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From mind to market: A global, dynamic analysis of R&D

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ABSTRACT

Existing models of R&D are not easily reconciled with four observable aspects of R&D: initial technologies (ideas) need to be developed further, only a minority of initial ideas are successfully brought to the market, production and process innovations take place simultaneously (whereby, initially, there is no production at all), and process innovations are implemented for technologies that are destined to leave the market. We present a detailed bifurcation analysis for a dynamic model of R&D that captures these observations in one, unifying framework. As we provide a global analysis, we do not limit initial technologies to carry marginal costs that are below the choke price. We show that there always exists a critical value of initial marginal cost above which the firm does not initiate any (R&D) activity; the path to the saddle-point steady state is never globally optimal. We also sketch some tentative policy implications of our analysis.

1. Introduction

Around 1900, Swiss chemist Jacques E. Brandenberger invented a transparent film which he named “cellophane”. On December 26, 1923, American chemical company DuPont acquired from La Cellophane Société Anonyme, an organization to which Brandenberger had assigned his various patents, the exclusive rights to its United States cellophane patents. DuPont's hopes for creating a lucrative market were shattered, however, by discovering that cellophane could not be used to wrap up products that require moisture proofing, such as cake and candy. It took DuPont chemist William H. Charch three years and thousands of tests to develop a lacquer that made cellophane moisture proof, an invention that revolutionized the packaging and merchandizing industry. As the manufacturing costs of cellophane continued to decline due to DuPont's ongoing process innovations, so did the price of cellophane. All this contributed to cellophane being used as wrapping material for a variety of products (from food to jewelry), and for its use in various products (including batteries, scotch tape, and dialysis machines). Since the mid-1930s, cellophane has been manufactured continuously. It is still used today.

The development of cellophane, from mind to market, is typical for the life cycle of many new technologies. Research starts long before a prototype sees the light of day; development begins long before the launch of a new product. Ideas

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abound, but only a small fraction of these ideas lead to successful innovations. For instance, in 1979, Apple was enthusiastic about a design for a computer mouse that they had discovered at Xerox research center. But Apple did not develop this prototype further as the projected production costs of a single mouse would be over $400.[2] Also, existing technologies tend to leave markets slowly due to incumbents' R&D efforts. For example, Edison's invention of an electric light bulb was bound to replace the gas lamp. Producers of the latter however prolonged the lifetime of this inferior technology through continuous product innovations, including the introduction of the Welsbach mantle that made gas lamps five times more efficient (Utterback, 1994).

These examples illustrate four stylized facts of R&D: (i) initial technologies ("ideas" or "prototypes") need to be developed before they are suitable for large-scale production; (ii) there are many initial technologies, but only a very limited fraction is developed further, and from this fraction only a subset will constitute a successful innovation, (iii) production and the search for further improvements take place simultaneously, and (iv) there are process innovations for technologies that are destined to leave the market in the foreseeable future.

Existing models of R&D are not easily reconciled with these observations. Static models of R&D are silent about the process from prototype to the first release of new products and production technologies.[3] Moreover, these models are forced to assume that marginal costs, the proxy for production technologies, are below the choke price (the lowest price at which the quantity sold is zero). This assumption is unlikely to hold for new technologies in their early stages of development.

Dynamic models of R&D are in principle equipped to capture the path from prototype to market penetration. To date, however, neither "innovation race" models nor dynamic versions of static models do so adequately. In essence, models of innovation races examine the time of completion of a cost-saving innovation of known magnitude, whereby the expected time of completion has a one-to-one relationship with R&D expenditures.[4] These models exclude the coexistence of production and R&D efforts. Moreover, the R&D process cannot fail, thus transforming the R&D investment decision into a static one. Dynamic versions of static R&D models maintain the assumption that marginal costs are below the choke price at all times.[5] Initial technologies that are "expensive" are excluded, by assumption, from the analysis. Hence, R&D efforts always lead to the stable equilibrium. Put differently, every initial technology will be developed further, and successfully so. Indeed, without exception this literature provides analyses that are only locally optimal.

In this paper, we provide a general description of the economics of R&D. In particular, for any initial technology level c_0, we characterize the investment and production path that is globally optimal for a monopolist. Hence, we do not exclude initial technologies with marginal costs above the choke price, and we do not restrict ourselves to solutions that are only locally optimal.[6] Our model is, therefore, more easily reconciled with the four stylized facts of R&D mentioned earlier.[7]

From a technical point of view, the problem of the monopolist is formulated as an optimal control problem with an infinite time horizon. Its distinctive characteristic is the presence of multiple equilibria while at the same time the Arrow–Mangasarian sufficiency conditions are not met. In models of this type, the qualitative properties of optimal solutions may change if parameters are varied. We therefore use bifurcation analysis,[8] which constitutes the mathematics of a qualitative change, to assess industry dynamics for all initial technologies in conjunction with other parameter combinations (including time preferences and the efficiency of the R&D process).

Our analysis yields four distinct scenarios, three of which remain hidden in local analyses: (i) initial marginal costs are above the choke price and the R&D process is initiated; after some time production starts and marginal costs fall with subsequent R&D investments; (ii) initial marginal costs are above the choke price and the R&D process is not initiated, yielding no production at all; (iii) initial marginal costs are below the choke price and the R&D process is initiated; production starts immediately and marginal costs fall over time, and (iv) initial marginal costs are below the choke price and the R&D process is progressively scaled down; production starts immediately but the technology (and production) dies out over time; the firm leaves the market. The strength of our analysis is that all these cases can emerge from the same unifying framework.

Our analysis is not without policy implications. It shows that market characteristics that affect future profitability have an impact on the monopolist's decision to further develop an initial technology. If market regulations are such that future mark-ups are reduced *a priori*, it could be that the range of initial technologies that is developed further will shrink. The loss of total surplus that this reduction brings about constitutes a hidden cost of market regulations if the initial technology consists of marginal costs above the choke price. In that case, there is no immediate production lost if the initial technology is not developed further. Yet, these indirect costs should be taken into account when assessing properly the trade-off between static and dynamic efficiency.

[2] Years later, Apple came up with a new design which would only cost $25 to produce. This prototype was subsequently developed into Apple's famous single-button mouse.

[3] The seminal papers in this literature are D'Aspremont and Jacquemin (1988) and Kamien et al. (1992); see De Bondt (1997) for an overview.

[4] Seminal contributions here include Loury (1979) and Lee and Wilde (1980). Reinganum (1989) surveys this literature.

[5] This literature is still scant; it includes Cellini and Lambertini (2009), Lambertini and Mantovani (2009), and Kováč et al. (2010).

[6] As it turns out, a non-trivial part of the parameter space yields stable paths with initial marginal costs so high that production would yield negative mark-ups. At that stage all the monopolist does is to invest in R&D in order to bring down the costs of production.

[7] As this is the first analysis ever to consider the entire range of initial technologies, we restrict ourselves to the monopoly case. Obviously, competitive forces play an important role as well in what we observe about R&D.

[8] Variations in parameter values can lead to qualitative changes in the solution structure (e.g., some steady states lose their stability, indifference points appear, and so on). Such qualitative changes in the solution structure due to smooth variations in parameters are called *bifurcations* (see Grass et al., 2008).