to be to contain and/or attract chaotic solutions. The fifth open problem is to show that a specific system has a solution with a fractal demension on one of the Poincaré sections. The sixth problem is on rigorous proof of existence of chaotic solutions of some sysyems which exhibit chaos in numerical solutions.

1 First Open Problem

Several years ago Zhang and Heidel ([10] (1999) and [23] (1997)) showed that (almost) all dissipative and conservative three dimensional autonomous quadratic systems of ordinary differential equations with at most four terms on the right hand sides of the equations are non-chaotic. The sole exception is the system

$$\begin{cases} x' = y^2 - z^2 \\ y' = x \\ z' = y \end{cases} \tag{1.1}$$

which does however appear numerically to have a single unstable periodic solution and is therefore conjectured to also be non-chaotic. The above system is equivalent to the third order or jerk equation $z''' = z'^2 - z^2$. Very recently Malasoma [14] has shown that every jerk equation $z''' = j(z, z', z'')$ where j is a quadratic polynomial with at most two terms, with

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the sole exception of (1.1), is non-chaotic. Thus carefully determining the behavior of solutions of equation (1.1) becomes an interesting problem instead of just being a passing curiosity.

Recently Heidel and Zhang ([11] (2008) and [25]) showed that dissipative and conservative three dimensional autonomous quadratic systems of ordinary differential equations with five terms and one nonlinear term on the right hand sides of the equations have one sysyem and four systems respectively that exhibit chaos. Most systems in [11] (2008) and [25] are proved to be non-chaotic. The remaining 20 systems which are listed here are proved to be non-chaotic when the parameter in each of the systems is in certain range. Extensive computer simulations indicate that there are no chaotic attractors in these systems. We conjecture that they are non-choatic systems.

Dissipative systems:

$$\begin{cases} x' = \pm x + y + Az \\ y' = xz \\ z' = y \end{cases} \tag{1.2}$$

$$\begin{cases} x' = y^2 \pm x \\ y' = x + Az \\ z' = y \end{cases} \tag{1.3}$$

$$\begin{cases} x' = y^2 + Az \\ y' = x \pm y \\ z' = x \end{cases} \tag{1.4}$$

$$\begin{cases} x' = y^2 + Az \\ y' = \pm y + z \\ z' = x \end{cases} \tag{1.5}$$

$$\begin{cases} x' = z^2 \pm x \\ y' = x + Az \\ z' = y \end{cases} \tag{1.6}$$

$$\begin{cases} x' = yz \pm x \\ y' = x + Az \\ z' = y \end{cases} \tag{1.7}$$

$$\begin{cases} x' = yz + Ay \\ y' = \pm y + z \\ z' = x \end{cases} \tag{1.8}$$

$$\begin{cases} x' = yz + Az \\ y' = x \pm y \\ z' = x \end{cases} \tag{1.9}$$

$$\begin{cases} x' = yz + Az \\ y' = \pm y + z \\ z' = x \end{cases} \tag{1.10}$$

$$\begin{cases} x' = \pm x + z \\ y' = Ay + z \\ z' = xy \end{cases} \tag{1.11}$$

$$\begin{cases} x' = \pm x + y + A \\ y' = xz \\ z' = y \end{cases} \tag{1.12}$$

$$\begin{cases} x' = \pm x + z + A \\ y' = xz \\ z' = y \end{cases} \tag{1.13}$$

$$\begin{cases} x' = yz + A \\ y' = x \pm y \\ z' = x \end{cases} \tag{1.14}$$

$$\begin{cases} x' = yz + A \\ y' = \pm y + z \\ z' = x \end{cases} \tag{1.15}$$

$$\begin{cases} x' = yz \pm x \\ y' = z + A \\ z' = x \end{cases} \tag{1.16}$$

$$\begin{cases} x' = \pm x + z \\ y' = x + A \\ z' = xy \end{cases} \tag{1.17}$$

$$\begin{cases} x' = \pm x + z \\ y' = z + A \\ z' = xy \end{cases} \tag{1.18}$$

conservative systems:

$$\begin{cases} x' = yz + Ay \quad A < 0, \text{ for } +, \ A > 0, \text{ for } - \\ y' = \pm x + z \\ z' = x \end{cases} \tag{1.19}$$

$$\begin{cases} x' = y + z \\ y' = -x + Az \\ z' = xy \end{cases} \tag{1.20}$$

$$\begin{cases} x' = yz + A \quad A < 0 \\ y' = x \pm z \\ z' = x \end{cases} \tag{1.21}$$

2 Second Open Problem

Ever since the chaotic attractor in the Lorenz equations ([13], 1963) was discovered, chaos theory has become a popular branch in dynamical systems which attracts many mathematicans in the area. The central problems in chaos theory have been the definition, the mathematical properties, and analytic proof of existence of chaotic solutions, and discovery of possible chaotic systems and possible geometric patterns of chaos by numerical simulations. It is well known that among the central problems giving a universal definition of chaos in mathematical sense for the solutions of dynamical systems is difficult because of the complexity of chaotic solutions. There are numerous definitions of chaos. Each definition emphasizes certain aspect(s) of a solution. As definitions of one phrase or terminology in Mathematics, at least mathematical equivalence or relation between each pair of defintions need to be investigated. Therefore none of them can be a general definition at this point. In [1] (1996) Brown and Chua listed nine definitions of chaos.

Here we list some definitions of Chaos:

1. It has a horseshoe map (Ozorio de Almeida, 1988)
2. It has positive Kolmogorov entropy (Schuster, 1988)
3. It has a positive topological entropy (Katok, 1980)
4. It has a positive Lyapunouv exponent (Gulick, 1992)
5. Its sequences have positive algorithmic complexity (Ford, 1986)
6. It has a dense set of periodic orbits, is topologically transitive, and has sensiive dependence on initial conditions (Devaney, 1989)
7. It has sensitive dependence on initial conditions and is topologically transitive (Wiggins, 1992)
8. The power spectral density of related time-series has a component which is absolutely continuous with respect to Lesbegue measure (Bergé et al, 1984)
9. A statistically oriented definition of Shil'nikov (1994)
10. It has an attractor with fractal dimension.

Giving a universal definition of non-chaotic solutions is another way to define chaotic solutions. It is known that it is also very difficult. In [11](2007) we gave a conjecture on the criterion recognizing non-chaotic behavior:

Consider the autonomous system

$$x' = f(x), \quad x \in \mathbb{R}^N, \quad t \in [0, \infty) \tag{2.1}$$

where $' = \dfrac{d}{dt}$, $f : \mathbb{R}^N \to \mathbb{R}^N$ is continuous. Let $x(0) = x_0$, and x_j, x_{0j} and f_j, $j = 1, 2, ..., N$ be the components of x, x_0 and f respectively.

Criterion 1 *An N dimensional system* (2.1) *with no cluster points in the set of isolated fixed points has no bounded chaos if for any of its solutions there are $N-2$ components $x_{n_k}(t)$,$n_k \in 1, ..., N$ and $k = 1, ..., N-2$, such that for each of the $N-2$ components only the following cases can happen:*
as $t \to \infty$ or $t \to -\infty$,

(i) It tends to a finite limit.

(ii) It is a periodic or asymptotic to a periodic function.

(iii) It is unbounded.

there exists an ω, $|\omega| < \infty$, such that,

(iv) It is unbounded, $t \to \omega$,

(v) It is bounded but dose not have a limit, $t \to \omega$,

(vi) It is bounded and has a limit, $t \to \omega$, but not defined at $t = \omega$.

When $N = 3$ this criterion has been widely accepted. For $N > 3$ it still needs verification.

Even if this criterion is very useful, it misses countless types of nonchaotic solutions. This open problem is to give a universal definition of nonchaotic solutions.

3 Third Open Problem

It is well known that three-dimensional quadratic autonomous systems are the simplest type of ordinary differential equations in which it is possible to exhibit chaotic behavior. Lorenz equations ([13], 1963) and Rössler system ([15], 1976) both with seven terms on the right-hand side do exhibit chaos for certain parameter values. By computer simulation in [18] (1994), [19] (1997), [20] (2000), and [21] (2000) J. C. Sprott found numerous cases of chaos in systems with five or six terms on the right-hand side. Heidel and Zhang showed in [23] (1997) and [10] (1999) that three-dimensional quadratic autonomous conservative and dissipative systems with four terms on the right hand side have no chaos. So among three-dimensional quadratic autonomous conservative and dissipative systems chaotic systems must have at least five terms on the right hand side. In [11] (2007) the authors proved a general theorem in determining a non-chaotic solution and showed that among all three-dimensional quadratic autonomous conservative systems with five terms on the right hand side and one nonlinear term there is at most one of them that can have chaotic solutions. In [25] the authors show that there are only four of them that exhibit chaos.

Let $P(x) = \sum_{|\alpha|\leqslant k} A_\alpha x^\alpha$ be a polynomial, where $x \in \mathbb{R}^N$ and $N \geqslant 1$ is an integer, $\alpha = (\alpha_1, ..., \alpha_N)$ and each of the α_i is a nonnegative integer, $x^\alpha = x_1^{\alpha_1}...x_N^{\alpha_N}$, the order of the multi-index α is denoted by $|\alpha| = \alpha_1 + ... + \alpha_N$ and $A_\alpha \in \mathbb{R}$. Consider the autonomous system

$$x_i' = P_i(x) = \sum_{|\alpha^i|\leqslant k} A_{\alpha^i} x^{\alpha^i}, \quad i = 1, 2, ..., N \tag{3.1}$$

1. For a given k and $N = 3$ after eliminating equivalent systems under the scalar transformations

$$x_1 = aX_1, \qquad x_2 = bX_2, \qquad x_3 = cX_3, \qquad t = \delta\tau$$

where a, b, c and δ are nonzero real numbers and third-order permutation groups P_g, where P_g has six elements

$$P_1 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad P_2 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \quad P_3 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$P_4 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix} \quad P_5 = \begin{pmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{pmatrix} \quad P_6 = \begin{pmatrix} 0 & 0 & 1 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$

which systems in the form of (3.1) have chaotic solutions and how many systems are chaotic? Among those chaotic systems how many of them are conservative, and how many of them are dissipative?

2. For any given integer $N > 3$ and k after eliminating equivalent systems under the scalar transformations

$$x_1 = a_1 X_1, \quad x_2 = a_2 X_2, \quad ..., \quad x_n = a_n X_n, \quad t = \delta\tau$$

and nth-order permutation groups P_g, where P_g has $m = n!$ elements

$$P_1 = \begin{pmatrix} 1 & 0 & \dots & 0 \\ 0 & 1 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & 1 \end{pmatrix} \quad P_2 = \begin{pmatrix} 0 & 1 & \dots & 0 \\ 0 & 0 & \dots & 1 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 0 & \dots & 0 \end{pmatrix} \quad ... \quad P_m = \begin{pmatrix} 0 & \dots & 0 & 1 \\ 0 & \dots & 1 & 0 \\ \vdots & \ddots & \vdots & \vdots \\ 1 & \dots & 0 & 0 \end{pmatrix}$$

which systems in the form of (3.1) have chaotic solutions and how many systems are chaotic? Among those chaotic systems how many of them are conservative, and how many of them are dissipative?

3. More generally for a given $N \geq 3$ after eliminating equivalent systems under affine transformations

$$x' = Ay + b, \qquad t = \delta\tau, \qquad ' = \frac{d}{dt}$$

where

$$x = \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \quad y = \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} \quad A = \begin{pmatrix} a_{11} & a_{12} & \dots & a_{1n} \\ a_{21} & a_{22} & \dots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \dots & a_{nn} \end{pmatrix} \quad b = \begin{pmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{pmatrix}$$

which systems in the form of (3.1) have chaotic solutions and how many systems are chaotic? Among those chaotic systems how many of them are conservative, and how many of them are dissipative?

4. A related open problem is what types of chaotic attractors can the systems (3.1) have? Two examples of "types" of attractors are Lorenz attractor and Rössler attractor.

4 Fouth Open Problem

Consider $x' = f(x)$, $x \in \mathbb{R}^3$, where $f(x)$ are polynomials or $f \in C^n(\mathbb{R}^3)$, where n is a nonnegative integer. If a solution of the system is asymptotic to a 2D C^r, $r \geq 1$ an integer, invariant manifold, can the solution be chaotic ? If such chaotic solutions exists, topologically how complicated the 2D manifold has to be ?

What we mean by a manifold being complicated topologically is that for example a torus can be considered more complicated than a plane.

In particular, can a quadratic differential equation system on a torus exhibit chaos? In general can a solution of a system on a torus be more complicated than a filling curve ?

The following four figures are from [11]. Figure 1 shows an orbit of system (4.1). It appears that the solution approaches a 2D surface which is topologically more complicated than a torus. From figure 2 and figure 4 even if they are not Poincaré section of one solution, one can still tell from them that there are solutions in both cases that approach very complicated surfaces.

$$x' = y^2 - z + A \; , \; y' = z, \; z' = x \tag{4.1}$$

$$x' = y, \; y' = -x + yz, \; z' = 1 - y^2 \tag{4.2}$$

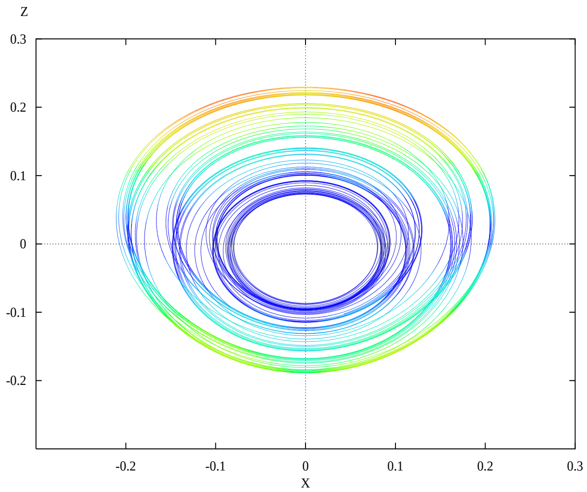

Figure 1: (4.1)'s "chaotic" orbit, $x(0) = 0.0428571$, $y(0) = -0.105714$, $z(0) = -0.102325$, $A = -0.0125$

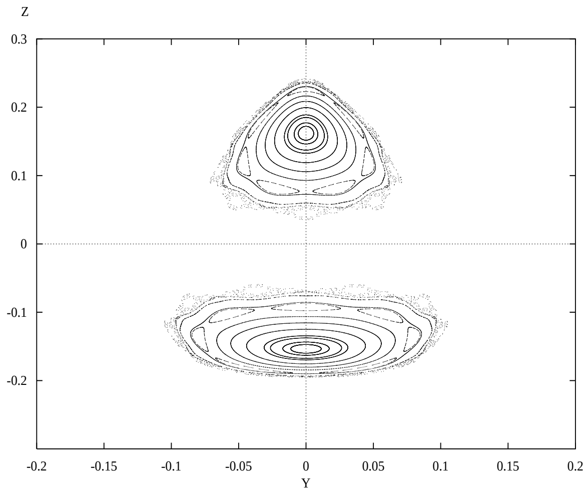

Figure 2: (4.1)'s Poincaré section at $x = 0$ with 10 different initial conditions $0.01 \leqslant x \leqslant 0.12$, $y = -0.105714$, $z = -0.102325$ and $A = -0.0125$

5 Fifth Open Problem

From figure 2, and figure 3 it appears that system (4.1) has at least one solution such that it intersects the Poincaré section $x = 0$ into a set with "thickness". Similarly from figure 4, it appears that system (4.2) has at least one solution that intersects the Poincaré section $z = 0$ into a set also with "thickness". This open problem is to show that these sets have fractal dimensions. A further question is to show that this system is chaotic.

6 Sixth Open Problem

Chaotic solutions were proved to exists in some famous systems such as Lorenz equations ([8](1994), [9]), and Chua's circuit with peice-wise nonlinearity ([3], 1986). It is well known that rigorous proof of existence of chaotic solutions in a dynamical system is generally very difficult. In a Chua's curciut with smooth nonlinearity, there appears not only butterfly-like

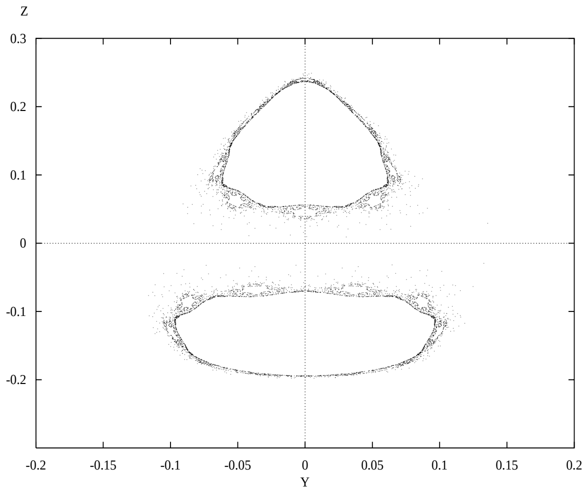

Figure 3: (4.1)'s Poincaré section at $x = 0$ with initial condition $x(0) = 0.01$, $y(0) = -0.105714$, $z(0) = -0.102325$, $A = -0.0125$

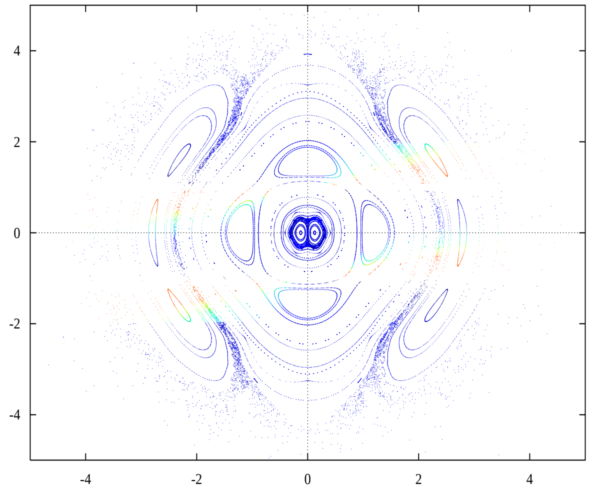

Figure 4: Poincaré section of (4.2) at $z = 0$ with 37 different initial conditions $-2.5 \leqslant x(0) \leqslant 2.5$, $1.25 \leqslant y(0) \leqslant 5.25$, $z(0) = 0$

chaotic attractors, but also "small" chaotic attractor around equilibria for certain parameter regime. It appears that the "small" chaotic attractor is of Rossler-type. There has been no one who proved the existence of such small chaotic attractors.

Sprott discovered numerous ODE systems having chaos ([18](1994)). Among them the following four systems are later studied in our work on three dimensional dissipative autonomous quadratic systems with five terms with one nonlinear term on the right hand sides of the equations. The attractor are all Rossler type. The open problems are to prove rigorously the existence of chaotic solutions in the systems:

$$\begin{cases} x' = y^2 - x + Az, \\ y' = x \\ z' = y \end{cases} \tag{6.1}$$

$$\begin{cases} x' = yz - x + Ay, \\ y' = z \\ z' = x \end{cases} \tag{6.2}$$

$$\begin{cases} x' = yz + Az \quad , \\ y' = x - y \\ z' = y \end{cases} \tag{6.3}$$

$$\begin{cases} x' = y^2 + Az, \\ y' = x - y \\ z' = y \end{cases} \tag{6.4}$$

Other systems that Sprott discovered chaotic solutions include the following systems. The parameter values when the system exhibit chaos are given in [18] (Sprott, 1994). Again we are seeking for rigorous proof of the existence of chaotic solutions.

$$\begin{cases} x' = yz \\ y' = x - Ay, \quad A = 1 \\ z' = 1 - xy \end{cases} \tag{6.5}$$

$$\begin{cases} x' = yz \\ y' = x - Ay, \quad A = 1 \\ z' = 1 - x^2 \end{cases} \tag{6.6}$$

$$\begin{cases} x' = -y \\ y' = x + z \\ z' = xz + Ay^2, \quad A = 3 \end{cases} \tag{6.7}$$

$$\begin{cases} x' = yz \\ y' = x^2 - y, \quad A = 4 \\ z' = 1 - Ax \end{cases} \tag{6.8}$$

$$\begin{cases} x' = y + z \\ y' = -x + Ay, \quad A = 0.5, B = 1 \\ z' = x^2 - Bz \end{cases} \tag{6.9}$$

$$\begin{cases} x' = Ax + z \\ y' = xz - By, \quad A = 0.4, B = 1 \\ z' = -x + y \end{cases} \tag{6.10}$$

$$\begin{cases} x' = -y + z^2 \\ y' = x + Ay, \quad A = 0.5, B = 1 \\ z' = x - Bz \end{cases} \tag{6.11}$$

$$\begin{cases} x' = Ay \\ y' = x + z, \quad A = -0.2, B = 1 \\ z' = x + y^2 - Bz \end{cases} \tag{6.12}$$

$$\begin{cases} x' = Az \\ y' = By + z, \quad A = 2, B = -2 \\ z' = -x + y + y^2 \end{cases} \tag{6.13}$$

$$\begin{cases} x' = xy - Az \\ y' = x - y, \quad A = 1, B = 0.3 \\ z' = x + Bz \end{cases} \tag{6.14}$$

$$\begin{cases} x' = y + Az \\ y' = Bx^2 - y, \quad A = 3.9, B = 0.9 \\ z' = 1 - x \end{cases} \tag{6.15}$$

$$\begin{cases} x' = -z \\ y' = -x^2 - y, \quad A = 1.7, B = 1 \\ z' = A(1 + x) + y \end{cases} \tag{6.16}$$

$$\begin{cases} x' = Ay \\ y' = x + z^2, \quad A = -2, B = -2 \\ z' = 1 + y + Bz \end{cases} \tag{6.17}$$

$$\begin{cases} x' = y \\ y' = x - Az, \quad A = 1, B = 2.7 \\ z' = x + xz + By \end{cases} \tag{6.18}$$

$$\begin{cases} x' = Ay + z \\ y' = Bx + y^2, \quad A = 2.7, B = -1 \\ z' = x + y \end{cases} \tag{6.19}$$

$$\begin{cases} x' = -z \\ y' = x - y, \quad A = 3.1, B = 0.5 \\ z' = Ax + y^2 + Bz \end{cases} \tag{6.20}$$

$$\begin{cases} x' = A - y \\ y' = B + z, \quad A = 0.9, B = 0.4 \\ z' = xy - z \end{cases} \tag{6.21}$$

$$\begin{cases} x' = -x + Ay \\ y' = Bx + z^2, \quad A = -4, B = 1 \\ z' = 1 + x \end{cases} \tag{6.22}$$

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