COGITO

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MEDICAL REVOLUTIONS

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CHAOS AND ORDER

An interview with Professor Michael Berry F.R.S.

Michael Berry, Professor of Physics at Bristol University, discusses the philosophical ideas underlying his research into the theories of catastrophes and chaotic systems. He is one of England's leading scientists, and has been instrumental in the growth of modern interest in qualitative phenomena.

Cogito: Catastrophe theory is a powerful general tool for thinking about continuous growth and sudden change. It can be traced back to the late 19th century, when King Oscar of Sweden offered a prize for the discovery of a proof of the stability of the solar system, a long-standing problem in celestial mechanics. The prize was given to Poincaré in 1889. His work on the problem laid the foundations for the modern "qualitative" or "geometric" viewpoint in physics. ("Qualitative" here does not mean non-rigorous "hand-waving", but entails rigorous *abstraction from the quantitative*). It culminated in the development of modern differential geometry and topology, the rocks on which catastrophe theory is built. René Thom's work on catastrophe theory and recent ideas of chaos in dynamical systems are the fruits of Poincaré's ideas. Could you tell us how you became involved in it?

Professor Berry: My interest in catastrophe theory started with the attempts, which continue to this day, to understand the connection between classical mechanics and quantum mechanics. In the beginning I was interested in other sorts of problems, such as the scattering of particles and beams of light; I realised that focussing was crucial, but was rather surprised that I couldn't find any proper treatments of this rather old-fashioned subject. In 1974 I visited the Institute of Theoretical Physics at Trieste, where I was shown Thom's book *Structural Stability and Morphogenesis.* At first I didn't take it seriously. A few months later it suddenly dawned on me that this was the mathematics I needed.

I then looked at optics in the limit when the wavelength of light is so small that the effects of wave motion can be neglected. Here you work in terms of rays: that is the old geometrical optics.

Cogito: That application of catastrophe theory to optics was an application to classical (i.e. pre-quantum) problems, wasn't it?

Professor Berry: Oh, yes. The surprising thing about this advance is that it is an application of mathematics which doesn't tell you new fundamental laws (of, in this case, physics); that's what scientists had always thought was an advance in the subject. It is rather an advance which enables you to understand *qualitatively new phenomena* which are contained in the already-known laws. That is quite profound. You believe, as an article of faith, that underlying the complexity of the world there are laws which, though subtle and mathematically sophisticated, are simple. The aim of physics has traditionally been to find these laws, and this is what is continued now in particle theory, with strings and superstrings, etc. Non-scientists often accuse us of having simplified away the real world. But if these laws of physics are such wonderful 'encodings' of the world, how do you do the decoding, and get

Chaotic Motion: A Study of Water Formations. Drawing by Leonardo. (Original in Royal Library, Windsor.)

the world back again? Catastrophe theory is mathematics which does that very beautifully for a very restricted but important range of problems.

Cogito: Yes, Thom's work is related to levels of organisation, with different laws governing different levels. The importance of this was recognised long ago - for instance, in the idea of 'emergence' which arose from the controversies over the theory of evolution.

Professor Berry: Everyone has seen the dancing lines formed on the bottoms of swimming pools by the sunlight as it is focussed by the waves on the top. Why are those lines distributed and connected in the way they are? Now if you had asked that question 20 years ago, you would have got one of two answers. The first answer would be "it's trivial, it's just Snell's Law of refraction, after Snell in 1610, modified by Descartes in 1638. The patterns of light are just the refractions of sunlight." But if you wanted to know why those lines are exactly in the positions that they are, you would have got the second answer, which is "That's a bit complicated, but you could easily write a computer program to get the pattern of light." But both of those answers would have missed a very essential point, which is that you would not have got an understanding of why it is that we see some kinds of connections of the lines, but not others. It is precisely this qualitative information that catastrophe theory gives you.

There is a mathematical framework, technically the singularities of gradient maps, which describes the focussing of systems of rays. This similarity of the mathematical frameworks of optics and catastrophe theory is very precise. It is one of the few examples where catastrophe theory can be used in a precise way, rather than a means of producing stimulating analogies, as occurs in other applications of catastrophe theory to sociology and economics etc. (These are subjects harder than physics where you don't have a mathematical framework. There, you can only use mathematics in a kind of 'incantatory' way.)

Cogito: Catastrophe theory is a powerful general tool for constructing mathematical models of sudden change and continuous growth. The relation between the model and the modelled varies, however. There is a spectrum of cases: at one end the model simply *describes* the observed phenomena, and at the other end, the model is necessitated by the known *laws*.

The idea of a general description of phenomena in terms of continuous development punctuated by singular events of qualitative change is to be found in Hegel's logic in his category of Measure. It occurs as the highest development of descriptive concepts (category of Being), on the boundary with explanatory concepts (category of Essence). Some applications of catastrophe theory seem to have undertaken a dialectical journey, starting out as description and returning as explanation. Your own work on catastrophe theory, however, derives from the laws of physics.

Focussing Rays

Professor Berry: Consider the focussing of light on a surface in space. You don't see those rays; you see what happens when you intersect the space with a surface such as a screen. The brightest lines you then see are called *caustics*, which are kinds of singular structures, which catastrophe theory tells you about. They are singular because, for example, as you go from one side to the other, the number of rays hitting a point changes discontinuously, by a factor of two. Catastrophe theory gives you a hierarchy of geometric forms whose investigation was begun by René Thom, and greatly developed by Vladimir Arnol'd in the Soviet Union. There is a 'library' of forms with nice names: there is a 'cusp', a 'swallow tail', 'umbilics', etc.

So far we have spoken about light rays, but rays are only approximations. The best theories that we have are *wave* theories. The wavelength may be very small, but the waves are there. So you might think it a waste of time to work on a wrong theory. That is a typical reductionist argument. It is silly, because there are many instances where the imperfect and approximate theory is a sensible description. For example, if you are planning to send a spacecraft to the moon, you don't solve Schrödinger's equation for the wave propagation of the wave packet which represents the spacecraft. The wavelengths are so small that quantum effects are going to be negligible.

Cogito: Yes, the wrongness of a theory is a matter of degree. You get to the moon with Newton, not Schrödinger.

Professor Berry: A much better response is to ask about the fine detail of these focussing patterns. Well, firstly, the caustic surfaces won't be sharp singularities but places of high intensity. Secondly, wherever several trajectories meet there will now be a pattern of interference fringes. As the wavelength becomes very small, the patterns shrink. The wonderful bonus we get from catastrophe theory, is that the classification of catastrophe singularities invented by René Thom, which he thought in the beginning just applies to rays, also gives very precise descriptions of the wave patterns that decorate those focussing regions. The details of those decorations are very important and beautiful, and a whole new class of mathematical objects came out of that analysis and are still being used today.

Twinkling Stars

Cogito: What other applications are there?

Professor Berry: The question of why stars twinkle is very old. Newton gave the essentials of the answer that we have today - the stars twinkle because the atmosphere is not a smooth refractive medium, but has turbulent regions which refract the light rays ever-so-slightly. Still, over long distances such as when the star is near the horizon, the rays can be disturbed so much that the light can be brought to focus. Now that interpretation stood for 300 years, without any quantitative description. How do you give a statistical description of these fluctuations? People haven't studied that very much, because the main aim has been to avoid making astronomical observations in such circumstances. Catastrophe theory gives an answer. Particularly bright twinklings occur whenever caustics pass across your eye, just as when you have a bright line on the bottom of the swimming pool. This subject is a thriving branch of optics that did not exist twelve years ago.

Chaos

Cogito: Poincaré touched on chaotic dynamics, which is what occurs if regular and simple laws lead to irregular and chaotic effects. René Thom's book contains some basic things about chaotic behaviour, doesn't it?

Professor Berry: Not really. He is interested in it, but he doesn't have anything on chaos such as the theorems about the classifications of catastrophes.

There is a sense in which chaos and catastrophe are at opposite ends of a spectrum. In mechanics and optics we get catastrophes where we have smooth families of trajectories with stable geometries. Chaos is quite different. You get chaos in mechanics when you have trajectories which are confined to the same region of space, which is repeatedly explored, but each time they come back to the same region, they come back in a slightly different direction. The net result is a great tangle like spaghetti in a pot. There is very precise sense in which chaos in a mechanical system is the *absence* of focal surfaces - a kind of geometric instability.

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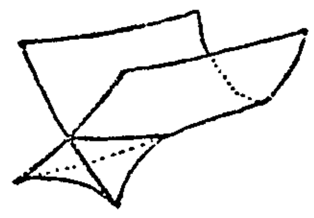


Elementary Catastrophes: the Swallowtail

Cogito: You have to be careful of the word 'instability' here, because chaos can be structurally stable.

Professor Berry: Yes, but in a different sense. A lot of the developments of the pure mathematics in these subjects has been to answer the question, "what do you mean by 'stable' in these different contests?".

Cogito: In catastrophe theory and in chaos you have a smooth progression through various phases, and then the phase changes suddenly to a different topological state.

Professor Berry: Yes, but that obscures a deeper difference. The results of these progressions are very different.

Cogito: In chaos, the smooth progressions are at the microscopic level, but you are interested in the large-scale phenomena.

Professor Berry: Anyway, there are trajectories of dynamical systems which look chaotic. This is very profound. I must say I find this rather deeper in its implications than catastrophe theory, as it touches on the notions of predictability, determinism and randomness. We had always taken for granted, with Laplace, that if you know the laws governing a system, you could predict its course. (This assumption is so deeply interiorised as not usually to be made explicit.) Understanding something and trying to predict something were equally objects of scientific endeavour. We know that is not true now. In catastrophe theory, you know the laws and can tell the new features of the patterns that those laws generate. In chaotic systems you also know the laws very precisely, but you have evolving patterns of trajectories which you can't predict, because these phenomena are so unstable that their courses are essentially random. Previously we thought that randomness was a kind of uncertainty introduced by external disturbances of which we were ignorant.

Cogito: Or else an uncertainty in the actual law itself, as in quantum mechanics.

Professor Berry: That's right. Now we know that there are common situations in physics where we have very simple and deterministic laws, which give intrinsic instability, in the sense that trajectories of close initial conditions diverge very quickly.

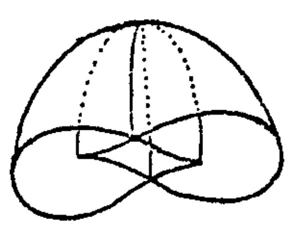
Cogito: Could you give an example?

Professor Berry: Yes. The most spectacular example is the way a mass of fluid such as air or water can move in a chaotic way, as opposed to other masses like treacle and honey, which move smoothly. This remains a mystery. You can't predict the weather; that is a very simple example. The laws governing masses of air are very well known. The instabilities do not arise, as previously thought, from the fact that air is really made of atoms; even at the continuum level (which is appropriate enough for air) there is intrinsic instability.

There are chaotic motions in the solar system. The belt of asteroids between Mars and Jupiter has gaps because particles in those gaps would have chaotic trajectories. In narrow zones of radius, the pulls of Jupiter and the Sun resonate with each other, and asteroids would be transported out of those regions. They can in fact come near to the orbit of the earth; that is where our meteors come from.

Cogito: How well defined is your notion of predictability here?

Professor Berry: In these unstable chaotic systems, in order to predict for a certain time into the future, you need to know your initial conditions to a certain accuracy, which increases very rapidly (exponentially, in fact) with the time over which one wants to predict. A precise statement is in terms of the theory of *algorithmic complexity*. You ask "how long does a computer program need to be to predict for a certain time?" If a system is chaotic, by far the greater part of the program is simply copying in the numbers which give the initial conditions. For chaotic systems, this will become very large. Complexity seems to be the deepest way of summing up chaotic systems.



The Hyperbolic Umbilic

Education

Cogito: Einstein asserted that he would never have had the courage to challenge Newton had he not read Hume. Philosophical conceptions, while they might not bear directly on a particular scientific problem, can lead to scientific innovation. Do you think there is any place in the teaching of science for dealing specifically with philosophical issues?

Professor Berry: I think that philosophy practised by professional philosophers interests scientists, but rarely helps them. The traffic mostly flows in the other way, in my opinion. However, when teaching physics, one should be aware of philosophical matters, and inject them at every possible opportunity. That is a very carefully considered reply. It is different from saying, one should have courses on the philosophy of science.

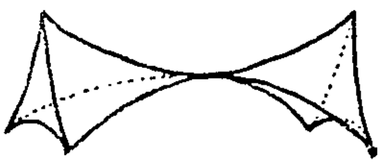
Cogito: We asked Mary Warnock in our last issue, whether there should be a philosophy A-level course. She said no, but she thought that aspects of philosophy should be introduced into existing courses.

Professor Berry: I partly agree with that, but I wouldn't object at all to philosophy at A-level. The question is different: whether one should have it in physics courses. It would only be artificial.

Cogito: There is a joint degree in physics and philosophy in this university. Do you want to say anything about that course?

Professor Berry: The course has been very valuable. At the beginning we said that it is not a course where we will teach physics and philosophy; but one where you learn physics in the physics department, philosophy in the philosophy department, and make your own connections. It would be artificial to give special courses, we felt. In the third year, you have the option of writing a dissertation on some connection between the two.

The more one teaches, the more one points out the connections with the other branches of knowledge, without losing the inner logic of your subject. We seldom give the practical engineering applications, or touch on the philosophical, literary and artistic aspects, (which in the case of the catastrophe theory are considerable). Keeping philosophical issues in mind reminds us that science is not isolated from other human activities.



The Elliptic Umbilic

Cogito: Yes, as soon as you reflect on the place of science in human activity, you encounter questions of moral and political philosophy. That brings us to the lectures on 'Science in Society' which have gone on in Bristol since 1968. Physicists have gone beyond their immediate scientific concerns, and looked at the wider issues of their science.

Professor Berry: But even before 1968 this department had such issues in mind.

It is wonderful for science to be applied but the applications are sometimes shocking. The military applications of science have become an obscene diversion of resources. The best advice I can give to people who are beginning science, who might have a great variety of political opinions, is to think about what you are doing.

One can't avoid involvement with the applications of science, because once you have done a piece of work it becomes public property. Anything of value you do will be used by the military and others. It would be an over-reaction to say that science should therefore not be done. Somebody who works in a steel mill knows, certainly, that some of the steel he is making is going to end up in guns and tanks, etc. But nobody would suggest that such primary productive industries shouldn't be done. Science, I believe, is qualitatively the same. You cannot give up the whole enterprise. My own particular position is not to work on any projects which are directly intended for military use, or receive funding from military agencies. You may say, why not take the military money, and do, as is often the case, rather pure science with it? After all, better that the money comes to this use than to others.

Cogito This is one of the arguments used for the recent 'star wars' money.

Professor Berry: There is this vast gravy-train, and the chance to get money out of it. I think it is a mistake, because you are then compromising yourself by offering support for the project.

Cogito: Military funding often imposes secrecy. Could you say something about this issue as it is important not just to science, but to all academic activity.

Professor Berry: Commercial research involves secrecy. Now unfortunately secrecy is completely antipathetic to the progress of science. You have to be very careful in taking their money, that you do not destroy the openness on which science depends. It happens that in this university matters are rather easier for us. There was a Senate resolution in 1969, which allows funds to be accepted from any source whatsoever, provided there are no contingent restrictions on the publication of the results. That is very useful. I fear it is honoured more in the breach than the observance, but it is certainly a good policy to have.

Interview conducted by John Cleave and Ian Thompson