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Understanding the System Dynamics of High-Technology Markets: Pólya Processes with Positive Feedback, Path Dependence and Lock-In

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Abstract. This paper relies on complexity theory to gain new insights into the dynamics of high-technology markets. We are making use of the Pólya process model to explain these dynamics. This classical model highlights the "mechanism" of positive feedback, which gives rise to the phenomenon of path dependence and lock-in.

Keywords: Pólya Processes, High-Technology Markets, Modeling, Simulation, System Dynamics.

1 Introduction

The complex, dynamic nature of markets and industries in our time calls for innovative approaches to their description and analysis. The purpose of this contribution is to demonstrate how complexity theory can be used in order to gain new insights into the system dynamics of high-technology markets. We will make use of a mathematical model which has been around for some time, but which to our knowledge has been used only sporadically in management science: Linear and non-linear Pólya processes. This classical model is based on processes with positive feedback, which give rise to the phenomena of path dependence and lock-in.

The Pólya process can be classified as a complexity theory. It represents a class of stochastic processes which are applicable to positive-feedback situations in economics, called "generalized urn schemes of the Pólya kind" [3]. Pólya processes have been used in economics [1] and implemented in a simulation context of System Dynamics [5, 6].

2 The Structure of Pólya Processes

We will conceptualize a market with two players (which could also be clusters of players, each representing a different technology). The conceptualization is based on the linear Pólya urn process [4]: Imagine an urn containing one white sphere and one black sphere, where random draws are made. If a white sphere is observed, then two white spheres are returned to the urn. Likewise, if a black sphere is drawn, it is

replaced and another black sphere is added to the urn. Over time, as can be shown, the ratio of black to white stones reaches equilibrium, but that ratio depends on the history of the colors selected. Thus, the random events of drawing a sphere from the set of spheres early in the history of the process tip the ratio toward one path rather than another. The equilibrium is path dependent. The accumulation of stones eventually locks the system into equilibrium at a particular proportion of each color. Pólya proved that the distribution of final proportions is uniform (the final fraction of black stones is equally likely to be anywhere between 0 and 1).

Note that the probabilities for drawing a sphere of a certain color is proportional to the relative quantity of that color among the whole set of spheres in the bin. If the linear Pólya urn process is repeated n times, then the probability of observing k white balls follows the beta-binomial distribution.

The non-linear Pólya process is characterized by an additional feature, a bias in the probabilities by which black and white spheres are drawn (Figure 1). This bias represents a sensitivity, as can be observed in certain kinds of real systems, e.g., in the distribution of market shares in high-technology industries.

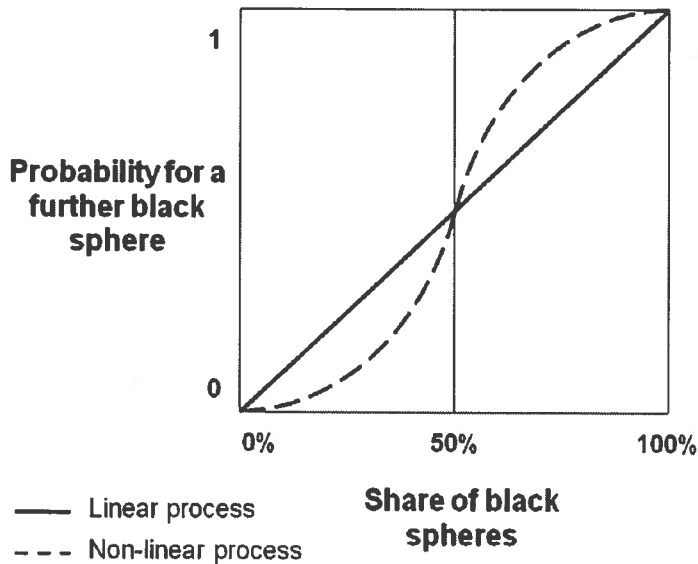


Fig. 1. Probability paths in Pólya processes (after [1])

Figure 2 shows an implementation of the linear Pólya process in a simulation model. The methodology used is system dynamics¹; the diagram is of the Stock-and-Flow type used in that methodology.

¹ System Dynamics is a methodology for the modeling and simulation of complex, dynamic systems [5, 6]. It is particularly adequate for modeling socio-technical systems, such as private and public enterprises, communities, etc. They are structured as meshes of interconnected feedback loops. Causal relationships, delays, and closed loop structures are characteristic of System Dynamics models.

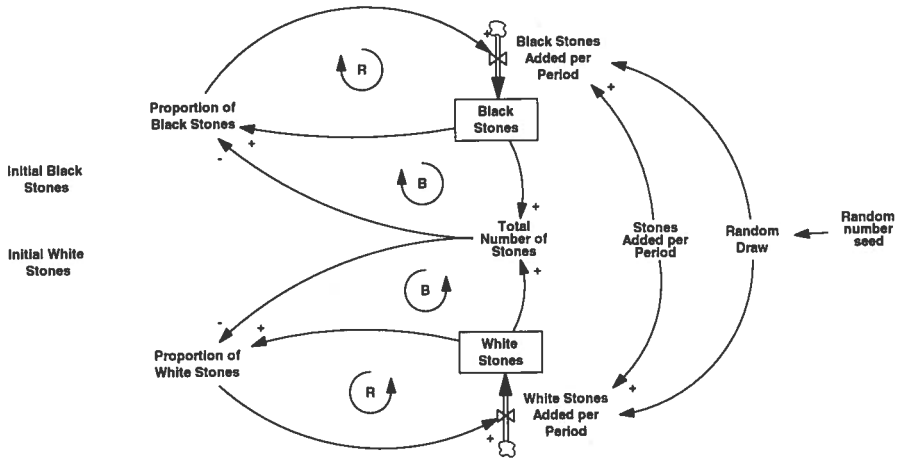


Fig. 2. System Dynamics Diagram of the Linear Pólya Process [6]

Every period one stone is added to the total. The probability of choosing a stone of a given color equals the proportion of that color in the total population, according to the formula [6: 355]:

$$\text{Black Stones Added per Period} = \begin{cases} 1 & \text{if Random Draw Proportion of Black Stones} \\ 0 & \text{otherwise} \end{cases}$$

The diagram in Figure 3 shows the working of the non-linear Pólya process. The difference between the two is the bias introduced into the non-linear model by means

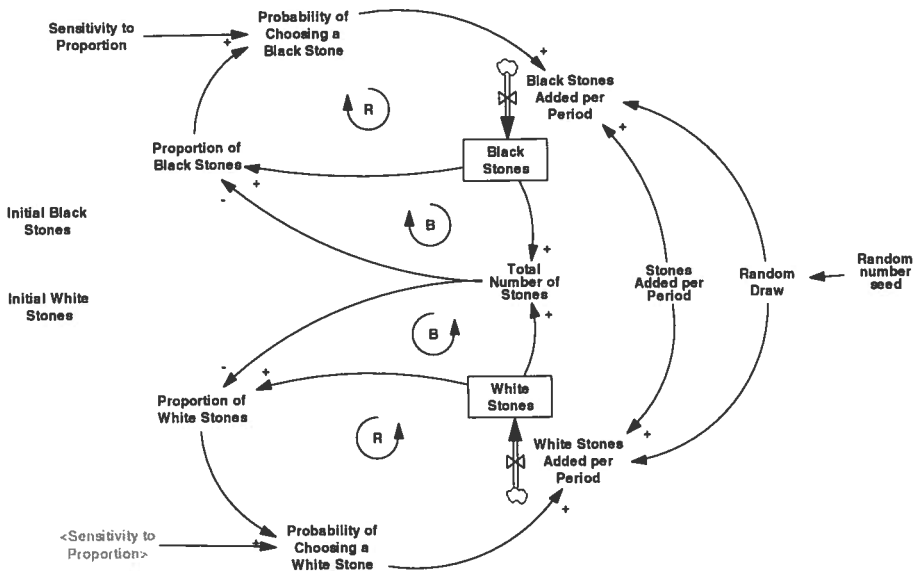


Fig. 3. System Dynamics Diagram of the Non-linear Pólya Process [after 6: 357ff.]

of a sensitivity parameter. Parameters of this kind play a role in certain contexts which we will specify shortly.

3 Patterns of Behavior

The commonality of the two variants of the process - linear and non-linear - is that a stable equilibrium will be reached. The difference between the two is that the equilibrium can occur

a) in the linear process at any ratio between 0 and 1: any final state in terms of the percental relation between the two types of spheres is equally probable. (Figure 4).

b) in the non-linear process only according to a ratio that is very large or very small: almost all spheres in the bin will be of one and only one color.

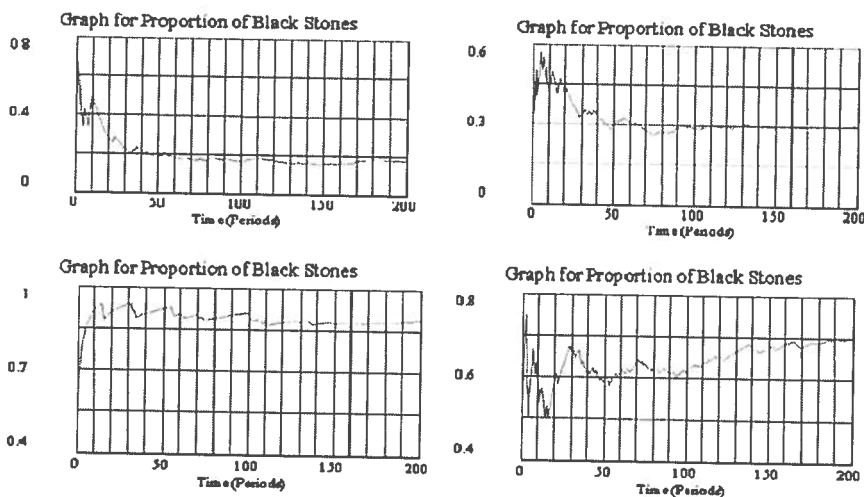


Fig. 4. Proportion of Black Stones Evolving over Time in the Linear Case (Outputs of four simulation runs. The probability for the random draw starts at a different seed number in each of the four runs).

Translated into the language of our application, the linear variant leads to stable relationships between the market shares of the two competitors, at any possible level, while the non-linear variant leads necessarily to a situation where one competitor is dominant and the other marginal.

Both types of process, linear and non-linear, show a number of basic features [1]:

- **Path Dependence:** the equilibrium that is finally reached depends on initial conditions and random events in the early stages of the process.
- **Positive Feedback:** Amplified by positive feedback, small, unforeseeable events early in the process determine the evolution of the process and the result.
- **Lock-in:** The process always converges to a fixed percental relationship between the two types of spheres.

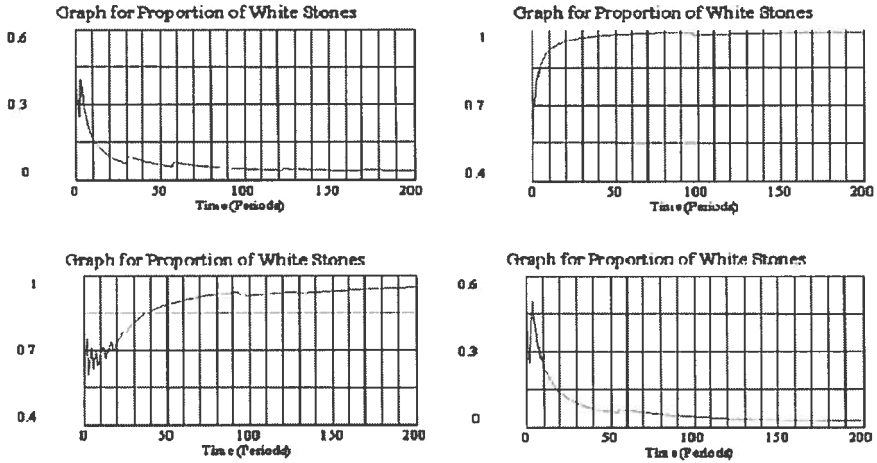


Fig. 5. Proportion of Black Stones Evolving over Time in the Non-linear Case (Four simulation runs, each with a different seed number)

4 Understanding Market Dynamics

These general features can be exemplified by the case of a new market: Small, seemingly unimportant events at the beginning of the market introduction are amplified and therefore determine the further evolution, and finally the new equilibrium. Path dependence implies that the technology which takes over the market is not necessarily the best one. Non-predictability is a given; the success of a product cannot be predicted early on. However, a prediction at a higher level is possible, concerning the necessary event of a monopolization: There will be one of two possible equilibria: Almost all products are of one and only one type (either black or white).

Do these features apply to any market? A deductive theoretical analysis leads us to the conclusion that this is not the case. Markets to which the model of the non-linear Pólya process applies obey four criteria, which can be considered necessary and sufficient (see also [2]):

1. **Decreasing Cost Ratio:** The cumulative value of Production Costs/Research & Development Cost tends towards Zero. Examples: Software, Pharmaceuticals.
2. **Network Effect:** The utility of a product increases the more it is widespread („Increasing Returns“). Examples: Telephone, fax, mobile communication.
3. **Product Complementarity:** The product is the prerequisite for the use of other products and is not subject to ISO-norm. Examples: Operating system - Application software, Database - Application software, Processor - Operating system.
4. **User Knowledge:** The efficiency of users in product deployment will reach much higher levels than in the case of simple products, following a parabolic curve until the saturation level.

Classical examples for the non-linear case can be found in knowledge-intensive industries with high entry-barriers, such as the hardware industry (IBM vs. rest of market, until the end of the Eighties), operating systems (Microsoft vs. rest of market), video-recording (Betamax vs. VHS cassettes), digital optical storage media (Blu-ray vs. HD, DVD and VMD). Other examples are in pharmaceuticals and web services, to name only a few. The products are generally relatively complex. The entry barriers are not always given *ex ante*; if not, they emerge early in the process.

5 Implications for the Management of Innovations

The analysis presented so far can be synthesized in a set of general insights for the management of innovations, e.g.:

- Seemingly unimportant events early in the history of the process can have durable effects.
- Once it has been taken, it is likely that a path can be left only at prohibitive cost - a dangerous trap!
- As a consequence, path-dependent products are extremely risky, but in case of successful lock-in the rewards are high.
- The later a path-dependent product gets to the market relative to competitors, the more difficult (or even impossible) will it be to succeed with it.

These features do not appear very promising or attractive. Success or failure seems to be governed by one law only; Randomness!

In principle, the market success of a path-dependent product is unpredictable in the early phase of its introduction. It is predictable that positive feedback will be at work, as well as the necessary occurrence of path dependence and lock-in. However, the evolution can be influenced, for path dependence and lock-in are not as deterministic as they seem.

The single most important rule is: Influence the market process in your favor early on in the process. Avoid lags in market share. The game is in either being ahead or dropping out of the market. Among the critical factors that have a crucial influence on the evolution of the path dependence, are early successes in building relative market share, securing the larger installed base, and taking the lead in distribution. Advantages of that kind are not an ultimate guarantee for eventually bearing away the palm, but they cogently enhance the likelihood of winning out.

In the following, we offer certain rules for the management of innovation which make success more likely. First, the rules for steering before market introduction:

- It is crucial to anticipate which could be the coming path-dependent product.
- It is more important to adapt to the future evolution than to optimize the present situation.
- "Soft" factors, such as interdependencies with other companies, intentions, and interpretations of data, are part of the core competencies.
- Create strategic alliances and networks, in order to generate network effects and to establish complementary products in the market. It is virtually impossible for a single firm to attain a lock-in by itself.

- Assess carefully whether the resources - money in particular - for the market introduction, and the interdependencies with other companies, are indeed sufficient for playing the game.

Second, the rules for steering during market introduction:

- It is worthwhile being first on the market, though not too early, with a superior technology.
- In the early phases of market introduction, apparently unimportant events must be heeded and responded to quickly.
- Underbid competitors in the beginning.
- Create a system of strategic alliances and networks that strengthen positive feedbacks on the base (i.e., enlarge the installed base).

Finally, a few takeaways concerning the management for lock-in:

- Create easy knowledge transitions from one product to the next, in order to conserve user knowledge.
- Lock-In of one's product is caused by the expectations of customers and competitors, who anticipate that a lock-in will occur. Therefore it is essential to make announcements that foster expectations, e.g., about:
 - new technologies,
 - new products,
 - new prices,
 - new strategic alliances,
 - new knowledge transitions from one product to the next,
 - new potent investors, and
 - new market shares.
- Rivals tend to retreat from a market of "increasing returns," once they believe that a Lock-in through others will occur.

For market regulators, the question is how lock-in can be avoided, and market monopoly inhibited, while still enabling innovations and risk rewards for innovators.

6 Conclusions

We have given an explanation of the market processes of path dependence and lock-in which is more an explanation of kind than of degree. In other words, we can tell in which cases these phenomena are likely to occur, but we cannot provide a point-precise prediction of the exact moment in which a bifurcation will occur, nor who is going to be the winner in a process of lock-in.

Even so, we have shown that one can determine in which situation a lock-in is likely to occur: Normally the respective markets are those of high technology, the products being knowledge-intensive and relatively complex. A player in such a

situation is not completely at the mercy of external forces. The core mechanism in path-dependence and lock-in is positive feedback, and that can be influenced. Such influence must be exerted early on in the process, however, and it must change the circumstances in one's favor.

Our conclusion is that the evolutionary path of a product-market system can be influenced at an early stage. The takeaway should be an understanding of how one can avoid getting imprisoned in a calamitous lock-in. In the kind of constellations discussed here, more often than not, a farsighted option of pulling out is far better than stubbornly clinging to an outdated dream.

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