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THE CHAOTIC MONOPOLIST

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Abstract

The search of a profit maximum by a monopolistic firm is studied, given a demand function with variable elasticity of demand. The system has multiple local optima, so the search algorithm may result in chaotic behaviour.

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The Chaotic Monopolist

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INTRODUCTION

Traditional microeconomic theory deals with two basic market types: Perfect competition and monopoly. In the case of perfect competition individual firms are assumed to be so small in comparison with the entire market that they cannot noticeably influence market price on their own; they just note the current price and react accordingly with respect to their supply. Only the supply of all the numerous firms together becomes a force on the market strong enough to determine the price in a balance with the demand of all the likewise numerous and small households.

The single monopolist, facing the lot of these households, on the other hand, is assumed to deliberately choose to limit the quantity supplied so as to keep price sufficiently high to yield monopoly profit. If in addition the monopolist is able to efficeintly discriminate various submarkets from eachother, even different prices may be charged in all those, so as to exploit its monopoly power maximally.

The monopolist must thus know at least the entire demand curve of the market. The information needed is infinitely more complex than that needed by a competitive firm; an entire demand curve instead of just one point on it. To collect this information might be assumed to be costly, and, in view of the variability of the real world, such information collecting would have to be repeated frequently in order to yield a relible basis for decisions.

It is more likely that a monopolist just knows a few points on the demand function, recently visited in its more or less erratic search of maximum profit. The price policy of any national transportation monopoly could testify to this, though such monopolies could always cloak up any irrational looking behavoiur in an alleged pursuit of public benefit.

As to the general form of a demand function, it is assumed to be monotonically downward sloping, demand decreasing as price increases. As there are always substitutes for most goods, like driving as an alternative to using the railway, there would be a maximum price above which nobody would demand anything. Likewise, there would be a maximum saturation demand when price goes down to zero. In text book cases the demand curve is just a downward sloping straight line, but this is too simplistic. The elasticity of demand would in general vary over different sections of the demand curve, giving it a convex/concave outline. This is particularly true if the market is a composite of different submarkets with different elasticities, by the way the standard case for the study of price discrimination and dumping.

The full analysis of such cases in terms of graphical reasoning was given in the pioneering work [1] by Joan Robinson in 1933, who recognized the existence of multiple local equilibria.

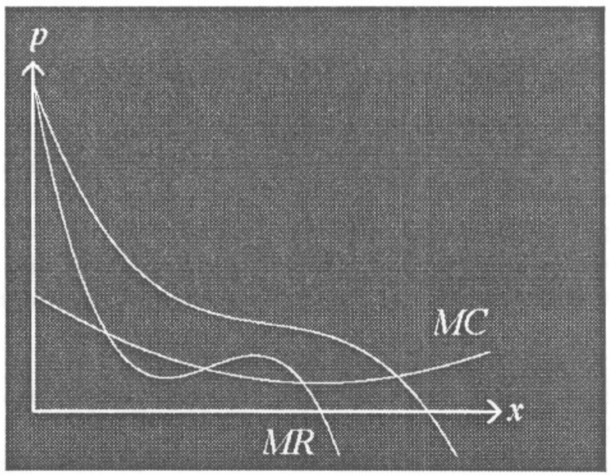

Fig. 1. Demand curve, marginal revenue and cost curves.

"*Cases of multiple equilibrium may arise when the demand curve changes its slope, being highly elastic for a stretch, then perhaps becoming relatively inelastic, then elastic again. This may happen, for instance, in a market composed of several subgroups of consumers each with a different level of incomes. There will be several critical points at which a decline in price suddenly brings the commodity within the reach of a whole fresh group of consumers so that the demand curve becomes rapidly more elastic. The marginal revenue curve corresponding to such a demand curve may fall and rise and fall again, and there will be several points of monopoly equilibrium.*

The net monopoly revenue at each point would be different, but it is unlikely that any monopolist would have sufficient knowledge of the situation to enable him to choose the greatest one from among them. If the monopolist had reached one equilibrium point there would be no influence luring him towards another at which his gains might be greater."

THE MODEL

Such a case, illustrated in Figure 1, which could in fact almost have been cut out from Joan Robinson's book, can be represented by the truncated Taylor series:

$$p = A - Bx + Cx^2 - Dx^3 \tag{1}$$

where p denotes commodity price, x denotes the quantity demanded, and A, B, C, D are some positive constants.

In order that the (1) function be invertible, i.e. that there be just one quantity demanded corresponding to each price, the curve must be down-sloping. The least steep slope is in the point of inflection, defined by:

$$\frac{d^2 p}{dx^2} = 2C - 6Dx = 0 \tag{2}$$

where the slope is:

$$\frac{dp}{dx} = -B + 2Cx + 3Dx^2 \tag{3}$$

or, substituting from (2) for $x = C/(3D)$,

$$\frac{dp}{dx} = -B + \frac{C^2}{3D} < 0 \tag{4}$$

The demand curve is down-sloping, as indicated by the imposed sign requirement, provided that the condition:

$$C^2 < 3BD \tag{5}$$

holds.

Economists usually analyse the monopolists behaviour, using the marginal revenue, *MR*, i.e. the derivative of total revenue, $\mathrm{d}/\mathrm{d}x(px) = p + x\,\mathrm{d}p/\mathrm{d}x$. For the demand curve (1) the marginal revenue curve would be:

$$MR = A - 2Bx + 3Cx^2 - 4Dx^3 \tag{6}$$

which, in fact, could lack a unique inverse, though the demand curve has one. The marginal revenue curve is displayed along with the demand curve in Figure 1. The lack of an inverse is an interesting case, because it provides an opportunity for multiple equilibria.

Now we want the marginal revenue curve to have a positive derivative at the inflection point. This point is defined by:

$$\frac{\mathrm{d}^2MR}{\mathrm{d}x^2} = 6C - 24Dx = 0 \tag{7}$$

The slope is:

$$\frac{\mathrm{d}MR}{\mathrm{d}x} = -2B + 6Cx - 12Dx^2 \tag{8}$$

or, substituting from (7) for $x = C/(4D)$,

$$\frac{\mathrm{d}MR}{\mathrm{d}x} = -2B + \frac{3C^2}{4D} > 0 \tag{9}$$

The condition for an upward slope at the point of inflection, i.e. for the marginal revenue curve (6) not to have a unique inverse is:

$$C^2 > \frac{8}{3}BD \tag{10}$$

So, there is in fact a latitude of choice for

$$C^2 \in \left(\tfrac{8}{3}BD, \tfrac{9}{3}BD\right) \tag{11}$$

such that the demand curve (1) has a unique inverse but the marginal revenue curve (6) hasn't.

Along with the marginal revenue curve, economists use the marginal cost curve, denoted MC. It is the derivative of the total cost as a function of the quantity supplied. Typically the marginal cost curve is assumed to be concave from above, with marginal cost first decreasing with increasing supply and eventually increasing. The truncated Taylor series for the marginal cost would be:

$$MC = E - 2Fx + 3Gx^2 \tag{12}$$

where again E, F, and G are positive. The integers are introduced for later convenience at integration.

The standard analysis would involve the condition for maximum profit, $MR = MC$, i.e. from (6) and (12)

$$(A-E)-2(B-F)x+3(C-G)x^2-4Dx^3=0 \tag{13}$$

Whenever the curves look like those in Figure 1 this equation has three distinct real roots. In theory, the monopolist would calculate these by solving the cubic, and then evaluate second order derivatives:

$$-2(B-F)+6(C-G)x-12Dx^2 \tag{14}$$

to check that the intermediate root is a profit minimum, whereas the higher and lower ones represent genuine maxima. Finally, the monopolist would choose between the two local maxima to identify the global profit maximum.

ADAPTIVE SEARCH

In reality, however, the monopolist does not know more than a few points on the demand function. The marginal revenue curve, representing the derivative of an uncompletely known function, would not be known except in terms of interpolation through recently visited points. The information collected would be of a local character and short lifetime, and the monopolist might not even know that globally there are two distinct profit maxima. As already stressed, the limits on information are due to the diffuculty and expense involved in market research, and to the frequency of demand shifts due to changes in the markets of close substitutes.

Given this, the task would be to design a search algorithm for the maximum of the unknown profit function:

$$\Pi(x)=(A-E)x-(B-F)x^2+(C-G)x^3-Dx^4 \tag{15}$$

This would be quite easy, provided the monopolist knew that the function was a quartic. The problem, however, is that nothing except a few points are known.

The simplest algorithm of all, of course, is estimate the difference of marginal costs and revenues from the two last visited points of the profit function, and, in the vein of Newton, to use a given step length to move in the direction of increasing profits.

Denoting the next last and last visited points by x and y respectively, and the step length by δ, we get the next point as:

$$y+\delta\,\frac{\Pi(y)-\Pi(x)}{y-x} \tag{16}$$

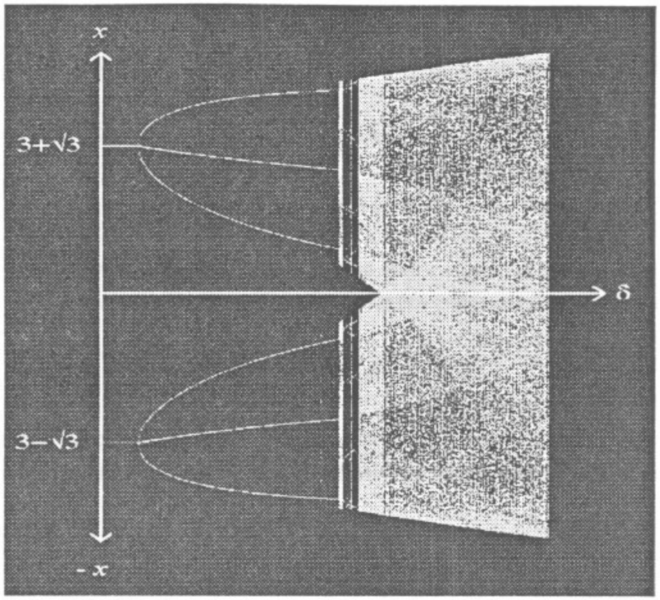

Fig. 2. Bifurcation diagram.

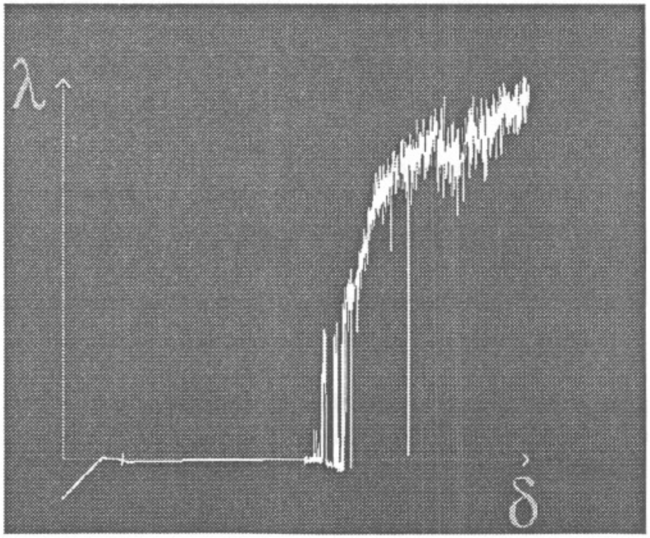

Fig. 3. Largest Lyapunov exponent.

In order to avoid unnecessary numerical instability the denominator in the quotient may be factored out:

$$\frac{\Pi(y)-\Pi(x)}{y-x}=(A-E)-(B-F)(x+y)+(C-G)(x^2+2xy+y^2)-D(x^3+x^2y+xy^2+y^3) \tag{17}$$

NUMERICAL RESULTS

Iteration of this search process may lead to any of the two local profit maxima, to oscillating processes, or to chaos, depending on the values of the coefficients A through G, and the step size d. The chaotic attractors may be unique, or else co-exist with different attraction basins. In the following computer simulations, as well as in drawing Figure 1, the following values of the coefficients were used: $A = 5.6$, $B = 2.7$, $C = 0.62$, $D = 0.05$, $E = 2$, $F= 0.3$, and $G = 0.02$.

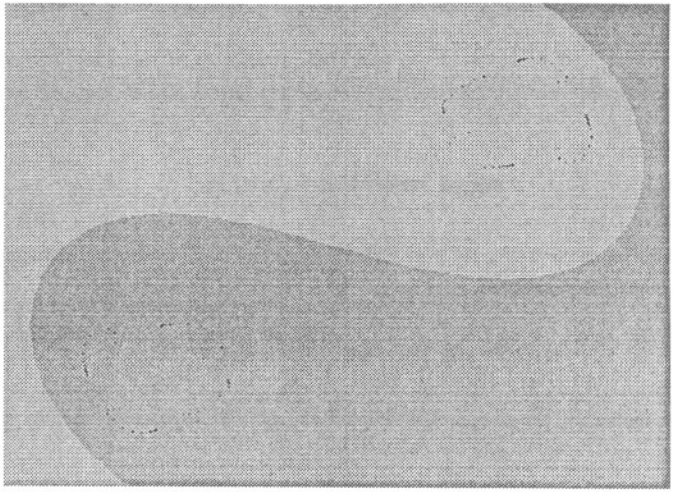

Fig. 4. Co-existent four-cycles, and their basins of attraction.

With these coefficients the profit function (15) would become:

$$\Pi(x) = 3.6x - 2.4x^2 + 0.6x^3 - 0.05x^4 \tag{18}$$

Equating its derivative to zero yields the equation:

$$\Pi'(x) = 3.6 - 4.8x + 1.8x^2 - 0.2x^3 = 0 \tag{19}$$

which could also have been obtained by substituting the numerical coefficients in condition (13) for $MR = MC$. Equation (19) has three distinct real roots:

$$x = 3 \text{ and } x = 3 \pm \sqrt{3} \tag{20}$$

The iterative search process with the coefficients now introduced is defined by the mapping:

$$x_{t+1} = \mathrm{f}(x_t, y_t) \tag{21}$$

$$y_{t+1} = \mathrm{g}(x_t, y_t) \tag{22}$$

where

$$f(x,y) = y \tag{23}$$

$$g(x,y) = y + \delta(3.6 - 2.4(x+y) + 0.6(x^2 + xy + y^2) - 0.05(x^3 + x^2y + xy^2 + y^3)) \tag{24}$$

FIXED POINTS AND CYCLES

Before proceeding with the simulations, we note that the fixed points of the iterative mapping (21)-(22), not unexpectedly, are given by the equations

$$x = y \quad \text{and} \quad 3.6 - 4.8x + 1.8x^2 - 0.2x^3 = 0 \tag{25}$$

and that they are the maxima and the minimum of the profit function. To find out the stability of these points we calculate the Jacobian

$$\frac{\partial(f,g)}{\partial(x,y)} = \delta(2.4 + 1.8x - 0.3x^2) \tag{26}$$

We have used the information that $x = y$ in the fixed points. Of those we know that the profit minimum $x = 3$ is unstable, but the profit maxima

$$x = 3 \pm \sqrt{3} \tag{27}$$

need further discussion. Substituting any of those roots in the Jacobian (26), we get:

$$\frac{\partial(f,g)}{\partial(x,y)} = \frac{3}{5}\delta \tag{28}$$

Loss of stability occurs for both roots when the Jacobian is unitary, i.e. at the common value:

$$\delta = 5/3 \tag{29}$$

This can be seen at the first branching point in the bifurcation diagram in the upper half of Figure 2 where the phase variable, x (or y) is plotted against the parameter δ.

We see the two alternative fixed points co-exist at parameter values no higher than 5/3. After that the fixed points are replaced by cycles, over a quite extensive interval, and chaotic bands, with each its own basin of attraction. After a certain point the attractors merge in a single one. Figure 3 displays the largest Lyapunov exponent, plotted against the step size parameter. The most striking feature is that, once chaos sets on definitely, the Lyapunov exponent remains positive, with no windows of order at all (at least not with the resolution chosen).

The cycles shown in Figure 2 seemingly are of period three, but this is deceptive. For each of the two coexistent cycles three different values are taken on, so let us denote those of one set a, b, and c. They are, however only passed in the sequence a, b, c, b, a, b, c ..., so that one of the values is taken on twice as often as are the other two. Recalling that our system is two-dimensional, we accordingly deal with a process where the points (a, b), (b, c), (c, b), and (b, a) are visited over and over, so the process is of period four, not three. This is also what we find in the phase diagrams, such as the one displayed in Figure 4.

In Figure 4 we display the approach to each of the coexistent cycles against a background of the attraction basins in different shadings. Color Plate I gives the same information.

To see some details of the periodic solution, let us locate the period four point. After four iterations we are back again, so the following four equations must be fulfilled:

$$z = y + \delta \frac{\Pi(y) - \Pi(x)}{y - x} \tag{30}$$

$$w = z + \delta \frac{\Pi(z) - \Pi(y)}{z - y} \tag{31}$$

$$x = w + \delta \frac{\Pi(w) - \Pi(z)}{w - z} \tag{32}$$

$$y = x + \delta \frac{\Pi(x) - \Pi(w)}{x - w} \tag{33}$$

Multiplying through by the denominators, and adding (31)-(32) and (32)-(33) pairwise, we arrive at the following two equations:

$$(x-y)(x-y+z-w)=\delta(\Pi(x)-\Pi(y)) \tag{34}$$

$$(w-z)(x-y+z-w)=\delta(\Pi(w)-\Pi(y)) \tag{35}$$

whereas adding all four of them, (39)-(33) makes all the profit functions in the right hand sides cancel, and we end up with a perfect square that has to equal zero:

$$(x-y+z-w)^2=0 \tag{36}$$

Using this last condition in (34)-(35) we get a pair of useful conditions:

$$\Pi(x)=\Pi(z) \tag{37}$$

$$\Pi(y)=\Pi(w) \tag{38}$$

So, profits in the sequence *x*, *y*, *z*, *w* are pairwiase equal with a lag of two periods. This may happen in two ways. Either, the points visited are themselves equal, as conjectured for the value visited twice as often as the other two. Or, they may be located sufficiently widely apart as to fall on different rising and falling branches of the quartic profit function.

We now turn to the numerical example to get more substance, and substitute expressions (18) for the pairwise equal profits in (37)-(38). The equations then factor into:

$$(x-z)(x+z-6)((x-3)^2+(z-3)^2-6)=0 \tag{39}$$

$$(y-w)(y+w-6)((y-3)^2+(w-3)^2-6)=0 \tag{40}$$

These give us three possibilities each. Taking *x* and *z* for an example, they may be equal, their sum can be equal to 6, or they may be located on a circle around the point (3, 3). Among these the middle option is not relevant for a periodic point that moves entirely above or below the line at 3 in Figure 2. Hence any sum of two amplitudes is strictly smaller or larger than 6, depending on which of the alternative cycles we consider. Actually, the middle option refers to the unstable fixed point at 3 of Figure 2.

Obviously, both $x=z$ and $y=w$ cannot hold simultaneously, as we would then no longer deal with a four-period point, but with a two-period point, which, by the way, like the three-period point, can be shown to be impossible. So, what we actually locate are the now likewise unstable fixed points $3\pm\sqrt{3}$, in addition to the aforementioned one at 3.

In the same way we cannot have both pairs located on the circles $(x-3)^2+(z-3)^2=6$ and $(y-3)^2+(w-3)^2=6$, because, after a somewhat more messy derivation, we again end up at the same conclusion, i.e. that we are dealing with one of the unstable fixed points. So, two points in the four-cycle must be equal, say x and z, and two, say y and w, must be on the circle. These considerations, along with (36), provide us with three equations::

$$x = z \tag{41}$$

$$(z-3)^2 + (w-3)^2 = 6 \tag{42}$$

$$x + z = y + w \tag{43}$$

In addition we have equation (30), which, using the fact that $x = z$ according to (41), becomes:

$$x = y + \delta \frac{\Pi(y) - \Pi(x)}{y - x} \tag{44}$$

Equations (42)-(44) are sufficient for calculating the four values of the cycle. For instance with $\delta = 2$, a value for which we according to Figure 2 definitely have a cycle, we get

$$x = z = 3 \mp \frac{\sqrt{65}}{5} \tag{45}$$

$$y = 3 \mp \left(\frac{\sqrt{65}}{5} - \frac{\sqrt{10}}{5} \right) \qquad w = 3 \mp \left(\frac{\sqrt{65}}{5} + \frac{\sqrt{10}}{5} \right) \tag{46}$$

The minus sign applies to the lower half of Figure 2, the plus sign to the upper half. These values agree with the results from simulation.

CHAOS

Figure 5 shows two co-existent chaotic attractors against a background of their basins. It can be noted that there is no intricacy in basin boundaries similar to the case of the usual Newton algorithm, though there are regions in the SW and NE where the "wrong" basins come very close to the final attractors. It is worthwhile to note the symmetry of shapes both of the basins and of the attractors. It is known that for symmetric systems any attractors that are not symmetric in themselves come in pairs which together make up a symmetric picture. This can be seen as a general consequence of symmetry breaking principles.

Figure 6, finally, is a portrait of a single chaotic attractor extended over the entire phase diagram, the adjustment step parameter being so large that the process spills over the watershed at the amplitude of 3. The attractor is also shown in Color Plate II. As the attractor is there alone it is symmetric as can be expected.

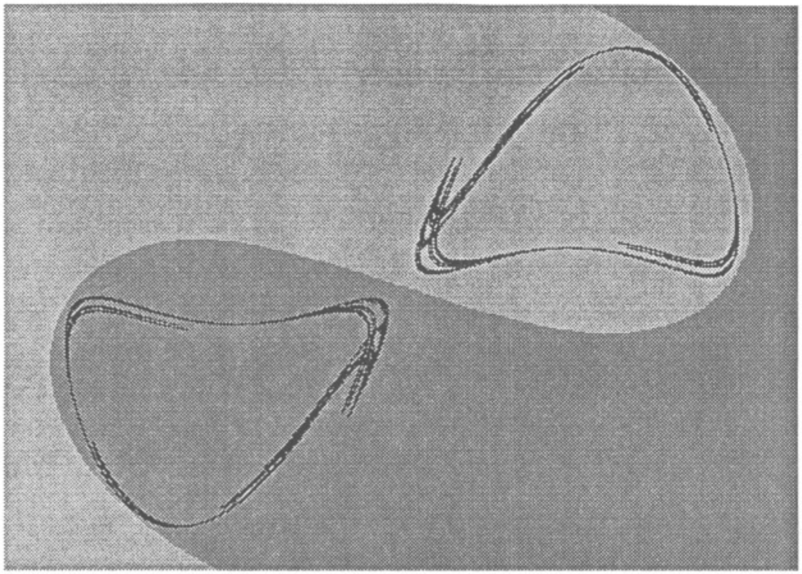

Fig. 5. Co-existent chaotic attractors, and their basins of attraction.

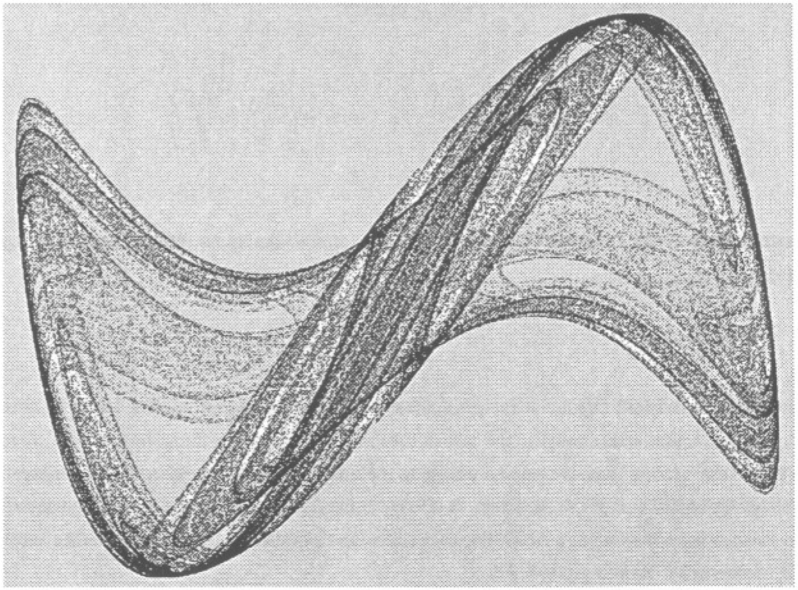

Fig. 6. Single chaotic attractor.

DISCUSSION

It may be a bit hard for economists, nourished with textbook monopoly theory, to digest that the monopolist does not know all about the market and may even behave in a way seeming erratic. But we have to admit that it can be prohibitively expensive to get all the information the monopolistic firm needs, and that the knowledge aquired may only be local. The monopolist might have no idea at all of the true *global* outline of the marginal revenue curve, as to how many humps there are and where they are located, as suggested by Joan Robinson.

If the monopolist has not found a local equilibrium, or if he is a little more adventurous than Joan Robinson assumes, then he might devise a search process like the one described, based on locally estimated marginal revenues. An algorithm like one that was good enough for Sir Isaac Newton can hadly be considered too unsophisticated a monopolistic transportation utility or the like.

The reader may wonder about the step size in the exemplified search process. As a matter of fact, applying such, or even larger steps, to all points of the profit function would approximate the general shape of the marginal revenue curve pretty well.

Should the monopolist become suspicious about the fact that he is behaving like a random number generator, the blame could always be on exogenous shifts in the demand function, due to changing prices of close substitutes or to general business cycles. Not even a regularly periodic behaviour need make him suspicious, because the imagery of economic phenomena is crowded with all kinds of regular periodic cycles. Observe also that nothing at all was said about the speed of the process, i.e. the real-time length of the adjustment step. It might accommodate to any degree of conservatism in the monopolist's behaviour we may wish to assume.

Finally, the monopoly profit might on average be quite good, despite this periodic or chaotic behaviour.

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