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Gardens of Eden in systems of bistable nanoscopic wires

J. Tomkowicz *, K. Kulakowski

AGH University of Science and Technology, al. A. Mickiewicza 30, 30-059 Krakow, Poland

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ABSTRACT

Garden of Eden (GoE) is the nickname of an irreproducible state, which can appear only as an initial configuration, and not as a result of time evolution. Here we investigate GoEs in systems of bistable nanoscopic wires, which interact magnetostatically. The wires are randomly distributed on a square lattice, with their directions parallel (*Nx* wires) or perpendicular ($Ny = N - Nx$ wires) to the applied magnetic field. The results are presented on the statistics of GoEs, as dependent on *Nx*. As a rule, most GoEs appear when *Nx* is close to *Ny*. Also, most GoEs include many wires parallel to the field and/or a few wires perpendicular to the field. The results can be useful for modelling safety devices.

1. Introduction

Magnetic nanowires are of interest for numerous scientific groups because of their existing and potential applications: optical and electronic components, connectors in electronics, thermoelectrics, optics, bio- and chemo-sensors and others ([1–5] and literature therein). In particular, magnetic hysteresis loops are investigated for assemblies of nanoscopic wires [6]. The magnetostatic interaction between the wires modifies the loops and therefore it is relevant for future ultrahigh density data storage [7,8]. The interaction combined with applied field allows preparation of fluid suspensions where the nanowires form ordered structures [9,10] (see also the option of electrostatic interaction [11]). When solidified to composites [12], the structures offer hysteresis loops with tunable properties. Our aim here is to explore irreversibility of the magnetisation curve of a solidified system of nanowires. Although our model approach is simplified, the investigated effect is expected also in real systems in moderate magnetic fields.

The concept of Garden of Eden (GoE) was used for the first time by Moore in 1963 in the context of cellular automata [13]. There, GoE is an irreproducible state, which can appear only as an initial configuration, and not as a result of time evolution within the automaton rule. If we modify such a state, the system will never return to it. Here we measure GoE as the number of wires, which remagnetize at different values of the applied field in subsequent hysteresis loops. GoE for wires parallel (GoEX) to the magnetic field is easy to observe, when we consider differences between the first and the second or third hysteresis loops.

In our calculations we distinguish two types of GoEs, for wires parallel (GoEX) and perpendicular (GoEY) to the external magnetic field.

2. The model

The simulated system is composed of *N* bistable magnetic nanowires, which are randomly distributed on a square lattice. Wires are distributed in two possible directions: parallel (*Nx* wires) or perpendicular ($Ny = N - Nx$ wires) to the direction (OX) of the applied magnetic field *H*. The diameter of the wires is $D = 57$ nm, the length $L = 115$ nm and magnetisation $M = 370$ emu/cm^3 [14]. The probability distribution of the switching field is Gaussian, with mean H_s and standard deviation $u(H_s)$. The size of the square lattice is 10×10 (570 nm $\times$ 570 nm). To simplify the model, each wire is composed of three parts: a part with positive magnetic charge, a neutral part, and a part with negative magnetic charge. The absolute value of the magnetic charge *Q* is obtained from a comparison with the model of ideal dipole and is given by the relation $Q = \pi M D^2/4$. The effective magnetic field acting at a particular wire is the sum of the external field (*H*) and a contribution from the magnetostatic interaction between the wires. The magnetostatic interaction is calculated with taking into account the finite distance between the magnetic charges. The algorithm used here is akin to the one given by Pardavi-Horvath [15].

In the case of small density of the wires, when the distances between the wires are much larger than the wire length, the magnetostatic interaction reduces to the ideal dipole term, which changes with distance as $1/r^3$. For a given *N*, the planar density of the wires changes with system size as $1/S^2$, where *S* is the linear system size. Therefore, when *S* is doubled, the density decreases by a factor 4 and the interaction between wires is reduced 8 times.

* Corresponding author.
E-mail address: joanna.tomkowicz@agh.edu.pl (J. Tomkowicz).

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On the other hand, the interactions are linear with the magnetisation, and hence linear with the wire volume. However, the resulting scaling relations fail in our case, as the mean distance between wires is comparable with the wire length. Similarly, in the limit of large number of wires N, a contribution from a single wire to the hysteresis loop is negligible along with its particular environment, and we expect that the effect of GoE vanishes. Our considerations below are related to the case of finite and rather small N. Then the properties of the system, including the GoE effect, do depend on particular spatial configuration of the wires and on the values of their coercive fields.

An example of a spatial configuration of the wires is presented in Fig. 1. Our numerical results are collected for an ensemble of such configurations, with different wire positions, different initial orientations of the magnetic moments and different values of their coercive (switching) field.

We distinguish two kinds of initial states of the directions of the magnetic moments of the wires: the case when the system is allowed to relax in the absence of the applied magnetic field H and the case when this relaxation appears in the presence of saturating field along the OX axis. The difference is analogous to the field cooling and zero-field cooling, applied usually for spin glasses. After the relaxation (in the presence of maximum field or at zero field), we start to simulate the hysteretic experiment of three hysteresis loops. This number three is found here to be sufficiently large; in all our results, all subsequent hysteresis loops are identical to the third one.

In each hysteresis loop we distinguish two branches: the upper branch (UB) when changing magnetic field from H_m to $-H_m$, and the lower branch (LB) when changing magnetic field from $-H_m$ to H_m. Also, the term "relaxation" means the relaxation in zero field from now on.

How can we observe gardens of Eden? In Fig. 2 we present the reversal process during first and second hysteresis loop in one of the simplest systems to understand better why GoEs occur in systems. The presented system contains only three wires parallel and two perpendicular to the magnetic field. Corresponding first two hysteresis loops are shown in Fig. 3. The black dots in Fig. 3 indicate the stage of the hysteresis loop we are in during the remagnetising process.

After generating spatial configuration and relaxation in the absence of magnetic field we obtain the initial configuration (Fig. 2(a)).

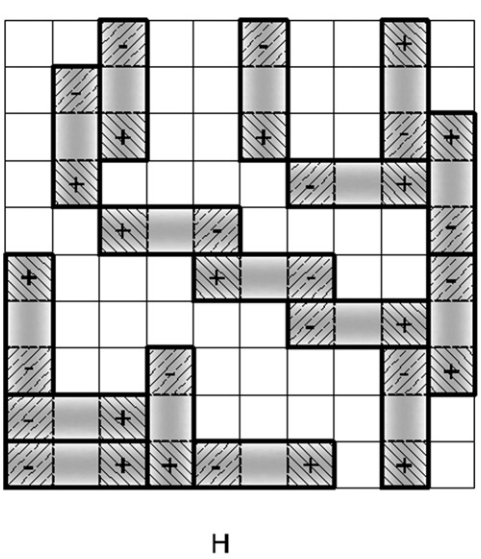

Fig. 1. An exemplary spatial configuration with $Nx=7$ wires parallel and $Ny=9$ wires perpendicular to the direction of the applied magnetic field H.

Then we apply maximal external field H_m (Fig. 2(b), point A in Fig. 3) and observe that wires number three and four remagnetise to point in the same direction as that of external magnetic field. Next we decrease the magnetic field (first UB) and in value $H=-456.1$ Oe; wire number four is remagnetising (Fig. 2(c), point B in Fig. 3). Next in $H=-674.4$ Oe wire number two is remagnetising (Fig. 2(d), point C in Fig. 3). Then wire number three is remagnetising in $H=-730.3$ Oe (Fig. 2(e), point D in Fig. 3). At the same value of external field, after switching of wire number three, we have remagnetisation of wire number zero, which is perpendicular to the magnetic field (Fig. 2(f), point D in Fig. 3). It remagnetises because of interaction with other wires in the system. Then we decrease magnetic field to $-H_m$ (point E in Fig. 3). In the next step (first LB) we increase the magnetic field, first the wire number four is remagnetising (Fig. 2(g), point F in Fig. 3), then the wire number two (Fig. 2(h), point G in Fig. 3) and at last we have remagnetisation of wire number three (Fig. 2(i), point H in Fig. 3). For the second hysteresis loop we obtain different shapes because wire number zero remagnetises in the upper branch of first hysteresis loop, and it does not remagnetise in lower branch. Due to behaviour of wire number zero (which remagnetises in the upper branch of first hysteresis loop and does not remagnetise in lower branch) in the beginning of second hysteresis loop we obtain different states of the system than in the beginning of the first hysteresis loop. This fact induces a difference in shape of the first and the second hysteresis loops. In the second loop wire number four remagnetises in larger value magnetic field $H=-336.9$ Oe (Fig. 2(j), point I in Fig. 3). We have a similar situation for wire number two which remagnetises in $H=-550.4$ Oe (Fig. 2(k), point J in Fig. 3) and wire number three which remagnetises in $H=-692.0$ Oe (Fig. 2(l), point K in Fig. 3). Now, we have the same state as that of upper branch of the first hysteresis loop, so the lower branch for the second hysteresis loop looks like the lower branch for the first one. The third and all subsequent hysteresis loops are the same as the second one.

Each point in the plots 4–11 is a result of averaging over 5×10 cases, with different spatial distributions of the wires, different values of the switching fields of the wires and different initial orientations of the magnetic moments of the wires.

3. Results

In Fig. 4 we show the number of systems (in percents) which display GoE as dependent on the percentage of wires which are parallel to the applied magnetic field (OX). This figure presents results for the case when we allow for relaxation in the absence of magnetic field. As we see in both Figs. 4 and 5, most GoEs are related to the difference between the upper branches of the first and the second hysteresis loops, UB1-2. Sum means the number of systems for which we observed difference between the first and second loops or between the second and third loop. The same values for upper branch for the first and the second hysteresis loops and for Sum indicate that if we do not have any differences between first and second upper branches we do not also have differences between other branches. However, for wires perpendicular to the field (OY) this rule does not hold, as shown in Fig. 5, although the difference between the curves UB1-2 and Sum remains small there. Still, for the loops identical at LB1-2, the third loop is already a copy of the second loop.

Further, most systems with GoE for wires parallel to the field are obtained when the number of wires perpendicular and wires parallel to the field are comparable. This is seen as the maximum of the main curve Sum in Fig. 4 for Nx between 0.4 and 0.6. For GoEY, the maximum is shifted to the left, as shown in Fig. 5.