Dynamic models of research and development

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Chapter 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 prices 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-1930’s, 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; development begins long before the launch of a new product. However, ideas abound, but only a small fraction leads to successful innovations. For instance, in 1979, Apple was enthusiastic about a design for a computer mouse, 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.[1] 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 further 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, whereby production starts only after an initial stage of successful product development, 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 first releases of new products and production technologies.[2] Moreover, these models are forced to assume that unit costs, the proxy for production technologies, are below the choke price (the lowest price at which the quantity sold is zero). This assumption is quite 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 conceived 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 is one-to-one related to R&D expenditures.[3] These models exclude the coexistence of production and R&D efforts. Moreover, the R&D process cannot fail, thus

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[1] 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.

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

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

transforming the R&D investment decision into a static one. The recently conceived dynamic versions of static R&D models maintain the assumption that unit costs are below the choke price at all times.[4] 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 locally optimal only.

A distinguished feature of the solution approach taken in this thesis, as compared to the received literature, is that we provide a truly *global* analysis. Be it in discrete or continuous time, models of process innovation usually solve for the investment path relating the state variable (unit cost c) to the control variable (the R&D effort k). Figure 1.1 illustrates a typical such case. A firm is assumed to start with some (low enough) initial unit cost, the value of which then decreases over time, due to continuous process innovation, to some long-run equilibrium level (indicated by a dot). Typically, the equilibrium paths of different competition regimes are then compared with respect to surpluses they bring about, and based on this, subsequently, certain policy recommendations are outlined. Notice, however, the underlying assumptions! Both regimes in Figure 1.1 are assumed to follow their respective stable path to the equilibrium. In fact, the problem of development has been more or less solved. The market is already formed, the production starts immediately and coexists with R&D investment. There is no decision whether to pursue a particular project at all or not. The R&D process cannot fail - both regimes converge to their respective equilibria. Furthermore, if sufficiency conditions in such a model are not satisfied, the equilibrium path is not guaranteed to be optimal even for those unit costs over which it exists. If one does not consider other trajectories which also satisfy necessary conditions for an optimum, nothing can be said about parameters for which the paths indicated in Figure 1.1 are optimal.

Our *global solution concept* remedies these shortcomings of the local approach in two ways. First, all possible values of unit costs are considered (the shaded region in Figure 1.1 is lightened up); in particular, also those above the choke price. This allows research efforts to

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[4] This literature is still scant; it includes Petit and Tolwinski (1999), Cellini and Lambertini (2009), Lambertini and Mantovani (2009), and Kováč *et al.* (2010).

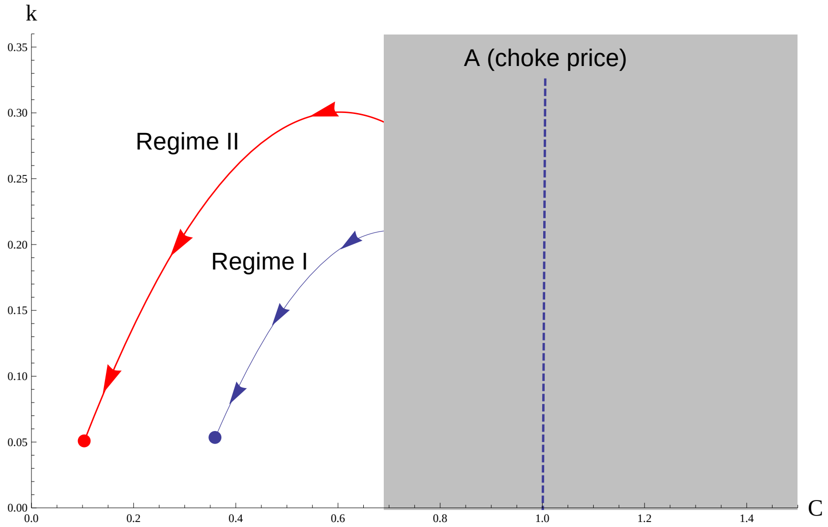

Figure 1.1: *Local approach.*

precede production. Second, we do not limit ourselves to equilibrium paths but consider all trajectories which satisfy necessary conditions and are as such also candidates for an optimal solution. Hence, we do not limit ourselves to solutions that are only locally optimal. This enables us to determine the location of *critical points* - points at which the optimal investment function qualitatively changes. That is, we do determine the value of unit costs for which R&D investments come to a halt or are not initiated in the first place. As the position of these critical points depends on the conduct of firms, different regimes can lead to qualitatively different long-run solutions despite starting with the same level of technology.

A special feature of the models considered in this thesis is that they are all non-convex dynamic optimization problems. In such problems, a small change in parameters can lead not only to quantitative changes in the solution structure, but also to qualitative ones (e.g., the number of equilibria changes, indifference points appear and disappear). If a small change in parameters causes a change in one of the qualitative properties of the dynamical system, the latter is said to undergo a 'bifurcation' (see Grass *et al.* (2008) and Kiseleva and Wagener, 2010, 2011). The bifurcation analysis, which is needed for obtaining a complete global solution, results in a bifurcation diagram that indicates for every possible parameter combination the qualitative features of the solution structure and also provides the 'bifurcating values' of the parameters at which these features change.

1.1 Outline of the Thesis

The results of this thesis are presented in three relatively self-contained chapters.

Chapter 2 introduces the global framework and characterizes the investment decisions of a monopolist that are globally optimal. It shows that there exist four distinct stable types of dynamics. These correspond well to the stylized facts of R&D mentioned earlier. Furthermore, the notion of an indifference point – a point at which a firm is indifferent between developing a technology further and opting out – is introduced and evaluated in relation to model parameters.

Chapter 3 extends the analysis of the previous chapter to R&D cooperatives. It re-examines the trade-off between the benefits of allowing firms to cooperate in R&D and the concomitant increased potential for product market collusion. It shows how misleading, or at least incomplete, the conclusions based on local analyses can be. In particular, it shows that prohibiting collusion on the product market per se is not univocally welfare enhancing.

Chapter 4 represents a further extension to the model of Chapter 2. It considers two firms which compete both in R&D and on the product market. This introduces the problem of finding a solution to a differential game with two state variables, non-convex dynamics, and a possibility of discontinuities in the firms' investment functions. A special numerical approach is taken to obtain an approximating solution. The chapter introduces a possibility of asymmetric firms and random noise in the evolution of unit costs. It analyzes the role the spillovers play in shaping the investments of the follower and the leader and the role they play in determining the structure of a (newly formed) market.