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CHAOTIC TOYS*

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The application of toys in physics education

Handling, investigating and modeling toys in physics lessons may help students to improve their understanding of physical problems In several respects [1]. We shall concentrate here on one important point: Toys may provide for an access to the main features of nonlinearity in physics which have been overlooked up to now and which seem to become more and more important for an appropriate understanding of problems of the modern world. In the following, we shall sketch some simple, easily available, and cheap toys at which the most striking effects of nonlinearity: phenomena of selforganization may be shown and experienced in a rather direct and appealing manner.

Some selforganizing toys [2]

The many particle states of real systems giving rise to macroscopically ordered structure can be modeled by well distinguished shapes and forms the following toys may take on as they are operated in definite ways. These shapes or ordered states will. be characterized by a "gestalt" parameter which corresponds to the order parameter of the theory of phase transitions and which has been applied in synergetics [see e.g. 3] as well. We begin by giving a short description of some selforganizing toys:

The bird in shell

This toy consists of an egg shaped body which may be set into rotation by pushing a thumb plunger. If the rotational velocity exeeds a certain, critical value the four shell sections of the body suddenly open revealing a little bird sitting within the shell. Thus, the possible states of motion are manifested in different shapes (open, closed) or „gestalten" of the toy. Therefore, it suggests itself to take the separation width of the opening shell section as gestalt parameter and the value of the rotational frequency as control parameter (see fig.1).

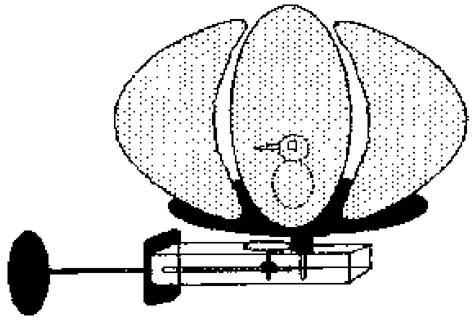

Fig. 1

The woodpecker

A wooden bird is fastened to a small tube which, in turn, is passed over a vertically standing metal rod. As the bird is given a small push it is set into vibration which either is damped down to rest again or terminates as a regular steady motion. In the latter case the tube Is descending at the rod by alternately slipping and sticking. Which of the two possibilities will actually be realized depends on the strength of the initial push. Thus, staying at rest or performing a periodic motion are the two possible states which may be distinguished by the amplitude of the vibration as gestalt parameter (see fig.2).

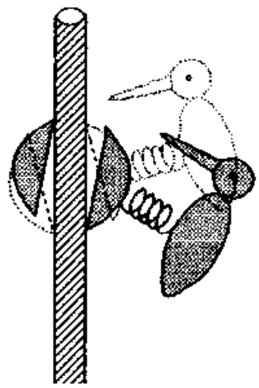

Fig. 2

The walking men

This toy is also available in the form of different animals. The men are pulled by a small weight hanging down the edge of a table. Their movement is very similar to walking in that the legs are alternately put one in front of the other. But wether the men walk or stay at rest depends again on an initial push which has to be strong enough to overcome a certain critical value. The velocity of the motion or the amplitude of the vibration -transverse to the direction of motion - which is responsible for the wobbling of the walk - may be taken as gestalt or order parameter (see fig. 3).

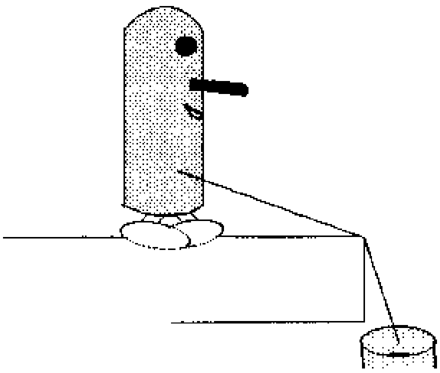

Fig. 3

The paper helicopter

Its construction is described in [3]. Releasing the helicopter from an arbitrary height it opens its wings up to a certain angle and, at the same time, gets Into a steady rotation. Thus, the helicopter maintains temporal and special form, which may be characterized by the sinking velocity, the rotational frequency and the opening angle. The gestalt parameter is given by this triple of quantities (see fig.4).

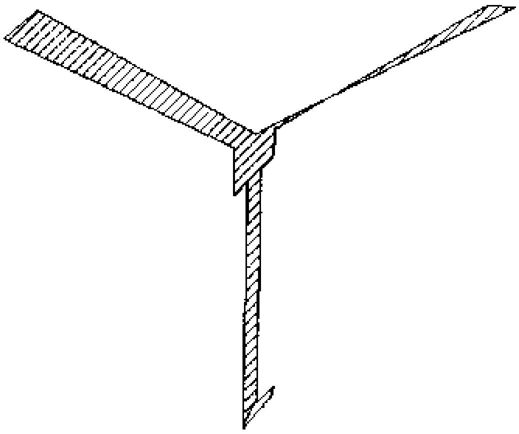

Fig. 4

The put-put boat

The core of the boat consists of a flat steam chamber. It Is connected to the water at the stern of the boat by two thin pipes. In order to put the boat into operation the steam chamber is filled with water and heated from below by means of e.g. a candle flame. After a while, the boat begins to move by periodically emitting water jets out of the pipes. The oscillation of the water columns in the pipes is translated into a characteristic “put-put” noise produced by a flexible thin brass membran covering the top of the steam chamber. The amplitude of the vibration may be taken as the gestalt parameter, which is controlled by the supplied heat and the heat losts (see fig.5).

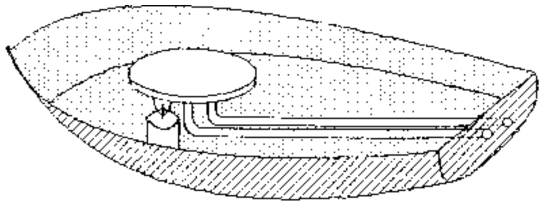

Fig. 5

The creaking tin

A small tube made of cardboard and covered at one end by paper is loosely fastened to a wooden rod by means of a thread. As the tube is thrown around by turning the rod the friction between the thread and the rod produces a creaking noise, which is amplified by the cardboard tube (fig.6). The same noise is generated as the tube is held in one hand and the rod is twisted by the other hand. The mechanism of sound generation relies on an alternating slipping and sticking between the thread and the rod. The sound frequency may be taken as gestalt parameter which is controlled e.g. by the frictional force.

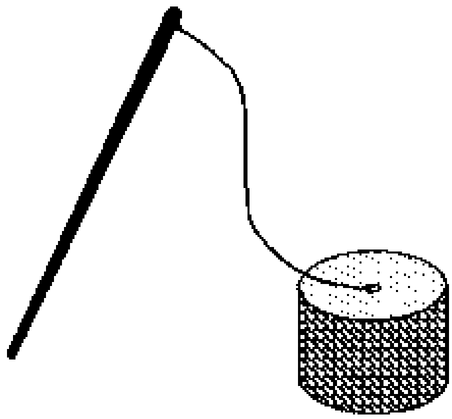

Fig. 6

The whistle

The tones of this little whistle is generated by blowing the air against a sharp edge (fig. 7). According to the velocity of the air there may be no tone at all (only an undefinite blowing noise), a low tone or a

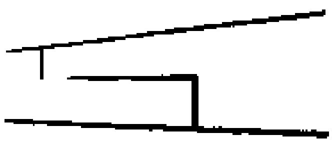

Fig. 7

high tone. The frequency of the tone may, therefore, be adopted as the gestalt parameter which is controlled by the air velocity.

The space ball

The space ball Is a kind of double pendulum. The main pendulum Is driven electromagnetically: The pendulum bob is supplied with a magnet. Passing the equilibrium position this magnet switches an electric circuit which gives rise to an magnetic field. This field, in turn, from time to time repels the pendulum bob, and, finally, leads to a steady oscillation. In order to start this oscillation, initially, the bob has to be given a sufficiently large push. Otherwise it would come to rest again. The motion of this pendulum Is directly transmitted to the suspension of the other pendulum. Therefore, the bobs of this pendulum, which are also supplied with magnets, eventually, may approach another repelling magnet mounted to the main pendulum. Depending on the strength of the impact the second pendulum may be set into different forms of motion. This motion may become unpredictable because of the sensibility of the interaction with respect to small perturbations. Thus, in spite of a regular drive a chaotic behaviour may be produced.

Already this short survey shows some common features of the totally different toys. Each of them represents one or more dynamical structures which may be described by one (or more) appropriate gestalt parameters. Their actual value depends on the control parameter(s), by which the effect of the surroundings on the systems is recorded.

In the following, we shall briefly discuss further characteristics of selforganization by illustrating them by referring to one of the toys presented above.

Dissipative structures

The most striking phenomenon exhibited by the toys is the transition, between two or more different steady states, showing a different shape or order. A certain state will be regarded the more ordered the more energy has to be expended to maintain it. More precisely, the order is not due to the energy itself but due to the dissipation of energy: The system takes in high grade energy which is degraded and transferred to the surroundings as low temperature heat (see fig. 8. Thus, energy (and e.g. in the case of the put-put boat: matter) is only crossing the (thermodynamically) open system. The drive of the system is provided by the dissipation Le. by the exportation of entropy. Therefore, according to Prigogine, we may call this systems dissipative structures. Prigogine coined this term to describe

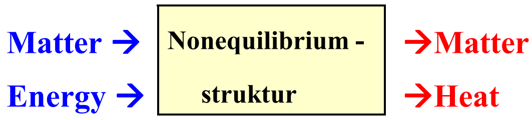

Fig. 8: **Degradation of Energy**

the analogous behaviour of many particle systems showing similar features as our toys

Selforganization and stability by feedback mechanisms

Another remarkable point is that the steady states are adjusted by the systems themselves. To clarify this we consider the example of the woodpecker more in detail. Different from what could be expected the woodpecker does not slip down the rod at once, transforming all the potential energy, offered by its high altitude, into kinetic energy, as a falling stone does. Instead, in order to maintain its individual steady ordered state, it just takes in as much energy as it needs to overcome the frictional losses due to the operation of the system. The relative stability of the ordered state may be demonstrated by disturbing the bird, either by retarding or by accelerating it. If this perturbations remain within certain limits the bird is capable to suppress them. These typical capabilities of selforganization presupposes that the bird must know - how much energy it has to take from the gravitational reservoir, - how it keeps itself Informed about the deviation from the normal situation. The system disposes of an Internal feedback mechanism by which it controls its possibilities of behavior and, therefore, can always adjust the governing parameters accordingly. For instance, if the amplitude of oscillation of the woodpecker is increased by some external effects the slipping time is decreased, because the ring is scanted also in an upper position. The decrease of the slipping time results in a decrease of the amplitude which, in turn, increases the slipping time and so on. Whereupon relies this capability of selforganization? Here, a special competition between, at least, two parameters come into play. one characterizing the driving force and one characterizing the frictional force. The behavior of this competing forces must be such that, depending on the actual value of the order parameter, they are able to “overtake” and, therefore, limiting each-other which eventually results in the control of the steady state. In order to provide for such a property at least one of the competing parameters has to be nonlinear. Therefore, the nonlinearity is a necessary condition for selforganization. As has already become apparent from the energetic standpoint, again the friction or dissipation is not just a bad effect which, in principle, may be neglected but represents a basic mechanism of selforganization.

Phase transition like behavior

As has already been pointed out in the description of the toys, there exist a kind of critical points separating regimes of a totally different behaviour illustrated by the dynamical shape of the toys. The transition between these regimes or phases proceed in a similar way as phase transitions of equilibrium thermodynamics: In the vicinity of such critical points, only small variations of the control parameter may induce a transition from one shape to another. For instance, in the case of the whistle, the sound produced b~ the air flow does not change continuously with growing air velocity. Instead, suddenly at a definite, critical value of the air velocity, a tone of a fixed frequency appears being maintained, for a while, during further increase of the air velocity. Finally, a second transition to a tone of a higher frequency proceeds in the same manner. It is true that the control parameter determines the stale actually realized by the system. But is does not tell us how far away the critical point actually is. Such an Information could be interesting. For instance, if one would try to preserve an ecosystem from a phase transition e.g. a sudden breakdown. One can "ask" the system itself by applying a short-time stimulus to the system. The system will "respond" by making the perturbations vanish. Depending on the "distance" of the critical point this will take more or less time critical slowing down). For example, if one tries to change the opening width of the shell sections of the bird in shell by applying a definite force to the shell sections they appear the softer the closer the critical point will be. The construction of a response function describing this behaviour can, therefore, be regarded as an indicator of the systems stability.

Chaotic behavior

Up to now we concentrated on the transition between different ordered states of toys behaving similar as dissipative structures. The rate of dissipation appeared to be a indicator of the degree of order maintained within the system. To show that this is not always the case we also presented a toy, which shows a transition to chaotic behaviour if certain conditions are complied. One main condition is the presence of sensitive points within the system where small differences in the governing parameters may lead to a totally different behaviour. Being unable to determine the parameters arbitrarily exact a control of the behaviour of the system and the predictability Is no more possible.

Summary

We presented some toys which may exhibit the main features of selforganization. Explaining these features in a rather intuitive and general way It should be shown that there is no need of higher mathematical tools to treat problems of selforganization and that they are accessible already on a relatively low level. The toys shown here are only a small selection of the multitude available in toys shops and other shops. In order to complete his theoretical and mathematical understanding of problems of selforganization by what may be called the sensory experience of those phenomena the reader is invited to "play" with "selforganizing" toys. On the other hand, playing with such toys may serve as a starting point to get acquainted with the phenomena and than interested in its physical explanation.

*This article is based on the following

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