SCIENCE

PHYSICS

Friendly chaos

Apparently disorganized behaviors may benefit living beings and chemical reactions

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Published in January 2004

The layer of the oceans closest to the surface house a high variety of microscopic organisms, continuously transported by the maritime currents. In their path through the seas, this rich mixture that comprises plankton, algae, bacteria, protozoa, crustaceans and mollusks – comes across obstacles like islands, submerged mountains, or even boats. Homogeneous to the naked eye, these extensive patches of plankton are obliged to break ranks and go round the barrier in an involving embrace, to reencounter later. But, after overcoming the obstacle, the previously com-

IMAGES BY CELSO GREBOGI/USP

Craft and art: sinuous forms result from mathematical rigor and resolve biology's old challenges

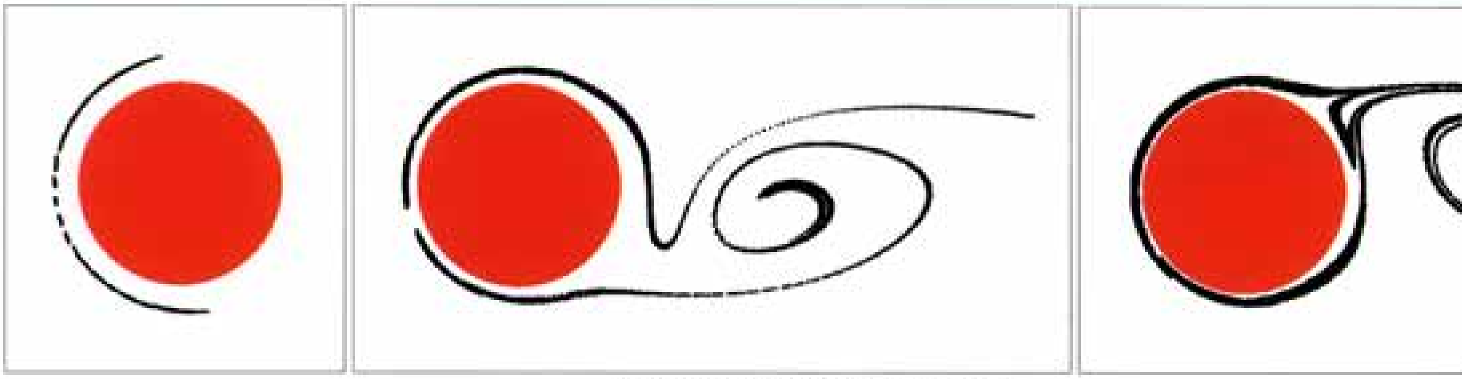
pact patch undergoes distortions and is transformed into a complex network of very thin filaments. Because close to these barriers there are whirlpools in the water that force these organisms to cover complicated and apparently irregular courses, in a movement classified by physicists as chaotic, repeated at each fresh obstacle.

A team of physicists from the University of São Paulo (USP) studied in detail the structure of the filaments that form after the obstacle, and found that their apparently irregular forms can be described with precision by mathematical formulas of the Dynamic Systems Theory – better known as the Chaos Theory, already applied to the study of the ups and downs of the financial market, the uncertainties of meteorology, and even the rhythm of heartbeats. By applying the Chaos Theory to foresee the dispersion of the species of plankton, the physicists from USP found a possible solution for a dilemma that has been disturbing biologists for almost half a century, the so-called Hutchinson's Paradox: why is plankton made up of about 8,000 species of organisms? According to biology's classic theories, this figure should not exceed one dozen, because of the competition for natural resources like oxygen, light and nutrients.

Cases like this show that chaos is not always a synonym for confusion and disorder, and hence undesirable. "In situation like the patch of plankton being dispersed in the sea", explains physicist Celso Grebogi, "chaos turns out as something benefic, favoring the survival of a larger number of species". A researcher from USP's Physics Institute, Grebogi is the main author of a theory that helps one to understand – and to foresee – not only the proliferation of species of plankton. Founded on the Chaos Theory, this model can also assist in explaining other biological and chemical phenomena, like the formation of the hole in the ozone layer that covers the Earth.

Grebogi and his team at USP developed this new theory, called Active Chaos, in partnership with specialists from the University of Eötvös, in Hungary. In it, the researchers launched an innovative idea: in specific situations, chaos can represent more than a set of mathematical equations capable of describing the behavior of a system that modify with time – for example, the dripping of a tap that is slowly closed. In the case of solid particles diluted in a fluid, whether are planktons in the ocean, or molecules of pollutants in the air, chaos may perform and active role and work like a catalyst, speeding up chemical reactions or biological interactions, the researchers revealed in the first article on the subject, published in 1998 in *Physical Review Letters*. Chaos would thus act in an analogous way to the enzymes produced by the stomach or by the intestines, increasing the speed of the reactions that break down the foodstuffs into smaller particles.

Once again, the example of the planktons, responsible for the production of about half the oxygen of the planet, helps to understand this catalysing action of chaos. There is organization behind the sinuous filaments, formed by these marine organisms to overcome the obstacle. The structure of these filaments is governed by very precise mathematical



At the mercy of the marine currents: microorganisms of plankton (*black line*) meet an obstacle (*in red*), disperse in turbulent movements, and reorganize themselves in filaments that allow thousands of species to coexist

laws: each one of them shows a complex form that repeats itself on smaller scales. Magnified, these filaments reveal themselves made up of other, finer ones, which, in turn, are made up of others, even thinner – the same organization that is to be seen in a bird's feather. It is what physicists call a fractal structure. In this case as in others, this fractal structure arises as a consequence of the rapid and intense separation of particles that before very, very close together, caused by the chaotic movement of the fluid that drags them.

Extinction mitigated - In his office at Physics Institute, Grebogi illustrates his theory with a sequence of computer images and explains how so many distinct species of plankton manage to live together, instead of the fitter ones leading the others to extinction. When they are formed, the filaments segregate the different species. Naturally, empty spaces – without plankton – arise between these filaments and make the competition between the species less direct: the regions without plankton work like an escape area for the less adapted species. "This form of organization makes it possible for all the species to get food, light and oxygen, even though some predominate over others", Grebogi says.

When the population of a given kind of plankton becomes very small, the escape area becomes proportionally larger, and this species gains more room to expand, explains the physicist, a grandson of Poles who was born 57 years ago in Curitiba, capital of the state of Paraná. "This is how it manages to reproduce and to get back to normal levels", he explains. "By speeding up the reproduction of these species, chaos prevents the extinction of the less efficient and [fosters] the conservation of diversity", says physicist Alessandro Moura, from the Physics Institute at USP and a member of Grebogi's team in this project.

The group's most recent articles about active chaos were published in 2004, in the March issue of the journal *Chaos*, and in April, in *Physical Review Letters*. But the idea of relating plankton to the Chaos Theory had arisen a long time before, about ten years back, when Grebogi and his collaborators, in conversation with biologist friends, discovered that there were more doubts than explanations with regard to the existence of the 8,000 or so species of animals and plants in plankton, with life cycles that vary from two minutes to two days. In the 1960s, Englishman George Evelyn Hutchinson tried to understand the paradox that was afterwards to receive his name. A specialist in aquatic ecosystems, he obviously thought, as a biologist, pointing out the annual variations in temperature and in the summer-winter cycle as arguments for explaining the survival of so many species. Albeit valid, these arguments seem to be insufficient.

Grebogi then began to consider the action of chaos as possibility for an explanation, based on a few indications. The ocean, after all, is a fluid full of particles carried by maritime currents, with many obstacles – instead of this, the biological theories supposed that plankton was distributed in a homogeneous way over the surface of the seas, which does not occur in fact. The first article with the dynamic foundations that were to lead to a solution for Hutchinson's Paradox came out in 1998, in *Physical Review Letters*, signed by Grebogi and his collaborators. The physicist from Paraná was then working at the University of Maryland, in the United States, and was already recognized as an international authority in this area. It was also in 1998 that he became an external lifelong scientific director of the Max Planck Institute for the Physics of Complex Systems, in Dresden, Germany, where he spends two months a year. It was only three years later, in 2001, that the elegant physicist, with

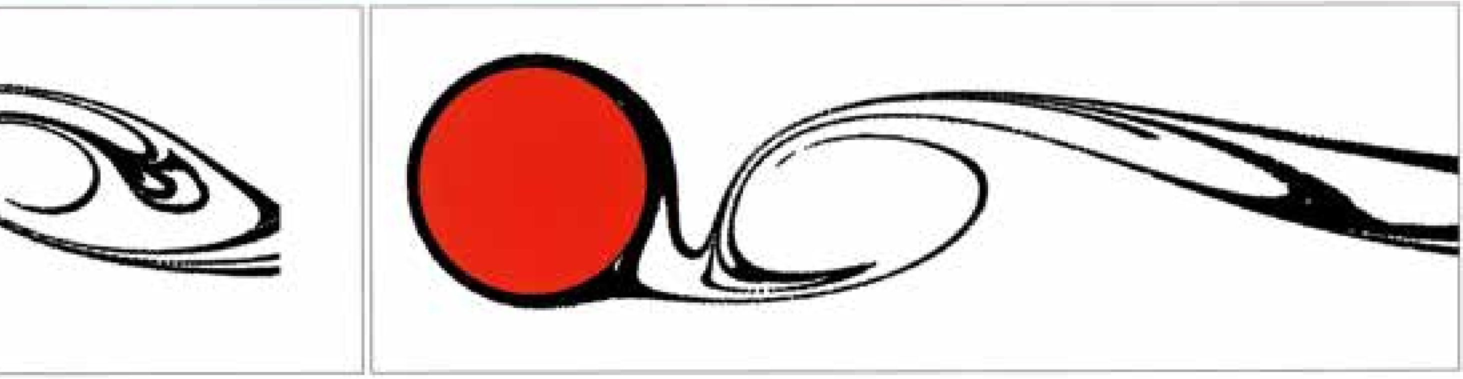
THE PROJECT

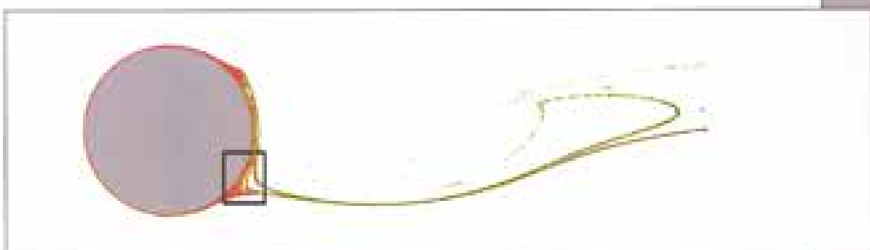
Chaotic dynamics

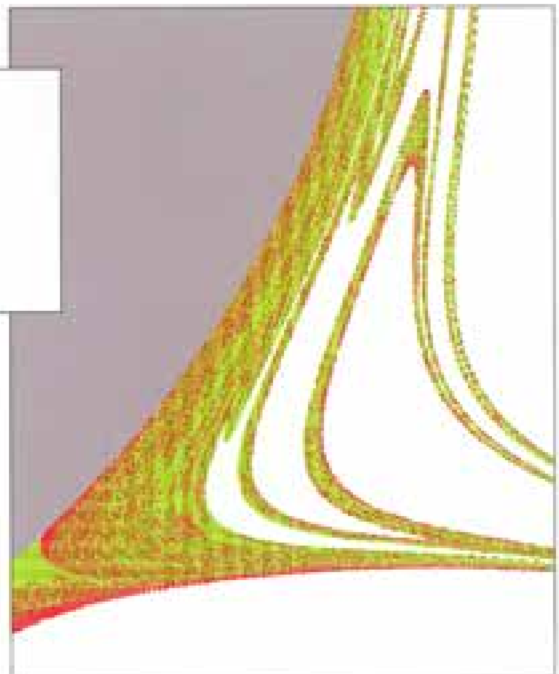
MODALITY
Thematic Project

COORDINATOR
Celso Grebogi – Phiysics Institute/USP

INVESTMENT
R$ 682,179.67







Curves of fertility: after overcoming the barrier, microorganisms of distinct species (*red and green*) blend into filaments (*magnified in detail on the right*). The free spaces favor the reproduction of the less abundant species

refined habits and passionate about opera – Mozart or Verdi for enjoyment, Wagner or Strauss when he wants something stimulating –, was contracted by USP. This year, according to the Brazilian Academy of Sciences, he was the first Brazilian whose scientific articles received over 10,000 citations, accompanied by the Science Citation Index.

CFC and ozone - Grebogi separates from a file another figure – a satellite image –, with which he demonstrates that his model may also help to understand the process of the destruction of the ozone layer in the Earth's upper atmosphere, some 20 kilometers from the surface. A gas made up of molecules formed by the union of three oxygen atoms, ozone works like a shield that prevents the passage of the Sun's ultraviolet rays, pointed out as being one of the main factors responsible for burns and cancer of the skin. In 1985, researchers from the British Antarctic Survey found for the first time a reduction of 30% in the ozone layer over Antarctica. In August 2003, the hole extended for 17.4 million square kilometers – over twice the area occupied by Brazil.

The ozone molecules are dissolved in contact with the chlorine of gases known as chlorofluorocarbons (CFC), the same ones used in some refrigerators to cool the air. In the upper atmosphere, under the action of the ultraviolet rays, the CFC is broken down, and the chlorine atoms are let free: each one of chlorine can dissolve over 100,000 molecules of ozone. It is at this moment that the Chaos Theory arises as an ally to explain the irregular destruction of the ozone layer. Were the distribution of CFC homogeneous and regular, the chlorine atoms that would break free in the upper atmosphere would probably act on a specific and given area of the layer – and then hole would correspond to a small, roughly circular region. But the CFC molecules follow chaotic trajectories and form fractal filaments, similar to those that are to be seen in plankton.

The dispersion of the gas into filaments expands the contact area between the CFC molecules and the ozone molecules, and speeds up the destruction of the gas that protects living beings against the ultraviolet radiation of the Sun. As a general rule, the larger the contact surface between two chemical compounds, the higher the reaction speed will be – just compare the speed with which a lump of salt dissolves in a glass of water with the same volume of salt in grains. "This finding allows us to direct better the efforts for understanding the destruction of the ozone layer", Moura comments. It is an example that the same chaos seen as a source of life and as an indispensable element for the comprehension of hitherto confused scenarios may be, at time, unwanted.

In industrial applications like the production of paint, the pigments have to be blended in the most homogeneous way possible. The problem arises when the chaotic movements of the pigment blenders result in the formation of undesirable filaments for not being homogeneous. "If we are capable of eliminating chaos", Grebogi ponders, "this theory could have industrial applications". His team is also studying turbulent fluids, defined by their random and extremely complex behavior, like the eddies that form in a stream of the movement of air caused by the takeoff of an airplane. As it occurs in the atmosphere, in the seas, and in other situations in which fluids move at a high speed, turbulence is a phenomenon of extreme practical importance, in particular for aviation and shipping. "For fluids with turbulence", says Moura, "we suspect that the catalyzing effect of chaos may be even more powerful". •

Artificial Neurons

Computer replaces nerve cells in crabs and lobsters

During half an hour, the blue crab remains covered by ice in a polystyrene box in the laboratory of physicist Reynaldo Daniel Pinto, from the University of São Paulo (USP). When it is taken out, it has already been anesthetized by the low temperature. On the bench, the researcher opens the carapace of this crustacean called *Callinectes sapidus* and examines its insides. Between the eyes, there is the brain, and, right below it, the stomach.

Daniel Pinto identifies the 30 neurons that control the crab's system for digesting and chewing, isolates them carefully, and starts a delicate operation: with the assistance of a microscope, he implants in one of these nerve cells a glass electrode filled with a solution of potassium chloride, whose tip is thinner than a strand of hair. Copper wires connect this electrode to an electronic circuit that converts the nerve impulses into digital figures, which can be understood by an ordinary computer, which now plays a special role: it replaces one of the extracted cells and acts as an artificial neuron. There's your bionic crab.

In this experiment, the physicist assesses the computer's capability for carrying out the same function as a neuron called the anterior burster, one of the 14 nerve cells that make up the pyloric system, which runs the transport of food from the stomach to the intestines. If one of these neurons is destroyed, or communication with the nerve centers in the brain is interrupted, the others start to emit disorderly electric signals and digestion stops. That is when the computer comes into play: duly programmed, it is transformed into a virtual neuron that behaves like its biological equivalent, just like a pacemaker.

Another electrode stuck into the neuron injects a current with ions – electronically charged atomic particles – of potassium and chlorine that migrate to the cell. This recreates in the cell the chemical environment needed for the transmission of the nerve impulse. As soon as it receives the stimulus, the crab's ner-

THE PROJECT

Non-linear dynamics

MODALITY
Thematic Project

COORDINATOR
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INVESTMENT
R$ 476,477.50