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ECONOMIC POLICY AND CATASTROPHE THEORY

by

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Introduction

When scientists want to describe a phenomenon, they often do this by constructing a mathematical model. If this model is successful it is often said that the problem has been "explained" by the model. Until recently a typical method in mathematical modelling has been the use of differential calculus and more specifically differential equations have been used to describe the behaviour of a phenomenon. But this method has a severe drawback, as it can only describe situations where the changes that take place are smooth and continuous. In other words solution functions to the differential equations must be differentiable. But obviously only rather few phenomenon behave that nicely. More often we observe sudden transformations and unpredictable divergences. This seems to call for a description by non-differentiable functions.

Catastrophe theory is a mathematical method for modelling such discontinuous phenomena. It applies to situations where gradually changing forces produce sudden effects. As our minds almost take for granted that continuous causes produce continuous effects, we are tempted to call it a catastrophe, when a continuous cause results in a discontinuous effect. Hence the name.

Catastrophe theory was invented during the sixties by Rêne Thom, a French mathematician, and the ideas are presented in his book "Stabilité Structurelle et Morphogénesè". Briefly the idea in catastrophe theory can be described as follows. A system may be resting quietly in equilibrium while the underlying forces are slowly changing, causing the equilibrium position to move slowly. Eventually a point is reached, where that equilibrium breaks down, and the system "jumps" suddenly to a new position of equilibrium.

From this description it is clear that the basic concept for the theory concerns the points of equilibrium. As underlying forces vary, the corresponding equilibria can be described by smooth surfaces in multi-dimensional spaces. The aim in catastrophe theory is to describe the shapes of all possible equilibrium surfaces. Thom has done this in terms of a few archetypal forms, the elementary catastrophes. Thom's theorem states specifically that for processes controlled by no more than four factors, there are at most seven elementary catastrophes.

Proof of Thom's theorem is complicated. It involves theorems from several branches of mathematics: topology, geometry, commutative algebra, and differential equations, so from a purely mathematical viewpoint, catastrophe theory can be seen as a catalyst to stimulate work in the theory of singularities. Fortunately the results of Thom's theorem are relatively easy to understand, and what seems very relevant to economists for example, is that the elementary catastrophes themselves can be understood and if carefully handled, applied to problems without reference to the proof.

The paper falls into three parts. First I shall state Thom's theorem in a simple form. Then I shall go on to a more application oriented point of view and outline when it seems reasonable to take catastrophe theory into account in constructing a model. Finally I shall present three examples to show how catastrophe theory may have implications for economic theory and policy making.

Thom's classification theorem

Roughly speaking the content of Thom's theorem can be stated as follows. Suppose we are given some parameter space "control space" C^2 (2 indicates the dimension), a state space X^n, and a smooth generic function $f: C^2 \times X^n \to \mathbb{R}$. Then the equilibrium surface given by $\partial f/\partial x = 0$ can have only fold and cusp singularities, i.e. the equilibrium surface is locally of the form as in Figure 1.

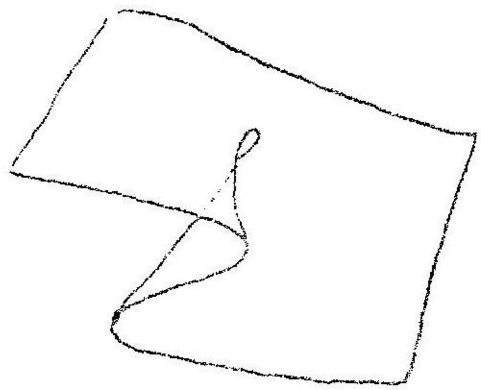

Fig.1.

To make this statement precise I shall have to introduce a few concepts. Let $f: \mathbb{R}^k \times \mathbb{R}^n \to \mathbb{R}$ be a smooth (i.e. C^∞) function, which represents a dynamical system in the sense that the system locally minimises (or maximises) the "potential" f. For fixed control point $c \in \mathbb{R}^k$ we have a local potential function $f_c: \mathbb{R}^n \to \mathbb{R}$ defined by $f_c(x) = f(c,x)$. The hypothesis can then be expressed explicitly by the differential equation

$$\dot{x} = -\text{grad } f_c$$

where $x = (x_1, \ldots, x_n) \in \mathbb{R}^n$ and $\text{grad } f_c = (\partial f/\partial x_1, \ldots, \partial f/\partial x_n)$, so the state x will flow towards a minimum of f_c. More generally we could just assume that we have a differential equation on $\mathbb{R}^n$, parametrised by c, such that f_c decreases along orbits.

We now define M_f to be the set of stationary values (equilibria) of f_c, i.e. M_f if given by the equation grad $f_c = 0$. Define the catastrophe map $\chi_f : M_f \to \mathbb{R}^k$ to be the map induced by the projection $\mathbb{R}^{k+n} \to \mathbb{R}^k$. Let S be the set of singularities of this map and call $B = \chi_f(S)$ the bifurcation set. Finally let $\mathcal{F}$ denote the space of smooth functions on $\mathbb{R}^{k+n}$ endowed with the Whitney C^∞-topology. We then have,

<u>THEOREM</u> Thom, (1975)

If $k \leq 5$ there is an open dense set $\mathcal{F}_o \subset \mathcal{F}$, which we call the generic functions. If f is generic, then

1. M_f if a k-manifold.
2. Any singularity of χ_f is equivalent to one of a finite number of types called elementary catastrophes.
3. χ_f is stable under small perturbations of f.

The number of elementary catastrophe depends only upon k as follows:

k	1	2	3	4	5	6	...
no. of ele. catastrop.	1	2	5	7	11	∞	...

Definition of equivalence. $\chi : M \to N$, $\chi' : M' \to N'$ are said to be equivalent, if there exist diffeomorphisms h,k such that the following diagram is commutative

$$\begin{array}{ccc} M & \xrightarrow{\chi} & N \\ h \downarrow & & \downarrow k \\ M' & \xrightarrow{\chi} & N' \end{array}$$

If χ, χ' have singularities $x \in M$, $x' \in M'$, the singularities are said to be equivalent, if this definition holds locally with $x' = h(x)$. χ_f is stable means that χ_f is equivalent to χ_g for all g in a neighbourhood of f.

The elementary catastrophes are given by simple polynomials. In order to illustrate the theorem I shall return to the picture above, which depicts the simplest elementary catastrophe of some subtlety. It is called the cusp catastrophe. Here $k = 2$, so let (a,b) be the coordinates of the control space. Take $n = 1$ and let x be the coordinate of the state space. Finally let $f: \mathbb{R}^2 \times \mathbb{R} \to \mathbb{R}$ be given by

$$f(a,b,x) = x^4/4 + ax^2/2 + bx$$

Then M_f is determined by the equation $\partial f/\partial x = x^3 + ax + b + 0$. A singularity of $\chi_f : M_f \to \mathbb{R}^2$ occurs when a local maximum and a local minimum of f coalesce, i.e. $\partial^2 f/\partial x^2 = 3x^2 + a = 0$. So the singularity set S consists of the two fold curves $\{(-3t^2, 2t^3, t)\}$, $t>0$, $t<0$, and a cusp singularity at $(0,0,0)$. The bifurcation set B is given by $(a,b) = (-3t^2, 2t^3)$, which is the cusp $4a^3 + 27b^2 = 0$.

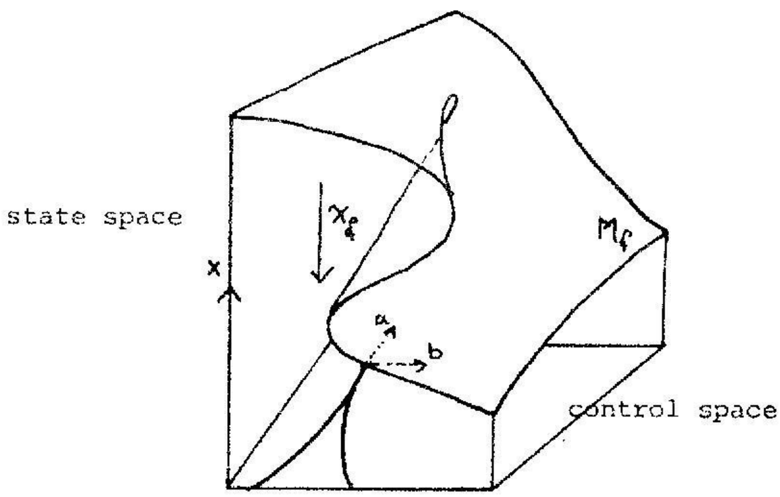

Fig.2.

The theorem states that the equilibrium surface is a smooth manifold, which contains only folds and cusps as singularities. Therefore locally, the picture above is the most complicated we can have.

If we increase the dimension of the control space by 1, this will result in an increase of M_f's dimension by 1. Now M_f will not be folded along curves but instead folded along surfaces and the bifurcation set will consist of surfaces in three dimensions with cusped edges. In this case a new type of singularity will appear, called the swallow tail catastrophe. I shall not go further into this geometric discussion, but just mention that a complete presentation of the elementary catastrophes may be found in Thom's book.

Before ending this mathematical discussion it should be stressed that the statement of the theorem says nothing about the dynamical system introduced above as a hypothesis. In fact the theorem does not assume anything but genericity of the function f. However, in most applications we start out with some dynmaics on the state space and then make no reference to the potential function. This is justified by the theorem as follows. In practice the dimension of the state space will often be very high. Then the internal dynamicsdescribing the phenomena will be very complicated, and the potential f impossible to calculate, i.e. the potential can only be implicit. But when we for example are studying the effect of two specific control variables, the theorem says that the cusp catastrophe is the most complicated to arise. This is independent of the dimension of the state space. So locally the implicit catastrophe map is equivalent to the explicit three dimensional model above. This allows us to forget the implicit complicated description related to the high dimensional state space and instead look at the explicit description with a one dimensional state variable. And in this three dimensional model there is no meaningful potential which represents the dynamics.

When to apply catastrophe theory

The best way to understand when it might be appropriate to try to apply catastrophe theory in constructing a model, is to describe the specific properties a catastrophe model is able to handle. Again in order to keep things simple I shall only discuss the qualities of the cusp catastrophe. This is characterized by five qualities, bimodality, catastrophe jumps, hysteresis, divergence and inaccessibility. These will now be explained.

The main qualitative feature of the cusp catastrophe is the bimodality, which emerges because the equilibrium surface is folded over to form a pleat. At points in the control space outside the bifurcation set (which is here a cusp) the surface is single-sheeted, while it is triple-sheeted inside. This represents the fact that outside the cusp there is only one stable equilibrium point, while inside there are two stable points and one unstable point. As there usually is some "noise" connected with a specific system it is not likely to remain in an unstable equilibrium situation. It is therefore acceptable to focus on the stable part of the surface, and the behaviour is then bimodal inside the cusp and unimodal outside.

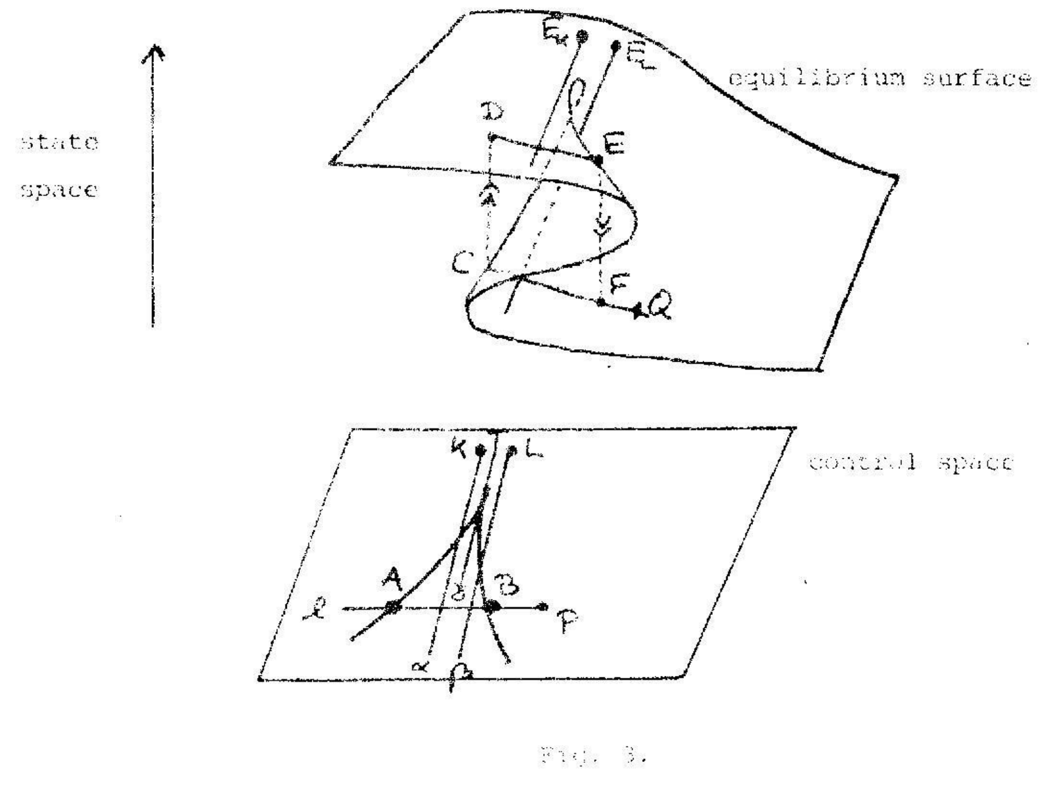

Fig. 3.

In order to describe the second quality, the catastrophe jump, consider the (control) point P moving along the line ℓ. The corresponding state Q on the equilibrium surface moves smoothly until it crosses the fold curve at the point C. Here the stability of the equilibrium breaks down and the point jumps into a new equilibrium position at the point D. This is the catastrophe jump.

If we now move the control point P backwards along the line ℓ the equilibrium point will move smoothly on the upper sheet until the point E is reached. Here stability breaks down and there is a sudden jump down to the point F. The difference in the control space between the points A and B where jumps take place, is called the hysteresis.

Now look at the two points K and L, near to each other, in the control space and the corresponding points E_K and E_L in the equilibrium surface. As we move K and L along the parallel lines α and β it will be seen that the points E_K and E_L stay on the two different stable sheets of M, and in this way move away from each other. This property is called divergence. What is important to notice is that the change of behaviour along the paths α and β has been smooth without any catastrophic jumps. So divergence may be described as the possibility that marginal differences at the outset may eventually produce major differences in the states.

The last quality, called inaccessibility, is described by the fact that as soon as a point T has passed the cusp point on the line γ, there will be some states that cannot be obtained on the equilibrium surface, the unstable equilibrium points.

Applications

Example 1. Savings behaviour in a disequilibrium model

The first example I shall develop is inspired by recent work in disequilibrium theory as presented by E. Malinvaud (1978). It is assumed that the reader is familiar with the basic ideas in this theory, where prices are assumed fixed such that equilibrium is obtained only by adjustment in quantities. The specific application is related to a paper by V. Böhm (1978). This paper presents one of the first attempts to incorporate some dynamics into these disequilibrium models in order to describe the development of disequilibrium states over time. A general presentation of Böhm's model is not intended; just a few facts which are necessary to explore my example, are explained.

As usual in a disequilibrium model Böhm distinguishes between three types of equilibria, Keynesian equilibria, where consumers are rationed on the labour market and producers are rationed on the goods market, Classical equilibria, where consumers are rationed on both markets, and Repressed Inflation equilibria, where consumers are rationed on the goods market and producers are rationed on the labour market. Corresponding to these three cases Böhm obtains the following diagram

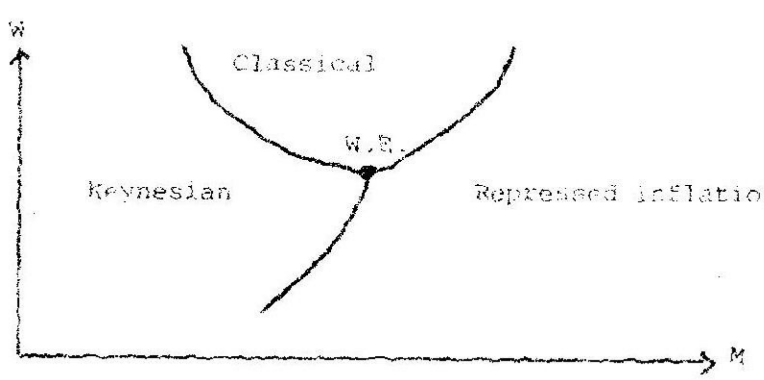

Fig.4.

Here W is the real wage rate, M is total real balances and W.E. is the Walrasian equilibrium with no rationing at all.

The dynamics is introduced to the model by looking at disequilibrium savings through time (i.e. changes in money holdings) under the assumption that the real wage rate is kept fixed. By restricting the range of the wage rate Böhm assures that the equilibrium is either of the Keynesian or the Repressed Inflation type. Böhm then obtains the following qualitative picture of the savings behaviour through time, supposing positive savings at the temporary Walrasian equilibrium.

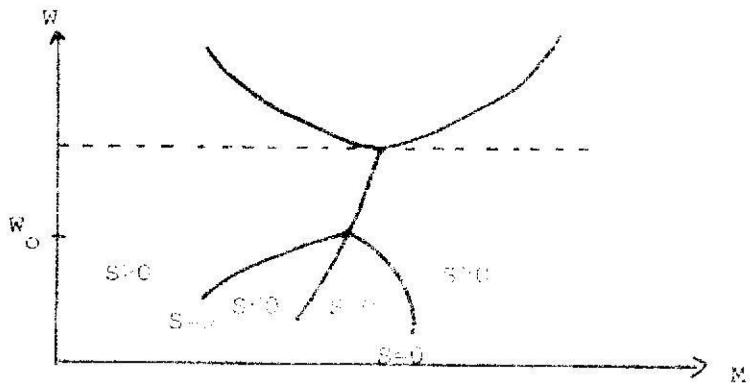

Fig.5

Fixing the wage rate at a level below W_o we get the following picture of savings as a function of M

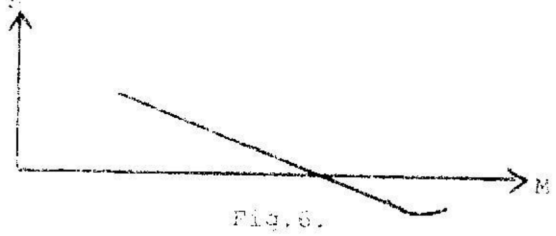

Fig.6.

This is the picture on which I shall elaborate, inspired by ideas expounded in a paper by E.C. Zeeman (1973a).

Looking at the situation in continuous time a first simple approximation to the description of M's variation with M is given by the following first order differential equation

$$\dot{M} = f(M)$$

The linear approximation to this equation around the equilibrium is

$$\dot{M} = -\varepsilon M$$

which has a solution of the form

$$M = M_0 e^{-\varepsilon t}$$

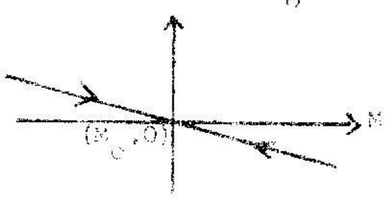

Fig.7.

This is a very simple description given by a one dimensional dynamical system defined on a line, with one stable point of attraction. But a description of this type rules out the possibility of, for example, any oscillation around the equilibrium. Inspired by methods applied to analogous situations in physics, we shall now try to replace this simple differential equation with the following system in order to embed the above picture in a more general situation for the plane. This is obtained by looking at the equations

$$\dot{M} = f(M)$$

$$\ddot{M} = g(M,\dot{M})$$

which define a dynamic system around the equilibrium. Again, considering the linear approximation we have the system

$$\dot{M} = -\varepsilon M$$

$$\delta\ddot{M} = -(\dot{M} + kM)$$

or in order to keep things simple

$$\dot{M} = -M \qquad (\text{"slow" equation})$$

$$\delta \ddot{M} = -(\dot{M} + M) \qquad (\text{"fast" equation})$$

with the interpretation that the first equation gives a slow adjustment while the other is fast. To explain what is meant by that consider a graphic representation of the system

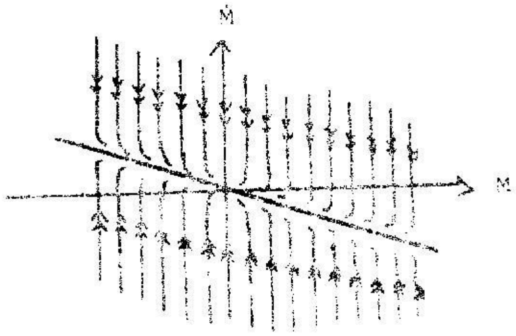

Fig.8.

The "slow manifold" is defined as the set of points where $-(\dot{M} + M) = 0$, i.e. where the fast equation is zero. Meanwhile the "fast foliation" is defined to be the family of lines parallel to the $\dot{M}$ - axis. That the first equation defines a slow movement compared with the second can be obtained by assuming $\delta > 0$ small compared with $\varepsilon = 1$. Except in a neighbourhood of the slow manifold, the vectorfield which represents the dynamical system is parallel to the $\dot{M}$ - axis, as the $\dot{M}$ component dominates the M component. We let double arrows represent the fast foliation, oriented towards $\dot{M}$ positive where $(\dot{M} + M) < 0$ and oriented in the opposite direction where $(\dot{M} + M) > 0$. If equilibrium is disturbed the return of the system can approximately be described by a rapid movement towards the slow manifold followed by a relatively slow movement along the slow manifold to equilibrium. As $\delta \to 0$ the speed of adjustment towards the slow manifold is increased and in the limit (δ=0) it jumps instantaneously. So we have

a) The *slow manifold* is determined by the *fast equation*.

b) The slow equation determines the behaviour on the slow manifold.

In this way we have now transformed the first picture, where the dynamical system was *only* defined on a line, into a more general situation *with a dynamical* system defined in the plane.

We now make a small change in the slow equation as we want to look at the following system

$$\dot{M} = S$$
$$\delta\dot{S} = -(S + M)$$

The *slow manifold* is the same (the fast equation is unchanged). The behaviour on the slow manifold is also unchanged because on the slow manifold we have $-M = \dot{M}$. So the slow equation is in effect the same. The subtlety of this change may not seem quite clear. But perhaps the following consideration will clarify the idea. Before the change was made, S was simply defined by $\dot{M}$. Now S is introduced directly into the system as a behaviour variable with an interest of its own, and it must therefore be taken into account when describing the behaviour of M.

Next we make another *small change* in order to get the following equations

$$\dot{M} = S$$
$$\delta\dot{S} = -(M^3 + \dot{M} + M)$$

The change is obtained by adding a cubic term to the second equation, and this gives us the first non-linear situation to consider. Let us look at a graphical representation of those equations

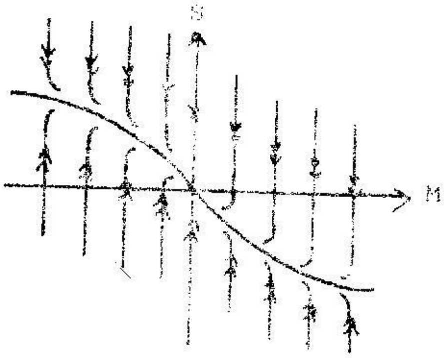

Fig.9.

Around the origin the linear approximation to this example is exactly the example given above. It can therefore be considered as a slight generalization of the original situation in Böhm's paper (1978). And it is clear that if we work out the precise solution, we get something very much like the first simple solution.

Let us now make the following change in the fast equation

$$\dot M = S$$

$$\delta \dot S = -(S^3 - S + M)$$

i.e. change the sign of the S-term.

The picture then becomes

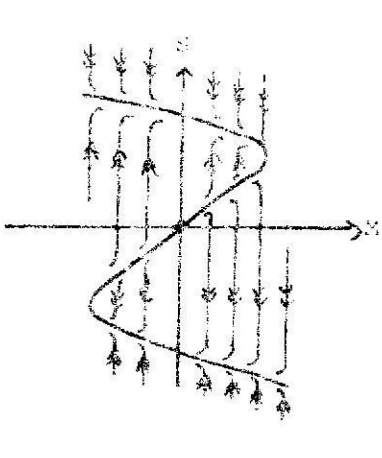

Fig.10.

which shows that the slow manifold has bent into an s - shaped curve. We note particularly that the equilibrium point has changed from being an attractor to being a repellor. From the viewpoint of the fast foliation a complete section of the slow manifold has shifted from being an attractor to a repellor.

This last change of the form of the equation can be obtained continuously by looking at the paramentrised equation

$$\delta\dot{S} = -(\dot{M}^3 + a\dot{M} + M)$$

where a varies from +1 to -1. The result is the following picture in three dimensions

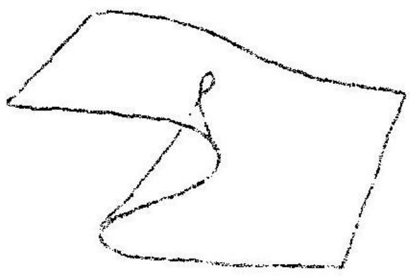

Fig.[illegible]

i.e. the cusp catastrophe.

What is the economic interpretation of this series of examples? Let us first look at the picture drawn for the situation

$$\dot{M} = S$$
$$\delta\dot{S} = -(\dot{M}^3 - \dot{M} + M)$$

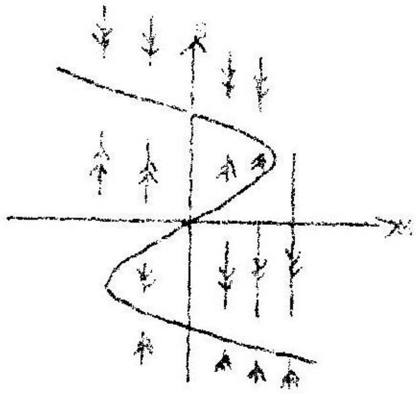

Fig.1[illegible]

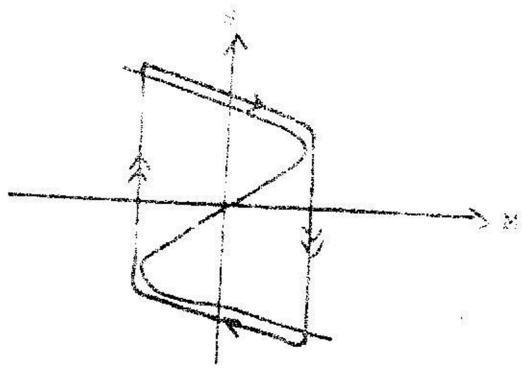

Fig.13.

The pictures describe a situation where there is a cyclical change between positive and negative savings. How may this be realized? In the initial situation consumers' savings moved directly towards the single point of attraction without any changes in sign. Suppose now some external force cause a perturbation of M away from the equilibrium. This external force may cause a change in the savings habits so that the changing in sign of S is delayed. Mathematically this is described by the addition of a cubic term as given above. One explanation of this delay is that consumers are conservative and therefore will continue to behave in the same way until they are forced to change habits, and this happens drastically.

In order to mention one possible external force that might cause this change in consumer behaviour, I shall draw attention to the implicit assumption made until now that the level of government consumption, G, has been kept fixed. It seems reasonable to suggest that an increase in this exogenous demand might produce this effect of delay in the consumer behaviour, and so we end up with the following catastrophe model.

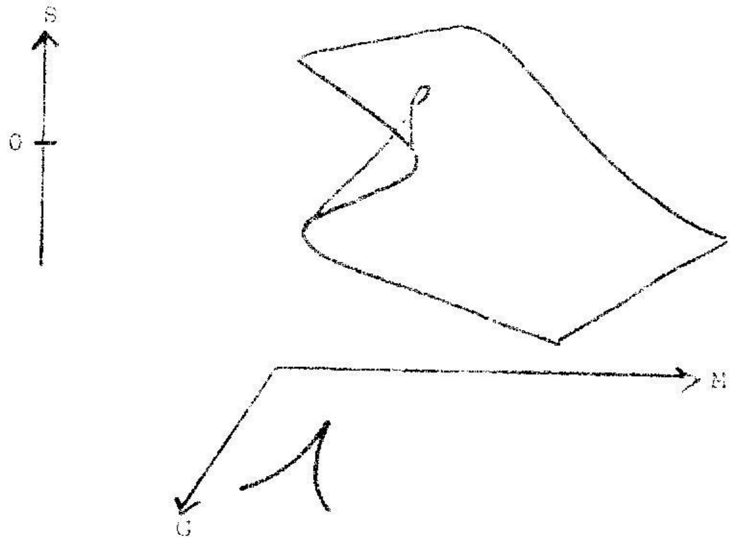

Fig.14.

If G is not too large we have a description of the savings behaviour as in Böhm's paper. But as G is increased it might introduce the possibility of a cusp singularity and hence a description of the savings behaviour as above.

This description seems to offer an interesting explanation to a statement in Böhm's paper, where it is proposed that a sufficiently large increase in government consumption may prevent the system from staying "trapped" in a Keynesian equilibrium. The answer is, using the results developed above, obtained in the following way. Letting A denote the stable equilibrium and B the unstable equilibrium, the situation in Böhm's paper is as follows

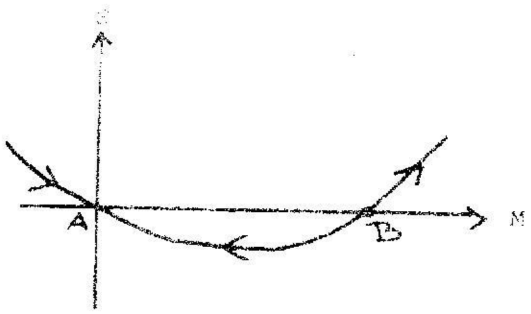

Fig.15.

With a sufficiently large increase in G we obtain the following picture for the model developed above.

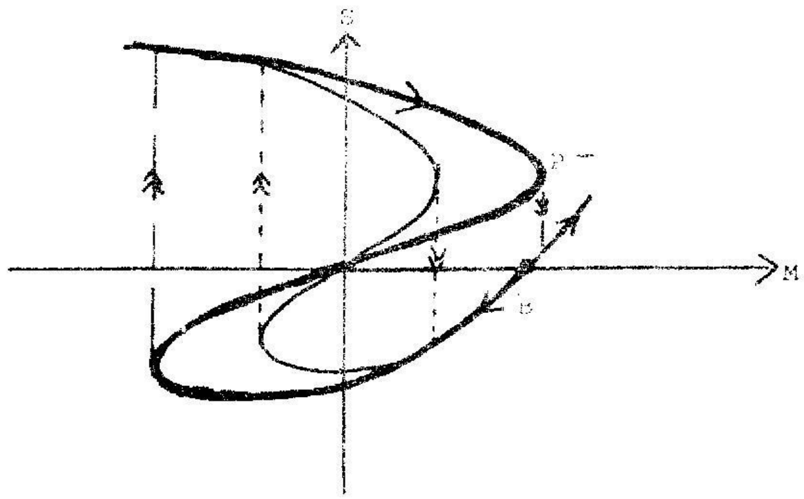

Fig.16.

It is seen that instead of staying trapped in the cyclical motion, the catastrophic jump at the "right" fold point P will take the system to the "right" of the saddle point B and so the movement after the jump will be away to infinity.

Example 2. A Dynamic Evolution of a Rationed Equilibrium Economy

The second example takes also its starting point from Malinvaud's book (1978). The aim this time is to present a generic (i.e. "typical") picture of the evolution of a rationed equilibrium economy over time, when prices and wages are changing in response to effective demands/supplies on the various markets.

The analysis is presented in a recent paper by M. Blad (1981) to which the reader is referred for the details of the model and specific explanations of the results. Here we shall only try to outline how the results may be interpreted as connected to economic policy making and catastrophe theory.

Following Malinvaud we define three types of rationed equilibria (as in example 1) in a highly aggregated macro model with only 'goods' (price p), labour (price w), and money (unit price). For fixed value of (p,w) exactly one of the three types of equilibria is realized by "fasts" quantity adjustments. Adding a "slow" adjustment process in (p,w), the evolution of the economy over time is determined by the interaction between these two types of adjustment processes.

It turns out that for each fixed value of (p,w) the generic picture of the evolution of the economy exhibits three equilibria, a stable, an unstable, and a 'dual' stable, and the local picture of the equilibrium surface is a cusp.

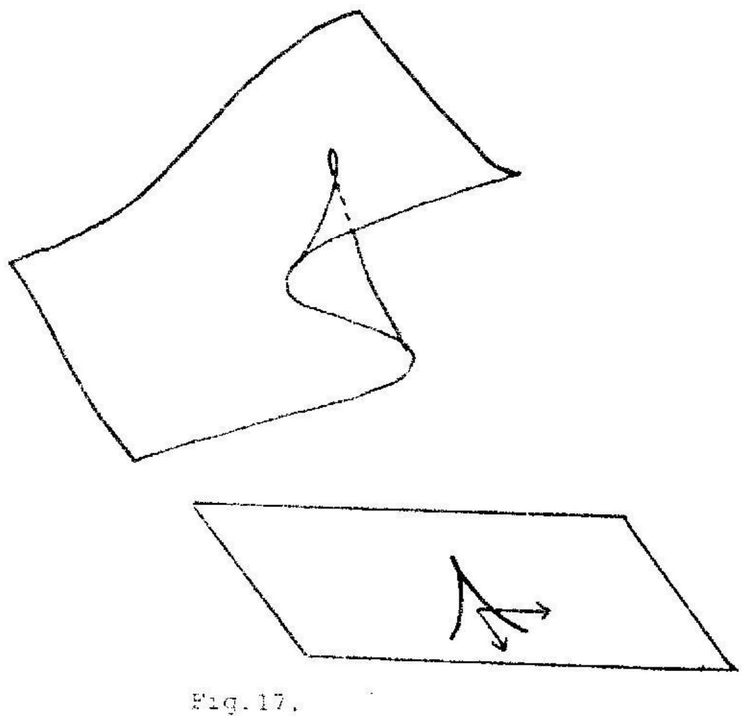

Fig.17.

Here (h,k) are two 'hidden' new parameters. We name them hidden, as they were non-visible in the original non-generic description of the evolution; (h,k) emerges as a result of requiring a stable description of the evolution of the economy.

When (p,w) varies we therefore now obtain a family of cusps, parametrised by (p,w,).

Next it can be shown that when we analyze the evolution of the economy along a specific (p,w)-trajectory, depending on the values of (h,k), the path traced out by the equilibrium point in state (i.e. quantity) space is either a smooth curve or a non-smooth curve containing catastrophe jumps, for (p,w) belonging to a neighbourhood of the boundary between two equilibrium regions in the (p,w,) plane.

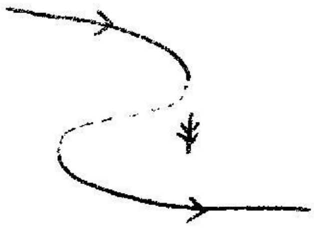

Fig.18.

The economic interpretation of the stable equilibria shows that these are either typical rationed equilibria (as introduced above) or they belong to a new 'dual' type of rationed equilibria, where either consumers or producers are forced to perform at a level above their utility/profit maximising one.

One way this can be considered an acceptable type of equilibria is by allowing the government to introduce specific measures that forces this type of behaviour upon the agents in the economy. With this possibility one may interpret the role of the hidden parameters as performing exactly that task. Therefore in this framework we obtain the description of a government policy, which may lead to a non-smooth evolution of the economy over time with drastic changes as (p,w) approaches a boundary between two equilibrium regions.

Example 3. Divergence and Economy Policy

While the two examples above mainly related to the quality of catastrophic jumps that are connected with equilibrium surfaces, which are shaped locally as cusps, we shall in the last example shortly outline an idea, which applies to the divergence property of the cusp. This application was presented by Zeeman, (1974).

To fix ideas suppose we have the following situation. Let X be the space of states of an economy and let C be a two dimensional control space, corresponding to two policy variables available to the government. Suppose the economy initially rests in an equilibrium situation. Next assume that some external changes are added. The government may then decide to respond to these external changes by varying the values of the two policy measures. We shall now show how a qualitative model can explain how the order in which the two measures are applied may lead to different new equilibrium states of the economy.

Suppose we have the following local picture.

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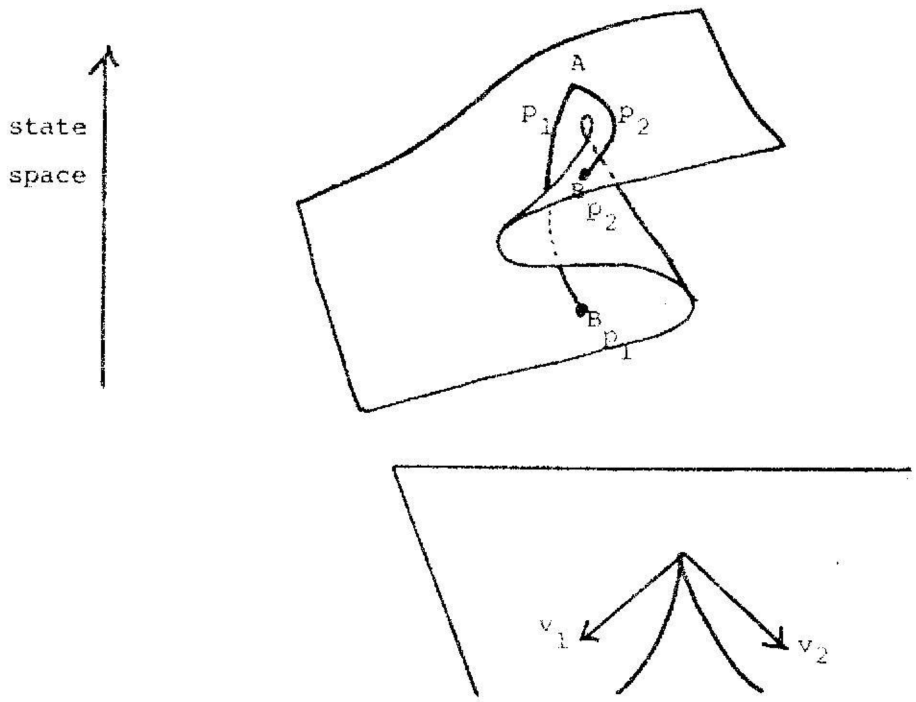

Fig.19.

Let the economy initially be in the equilibrium point A. If the government changes the policy variables v_1 and v_2, we immediately see that the result leads to an evolution along one of the qualitatively different evolutionary paths, p_1 or p_2. If v_1 is applied first and thereafter v_2 the equilibrium point will move along the path p_1 towards the point B_{p_1} on the lower sheet of the equilibrium surface. Contrary, if v_2 is applied first and thereafter v_1, the equilibrium point will move along the path p_2 towards the point B_{p_2} on the upper sheet.

To substantiate this type of application Zeeman presents one quantitative example, comparing U.K. policy in 1967 with the policy applied in France the following year. Here (v_1, v_2) corresponds to a deflationary policy followed by a devaluation, while (v_2, v_1) corresponds to the reversed order of these policies, and the state of the economy is given by its growth.

p_1 would then typically be a path with a small growth of the economy, because the firms would not be able to take the advantage of the devaluation, whereas p_2 would be a path along which there would be substantial growth, as firms would be able to increase their exports.

No doubt the interested reader will be able to find lots of similar examples.

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