

Adjustment Costs, the Theory of Investment, and Sustained Competitive Advantage

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Abstract This study examines both the theoretical possibility and the empirical fact that investment adjustment costs create sustainable competitive advantage. The theoretical models draw from the theory of investment in the 1960s economics literature—a theory that focused on adjustment costs in investment and asset accumulation. We particularly examine the work of Uzawa, who himself drew from Penrose. We apply a modified version of the Uzawa-Penrose model of investment to the US pharmaceutical industry during 1970 to 1998. Our empirical investigation finds significant confirmation in particular for the modified Uzawa-Penrose model, and in general for the notion that the accumulation process for strategic assets creates and sustains competitive advantage.

A prominent strand in the theory of competitive advantage focuses on investment in strategic assets. The Resource Based View of the firm has long identified certain assets as strategic, or valuable yet only imperfectly traded on markets. Firms with superior stocks of these strategic assets enjoy competitive advantage over other firms. For these assets stocks to sustain competitive advantage over time, however, they must be protected by an isolating mechanism that deters imitation. Several scholars have argued that investment process itself for these strategic assets constitutes the most critical isolating mechanism. When the investment process follows certain conditions, firms that accumulate a sizable stock of relevant strategic assets obtain and retain significant competitive advantage over other firms. This focus on the accumulation process emphasizes the history of the firm and the durability of past decisions to explain current differences in competitive performance. In the simplest terms, firms with competitive advantage have superior investment histories.

Given the prominence of this theoretical literature in strategic management, it is quite surprising that it is so incomplete. The most critical findings of certain key papers amount to derivative restrictions for terms of a differential equation. Yet the consequences of these restrictions are never investigated. There is no demonstration that these restrictions are sufficient to yield the predicted outcome of sustained competitive advantage. Even more striking is the absence of any empirical demonstration that a phenomenon so central to strategic management actually exists. Indeed, a recent effort to estimate parameters of the accumulation process for strategic assets for the US pharmaceutical industry completely rejects central hypotheses of this literature (Knott and Bryce, 2003).

This study offers two contributions. First, it provides formal mathematical modeling of the accumulation process and the resulting asset positions of firms in an industry. This modeling

draws directly from economics theory of investment from the 1960s. The original use for this theory of investment was to provide micro-foundation for macro-economic treatments of business cycles. These models are readily applicable to sustained differences in competitive position across firms in an industry, but have never been so applied. In returning to the economics theory of investment, we are drawn particularly to the work of Uzawa (1968, 1969), who based his approach to corporate investment and growth on Penrose (1959).

Second, this study draws on the insight that patterns of competitive advantage across firms and patterns of strategic investments across time represent a single underlying phenomenon. Our formal modeling of this phenomenon provides linkage and even explicit parameterization of these two processes. In terms of empirical work, this linkage means we must estimate competitive advantage and strategic investment as a system of two equations. We use these two equations not merely to statistically correct for endogeneity, but more so because a single set of parameters underlies both equations. At minimum, we expect the associated parameter estimates for each equation to be similar in sign and magnitude. At best, we expect these estimates to be identical.

The next section of this paper provides an overview of the central research question: sustainable competitive advantage. The following section reviews the theoretical literature on investment and corporate growth. The fourth section provides empirical application of the theoretical model to the US pharmaceutical industry during 1970 to 2000.

Sustained Competitive Advantage

A firm enjoys competitive advantage over other firms in its industry if outperforms them and the superiority of its performance persists over time (Porter, 1985). Competitive advantage thus creates sustained performance heterogeneity within an industry. Random shocks to firms

and industries add significant volatility to corporate performance, but the effects of these shocks usually decay to zero quite rapidly. Strategic management is appropriately concerned only with performance differences that persist over time.

Empirical evidence that sustained competitive advantage exists has been provided by several studies. The seminal work by Mueller (1986) examines deviations from industry mean return on assets for 600 large US firms for the period 1950 to 1972. Mueller found that, in general, individual firm performance converged to the industry mean, as predicted by classical economics. But this convergence was slow in some cases, and high-performing firms converged most slowly. Geroski and Jacquemin (1988) made similar findings for European firms, and Waring (1996) provided comparable confirmation for a more recent sample of US industries during 1970 to 1983. Perhaps the only negative results in this literature are by Jacobsen (1988), using the PIMS database. Jacobsen rejected findings of sustained competitive advantage, finding that profit rates for individual US firms rapidly converge to “normal returns.” Most recently, Wiggins and Rueffli (2002) examined 6700 US firms for the years 1975 to 1997 using improved statistical technique. These scholars provided new confirmation for the existence of sustained competitive advantage, though they caution that the phenomenon is relatively rare.

Three theories have been offered in the literature for sustained competitive advantage. Industrial organization (IO) economics suggests that firms in a concentrated industry practice collusion to sustain high prices and exclusion to obstruct entry of new firms. This theory is most famously expounded by Porter (1980). From this IO economics perspective, superior performance is a “shared asset” of all firms in an industry, or more plausibly of a particular strategic group within an industry.

Resource-based studies in strategic management offer two newer explanations for sustained advantage. Barney (1986, 1991) suggests that imperfections in strategic factor markets sustain competitive advantage. The strategic factor markets theory is based on asymmetric information among firms. Either some firms are systematically better at managing information on strategic assets (Makadok and Barney, 2001) or some firms are simply lucky and other firms cannot figure out how to duplicate their success (Lippman and Rumelt, 1982). In either case, strategic factor market theories rely on some form of casual ambiguity, so that the exact reasons for competitive advantage across firms remain unclear.

Finally, several scholars focus on the investment process itself, a focus shared by this paper. These scholars argue that the investment process for strategic assets constitutes the most important isolating mechanism (Itami, 1987; Winter, 1987, Dierickx and Cool, 1989; Ghemawat, 1991; Teece and Pisano, 1994). Firms accumulate strategic assets in a heterogeneous manner, so that investment expenditures of the same magnitude by two different firms have different effects on the asset stocks of each firm. Firms that are more efficient at accumulating strategic assets attain larger asset stocks, and sustain their competitive advantage over less efficient firms.

Opposing these three theories for the existence of sustained competitive advantage are two that argue against existence. Neoclassical economics predicts the expansion or entry of superior firms, the contraction or exit of inferior firms, and the imitation of superior strategy by once inferior firms. These predictions all suggest that “competition” will rapidly eliminate any advantage or disadvantage among firms. The resulting industry “equilibrium” will be uniform returns across all firms, so that returns for capital exactly equal the cost of capital. A second basis for rejection of the theoretical possibility of sustained competitive advantages has been provided by Schumpeter (1934) and his fellow Austrian economists (see the survey by Jacobsen,

1992). The Austrians expect constant innovations in products and production to undermine any established market positions. Such innovation creates continuous disequilibria, where short-run superior and inferior positions both exist, but both rapidly erode with time. Recent restatements of the Austrian approach in terms of hypercompetition (D'Aveni, 1994; Brown and Eisenhardt, 1998) add currency to these arguments.

This study uses the US pharmaceutical industry to examine interfirm differences in investment and performance. Both Mueller (1986) and Wiggins and Rueffli (2002) identify pharmaceuticals as an industry where some firms enjoy sustained superior returns. These returns have persisted despite significant change in the industry over the last 20 years. The 1980s saw the emergence of steady price increases for drug innovations, after two decades of regular declines in inflation adjusted drug prices. A 1984 law provided for great expansion of competition from generic products that sharply abbreviated the life cycle of established products after the late the 1980s (Grabowski and Vernon, 1986, 1996). New firms entered the industry in the 1980s, for the first time since the 1950s, based on biotechnology and genetic engineering. The average cost for discovery of new drugs ballooned from \$200 million to \$500 million between the early 1980s and the late 1990s, triggering frequent mergers among established firms. And consumer knowledge regarding drugs became more sophisticated in the 1990s, based on the Internet and direct to consumer advertising, with the latter allowed only after 1994 (Calfee, Winston, and Stempski, 2002; Ling, Berndt, and Kyle, 2002).

Despite these enormous shocks to the industry, the competitive landscape among the integrated pharmaceutical firms that discover and market new drugs has remained remarkably stable. The key strategic asset for these firms is their ability to discover new drugs, and expenditures on research and development represent the key investment in strategic assets for

them. Across the integrated firms, there is tremendous stability in R&D expense. Figure 1 traces the R&D expense over nearly 30 years for a first tier firm (Merck), a second tier firm (Schering Plough), and a smaller firm (Syntex). Note from the figure that the gaps among these firms are almost completely unchanged over these three decades.

This investment stability appears to represent an interfirm equilibrium, persisting over thirty years. The existence and durability of this equilibrium is surprising given the turbulence and changes in the US pharmaceutical industry described above. The core goal for this paper is to provide a theoretical explanation for how such interfirm differences can be sustained over time, and to empirically demonstrate that this dynamic equilibrium holds for the integrated firms in this industry as a whole.

Theory of Corporate Investment and Growth

This section develops a model of investment and growth for firms in an industry where competitive advantage is sustained forever. This model thus represents “perfect advantage,” as a counterpoint to neoclassical economics models of “perfect competition.” A model of perfect advantage is no more expected to apply to all industries than a model of perfect competition would. Indeed, Wiggins and Rueffli (2002) have empirically demonstrated that competitive advantage lasting through even a moderate time frame is quite rare. Rather our goal is to understand how competitive advantage can be sustained in those industries where it does exist and does persist. A model of perfect advantage provides an ideal against which most industries can be compared.

A model of perfect advantage embodies three features. First, competitive advantage among firms in the industry is a positive function of the accumulated stock of strategic assets. Firms with higher levels of the asset stock are more valuable. Firms with lower levels of the

asset stock are less valuable. Second, this competitive position among firms does not converge over time. For some plausible parameterization of the model, there is no convergence whatsoever among firms so that competitive advantage is sustainable forever. And third, each firm behaves optimally, competitively, and with full information. The sustainability of competitive advantage thus does not result from organizational myopia or industrial monopoly.

General Model and Notation

For our model, the competitive position of firm j at time t is a function of its stock of strategic assets. Denote that asset stock as $S_j(t)$. To facilitate exposition in this paper, we will denote all time-dependent variables with capital English letters. Parameters will be denoted with Greek letters, and will be treated as time-invariant. In this theory section, we will often dispense with the parenthetical notation for time. We will also fully suppress subscripts for firms in the theory section, and simply model the growth process of one firm. In the empirical section that follows, we will reintroduce firm subscripts and will fully note the time-dependence of variables.

The accumulation process for each firm in the industry indicates how the flow of investments at each instant in time by each firm adds to the firm's stock of strategic assets. Equation 1 gives the most general accumulation process. A dot over a variable denotes a time derivative, $\dot{S} = dS/dt$. We will denote partial derivatives with subscripts, as in $f_z = \partial f(Y,Z)/\partial Z$.

$$(1) \quad \dot{S}(t) = f[I(t), S(t)] \quad \text{where } f_I > 0$$

The asset stock S is increased at each instant of time t by investment I , in a way that may be affected by the level of the stock S at that particular point in time.

An optimizing firm will choose the stream of investments $I(t)$ over time to maximize the value of firm wealth $V(t)$ given in Equation 2 immediately below. Note that each firm chooses at

once the full function $I(t)$ over the full range of time, not just an isolated value of I for one instant in time. The value of the firm is simply the present-discounted stream of profits from years t to ∞ .

$$(2) \quad V(t) = \int_{u=t}^{\infty} [\Pi(S(u)) - cI(u)] \exp(-\kappa u) du \quad \text{where } \Pi_S > 0, c > 0$$

$\Pi(S)$ denotes profits at an instant in time due to S the asset stock level at that instant. In our initial models, the profit function is strictly concave in S ($\Pi_{SS} < 0$) to insure existence of an optimum. As the model is extended below, concavity of the profit function is no longer required for existence of an optimum. c is a parameter that denotes the unit cost of investment at an instant in time. κ is a parameter that denotes the cost of capital.

We will employ optimal control theory to solve for the investment stream that maximizes Equation 2 subject to the dynamic constraint in Equation 1. In general, the optimal investment stream will have the form of Equation 3.

$$(3) \quad \dot{I}(t) = m[I(t), S(t)]$$

Let us examine how this setup has been deployed, first by economic growth theorists, second by Dierickx and Cool, and third by Uzawa based on Penrose. We will then adapt the Uzawa-Penrose model to provide one of perfect advantage.

Neoclassical Investment Models

The most basic formulation of the investment process is completely linear, with “evaporative” depreciation so that the proportion δ of the asset stock simply disappears into thin air. This basic formulation is given in Equation 4.

$$(4) \quad \dot{S}(t) = I(t) - \delta S(t) \quad \text{where } 1 > \delta > 0$$

It is worth stressing that while this model is very common in the neoclassical economics literature, the concept of evaporative depreciation remains very strange, and is particularly ill-suited for application to intangible assets and hence strategic growth among firms. Physical capital depreciates with actual use. Yet, most physical capital (such as land and equipment) can be easily traded in well-established markets and is therefore not strategic. Intangible capital (such as knowledge, patents, and brands) is far more likely to be strategic. Yet intangible capital not only does not depreciate with use, but may actually appreciate. The more consumers drink Coca-Cola, the more valuable the brand becomes. The more consulting clients McKinsey serves, the better it understands the consulting process, the greater its market presence, and the stronger its pricing premium.

Let us for the moment nonetheless take Equation 4 as the true accumulation process. Maximization of firm value in Equation 2 subject to the dynamic constraint in Equation 4 yields a very simple solution: at time zero, the firm instantly invests a huge level of $I(0)$ to bring the asset stock up to optimal levels. Future investments are made at the rate δ times the optimal asset stock, so that optimal level is always maintained. A classic reference for this result is Jorgenson (1967). Note that central to this finding is the specification in Equation 2 that capital may be instantly and without friction adjusted to its optimal level.

Clearly this outcome is useless if we are to obtain the desired model of perfect advantage. Applied to firms in an industry, not only would this particular and basic accumulation process fail to provide an isolation mechanism, there would not even be any differences among firms to isolate. Indeed, neoclassical economists found this model limited in its application to study of growth rates across national economies. Many scholars modified Equation 4 so that investment affected the asset stock in a nonlinear manner (Gould, 1968; Lucas, 1967a, 1967b; Uzawa, 1968,

1969). The resulting diminishing returns for instantaneous investment are a form of “adjustment costs,” or frictions in the investment process. Formally, adjustment costs are properties of the investment function that reduce the contribution to the asset stock below the actual value of the investment flow. As firms increase their instantaneous level of investment, we expect adjustment costs to increase both absolutely and relative to overall investment costs. Adjustment costs therefore shape the contours of investment across firms, raising the possibility of sustained competitive advantage. In a sense, the study of competitive advantage across firms is a study of adjustment costs, just as the study of the scope and boundaries of firms is a study of transactions costs.

A simple restatement of Equation 4 to allow for the mildest form of adjustment costs yields Equation 5.

$$(5) \quad \dot{S}(t) = g[I(t)] - \delta S(t) \quad \text{where } 1 > \delta > 0, g_I > 0, g_{II} < 0$$

Here, investment at each instant of time contributes to the asset stock in a strictly concave manner. Actually, the more standard formulation of this model with adjustment costs retains the linear effect of investment in Equation 4, and instead alters the linear effect of investment in the integrand of Equation 2 to become $[\Pi(S(t)) - b(I(t))]$ where the function b is strictly convex in $I(t)$, or $b_I > 0$ and $b_{II} > 0$. Classic references for the latter formulation are provided by Gould (1968) and Lucas (1967a). We will employ the non-classic version in Equation 5 as it provides a better bridge between the pure neoclassical model of investment and the Uzawa-Penrose model discussed below.

Both formulations of adjustment costs render expensive any high levels of investment by the firm at any single point in time. We will not be surprised then to find that adjustment costs smooth the resulting optimal path of investment over time. Maximize the value of the firm in

Equation 2 subject to the neoclassical accumulation process with adjustment costs in Equation 5, and we obtain the following optimal path for investment.

$$(6) \quad \dot{I}(t) = (\kappa + \delta) \frac{g_I}{g_{II}} - \frac{\Pi_S g_I^2}{c g_{II}}$$

We graph Equations 5 and 6 in a phase diagram in Figure 2, relying on the concavity of the profit function $\Pi(S(t))$ and of the adjustment cost function $g(I(t))$. The dotted lines with arrows give the direction of motion for the system. The heavy multi-arrowed line gives the optimal path over time for investment and the associated asset stock.

Examination of Figure 2 reveals that firms with higher asset stocks will always optimally invest less than firms with lower asset stocks in the neoclassical model with adjustment costs. This higher level of investment is absolute, as well as proportional to the existing asset stock. This outcome should not be surprising. The inherent logic of the model behind Figure 2 contains nothing that prevents disadvantaged firms from closing the gap between themselves and advantaged firms in due time. All the adjustment costs in Equation 5 do is create optimal delay for erasing the gap. Because small firms in this model have further to go to attain the optimal size for strategic assets, they will invest more. The simple model behind Figure 2, therefore, does not provide an isolating mechanism that protects the competitive advantage of larger firms. To obtain such an isolating mechanism, additional features will need to be added to the model in order to alter the optimal investment path. Dierickx and Cool (1989) suggest such features, and we now turn to analysis of them.

Dierickx and Cool on Asset Stock Accumulation

Perhaps the most widely cited analysis of strategic asset accumulation is that of Dierickx and Cool (1989). They identify a variety of characteristics of the accumulation process that

might enable sustained competitive advantage. The three most important of these features are time compression diseconomies, asset mass efficiencies, and asset erosion. These three features can be examined by respecifying the accumulation process as Equation 7.

$$(7) \quad \dot{S}(t) = h[I(t), S(t)] - \delta S(t)$$

Dierickx and Cool define time compression diseconomies as diminishing returns to investment at a single instant in time. This concept is identical to adjustment costs in neoclassical growth theory, and can be stated again as the requirement that $h(I, S)$ is strictly concave in I , or that $h_I > 0$ and $h_{II} < 0$. Dierickx and Cool next define asset mass efficiencies as a positive interaction effect at each instant of time by the asset stock on the effectiveness of the investment flow. Investments by firms with an established asset position will be more valuable than the same level of investment by firms with inferior asset positions. Asset mass efficiencies can be stated in terms of Equation 7 as the requirement that $h_S > 0$ and $h_{IS} > 0$. This interaction effect represents an additional form of adjustment costs, rarely considered in the economics literature. Finally, asset erosion is the depreciation of the asset stock in the absence of new investment. In Equation 7, the parameter δ gives the linear rate of instantaneous decay in the asset stock (or the rate of evaporative depreciation, as described above). Dierickx and Cool argue that δ must be small in order for asset accumulation to serve as an isolating mechanism.

Dierickx and Cool present these features of the accumulation process as necessary for that process to serve as an isolating mechanism. Yet, their purely verbal discussion of these features does not demonstrate that such isolation actually occurs. Further, actual specification of the accumulation process in Equation 7 will yield several parameters, such as the erosion rate δ and the degree of concavity (decreasing returns) for investment. It is likely that certain values

for these parameters, such as a rapid erosion rate or minimal concavity for investment, will fail to yield an isolating mechanism.

Knott and Bryce (2003) have suggested the following parameterization of Dierickx and Cool's accumulation process, noted here as Equation 7*.

$$(7^*) \quad \dot{S}(t) = \chi I^\alpha S^\beta - \delta S \quad \text{where } 1 > \alpha > 0, \beta > 0, 1 > \delta > 0, \chi > 0$$

For time compression diseconomies, we must have $1 > \alpha > 0$. For asset mass efficiencies, we must have $\beta > 0$ and $\chi > 0$. For asset erosion, we must have $1 > \delta > 0$. In the spirit of this approach, let us also parameterize the value of the firm into a somewhat simpler Equation 2*.

$$(2^*) \quad V(t) = \int_{u=t}^{\infty} [\pi S^\rho - cI] \exp(-\kappa u) du \quad \text{where } \pi > 0, \rho > 0$$

The parameter ρ gives the elasticity of advantage for the industry, or the extent to which firm value relative to the asset stock rises or falls with firm scale. With concavity of the profit function ($1 > \rho > 0$), smaller firms will have higher ratios V/S than their larger counterparts. With convexity of the profit function ($\rho > 1$), larger firms will have higher V/S ratios than smaller firms. We must again note that the early models of this study require concavity of the profit function in order for an optimum schedule of investment over time $I(t)$ to exist.

Maximization of the value of the firm in Equation 2* subject to the dynamic constraint in Equation 7* yields the following optimal path for investment.

$$(8) \quad \dot{I}(t) = \left(\frac{\kappa + \delta - \beta\delta}{1 - \alpha} \right) I - \left(\frac{\alpha \pi \rho S^{\rho-1}}{c(1 - \alpha)} \right) \chi I^\alpha S^\beta$$

Because of the multiplicity of parameters, the behavior of this system varies considerably with different parameter values. To draw a phase diagram similar to Figure 2, we must first determine the shapes of each arm. We are assisted in this task by the fact that each arm is separable into

terms expressed only in S and only in I . For example, if we divide Equation 8 through by the term $I^\alpha / (1-\alpha)$ we obtain the following Equation 9.

$$(9) \quad \dot{I}(t) = 0 \text{ implies } c(\kappa + \delta - \beta\delta) I^{\alpha-1} = \alpha \pi \rho \chi S^{\beta+\rho-1}$$

The left side of Equation 9 is a function of the asset stock S alone, and is plotted in the top left corner of Figure 3. When the sum $(\beta+\rho)$ is only slightly above the value one, the top left curve will be highly concave in S . The right side of Equation 9 is a function of the investment flow I alone, and is plotted in the bottom right corner of Figure 3. When α is near zero, the bottom right curve will be nearly linear. With these parameter values, the resulting curve for $\dot{I} = 0$ in Equation 9 itself can be traced in the top right corner of Figure 3 as highly convex in I .

A convex curve $\dot{I} = 0$ for will hold for this system whenever the parameters obey the following inequalities.

$$(10) \quad (1 - \alpha) > (\beta + \rho - 1) > 0$$

When these inequalities are valid, the phase diagram for the system is as in Figure 4. Here at last, the accumulation process begins to function as an isolating mechanism. Firms with large asset stocks invest more than do firms with smaller asset stocks. While all firms eventually converge to the intersection of the $\dot{I} = 0$ and $\dot{S} = 0$ curves, that convergence may be slow enough (depending on parameter values) to sustain significant competitive advantage.

While the inequalities in 10 above that lead to stable equilibrium are perhaps plausible, they are hardly inevitable. The most widely used specification for the accumulation process is Equation 4, where α is taken to be one. That value for α would make attainment of these inequalities impossible. Were α only nearly equal to one, the permissible range for parameter values to yield an isolating mechanism would be extremely narrow. Even if parameter values for the system allow the accumulation process to function as an isolating mechanism, we must still

make further restrictions on an even wider range of parameters to insure that convergence across firms to a common long-run equilibrium is sufficiently slow. Finally, for certain parameter values, the entire system becomes unstable, as in Figure 5. Here all firms move steadily away from the long-term equilibrium noted by the intersection of the two curves.

It would be quite helpful if we could identify a parameterization of the accumulation process that would yield truly sustainable competitive advantage across firms. Oddly enough, much of the solution to this problem has existed for some thirty-five years.

Uzawa and Penrose on the Growth of the Firm

Most of growth theory in neoclassical economics relies on highly aggregative functions, such as those for economy-wide consumption or economy-wide labor supply. In contrast, Uzawa (1968, 1969), sought to disaggregate these functions, and provide detailed theory of individual consumers and individual firms in his models. His theory of consumers was completely neoclassical, based on rational, fully informed, frictionless choice. But, for his theory of the firm, he ventured far from the neoclassical literature, and based his analyses on Penrose (1959). Penrose had argued that the managerial abilities needed for growth of the firm fundamentally differed from those needed for daily administration. In modern terms, we would distinguish between dynamic capabilities and static resources. Penrose further argued that growth of the firm is constrained by its stock of managerial ability available at any time. In terms of this study, managerial capability is a strategic asset that is only imperfectly traded in markets.

Uzawa draws on Penrose to argue that the firm can never expand its managerial capability as rapidly as it purchases physical capital. In terms of this study, expansion of the stock of strategic assets can never grow as rapidly as the flow of investment in them. Uzawa

further argues that the gap between expansion of managerial capability and physical capital becomes wider as the firm tries to grow more rapidly. With an elegantly simple assumption, Uzawa defines the accumulation process for each firm as given in Equation 11.

$$(11) \quad \frac{\dot{S}(t)}{S(t)} = h\left(\frac{I(t)}{S(t)}\right) \quad \text{where } h_I > 0, h_{II} < 0$$

With this accumulation process, Uzawa obtains the result that all firms in an industry, including their investment levels and asset stocks, grow at a common rate ω . The ratio of investment flow to asset stock is thus constant at rate z , where $\omega = h(z)$ or $h^{-1}(\omega) = z$. Spelled out completely, we have the following conditions for each firm.

$$(12) \quad S(t) = S(0) \exp(\omega t) \quad \text{where } S(0) \text{ is a given initial condition}$$

$$(13) \quad I(t) = I(0) \exp(\omega t) \quad \text{where } I(0) = S(0) h^{-1}(\omega)$$

$$(14) \quad z \text{ maximizes } \frac{\pi - CZ}{\kappa - h(z)} \quad \text{where } h(\bullet) \text{ is the function in (11)}$$

Thus, the current stock of intangible capital for each firm $S(t)$ is directly proportional to its initial asset stock $S(0)$, and this intertemporal proportion is the same for all firms in the industry.

The following parameter restrictions are sufficient to reduce the model based on Equations (2*) and (7*) to the Uzawa-Penrose model.

$$(15) \quad \alpha + \beta = 1 \quad \text{and} \quad \rho = 1$$

It is interesting to note that no restriction is required for the evaporative depreciation δ parameter. Contrary to the arguments of Dierickx and Cool (1989), the magnitude of that parameter has no effect on sustainable advantage at all. The δ parameter serves to determine the optimal investment rate $[I/S = z]$ and the optimal growth rate ω , but not the presence or absence of sustainable advantage. There is a practical upper bound for the level of evaporative

depreciation—it must not be so high as to render unprofitable any investment in the asset stock. But this upper bound holds for any industry, not just one with sustainable competitive advantage.

These parameter requirements in Equation 15 represent a “knife edge” of exquisite balance. Only if they hold exactly, do firms grow together at a uniform rate, rendering competitive advantage infinitely sustainable. Should, however, the actual parameters of the accumulation process in an industry approximate requirements of the Uzawa-Penrose model, we will have gradual convergence towards or divergence from a common equilibrium like those in Figures 4 and 5. With such close approximation, the rate of convergence will be slow, and competitive advantage long-lived even if not infinite.

This study labels the model described immediately above as the “Uzawa-Penrose model.” Rugman and Verbeke (2002) have recently reminded us that Penrose herself may not have agreed with a model of this sort or even recognized her own work in it. Penrose indeed provided a non-neoclassical analysis of the growth of the firm, and indeed placed adjustment issues with the stock of management at the center of her analysis. However, she did not launch this analysis to explain sustainable efficiency rents in firms. In the first place, Penrose (1956, 1959) seems to have regarded most economic rents as transitory, being competed away over time. In the second place, Penrose (1959, 1973) acknowledged that corporate profits may on occasions be monopolistic, and may require regulation by the state. The empirical work of this paper presents the enormous recorded profits of US pharmaceutical firms as entirely efficiency rents. It is not clear whether Penrose would react to this finding with delight or abhorrence.

Let us acknowledge that Penrose never specified parameters of a differential equation for corporate growth—that specification was the work of Uzawa. Let us also acknowledge that Uzawa never used his model to examine interfirm difference in profit rates—that usage is the

work of this paper. The next section adapts the Uzawa-Penrose model to allow for interfirm difference in profit rate.

Competitive Advantage in a Modified Uzawa-Penrose Model

Uzawa specified his model with constant returns for the profit function, where $\rho = 1$ in Equation 2*. The resulting dynamic equilibrium indeed preserves a form of competitive advantage across firms, where large firms remain large and small firms remain small. However, the value of each firm in currency units at time t (not the present value at time 0) is a linear function of its asset stock at time t , or:

$$(16) \quad V(t) = \left(\frac{\pi - cZ}{\kappa - h(Z)} \right) S(t)$$

Thus, the ratio of the value of the firm to its stock of strategic assets is identical across all firms, implying that the profit rate is also identical. The profit level will be higher for firms with large stocks of strategic assets, but not their profit rate. While this outcome represents some form of “competitive advantage,” it is not the form that scholars in strategic management expect. Not only the level, but also the rate of profits must be higher for firms with large stocks of strategic assets in order for the resulting dynamic equilibrium to truly represent perfect advantage.

To obtain the desired model of perfect advantage, we must modify the Uzawa-Penrose model and introduce more nonlinearity. Respecify the objective function for the value of the firm from Equation 2* to the following Equation 17, allowing the instantaneous costs of investment to increase with scale.

$$(17) \quad V(t) = \int_{u=t}^{\infty} [\pi S^{\rho} - cI^{\phi}] \exp(-\kappa u) du \quad \text{where } \pi > 0, \rho > 1, \phi > 1$$

Additionally, respecify the accumulation process of Uzawa in Equation 11 to Equation 18.

$$(18) \quad \frac{\dot{S}(t)}{S(t)} = h\left(\frac{I(t)^v}{S(t)}\right) \quad \text{where } h_I > 0, h_{II} < 0, v > 0$$

We maximize Equation 17 subject to the dynamic constraint in Equation 18. Two conditions are required to preserve the stability of the Uzawa-Penrose dynamic equilibrium when we allow the elasticity of scale ρ to be greater than one. First, we have generalized the value function to allow for two elasticities of scale, ρ with regard to the asset stock and φ with regard to the investment flow. To preserve the basic features of the Uzawa-Penrose equilibrium, those two elasticities must be linked in the following precise manner.

$$(19) \quad \varphi = \rho v \quad \text{where } v \text{ is the parameter in Equation 18}$$

Note that the original Uzawa-Penrose model is a special case of this broader model, when $v = \varphi = \rho = 1$. The second condition is that unit profit and cost parameters π and c are not now constant over time, but rather adjust in the following manner.

$$(20) \quad \pi(t) = \pi \exp[(1-\rho)t] \quad \text{where } \pi = \pi(0)$$

$$(21) \quad c(t) = c \exp[(1-\rho)t] \quad \text{where } c = c(0)$$

The outcome of this requirement is that the ratio of corporate value to the asset stock does not vary over time. When the elasticity of scale is one, we have that outcome with constant values for π and c . When the elasticity of scale exceeds one, corporate values will drift upwards over time with accumulation of assets. The common sense of this second condition is that competition among existing firms keeps the profit rate of the marginal firm constant. Note that again, the original Uzawa-Penrose model is a special case of this broader model, when $\rho = 1$.

With this modified Uzawa-Penrose model, we again have steady-state growth of the asset stock at a common rate ω across firms and across time.

$$(22) \quad S(t) = S(0)\exp(\omega t) \quad \text{where } S(0) \text{ is a given initial condition}$$

Given the new specification for the accumulation process in Equation 18, the investment flow now grows at a slightly different rate that is still common across firms and time.

$$(23) \quad I(t) = I(0) \exp\left(\frac{\omega}{\nu} t\right) \quad \text{where } I(0) = [S(0) h^{-1}(z)]^{(1/\nu)}$$

Now, the value of each firm is a nonlinear function of the accumulated stock of strategic assets,

$$(24) \quad V(t) = \left(\frac{\pi - cz^p}{\kappa - h(z)} \right) [S(t)]^p$$

and also of the optimal investment flow,

$$(25) \quad V(t) = \left(\frac{\pi - cz^p}{z^p (\kappa - h(z))} \right) [I(t)]^\varphi \quad \text{where, again, } \varphi = \rho\nu$$

When the parameters ρ and φ are greater than one, we have the desired model of perfect advantage. Large firms, with large stocks of strategic assets, have higher profit rates as well as profit levels. And these elevated profits persist forever, as long as the parameter restrictions below hold true.

The following parameter restrictions for estimable Equation 7* are sufficient to create a modified Uzawa-Penrose model of perfect advantage.

$$(26) \quad \rho\alpha + \varphi\beta = \varphi$$

These parameters again represent a “knife edge” of exquisite balance. By comparison with the restrictions in Equation 15, we see that the unmodified Uzawa-Penrose model is a special case of our more general model.

Let us now turn to empirical examination of an industry that might possibly exemplify perfect advantage, or growth in the modified Uzawa-Penrose manner.

Estimation of Models with Accumulation of Strategic Assets

Suppose we found an industry where the Uzawa-Penrose model held exactly. How might we confirm that all firms in this industry indeed accumulated strategic assets in the prescribed manner? Central to any such confirmation is disentangling the separate roles of investment flow and asset stock in the accumulation process itself. The practical task of such disentanglement is significantly complicated by three problems.

First, key variables will be highly if not perfectly intercorrelated. The hallmark of the Uzawa-Penrose model of firm growth is that almost every variable grows at the same rate across all firms. Successful firms will have high levels of firm value, asset stock, and investment flow. Weaker firms will have lower levels of these variables. Indeed, the cross-firm ratios of these three variables will be completely invariant over time. All of these variables thus serve as highly efficient proxies for each other, without revealing any aspect of underlying causation.

For example, suppose we attempted to uncover the durability of intangible capital in a true Uzawa-Penrose industry by regressing firm value on just investment flow using pooled cross-section/time series data. We would “find” that the current period’s investment flow for each firm would by itself positively and well predict firm value, and might therefore conclude that there was no durable strategic asset for this industry. In fact, as we know from specification of the Uzawa-Penrose model, we know nothing at all about the durability of strategic assets in this industry from the mere existence of a dynamic equilibrium, and depreciation rate may well be zero. So, our empirical “finding” might be the exact opposite of the true underlying phenomenon.

A second problem is that the stock of strategic assets is “invisible,” in the sense of Itami (1987). The essential nature of strategic assets is that they are only rarely and with great

difficulty traded on markets, and thus poorly valued or quantified by such markets. Direct measurement of the true stock of strategic assets is thus difficult if not impossible, and is usually accomplished with use of proxy variables. In contrast, investment flow represents an aggregate of market purchases, and so can be measured as well as any other important variable in strategic management. Asset stocks will thus always be measured with greater error than investment flows.

A third problem lies in the stochastic nature of the accumulation process itself. Suppose several firms in an industry hire similar advertising agencies and spend the same amount on advertising campaigns. The typical results of these campaigns will be highly skewed, with most enjoying only modest success and rare “blockbuster” successes. The firm that attains blockbuster response adds immensely to its intangible capital. Other firms add only moderately. The asset stock of each firm represents the accumulation over time of such stochastic shocks, while the investment flow at an instant of time represents at most one such shock. Again, asset stocks will be measured with greater error than investment flows.

Consider the firm that benefits from a blockbuster advertising campaign. In subsequent periods, the optimal level of investment flow by this firm would be higher due to its contemporaneously elevated stock of intangible brand capital. The value of the firm would be also be higher due to the elevated asset stock. It would be easy in careless empirical analysis to misread the causation here and “find” that the value of the firm is somehow entirely driven by the current investment flow. Instead, both the value of the firm and current investment are driven by the history of past investments.

These empirical issues should shape our approach to estimation of parameters for the accumulation process in an industry. The most obvious approach here is to attempt direct

estimation of the accumulation process, using perhaps the specification in Equation 7*. For the accumulation process, investment flows and past asset stocks determine current asset stocks, hence current firm output and current firm value. Using cross-section data, we can thus regress either some sensible proxy for the asset stock, firm output, or firm value on investment flow and past values for the asset stock. This approach has been used in the previously cited study by Knott and Bryce (2003) for the US pharmaceutical industry. While this approach is obvious, it is also highly likely to fall prey to the estimation issues above. Consider estimation of the β term in Equation 7*. Here we must multiply together two highly correlated variables, empower both, and estimate the power of the variable that is most subject to mismeasurement. This is not an attractive estimation approach. The multicollinearity among key variables will render the statistical objective function extremely flat, making it difficult to sensibly select optimal parameter estimates.

Geroski and Mazzucato (2002) employ a comparable direct approach to estimation of the accumulation process, with intertemporal data for individual US automobile firms. Here output of each firm is regressed on linear functions of past output and investment flow (measured by specific innovations) for each firm. Geroski and Mazzucato make no effort to measure the asset stock. The common sense of their approach is that shocks to past output or investment flow will be realized in current output through the accumulation process. While indeed sensible, this direct approach again falls prey to the estimation issues discussed above. In order for cumulative learning or some other phenomenon to serve as a strategic asset at all, there must be adjustment costs for the investment process, so that some firms are more efficient than others in accumulation of strategic assets. Specifically, we must have instantaneous diminishing returns for investment flow (time compression diseconomies) and complementarity between asset stocks

and investment flows (asset mass efficiencies). Both phenomena will sharply moderate and smooth the effects of any shocks in asset flow on current firm output or current firm value, undermining if not destroying the common sense of the Geroski and Mazzucato estimation approach. Certainly, simple linear functions will not capture these adjustment costs for the investment process.

An alternate approach is to directly estimate the investment process, and thereby to indirectly infer features of the accumulation process. Observed investment by firms in an industry represents optimal behavior subject to the constraint of a given accumulation process, say Equation 8 derived from Equation 7*. Examination of investment patterns is far less likely to fall prey to the estimation problems discussed above, and much more likely to reveal the true underlying accumulation process. Consider Equation 8. If $\beta=0$, then we are back to the neoclassical economics growth model and Equation 8 reduces to a particular form of Equation 6. As our earlier discussion made clear, these circumstances require that smaller firms systematically outinvest larger firms in every year and rapidly eliminate any industry competitive advantage. If this investment pattern does not hold, then it simply cannot be true that the accumulation process is well-described by Equation 7* with $\beta=0$. If instead, large firms systematically outinvest small firms, then either $\beta>0$ or the true accumulation process is profoundly misspecified by using Equation 7*. The effect of changes in β is far clearer in Equation 8 than Equation 7*, and it is easier to estimate parameters indirectly using optimal investment patterns rather than directly using the accumulation process itself.

This study argues that the most useful approach is to estimate at the same time both a specification for the accumulation process and the derived optimal investment process. In terms of empirical work, we must treat these two equations as a single system. We use these two

equations not merely to statistically correct for endogeneity, but more so because a single set of parameters underlies both equations. At minimum, we expect the associated parameter estimates for each equation to be similar in sign and magnitude. At best, we expect these estimates to be identical.

Specifically, we propose to estimate the following nonlinear, simultaneous, two equation system, adapted from Equations 7* and 8, with parameters α , β , χ , δ , φ , and ρ .

$$(27) \quad S_j(t) - S(t-1) = \chi [I_j(t)]^\alpha [S_j(t-1)]^\beta - \delta S_j(t-1)$$

$$(28) \quad I_j(t) - I(t-1) = \theta I_j(t-1) - \eta [I_j(t-1)]^{(1+\alpha-\varphi)} [S_j(t)]^{(\beta+\rho-1)}$$

$$\text{where } \theta = \left(\frac{\kappa + \delta - \beta\delta}{\varphi - \alpha} \right) > 0 \quad \text{and} \quad \eta = \left(\frac{\alpha \pi \rho \chi}{c\varphi(\varphi - \alpha)} \right) > 0$$

If we do not impose the parameter restrictions in the second line of Equation 28 across Equations 27 and 28, then we have two additional parameters to estimate, θ and η , that we expect to be positive and in the magnitudes indicated by the second line of Equation 28. The parameter κ we will take to be 0.10, a reasonable value for the real cost of capital. The parameters π , ρ , and φ are obtained by estimation of Equations 24 and 25.

Data and Variables

We will estimate Equations 24, 25, 27, and 28 using data for US integrated pharmaceutical firms, 1970 to 1998. These integrated firms both discover and market new drugs. The 27 firms in our sample are Abbott, Airco, American Cyanamid (until 1994), American Home Products, Armour (until 1982), Baxter, Bristol Myers, Carter Wallace, Johnson & Johnson, Eli Lilly, Merck, Norwich-Eaton (until 1982), Pennwalt (until 1988), Pfizer, 3M/Riker, Richardson Merrell (until 1978), A. H. Robins (until 1988), Rorer (until 1989),

Schering Plough, G.D. Searle (until 1984), Smith Kline (until 1988), Squibb (until 1988), Sterling (until 1986), Syntex (until 1993), Upjohn, and Warner Lambert. The dates given parenthetically after several of these firms indicate when the firm exited the industry, in every case due to merger of the firm's pharmaceutical operations into another firm.

The sample excludes two types of firm that also innovated new drugs during 1970 to 1998. Several diversified firms discovered three or more new drugs in this period: Dow, Dupont, Procter and Gamble, Monsanto, and Kodak. Each of these five firms invests significantly more in non-pharmaceutical R&D than in pharmaceutical R&D. To properly link intangible investment flow and asset stock for these firms, we would need to separate out these two types of R&D. That breakout task is beyond the scope of this study, and these firms are therefore excluded. The sample also excludes the new biotechnology firms that entered in the late 1980s. These new firms lack sufficient history to adequately measure the accumulation and depreciation of strategic assets.

The flow of investment in strategic assets $I(t)$ for the integrated drug firms is taken for this study to be annual expenditures on research and development. These data are taken from Compustat for 1969 to 1998. The Compustat data are deflated by the price index for biomedical research compiled by the US National Institutes of Health. This deflation converts the nominal data in Compustat to constant-1990 dollars and corrects for the significant inflation in research costs since 1970.

The value of the firm $V(t)$ is taken for this study to be the sum of the stock market value of common equity (calendar year-end closing price) and the book value of long-term debt. These data are also from Compustat. These Compustat data are deflated by the US GDP price index, taken from the International Monetary Fund.

The stock of strategic assets $S(t)$ is taken for this study to be the accumulation of new drugs launched by each firm in the developed world from 1962 onwards. Specifically, we have:

$$(29) \quad S(t) = \int_{u=1962}^t D(u) \exp[\delta(u-t)] du \quad \text{where } \delta \text{ is to be estimated}$$

Annual drug launches $D(u)$ for each firm in year u are tabulated from DeHaen (1988) for 1962 to 1969, from FDA (1985) for 1970 to 1982, and from IMS, Inc. for 1983 to 1998. We attribute each drug to its innovator, not its marketer, in the case that these differ. It is important to note that this study treats the stock of strategic assets as the accumulation of successes with innovation, not the mere accumulation of R&D spending. The drug firm Squibb was spun off from the chemical firm Olin Mathieson in 1968. We attribute the pre-1968 drug introductions of Olin Mathieson to Squibb itself in calculation of the asset stock for Squibb. The innovations of Johnson & Johnson include those of its overseas subsidiary, Janssen, and those of Merrell include those of its overseas subsidiary, Lepetit. Note that innovations of any firm need not be introduced in the United States to be tabulated for this study, rather they must be introduced into at least one nation of Western Europe, Japan, Canada, or the USA.

Three of the sample firms merged into other sample firms during the period of study: Squibb into Bristol-Myers (1989), Robins into American Home Products (1989), and American Cyanamid into American Home Products (1995), with merger year given parenthetically. These mergers affect both the asset stock and investment flow variables. Consider the 1988 merger of Squibb and Bristol Myers, depicted in Figure 6. Note that these data are deflated by the NIH biomedical price index, and are thus not the raw data from Compustat. Compustat treats Bristol Myers as the precursor firm for the merged entity Bristol-Myers Squibb. Thus, Compustat reports the R&D expenditures (not adjusted for inflation) for Bristol-Myers Squibb as \$789

million in 1989 and only \$394 million in 1988, implying that these expenditures almost doubled in a single year. Yet, Bristol-Myers Squibb represents the integration of both firms, with their distinct histories and research competencies intact and operating. We can impute a “merged” precursor firm by summing the R&D expenditures of the two separate firms before 1989. In 1988, this imputed firm spent \$687 million, since Squibb spent \$293 million and Bristol Myers spent \$394 million. For each of the four mergers noted at the start of this paragraph, we take $I(t-1)$ for the year of the merger to be the value for the imputed merged firm, not the value for the precursor firm as reported in Compustat. We need this lagged value to estimate Equation 28.

We combine drug discoveries for the imputed “merged” firm to tabulate the stock of strategic assets in Equation 29. Before the merger, each firm is of course treated separately. In the year of the merger and thereafter, the values for $S(t)$ and $S(t-1)$ are tabulated for the imputed firm, using the summation of discoveries for both firms for all components $D(u)$ in each year.

Arikan (2002) has recently argued that aggregations of intangible or strategic assets through mergers are less efficient than direct accumulation by a single firm. Thus, a merged entity that combines the histories of two separate firms will end up with a smaller stock of strategic assets than would a firm that had itself innovated all these previous drug discoveries. Note that this inefficiency represents an additional form of adjustment costs. To allow for the relative inefficiency of asset accumulation through merger, we must respecify Equation 29 as follows.

$$(29^*) \quad S(t) = \int_{u=m}^t D(u) \exp[\delta(u-t)] du + \sigma \int_{u=1962}^m D_A(u) \exp[\delta(u-m)] du \\ + \sigma \int_{u=1962}^m D_B(u) \exp[\delta(u-m)] du \quad \text{where } * \text{ and } \sigma < 1 \text{ are to be estimated}$$

A merger between firms A and B occurs in year m . The stock of strategic assets for the merged firm is the cumulative discoveries of the merged firm since year m , plus some fraction σ of the discoveries of the component firms A and B between 1962 and year m . The fraction $\sigma < 1$ represents the inefficiency in accumulation through merger.

Finally, we must correct the R&D expenditure data for significant spinoffs of research divisions by ongoing drug firms. In 1995, 3M/Riker sold its clinical diagnostic division to Johnson & Johnson. The 1994 R&D flow of that single division alone was \$225 million (not adjusted for inflation). The 1995 and 1994 data for 3M thus do not compare like with like, as the scope of the firm is smaller in 1995 than it was in 1994. The reported data in Compustat (not adjusted for inflation) are \$1054 million for R&D in 1994 and \$883 million for 1995, falsely implying a significant retreat from drug research by 3M. To correct for this spinoff, we must treat $I(t-1)$ in Equation 19 for 3M in 1995 as \$829 million ($\$1054 - \225). For Johnson and Johnson in 1995, we will do the reverse, adding \$225 million to reported data for $I(t-1)$. We will make comparable adjustments to correct for the sales of Lilly's Guidant division in 1994 (with R&D flow of \$140 million), and of Bristol-Myers Squibb's clinical diagnostic division in 1994 (with R&D flow of \$110 million). Both these spinoffs were to firms outside our sample.

Table 1 reports means, standard deviations, and correlations for study variables.

Estimation and Findings

We will split the estimation process into three distinct parts. Technically, we might attempt estimation all at once of Equations 24, 25, 27, and 28 as an integrated system. Given the complex nonlinearity of this system and the very few number of distinct variables that underlie it, we will instead split the estimation into distinct parts. First, we will estimate the parameter $*$, the evaporative depreciation rate for the stock of strategic assets. Second, we will estimate the

parameters Δ and ϕ , the elasticities of advantage across firms. Third, we will estimate the system of two equations 27 and 28, using the values for σ , Δ , and ϕ we have already obtained.

Estimation of δ , Evaporative Depreciation Rate

The evaporative depreciation rate, δ , is not central to the Uzawa-Penrose model. A wide range of values for this parameter is consistent with perfect advantage. So, the estimate for the δ parameter is not critical for this study. If δ is zero, however, the functional forms we must estimate are considerably simplified. And there is good reason to believe that this parameter would be quite small for the US pharmaceutical industry. Innovation in this industry is posited to result from the cumulative, depreciated stock of past innovations. The smallest firms in the sample innovate roughly one new drug a decade. Were the estimated depreciation rate to be above 10 percent, most of these firms would have an estimated stock of intangible capital to be zero for most years. So, we expect the depreciation rate for this industry to be small, and certainly under 10 percent. Given the measurement noise that we expect for the stock of intangible assets, it will not be surprising if our estimate is statistically insignificantly different from zero. Further, as mentioned earlier, intangible assets do not depreciate with use the way physical assets do.

When we plug Equation 29* that defines the stock of strategic assets for the drug firms of our study (allowing for mergers) into parameterized Equation 27 for the accumulation process, we have the following estimable equation.

$$(30) \quad D_j(t) = \chi [I_j(t)]^\alpha \left[\sum_{u=1962}^{t-1} D_j(u) \exp[\delta(u-t)] \right]^\beta M^\mu - \delta \left[\sum_{u=1962}^{t-1} D_j(u) \exp[\delta(u-t)] \right]$$

where $\mu = \ln(\sigma) < 0$ (σ is defined and used in Equation 29*)
 where $M=1$ if no merger occurs and $M=\exp(1)$ if a merger has occurred

The dependent variable ($D_j(t) = S_j(t) - S_j(t-1)$) gives the number of new drugs discovered and launched by firm j in year t . This addition to the stock of strategic assets is driven by current investment in R&D for year t and depreciated accumulation of past drug discoveries during the years 1962 to the year before t . Put in simple terms, the discoveries of new drugs by a firm depend on its investment flow and its firm-specific capability for innovation, accumulated through experience with innovation over time.

The dependent variable $D_j(t)$ in Equation 30 is highly nonnormal in distribution. Most firms will discover no new drugs in any given year, so the mode of the dependent variable will be zero. The range for $D_j(t)$ is zero to four, with the latter attained by Pfizer in 1998. A plausible distribution for $D_j(t)$ is thus Poisson. Equation 30 is estimated using iteratively reweighted nonlinear least squares, a procedure prescribed in Gourieroux, Monfort, Trognon (1984a, 1984b) and McCullagh and Nelder (1984), and previously implemented for US pharmaceutical discoveries in Thomas (1990). Results of this estimation are displayed in Table 2. Note that the parameter estimate of δ is actually negative, though statistically insignificantly different from zero. This outcome was expected, and we will thus take δ to be zero in subsequent estimation, considerably simplifying the specifications we use. The parameter estimate for μ , representing adjustment costs for merger of intangible asset stocks, is also statistically insignificantly different from zero. We did not expect this outcome. Further the estimation philosophy of this study is that adjustment costs will be more observable in the investment process than in the accumulation process. We will thus retain μ as a parameter to be estimated in our system of two equations below.

Estimation of ρ and φ , Elasticities of Advantage

The modified Uzawa-Penrose model presents the US pharmaceutical firm as a dynamic equilibrium. In the equilibrium, the value of the firm rises is larger for firms with larger asset stocks and with higher investment flows. These equilibrium results are given in Equations 24 and 25. To estimate these equations, we must allow for the fact that all integrated US pharmaceutical firms have some diversification that renders the value of the firm positive even if the asset stock for drug innovation is zero. We can then specify Equation 24 as follows.

$$(31) \quad V(t) = v_0 + v_1[S(t)]^\rho$$

And Equation 25 may be similarly respecified.

$$(32) \quad V(t) = v_2 + v_3[I(t)]^\varphi$$

Equations 31 and 32 may be estimated with ordinary nonlinear least squares, and findings are reported in Table 3. Note that we find the elasticities of advantage to be statistically significantly different from zero and also from one, all at the 0.01 level. Also note that comparison of Equations 24 and 25 suggests that the ratio of the parameter estimates v_1 and v_3 has the following value.

$$(33) \quad z^\rho = v_1 / v_3$$

In the modified Uzawa-Penrose model, the asset stock grows at rate $\omega=h(z)$, and the investment flow at the rate ω/v . In our sample, the growth rate for $S(t)$ averages 0.055, while the growth rate for $I(t)$ averages 0.075. Note that the parameter v is thus appropriately estimated to be less than one. Also, in the modified Uzawa-Penrose model, the same v parameter links the two elasticities of scale ρ and φ , in that $v\rho=\varphi$. With some heroic effort, we can generate an estimate of π , the instantaneous profit rate for the intangible asset stock. Note from Equation 24

that gives the value of the firm in dynamic equilibrium as a function of the stock of intangible assets that we have the following relationship.

$$(34) \quad v_1 = \left(\frac{\pi - c z^p}{\kappa - \omega} \right)$$

With the calculations in the paragraphs immediately above, we can rewrite Equation 34.

$$(35) \quad \pi = c z^p + (\kappa - \omega) v_1$$

From equation 33 and the estimates in Table 2, we have $z^p=(8.4/1.4)=6.0$. The investment data for this study are in dollar terms, rather than units of investment. A sensible value for the c parameter, the instantaneous unit cost of investment, is therefore 1.0. This study has assumed the κ parameter for the cost of capital to be 0.10. From the paragraph above, we know the growth rate ω for the asset stock to be 0.055 for the study period. A plausible, though admittedly heroic, estimate for the π parameter is therefore 6.38.

Estimation of the Investment System

Finally, we must estimate the accumulation process and investment process as a system. We will treat $S(t)$ and $I(t)$ as endogenously determined, with exogenous variables $S(t-1)$, $I(t-1)$, $\ln(S(t-1))$, $\ln(I(t-1))$, the binary variables for years, and the binary variables for firms. To simplify estimation, we take logarithms of both sides of Equation 27. This tactic enables us to linearize Equation 27 into the following equation:

$$(27^*) \quad \ln(D_j(t)) = \ln(\chi) + \alpha \ln(I_j(t)) + \beta \ln(S_j(t-1)) + \mu \ln(M_j(t-1))$$

The two-equation system is estimated three different ways, with estimation results are reported in Table 4. First, only as a basis for comparison, Equations 27 and 28 are estimated

separately, with $I(t)$ and $S(t)$ treated as exogenous and with no parameter restrictions. These first results are reported at the left of Table 4. Equation 27 is estimated using weighted nonlinear least squares, to deal with the nonnormal distribution for $D(t) = S(t) - S(t-1)$. Second, equations 27 and 28 are estimated as a system using two-stage nonlinear least squares, but without parameter restrictions. These results are reported in the center of Table 4. Equation 27 is again weighted, but not Equation 28. Separate tests are performed for the key variable hypotheses that characterize the modified Uzawa-Penrose model. The Wald test statistic for each of these separate hypotheses is reported in brackets at the bottom center of Table 4, and has the Chi-square distribution.

The most important of the hypothesis tests generated by the modified Uzawa-Penrose model is the last one, labeled H6. This is a formal test of Equation 26 that generates the knife-edge of uniform growth across firms. If Equation 26 holds, then the accumulation process occurs precisely according to the modified Uzawa-Penrose specification in Equation 18. We are unable to reject this key hypothesis. The remaining hypotheses at the bottom of Table 4 test whether or not the coefficients in the investment process of Equation 28 are consistent with dynamic optimization of the accumulation process in Equation 27. The α parameter gives the degree of instantaneous diminishing returns for the investment flow. The cross-equation test H1 for the α parameter cannot be rejected. The β parameter gives the degree of complementarity between the stock and flow of investment in the accumulation process. The cross-equation test H2 for the β parameter also cannot be rejected.

The parameters of the investment process, θ and η , bear specific relationships to the parameters of the accumulation process, α , β , and χ . If corporate investments in strategic assets indeed dynamically optimize the exact accumulation process in Equation 27, then these

relationships are precisely as reported in Table 4 immediately underneath Equation 28. The cross-equation test H3 linking accumulation α in Equation 27 with θ in Equation 28 depends on the assumed value for the cost of capital κ . A value for the κ parameter of 10 percent gives us a completely plausible test in H3 that cannot be rejected. A value for the π parameter of 6.38 for gives us a more complicated test in H4 that also cannot be rejected.

The one cross-equation hypothesis test that is clearly and strongly rejected concerns the adjustment-cost-for-mergers parameter μ . We initially found this parameter to be zero, found in our initial estimation of the accumulation process reported in Table 2. Here, in our more sophisticated estimation of the accumulation process reported in Table 4, we again estimate μ to be insignificantly different from zero. Our estimate is even inappropriately positively signed in the two-stage least squares results. In contrast, the estimates we receive for μ in the investment process are all correctly signed and highly statistically significant. Clearly, it is vastly easier to find evidence for the adjustment costs of merged stocks of intangible assets by examining the optimal investment patterns of firms.

Reexamination of Figure 6 assures us that this finding on adjustment costs for mergers is not some statistical artifact. There were two mergers of significance among the integrated firms during the study time period: Bristol Myers acquisition of Squibb in 1998 and American Home Products of American Cyanamid in 1995. With both of these mergers, the newly integrated firm slashes R&D spending within 3 to 5 years after the merger. Figure 6 compares the actual R&D spending of the new Bristol-Myers Squibb with an imputed trend where BMS would have increased its R&D at a rate equal to the average rate for Abbott, Johnson & Johnson, Lilly, Merck, Pfizer, Schering Plough, and Warner Lambert—the other large firms in the industry. All of these seven firms continue steady growth for their R&D investments. Only BMS and AHP

cut back their R&D spending. This study posits that these cutbacks are rational and optimal reactions to a degraded stock of intangible assets.

Finally, at the right of Table 4, we estimate the system imposing at once all the Uzawa-Penrose restrictions, except H5 for the merger parameter μ . The t-statistics for each restriction are given in braces at the bottom right of Table 4. We are unable to reject any of these restrictions.

Conclusion

This study has formulated a model of perfect advantage for an industry, where some firms enjoy competitive advantage that can be sustained infinitely. This model draws directly on the work of Uzawa (1969) and Penrose (1959). The basis for advantage in this model lies neither in monopoly nor myopia, but rather in the mechanics of the investment process itself. The two central features of an investment process that sustains perfect advantage are: 1) instantaneous diminishing returns for investment, or time compression diseconomies, and 2) complementarity between the stock of strategic assets and instantaneous investment in them, or asset mass efficiencies. Not only must these two features be present in an industry to achieve perfect advantage, but also certain precise relationships must hold among the parameters associated with these features of the accumulation process. An empirical investigation of investment in the US pharmaceutical industry is unable to reject the assumption that these precise relationships do indeed hold there. We conclude that the modified Uzawa-Penrose model provides a useful description of the process by which rents are created and sustained in that industry.

Our analysis highlights the central role of complementarity between the asset stock and investment flow for intangible assets. Yet this complementarity is completely ignored in industrial economics, and given insufficient attention in strategic management. In industrial

economics, the fascination with “entry barriers” and “mobility barriers” derives directly from the implicit assumption in that scholarly field that all firms are equally efficient in the accumulation process for strategic assets. If we drop that assumption, then the failure of new firms to enter and of weaker established firms to rapidly grow ceases to be mysterious.

Even in strategic management, insufficient attention has been paid to stock-flow complementarity in the accumulation process. For example, the literature on hypercompetition stresses a more rapid depreciation rate for strategic assets as the key reason for the dethronement of industry leaders by upstart firms (D’Aveni, 1994). In terms of the models of this paper, the δ parameter is assumed to increase. Yet, this study suggests that the depreciation rate for strategic assets has very little relationship with sustained competitive advantage, while stock-flow complementarity is quite essential. It is far more likely that the disruptive innovation and other shifts behind hypercompetition act primarily to reduce or eliminate this complementarity in the accumulation process. In terms of the models of this paper, the β parameter appears to decrease. Indeed, the work of Christensen (1997) suggests that the accumulated stock of strategic assets may actually reduce rather than enhance the efficiency of investment flow for established industry leaders under some conditions. In these conditions, the asset stock serves as a strategic substitute for investment in new strategic assets (rendering the β parameter negative).

Most firms accumulate multiple types of strategic assets, at different points along the value chain and in different industries. The analysis of this study suggests that the extent to which these assets are strategic complements or strategic substitutes in the accumulation process is a vital determinant of sustainable competitive advantage. In the US soft drink industry, the century-old distribution assets of Coca-Cola and Pepsico proved complementary to the new product-innovation assets necessary for success after 1980. Coca-Cola and Pepsico have thus

been able to sustain and even widen their competitive advantage over other soft-drink firms, despite profound changes in their industry. In contrast, in the computer manufacturing industry, established intangible assets proved to be strategic substitutes for new intangible assets, and leadership in the industry passed from IBM in mainframes, to DEC in minicomputers, to Dell in microcomputers. The work of Christensen (1997) provocatively suggests that organizational politics and cognition play a very large role in determining the actual complementarities between the stock of established strategic assets and the efficiency in accumulation flow of new assets.

These observations highlight the importance of empirical work on the accumulation process for intangible assets and the differing efficiencies of firms in that process. This accumulation process plays a fundamental role in shaping the structure of industries and the performance of firms in them. It is quite remarkable how little we understand of so important and central a process.

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Table 1: Means, Standard Deviations, and Correlations for Study Variables, 587 Observations

	Mean	S.D.	Correlations			
			D(t)	S(t)	I(t)	V(t)
Discoveries of New Drugs D(t) [D(t) = S(t) – S(t-1)]	.48	.73	1.00			
Asset Stock S(t) [Cumulative Discoveries]	14.5	12.0	.43	1.00		
Investment Flow I(t) [Annual R&D Expense]	81.7	83.2	.24	.80	1.00	
Market Value of Firm V(t)	3,754	5,971	.24	.65	.84	1.00

Table 2: Estimation of Accumulation Process, Equation 30

$$(30) \quad D_j(t) = \chi [I_j(t)]^\alpha \left(\sum_{u=1962}^{t-1} D_j(u) \exp[\delta(u-t)] \right)^\beta M^\mu - \delta \left(\sum_{u=1962}^{t-1} D_j(u) \exp[\delta(u-t)] \right)$$

Parameter	χ	α	β	δ	μ	Chi-Square	Pseudo-R-Square
Estimate & Standard Deviation	-3.38 (.34)	.29 (.11)	.83 (.11)	-.03 (.04)	-.31 (.33)	195.9	.32

Standard errors of estimates given in parentheses.

Estimation is by maximum quasi-likelihood, single equation.

Binary variables for year and firm are included in estimation and are each jointly significant.

Table 3: Estimation of Market Value, Equations 31 and 32

$$(31) \quad V(t) = v_0 + v_1[S(t)]^\rho \quad \text{and} \quad (32) \quad V(t) = v_2 + v_3[I(t)]^\varphi$$

Parameter	v_0	v_1	ρ	v_2	v_3	φ	F-Statistic	R-Square
Equation 31: Estimate & Standard Deviation	12,329 (726)	8.4 (.45)	1.76 (.25)				65.5	.79
Equation 32: Estimate & Standard Deviation				6,843 (756)	1.4 (.05)	1.57 (.12)	95.8	.86

Standard errors of estimates given in parentheses.

Estimation is by nonlinear least squares, single equation.

Binary variables for year and firm are included and each jointly significant.

Table 4: Estimation of Accumulation/Investment System, Equations 27 and 28

$$(27) \quad S_j(t) - S(t-1) = \chi [I_j(t)]^\alpha [S_j(t-1)]^\beta [M_j(t-1)]^\mu$$

$$(28) \quad I_j(t) - I(t-1) = \theta I_j(t-1) - \eta [I_j(t-1)]^{(\alpha+1-\varphi)} [S_j(t)]^{(\beta+\rho-1)} [M_j(t)]^{(\mu+\rho-1)}$$

where $\theta = \left(\frac{\kappa}{\varphi - \alpha} \right) > 0$ and $\eta = \left(\frac{\alpha \pi \rho \chi}{c \varphi (\varphi - \alpha)} \right) > 0$ and $\kappa=.10, \delta=0, \rho=1.76, \varphi=1.57, \pi=6.4$

estimation method	single equation nonlinear least squares	single equation nonlinear least squares	two stage nonlinear least squares with tests (listed at bottom left of table)		two stage nonlinear least squares with restrictions (listed at bottom left of table)	
	change in asset stock S(t)	change in investment I(t)	change in asset stock S(t)	change in investment I(t)	change in asset stock S(t)	change in investment I(t)
α for Equation 27 ($\alpha+1-\varphi$) for 28	.31 (.10)	-.23 (.58)	.18 (.08)	.22 (.14)	.48 (.07)	
β for Equation 27 ($\beta+\rho-1$) for 28	.84 (.12)	.88 (.26)	.80 (.18)	.72 (.23)	.45 (.06)	
$\log(\chi)$	-3.56 (.36)		-2.90 (.35)		-3.25 (.43)	
η		-.35 (.16)		-.10 (.06)		
θ		.10 (.01)		.10 (.01)		
μ	-.30 (.29)	-1.26 (.19)	.23 (.27)	-1.12 (.18)	.26 (.30)	-1.08 (.17)
R-squared statistic	.38	.72	.25	.65		
H1: α for Equation 27 = ($\alpha+1-\varphi$) + .57 for Equation 28			[0.18]		{0.49}	
H2: β for Equation 27 = ($\beta+\rho-1$) - .76 for Equation 28			[1.25]		{1.46}	
H3: θ for Equation 28 = .12 / (1.57- α) for Equation 27			[0.63]		{-0.18}	
H4: η for Equation 28 = $\alpha(6.4)(1.76)\chi/(1.57)(1.57-\alpha)$ for 27			[0.99]		{-0.25}	
H5: μ for Equation 27 = ($\mu+\rho-1$) - .76 for Equation 28			[15.93]		restriction not imposed	
H6: $1.76\alpha + 1.57\beta = 1.57$ for Equation 27			[0.10]		{0.22}	

Number of observations is 587. Standard errors in parentheses. Binary variables for year and firm included and jointly significant. Wald tests reported in brackets immediately above. T-statistics for restrictions reported in braces immediately above.

Figure 1: Growth of Corporate R&D Expenditures over Sample Period for Three Selected US Pharmaceutical Firms

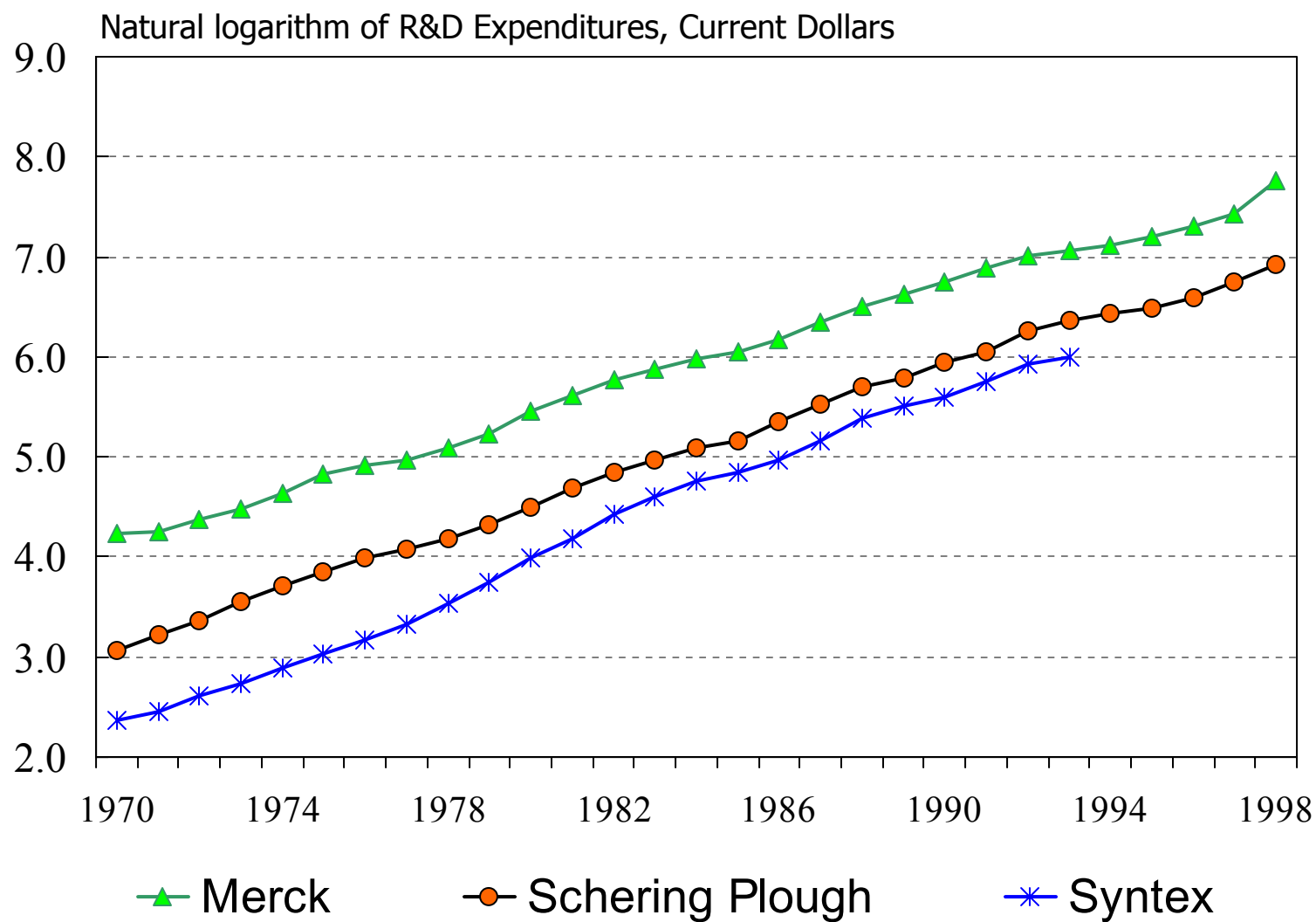


Figure 2: Phase Diagram for Neoclassical Growth Model with Adjustment Costs for Investment and Diminishing Returns for Assets

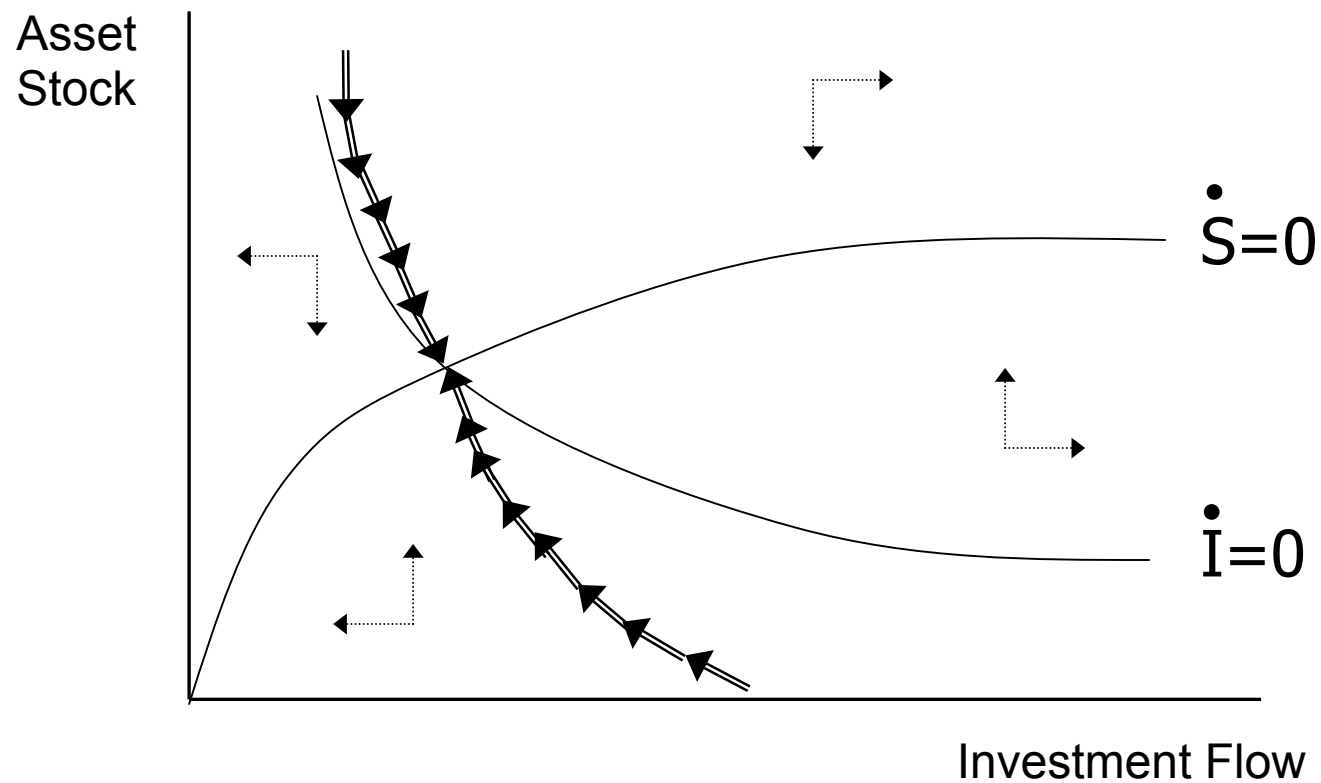


Figure 3: Derivation of $\dot{I}=0$ Arm for Phase Diagram for Strategic Accumulation Model, with α Small and β Large

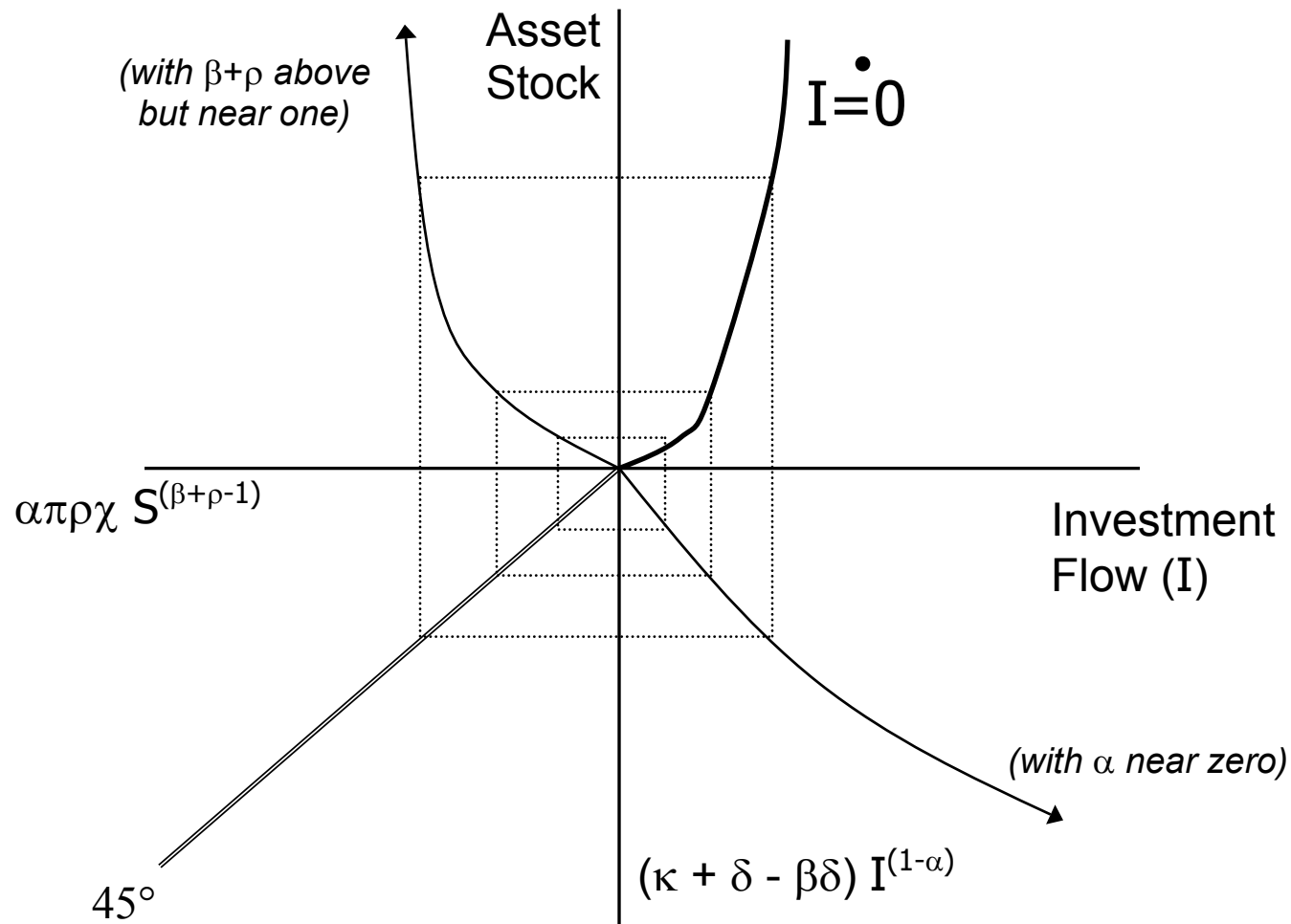


Figure 4: Phase Diagram for Strategic Accumulation Model with Adjustment Costs for Investment, Asset-Investment Interaction, and Diminishing Returns for Assets (with $1-\alpha > \beta + \rho - 1 > 0$ and $1 > * > 0$)

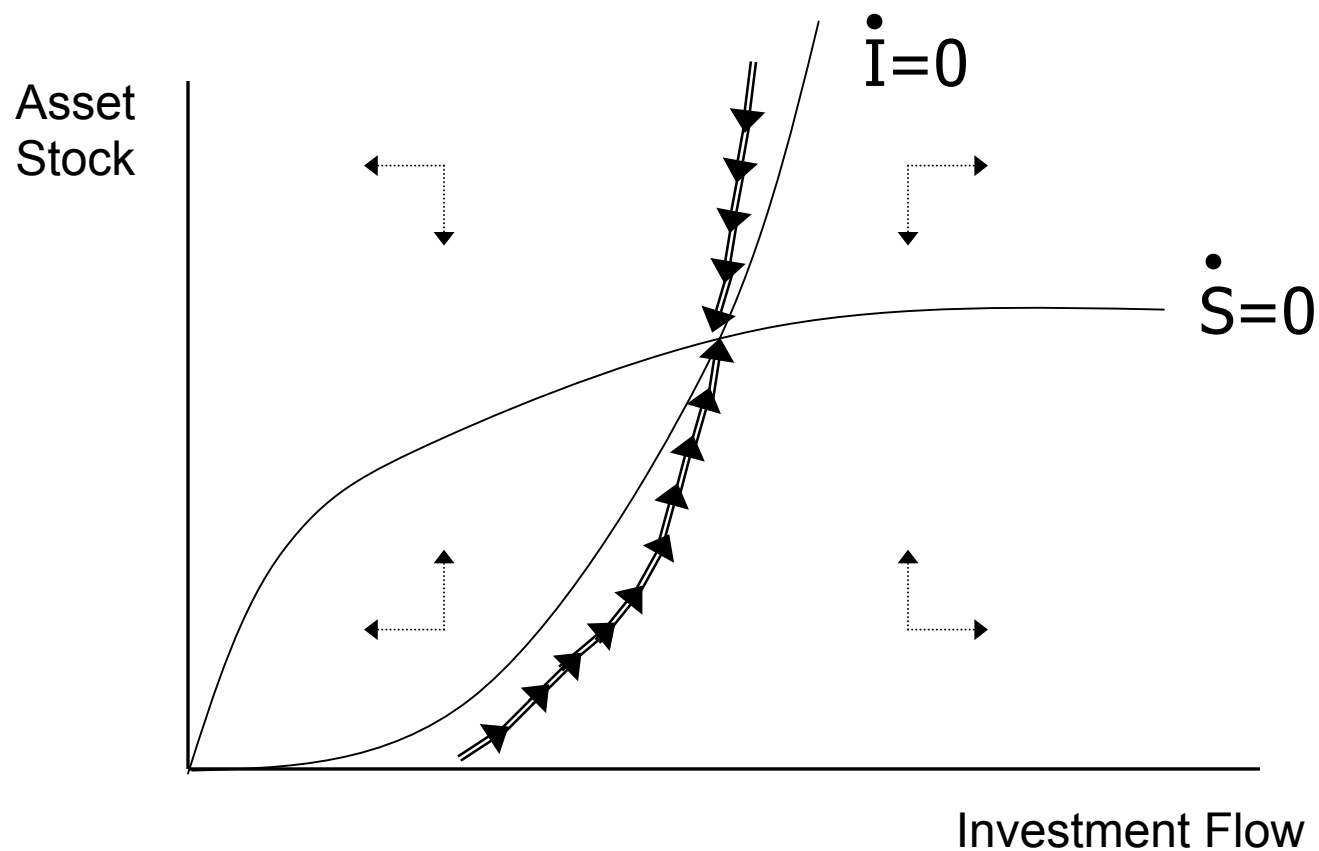


Figure 5: Phase Diagram for Strategic Accumulation Model with Adjustment Costs for Investment, Asset-Investment Interaction, and Diminishing Returns for Assets (with $\beta + \rho - 1 > 1 - \alpha > 0$ and $1 > * > 0$)

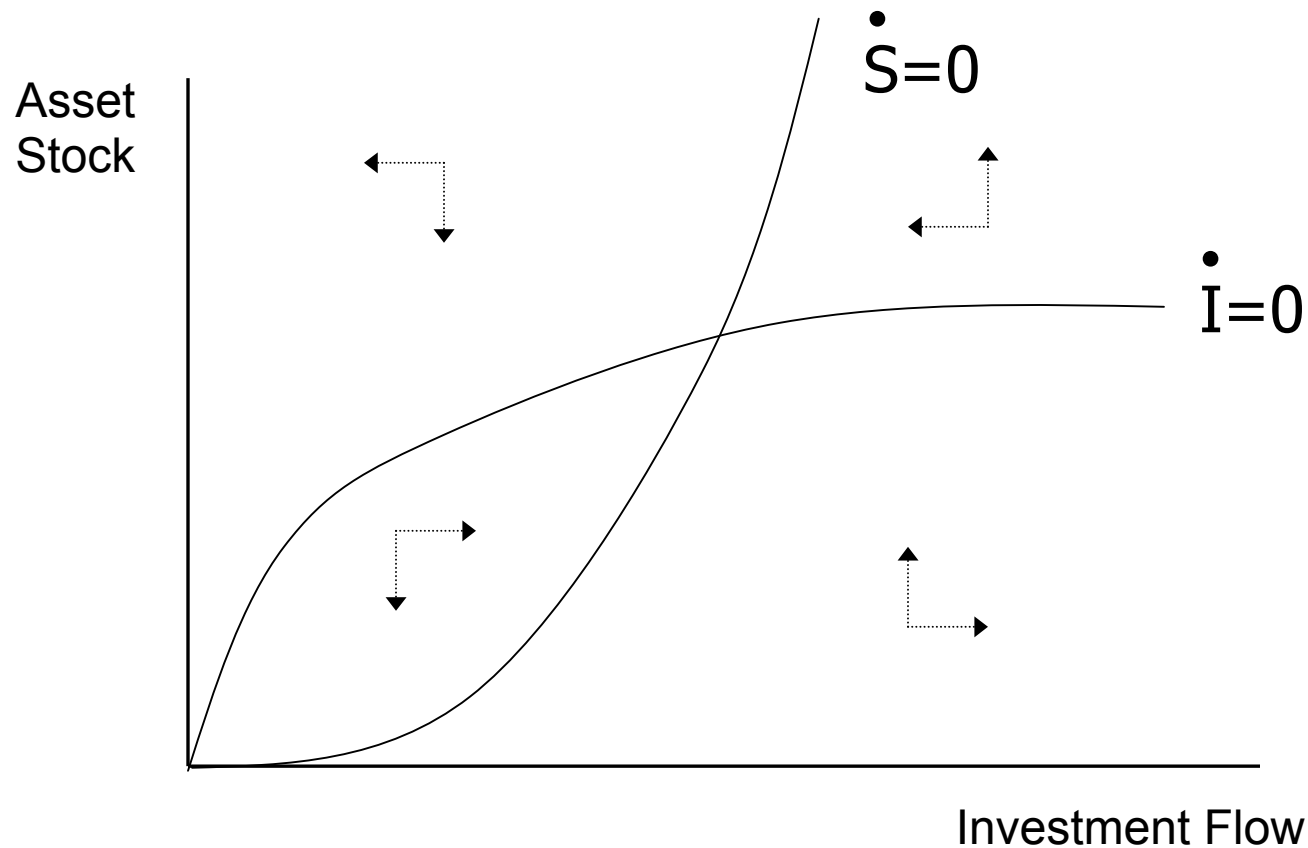


Figure 6: Investment Flow for Strategic Assets Before and After Merger: The Case of Bristol-Myers and Squibb

