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Equilibrium R&D and the Patent–R&D Ratio: U.S. Evidence

By SAMUEL KORTUM*

The patent–R&D ratio in the United States has declined steadily over the past three decades. Figure 1 shows that in the late 1950's one million 1982-dollars of company-funded research produced over three patents. By the late 1980's, however, the same R&D funds produced about one patent. Three distinct explanations for the decline in the patent–R&D ratio have been advanced: (i) Robert Evenson (1984, 1991) has argued that exhaustion of technological opportunities has reduced the productivity of the research sector; (ii) I have suggested (Kortum, 1992) that expansion of markets has raised the value of patents and that competition in the research sector has resulted in greater R&D expenditures per patent; and (iii) Zvi Griliches (1989, 1990) points to the rising costs of dealing with the patent system, which has led researchers to patent fewer of their inventions. Although other hypotheses may need to be considered, the ubiquitous decline in the patent–R&D ratio (across industries and countries), suggests a simple general explanation such as one (or a combination) of those listed above.

To evaluate the sources of decline in the patent–R&D ratio, I construct an equilibrium model of industry growth. The industry includes a research sector whose input is R&D and whose output is inventions which are used in the production of the industry's final good. To examine explanation (i) I allow for a decline in the productivity of the industry's research sector. I find that the endogeneity of R&D weakens the link from declining opportunities to a declining invention–R&D ratio. The reason is that exhaustion of technological opportunities will generally cause both research input and inventive output to fall, with an ambiguous effect on their ratio. To examine explanation (ii) I allow for growth in the industry's market. I find that demand growth will raise the value of an invention and, with decreasing returns to research at the industry level, will lead to increased research expenditures per invention.[1]

The theoretical model predicts that an industry will converge to a steady state in which the invention–R&D ratio continually falls if there is sufficient growth in demand. Data from 20 U.S. manufacturing industries show that the patent–R&D ratio has, in fact, been falling rapidly in all industries. Yet the growth of shipments, which in the model is related to the growth of demand, is not rapid enough to explain a substantial fraction of the decline in the patent–R&D ratio. The data also reject two other conditions for a steady state in the model industry: R&D intensity (R&D as a fraction of industry shipments) has generally risen while the growth of patent stocks has declined. I explore the industry dynamics predicted by the model in an attempt to explain these

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*Department of Economics, Boston University, 270 Bay State Road, Boston, MA 02215. I have benefited from comments by James Adams, Jonathan Eaton, Zvi Griliches, Adam Jaffe, Boyan Jovanovic, and participants at the NBER productivity lunch. I owe special thanks to Robert Evenson and Ariel Pakes.

[1] Using estimates of the value of patent rights derived from patent renewal data, Ariel Pakes and Mark Schankerman (1986) find that a rise in value has largely offset the fall in patents per scientist and engineer in the United Kingdom and Germany (less so in France). This evidence is consistent with rising invention value due to expanding markets, though it is also consistent with a falling propensity to patent less valuable inventions.

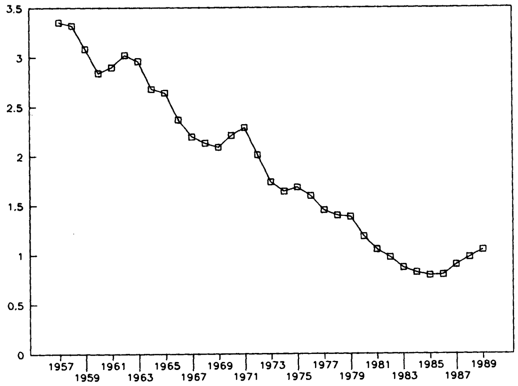

FIGURE 1. PATENTS PER $1 MILLION R&D

TABLE 1—GROWTH OF RESEARCH INPUTS AND OUTPUTS IN THE UNITED STATES

Measure	1957–1973	1973–1989	1957–1989
Successful U.S. priority patent applications	1.0	1.5	1.3
Successful total patent applications	2.5	2.8	2.7
Company-funded R&D (constant-dollar)	5.1	4.7	4.9
Total R&D (constant-dollar)	3.0	3.9	3.5
Total R&D (S&E)	2.6	4.4	3.5

Notes: Growth rates are mean log differences.
Sources: Research inputs are from the National Science Foundation's *Research and Development in Industry*. Successful patent applications are from Kortum (1992), updated using data from the Technology Assessment and Forecast Program of the Patent Office.

other features of the industry data. Having only mixed success with the technological opportunity and demand explanations, I conclude by exploring the merits of a declining propensity to patent [explanation (iii)] as an alternative means of accounting for the decline in the patent–R&D ratio.

I. A Closer Look At the Facts

Figure 1 shows the ratio of successful (eventually granted) U.S. priority (domestic) patents by date of application to deflated company-funded R&D.[2] The choice of data was motivated by the following considerations: (i) R&D measures research activity in the United States, and hence it is appropriate to exclude foreign patents in measuring the output of that R&D; (ii) government-funded R&D is believed to generate few patentable inventions and should therefore be excluded from the measure of research input. Nonetheless, alternative measures of research input and output can be justified. Foreign-origin patents can be included in order to test whether they have crowded out domestic patents either because of research competition or because of the limited resources of the patent office (Griliches, 1989). Endogenous-growth theories suggest measuring research input as the number of R&D scientists and engineers (S&E). Since the S&E data include researchers funded by the government, I use total (company and government funded) R&D expenditures for comparisons.

Table 1 shows that the number of total (U.S. and foreign-origin) patents has grown 1.4-percent faster per year than the number of U.S. priority patents, reflecting the rapid growth of foreign patenting in the United States.[3] The table also shows that the number of S&E's has grown more slowly than has company funded R&D, particularly in the 1960's. This phenomenon is primarily a

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[2] U.S. priority means that the invention is first patented in the United States; this definition excludes most patents issued in the United States to foreign inventors. Details of constructing the patent data by year of application during 1957–1983 are described in Kortum (1992). I am grateful to the Technology Assessment and Forecast Program at the Patent Office for providing data on U.S. origin patents by date of application, which I used to extend the series through 1989 (scaled up by 8 percent to correct for the distinction between U.S. priority and U.S. origin and by an additional 16 percent in 1989, 6 percent in 1988 and 3 percent in 1987 to account for applications yet to be granted by June 1992).

[3] The number of total patent applications (including unsuccessful applications), a measure advocated by Griliches (1989), grew somewhat more slowly than successful applications, making the decline in the patent–R&D ratio even larger.

result of the declining share of government funding in total R&D. Since total R&D and S&E's have grown at similar rates, there is no evidence that the patent–R&D ratio has been driven down by rising real wages of researchers.

Including foreign patenting, which is justified under the extreme assumption that each U.S. patent issued to a foreign inventor crowds out a domestic U.S. patent, leads to a 40-percent reduction in the decline of the patent–R&D ratio. On the other hand, no combination of the alternative measures in Table 1 can reverse the result that the patent–R&D ratio has in fact fallen.

II. The Patent–R&D Ratio in a Model of Industry Growth

In this section, I assume that the decline in the patent–R&D ratio reflects a decline in the invention–R&D ratio. I begin by ignoring explanation (iii) from the Introduction and instead assume a constant propensity to patent. To illustrate the factors that may contribute to a secular decline in the invention–R&D ratio, I develop a dynamic model of an industry with a research sector.[4] Using industry data on patents, R&D, and shipments, I check whether the factors that cause the invention–R&D ratio to decline in the theoretical model are likely to have been operative in the U.S. manufacturing sector over the last 30 years.

A. *The Invention Production Function*

The invention production function, transforming research input into inventive output, is an important ingredient of the industry growth model. In the general-equilibrium models of endogenous technological change of Paul Romer (1990) and Gene Grossman and Elhanan Helpman (1991), the invention production function takes the form, $\dot{N} = f(N)(\text{S\&E})$, where N is the stock of inventions and the assumption that $f' \geq 0$ represents possible spillovers from accumulated knowledge. The current endogenous-growth models cannot explain falling inventive output per researcher, since the spillover function, $f(N)$, is nondecreasing over time.

A large empirical literature on patents and R&D at the firm and industry levels, including Pakes and Griliches (1984), Hall et al. (1988) and Kortum (1992), motivates the following alternative specification for the invention production function:

$$\dot{N}(t) = B_0 e^{\tau t} R(t)^{\alpha} \quad (1)$$

where R is R&D, $B_0 e^{\tau t}$ is the level of technological opportunities and $0 \leq \alpha < 1$ is a parameter. Point estimates of α lie between 0.1 and 0.6, supporting the assumption of decreasing returns due to duplicative research. The parameter τ represents a possible drift in technological opportunities ($\tau < 0$ represents the force of exhaustion).[5] In this specification, the invention–R&D ratio falls if opportunities fall holding R&D fixed or if R&D rises holding opportunities fixed.

B. *The Productivity Equation*

A second ingredient in the industry-growth model is a model of how inventions are used. The empirical literature is not helpful on this issue, because that literature focuses on a direct link from R&D to productivity. The endogenous-growth literature provides two models: in the variety model (Romer, 1990), inventions enlarge the set of intermediate inputs, while in the quality-ladder model (Grossman and Helpman, 1991 Ch. 4), inventions improve the quality of a fixed set of inputs. The mathematical formulation of these models implies that productivity growth is proportional to the growth of the stock of inventions in the

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[4] A more general stochastic discrete-time version of the model is analyzed and estimated in Kortum (1993).

[5] The growth in James Adams' (1990) stocks of academic science might be a measure of τ, but note that trends in the real wage of S&E's will also be reflected in τ.

variety model and proportional to the flow of inventions in the quality-ladder model.

The quality-ladder model is of particular interest because it predicts steady-state growth with a falling invention–R&D ratio. Since productivity growth is proportional to the flow of inventions, it is proportional to the number of S&E's if there are no knowledge spillovers in the earlier invention production function. In steady state, with the number of S&E's constant, the real wage of S&E's grows in proportion to productivity growth, pushing down the invention–R&D ratio. Though not a sufficient explanation, since the patent–S&E ratio has fallen along with the patent–R&D ratio, the quality-ladder model captures an idea that carries over to the industry model: the invention–R&D ratio is driven down by a rising value of inventions, which leads the research sector, in equilibrium, to spend more per invention. The value of inventions rises in the quality-ladder model because the output value of a percentage productivity gain rises as the economy grows.

To discriminate empirically between the variety and quality-ladder models, I estimated the patent–productivity relationship with panel data for U.S. manufacturing industries.[6] I assume that the growth of the stock of inventions is not correlated with exogenous productivity growth, and I use ordinary least squares (OLS) to estimate the variety specification, $\dot{A}/A = a_0 + \sigma\dot{N}/N$, where $\dot{A}/A$ is productivity growth (note that variation across industries in the propensity to patent drops out of this equation). The OLS slope estimate from the pooled regression is $\hat{\sigma} = 0.91$ with a standard error of 0.44. While the growth of the patent stock accounts for mean productivity growth, it does not capture much of the variation in productivity growth ($R^2 = 0.02$). Though the evidence for the variety specification could be stronger, the data lend even less support to the quality-ladder specification.[7]

C. *Industry Equilibrium Growth*

I now incorporate the empirically based invention production function and the variety model of invention use into an equilibrium model of industry growth. The industry aggregate production function is, $Y(t) = [\int_0^{N(t)} K(j,t)^{\rho}\, dj]^{1/\rho}$, where $1 < 1/(1-\rho) < \infty$ is the elasticity of substitution between intermediate inputs (indexed by j). A research firm with an invention has a monopoly on the supply of a specialized input which it can produce at a cost of unity. It maximizes profits by selling the input, at a price of ρ^{-1}, to firms in the competitive production sector. In equilibrium, $K(j,t) = K(t)/N(t)$ where $K(t)$ is aggregate industry input, $Y(t) = N(t)^{(1-\rho)/\rho}K(t)$, and industry revenue (which is equal to the production sectors' total cost) is $S(t) = K(t)/\rho$. This implies that a research firm obtains a flow of profits

$$\pi(t) = \gamma S(t)/N(t) \tag{2}$$

where $\gamma = 1 - \rho$ is the research sector's share of industry revenue.

The industry faces a constant-elasticity demand curve, $Y(t) = D_0 e^{\theta t} p(t)^{-\beta}$, where D_0 is the initial state of demand and θ is the rate of demand growth. The reduced-form equation for industry revenue is

$$S(t) = \rho^{\beta-1} D_0 e^{\theta t} N(t)^{\phi} \tag{3}$$

where $\phi = (\beta - 1)(1 - \rho)/\rho$.

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[6] The Yale-Canada concordance assigns patents to 20 U.S. industries of use (see Table 2 for the list of industries). I exclude foreign patenting to be consistent with the R&D data even though foreign patents undoubtedly have some impact on U.S. productivity. I then create stocks of patents using patent data extending back to 1919 and a zero depreciation rate. Total factor productivity growth is taken from Wayne Gray's Annual Survey of Manufacturing data, (Gray, 1987) and aggregated using Evsey Domar's (1961) methodology, as suggested to me by Ernie Berndt.

[7] The relative constancy, since the 1920's, of the rate patenting would seem to favor the quality-ladder specification. However, regressing productivity growth on the rate of patenting did not yield a significant positive relationship, even when the slope coefficient was allowed to vary by industry so as to capture differences in the propensity to patent.

A research firm expects to get the average product of the research sector where the sector's production function is equation (1). If industry R&D is $R(t)$ and a research firm invests at the rate x for an interval of time dt, it expects to get $B_0 e^{\tau t} R(t)^{\alpha-1} x\,dt$ new inventions. I assume $\alpha < \min(1, \phi^{-1})$ to insure an industry equilibrium. The value of an invention is, $V(t) = \int_t^\infty e^{-r(s-t)} \pi(s)\,ds$, where r is the riskless real rate of interest. Differentiating the invention valuation equation, one obtains

$$(4) \qquad \pi(t) + \dot{V}(t) = rV(t).$$

In equilibrium, industry R&D must satisfy

$$(5) \qquad V(t) B_0 e^{\tau t} R(t)^{\alpha-1} = 1.$$

Equations (5) and (1) imply that the value of an invention is inversely related to the invention–R&D ratio, $V(t)\dot{N}(t)/R(t) = 1$. The intuition is that with free entry into research, more valuable inventions bring forth more R&D until the expected research expenditure per new invention is equal to its value. Thus, the rate of decline of the invention–R&D ratio is equal to $\dot{V}/V$.

To analyze industry growth, define two state variables, $x = R/(VN)$ and $y = S/(VN)$. From equations (1) and (5), $\dot{N}/N = x$. From equations (4) and (2), $\dot{V}/V = r - \gamma y$. From equation (3), $\dot{S}/S = \theta + \phi x$, and from equation (5), $\dot{R}/R = (r + \tau)/(1 - \alpha) - \gamma y/(1 - \alpha)$. These results imply the following simultaneous differential equation system in x and y:

$$(6) \qquad \dot{x}/x = (\alpha r + \tau)/(1 - \alpha) - x - \alpha\gamma y/(1 - \alpha)$$

$$(7) \qquad \dot{y}/y = \theta - r - (1 - \phi)x + \gamma y$$

The phase diagram for this differential equation system is shown in Figure 2. In case 1, $\phi > 1$ and the $\dot{y} = 0$ locus is downward-sloping, while in case 2, $\phi < 1$ and the $\dot{y} = 0$ locus has a positive slope. The intercept of the $\dot{x} = 0$ locus is greater than the intercept of the $\dot{y} = 0$ locus (as shown in the figure) as long as there is enough growth in demand or technological opportunities to keep the research sector viable. In particular, this requires $(\alpha\theta + \tau)/(1 - \alpha\phi) > 0$.

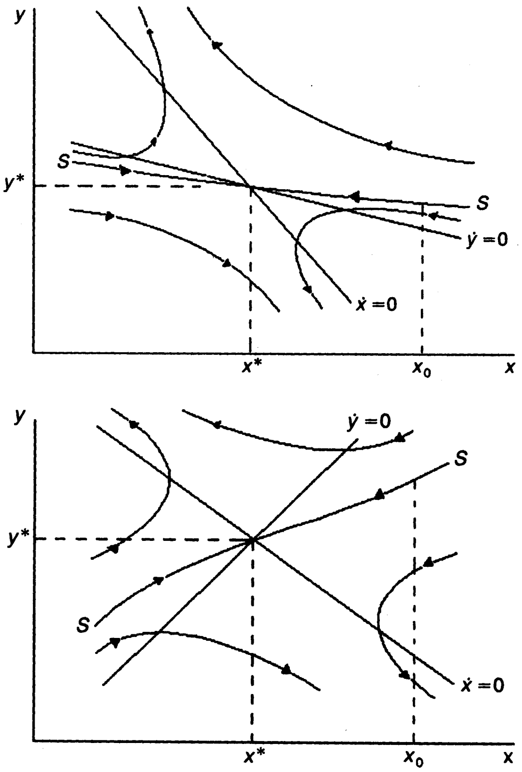

FIGURE 2. PHASE DIAGRAM FOR EQUATIONS (6) AND (7)

Notes: In case 1, $\phi > 1$ and the $\dot{y} = 0$ locus is downward-sloping; in case 2, $\phi < 1$ and the $\dot{y} = 0$ locus has a positive slope.

D. *Industry Steady State*

The phase diagrams in Figure 2 show that there is a unique saddle path, SS, along which the industry converges to a steady state, (x^*, y^*), such that $\dot{x} = \dot{y} = 0$. In the steady state, R&D grows at a constant rate, R&D intensity is constant and the stock of inventions grows at a constant rate.[8] The

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[8] An additional restriction on the growth of demand and technological opportunities is required in order to guarantee that, at a point in time, inventions have finite value: $[(1 - \alpha)\theta + (\phi - 1)\tau]/(1 - \alpha\phi) < r$. This condition is equivalent to $\dot{V}/V < r$ in the industry steady state.

value of an invention also grows at a constant rate given by

$$(8)\qquad \frac{\dot{V}}{V}=\frac{[(1-\alpha)\theta+(\phi-1)\tau]}{(1-\alpha\phi)}.$$

Holding technological opportunities constant, $\tau=0$, an industry with growing demand, $\theta>0$, will have a falling invention–R&D ratio. Inventions become more valuable as the market grows and researchers are therefore willing to expend ever greater resources per invention. Now, hold demand growth fixed and focus on the effect of declining technological opportunities, $\tau<0$. If $\phi<1$, the decline in technological opportunities contributes to the decline in the invention–R&D ratio, but not directly as suggested by the exhaustion hypothesis. Researchers spend more per invention because they correctly perceive that declining technological opportunities contribute to slower growth in the invention stock and therefore higher value per invention (when $\phi<1$, the flow of profit per invention, π, is declining in the invention stock). In the case of $\phi>1$, slower growth in the invention stock indicates lower profits per invention; in this case declining technological opportunities reduce the rate at which the invention–R&D ratio falls (possibly causing the ratio to increase). Using industry data, Kortum (1992) estimates the parameter ϕ to be slightly above unity, suggesting that falling technological opportunities are unlikely to contribute to the decline in the invention–R&D ratio.

TABLE 2—GROWTH RATES BY INDUSTRY

Industry	$\dot{N}/N$	$\dot{R}/R$	$\dot{S}/S$	$\dot{V}/V$
Food and kindred	1.4	4.7	1.3	5.8
Textiles and apparel	1.1	2.8	0.4	4.9
Lumber and furniture	0.9	6.3	1.8	8.1
Paper products	1.4	5.4	2.3	6.9
Industrial chemicals	3.0	2.4	3.3	2.4
Drugs	4.5	7.3	3.8	4.9
Other chemicals	2.7	4.4	2.8	4.3
Petroleum	1.7	3.8	5.5	3.2
Rubber products	2.1	4.6	3.5	4.5
Stone, clay, glass	1.5	3.4	1.1	3.6
Primary metals	1.6	2.1	0.3	2.6
Fabricated metals	1.2	2.6	2.0	3.4
Office and computing	2.5	10.0	6.8	8.3
Other nonelectric	1.2	2.9	2.4	4.3
Communication	2.7	7.4	5.2	6.7
Other electrical	1.6	1.8	1.7	2.1
Transportation	0.8	3.5	2.0	4.8
Aircraft	1.4	5.3	1.0	7.7
Instruments	2.1	7.9	4.0	7.7
Other manufacturing	1.0	6.2	1.5	6.4

Notes: Growth rates are mean log differences of data from 1958–1959 to 1982–1983. N is the patent stock (zero rate of depreciation); R and S are company-funded R&D and shipments, respectively (both in 1982 dollars); $\dot{V}/V$ is the rate of decline in the patent–R&D ratio.

Source: Data construction is described in Kortum (1992).

The decline of the invention–R&D ratio in the industry steady state formalizes explanation (ii) from the Introduction. In particular, by raising the value of an invention, demand growth could have contributed to the observed decline in the patent–R&D ratio. I pursue this explanation by checking it against data from 20 U.S. manufacturing industries. Table 2 shows the average growth of the patent stock, R&D, and shipments, as well as the rate of decline in the patent–R&D ratio (labeled $\dot{V}/V$). In all industries, the patent–R&D ratio has fallen dramatically while shipments have grown. Yet, a realistic value of $\phi=1$ implies, from equation (8) and (3), that $\dot{V}/V=\dot{S}/S-\dot{N}/N$. According to the data in Table 2, shipments growth is generally not much greater than the growth of patent stocks and is sometimes even smaller. Shipments growth is clearly not rapid enough to explain a substantial fraction of the dramatic fall in patent–R&D ratios. If $\phi=0$ (unit elastic industry demand), then $\dot{V}/V=(1-\alpha)\dot{S}/S-\tau$, once again demonstrating that the relatively weak growth in shipments cannot account for the rapid declines in patent–R&D ratios (though, in this case, the decline in technological opportunities could play a role).

A rigorous empirical treatment of the steady-state decline in the patent–R&D ratio is complicated by the fact that the data deviate significantly from what would be expected if industries were in steady state. If each industry were in steady state, then constant R&D intensity would imply $\dot{R}/R=\dot{S}/S$, and constant growth of the invention stock would imply $\dot{R}/R - \dot{V}/V = \dot{N}/N$. In fact, R&D intensity has risen in all industries except industrial chemicals and petroleum. Furthermore, the growth rate of the patent stock declined in every industry (the stock of patents has grown faster than the flow of patents). I turn to the dynamics of the industry out of steady state in an attempt to explain these phenomena.

E. *Industry Dynamics*

Returning to Figure 2, remember that the curve SS in each phase diagram is the unique saddle path. An initial condition (at $t = 0$ for simplicity) on the phase diagram is determined by the initial stock of inventions in the industry, N_0, and the initial state of demand, D_0. The initial conditions determine S_0; then R_0 and V_0 must satisfy the entry condition (5). This implies that an initial condition on the phase diagram, (x_0, y_0), is at the intersection of the saddle path and the curve

$$y_0 = \rho^{\beta-1} D_0 B_0^{1/\alpha} N_0^{-(1-\alpha\phi)/\alpha} x_0^{-(1-\alpha)/\alpha}.$$

An industry with a small enough stock of inventions or high enough initial state of demand or technological opportunities will begin with $x_0 > x^*$, as shown in Figure 2. Such an industry is young in the sense that it has yet to build up a stock of inventions which is commensurate with its state of demand and state of technological opportunities. In seeking to explain a phenomenon that is common to all industries, there is some basis for assuming that all industries are young and still adjusting to the unprecedented marketing and research opportunities of the post-World War II era. I track the evolution of one such industry as it follows the saddle path toward the steady state (x^*, y^*). Since x_0 is above the steady state, x will fall toward x^* implying, as is actually observed in all industries, a fall in the growth of the invention stock over time.

Tracking the behavior of R&D intensity (which is the ratio of x to y in the phase diagram) requires considering various values of the parameter ϕ. If $\phi \geq 1$ (case 1 in Fig. 2), then x/y declines as the industry converges toward the steady state from x_0; hence R&D intensity declines. Now consider case 2 of Figure 2 where $\phi < 1$. Denoting R&D intensity by $z = x/y$, the rate of change in R&D intensity is, $\dot{z}/z = (r + \tau)/(1-\alpha) - \theta - \phi x - \gamma y/(1-\alpha)$. The $\dot{z} = 0$ locus is linear, passes through the steady state, (x^*, y^*), and has an intercept of $[r + \tau - (1-\alpha)\theta]/\gamma$. Points above this locus on the phase diagram correspond to states of falling R&D intensity, and points below correspond to states of rising R&D intensity. If the intercept of the $\dot{z} = 0$ locus is positive, then the saddle path must lie above that locus for $x > x^*$. In these cases, a sufficient condition for which is that $\phi \geq 0$, R&D intensity will decline as the industry converges to the steady state from the right. If industry demand is inelastic, $\phi < 0$, there is a possibility that, with large enough demand growth or a large enough rate of decline in technological opportunities, $r < (1-\alpha)\theta - \tau$. In this case, unlike the cases treated above, R&D intensity will increase as the industry converges from an initial position of $x_0 > x^*$.

The dynamics of the industry model, in most cases, predicts falling R&D intensity in periods of declining growth of the invention stock. In 18 of 20 industries, R&D intensity rose while the growth of the invention stock fell. This suggests three options: (a) rejecting the model; (b) looking more carefully at the one case (with inelastic industry demand) in which R&D intensity is predicted to rise; or (c) entertaining Griliches's hypothesis that the propensity to patent has fallen, which suggests that the decline in the growth of patent stocks may be misrepresenting the growth of stocks of inventions. I now briefly turn to the third option.

III. Conclusion

I have attempted to evaluate, both theoretically and empirically, two of the three explanations for the decline in the patent–R&D ratio. The first was that technological opportunities have fallen, and the second was that the economic value of inventions has risen due to growth in the size of markets. I demonstrated that growth in the size of markets provides a logical explanation for the decline in the patent–R&D ratio in the context of an equilibrium model of industry growth. Yet, industry data suggest that the demand story is not capable of explaining a large fraction of the decline in the patent–R&D ratio. The data also show that the decline in the patent–R&D ratio in every industry has been accompanied by a decline in the growth of patent stocks in every industry.

The third explanation for the decline in the patent–R&D ratio is that the propensity to patent has fallen. While there are several factors, such as rising costs of dealing with the patent system, that may have contributed to a decline in the propensity to patent, there is not strong direct evidence for this hypothesis. In fact, Edwin Mansfield (1986) finds that most firms report an increase from 1965–1969 to 1980–1992 in the percentage of inventions that they patented. Nonetheless, a fall in the propensity to patent could simultaneously explain the decline in the patent–R&D ratio and the decline in the growth of the patent stock. Econometric estimates of the model (Kortum, 1993) favor this explanation, since it accounts for the strength of R&D intensity.

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