Is R&D Getting Harder or Are Firms Getting Worse at R&D

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Romer's theory linking R&D to economic growth leads to a "scale effects" prediction that growth should increase in the level of R&D. However, the recent empirical record conflicts with that. The leading explanation for this disconnect between theory and empirics is that R&D has gotten harder. If correct, ultimately growth from R&D will converge to zero. We propose an alternative explanation--that firms have gotten worse at R&D. We test the two explanations and find that the weight of the evidence is consistent with firms getting worse. This result is consistent with Romer's theory in its original form. Accordingly, we should be able to achieve steady-state growth from R&D. However, it also suggests that to revive growth, firms need to restore their R&D productivity.

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I. Introduction

A recent explanation for the decline in GDP growth is that R&D has gotten harder (Jones 1995, Gordon 2016). This explanation is motivated by empirical evidence that is at odds with the "scale effects" prediction from Romer's theory of endogenous growth. In particular, Romer expects growth, g, to be proportional to the level of research labor, H_A (equation 1). However, recent history indicates that while R&D spending in the U.S. has been rising, GDP growth has been declining (Figure 1)

(1) $$g = \delta\, H_A$$

Jones formalization of the R&D harder argument is that Romer's growth model is a specific form of a more general model, which includes "fishing out" and "externalities". Fishing out, λ, is the notion that the quality of remaining ideas is declining over time. Externalities, θ, is the notion that as the number of researchers increases, the likelihood of conducting redundant efforts also increases. The former suggests diminishing returns to the knowledge stock, the latter suggests diminishing returns to current R&D.

(2) $$g = \delta H_A^{\lambda} A^{\theta}$$

While Romer's and Jones' theories are intended to model the macro economy, two-thirds of R&D in the U.S. is conducted by firms. Accordingly, the relationships in equations 1 and 2 must hold at the firm-level. Indeed, Bloom, Jones, VanReenan and Webb (2020) examine micro data and find that the aggregate trend in Figure 1 holds there as well. The authors look within several domains, using context-specific measures of knowledge for each domain: semi-conductors (transistor density), agriculture (bushels/acre), health care (life expectancy) and pharmaceuticals (new molecular entities), and find that IdeaTFP (growth in knowledge divided by research labor) has declined in each of them. "Research productivity is declining at a substantial rate in virtually every place we look" (2020:17). They interpret these results as support for Jones' fishing out hypothesis—that "ideas get harder and harder to find" (2020:46). However, they don't test the fishing out hypothesis directly. Rather, they infer it from the decline in research productivity.

This opens the door for an alternative interpretation of Figure 1. We argue rather than R&D getting harder, firms have become worse at it. The distinction between the two interpretations is important. If Jones' explanation is correct, growth from technological change is largely exogenous, and ultimately will converge to zero. Conversely if firms have gotten worse at R&D, and we can identify factors contributing to their decay, it is possible to restore their R&D productivity, and thereby revive growth.

We can't directly test whether firms are getting worse at R&D. However we can test whether the decline in R&D productivity is explained by R&D getting harder, by estimating a structural model derived from equation 2.

Using Bloom et al data for firms' IdeaTFP[1], and three different proxies for the knowledge stock, we failed to find support for R&D getting harder. While we did find support for externalities, diminishing returns to labor is a within period phenomenon , so can't on its own explain decline over time.

Given the lack of support for R&D getting harder in the formal test, we next examine the trend in "*maximum IdeaTFP*" over time—where *maximum IdeaTFP* in each year is the highest observed value of IdeaTFP across firms. The logic underpinning this test is that if R&D has

[1] https://www.aeaweb.org/articles?id=10.1257/aer.20180338

indeed gotten harder, this should be evident for the entire distribution of firms' R&D productivity, not merely the mean.

We find that *maximum IdeaTFP* across the economy is increasing over time, which you would not expect if R&D is getting harder. Since this is unanticipated by theory, we also look within increasingly narrower sets of firms: sectors (1 digit SIC) to industry (4-digit SIC). While at the sector level, *maximum IdeaTFP* is also increasing over time, at the 3 and 4-digit levels, *maximum IdeaTFP* is decreasing over time. The decline within narrow definitions of industry matches the observations in Bloom et al, since they look within domains.

The result that *maximum IdeaTFP* increases across industries while decreasing within them is interesting. It suggests that as opportunities decay, firms create new industries with greater opportunity (which matches literature on logistic curves in sociology of science, technological trajectories in evolutionary economics and S-curves in the practitioner literature).

Thus, to the extent that firms actively choose what industries to enter, then *IdeaTFP* appears to be at least partially under firms' control. As a simple test of this we model firms' *IdeaTFP* as a function of the age of their primary industry. We find that firms' *IdeaTFP* declines with the age of their primary industry. Thus, one way in which firms are getting worse at R&D (our alternative explanation for the decline in R&D productivity) is by failing to exit industries when opportunity within them decays. We don't conduct tests of any other ways firms are getting worse at R&D. However, we identify three firm behaviors, which prior literature has shown a) adversely affect firms' R&D productivity, and b) have become increasingly adopted by firms over the period in which R&D productivity has declined.

In summary, we are unable to find empirical support for the view that R&D is getting harder. First, in testing a structural model of Jones (1995), we find that fishing out is never significant. Further, in a less formal test, we find that *maximum ideaTFP* is increasing over time, which we would not expect if R&D is getting harder. We then provide suggestive evidence that firms are getting worse at R&D.

These results have important as well as optimistic implications. First, they reinforce the theory of endogenous growth from R&D, at the expense of a theory in which growth is essentially exogenous. However, the results also suggest that in order to revive growth, firms need to restore their prior R&D productivity. Accordingly, an important area of research is understanding why firms have become worse at R&D, and determining how much of that is reversible.

This paper proceeds as follows. First, we discuss the empirical approach. Second, we present results. Third, we review recent studies of widespread changes in firms' R&D behavior that are correlated with lower R&D productivity. Finally, we discuss implications.

II. Empirical Approach

A. Primary test of R&D getting harder

Our primary test of R&D getting harder relies on a structural model that merges the *IdeaTFP* construct in Bloom et al. with Jones' expanded model of growth from R&D (equation 2). Bloom et al adopt new terms for equation 1, expressing growth, g, in terms of knowledge growth, $\dot{A}/A$, research productivity, δ, as ideaTFP, α, and research labor, H_A, as scientists, S.

(3) $$\dot{A_t}/A_t = \alpha S_t$$

Their focal interest is characterizing the decline in ideaTFP, α, so they rearrange terms[2]:

(4) $$\alpha = \left(\frac{\dot{A}_t}{A_t}\right)/S_t$$

In contrast, our primary interest is understanding whether the decline is due to R&D getting harder of firms getting worse at R&D. Accordingly, we rearrange equation 3, and insert Jones (1995) terms for fishing out, θ, and externalities, λ.

(5) $$\dot{A}_t = \alpha A_t^{\theta} S_t^{\lambda}$$

If R&D is getting harder, then the fishing out term, θ, must be less than 1, meaning that as the knowledge stock grows, the amount of new knowledge produced from any given level of scientific labor is decreasing. Note that λ may also be less than 1, but the level of scientific labor is a within period choice, thus in and of itself cannot be responsible for the decline. To assess whether the decline in research productivity is due to fishing out, we want to isolate ideaTFP on the left-hand side. We first add identities to equation 5.

(6) $$\dot{A}_t = \alpha A_t A_t^{\theta-1} S_t S_t^{\lambda-1}$$

We then rearrange and combine terms.

(7) $$\left(\frac{\dot{A}_t}{A_t}\right)/S_t = \alpha A_t^{\theta-1} S_t^{\lambda-1}$$

Expressing equation 7 in ln form, yields:

(8) $$ln(IdeaTFP) = ln(\alpha) + [\theta - 1]ln(A_t) + [\lambda - 1]\, ln(S_t)$$

If we estimate equation 8 as follows:

(9) $$ln(IdeaTFP) = \beta_0 + \beta_1 ln(A_t) + \beta_2 ln(S_t) + \gamma_i + \varepsilon_{it}$$

[2] Their equations 5 and 14

Then $\theta = \beta_1 + 1$, and $\lambda = \beta_2 + 1$.

To test equation 9, we form three alternative proxies for the knowledge stock, each based on the stock of knowledge within the technology classes of the firms' patents (appendix A). If the knowledge production function (equations 1 and 2) is subject to fishing out, we expect $0 < \beta_1 < -1$, but significantly less than 0, such that θ is significantly less than 1. If the knowledge production function (equations 1 and 2) is subject to externalities, we expect $0 < \beta_2 < -1$, but significantly less than 0, such that λ is significantly less than 1. Our primary interest is in the fishing out effect, since it is required for R&D to be getting harder.

B. Test of Decline across the IdeaTFP distribution

As a secondary test of whether R&D is getting harder, we estimate a time trend for "*maximum IdeaTFP*" over time—where *maximum IdeaTFP* in each year is the highest observed value of *IdeaTFP* across firms. The logic underpinning the test is that if R&D has gotten harder, this should be true for the entire distribution of firms' R&D productivity, not merely the mean.

(10) $$\text{Maximum IdeaTFP}_{it} = \beta_0 + \beta_1\, year_t + \gamma_i + \varepsilon_{it}$$

If R&D is getting harder, we expect the coefficient on β_1 to be negative and significant.

C. Data and variables

The data to conduct all tests come from three sources, COMPUSTAT North American Annual database, the U.S. patent dataset released by Kogan, Papanikolaou, Seru, and Stoffman (2017), and the data supplement to Bloom et al. To merge the datasets we follow Kogan et al (2017) and use the CRSP-COMPUSTAT link table in the CRSP/Compustat Merged Database (CCM). The data comprise all US-traded firms who conduct R&D over the period 1972 to 2016,

subject to their having sufficient observations to form IdeaTFP (10 years forward).

III. Results

A. Primary test of R&D getting harder

Table 1 presents results for test of Equation 9. Looking first at externalities, results indicate the coefficient β_1 on *ln(R&D)* is negative and significant in all models. The coefficient values (-0.13 to -0.20) translate into values for λ of 0.80 to 0.87, which is on the high side of observed values for labor elasticities in other settings. This is likely due to the fact there is little capital employed in research. Nevertheless, the coefficient estimate is consistent with the view there are externalities in the knowledge production function.

Looking next at fishing out, results indicate that the coefficient, β_2, on the knowledge stock, is not significant when using either *Knowledge average* or *Knowledge_citation* as the proxy. The 0 value for β_2 translates into an estimated value for λ of 1.0, thus failing to provide support for fishing out. *Knowledge_sum* appears to be a poor proxy, because the coefficient estimates of 0.019 and 0.039 imply values for λ greater than 1, or increasing returns to the knowledge stock. But even this proxy fails to provide support for fishing out. Thus, in our primary test we fail to find support for R&D getting harder

[Insert Table 1 About Here]

B. Test of Decline across the IdeaTFP distribution

The observed decline in firms' *IdeaTFP* in Bloom et al pertains to the mean. If indeed R&D is getting harder, it should be evident across the entire distribution of firms' *IdeaTFP*. Accordingly, as a supplementary test, we examine the time trend in *maximum IdeaTFP*. (We ignore the minimum because it is bounded by 0) (Table 2)

[Insert Table 2 About Here]

Looking first at *maximum IdeaTFP* across the entire economy (Model 1), the coefficient on year is positive and significant, indicating that opportunity appears to be *increasing* over time. The coefficient at the sector level (Model 2) is also positive though imprecisely estimated. The coefficient estimates decrease as the industry definition is narrowed, and are significantly negative for 3 or 4 digit definitions of industry.

Thus, in this alternative test of whether R&D is getting harder, we see that while this appears to be true within narrow definitions of industry, it does not appear to be true across the economy. This in some sense reconciles the two explanations for the decline in R&D productivity—while R&D appears to get harder within domains (where Bloom et al conduct most of their tests), it does not appear to be getting harder overall. Rather, it seems that while opportunities within industries decline over time, as they do, companies respond by creating new industries with greater opportunity. Two common examples are the death of the typewriter and its replacement by personal computers, and the death of landlines and their replacement by cell phones. The maximum installed base of electronic typewriters in the U.S. was 10 million machines (in 1978). In contrast, personal computers, which replaced them, enjoy an installed base in the U.S. of 310 million machines. Similarly the maximum worldwide penetration of landlines peaked was 19.4%,[3] while cellphones have already been adopted by 96% of adults in advanced economies and 78% of adults in emerging economies.[4]

[3] https://data.worldbank.org/indicator/IT.MLT.MAIN.P2?view=chart
[4] https://www.pewresearch.org/global/2019/02/05/smartphone-ownership-is-growing-rapidly-around-the-world-but-not-always-equally/

IV. Have firms gotten worse at R&D?

While the tests so far fail to support the view that R&D has gotten harder, they don't allow us to say anything about firms getting worse. We are unable to test that formally. However, we conduct one suggestive test, and then refer to existing literature for additional support.

The suggestive test examines the implicit implication from the *maximum IdeaTFP* regressions that firms may be remaining in industries too long. To test that implication, we model firms' *IdeaTFP* as a function of the age of their primary industry, where the age of an industry is the first year it appears in COMPUSTAT. This clearly understates industry age, because it takes time for new firms in a new industry to go public, or for existing public firms to shift their primary industry to a new one. Nevertheless, age in COMPUSTAT likely lags true age in a predictable fashion. Results for that test are presented in Table 3. The table indicates that firms' *IdeaTFP* is negatively and significantly associated with the age of their primary industry. This result suggests the decline in R&D productivity may be due in part to firms' failure to exit industries (or reduce R&D) when their technological opportunity is exhausted.

[Insert Table 3 About Here]

More compelling evidence of how firms may have gotten worse at R&D comes from recent research on firms' R&D practices. That literature has identified at least three widespread changes in firm behavior that are correlated with lower R&D productivity: a trend toward decentralization of R&D (Argyres and Silverman 2004, Arora, Belenzon and Ruis 2011, Cummings 2018), a rise in R&D outsourcing (Knott 2016), and increased prevalence of CEOs being hired from outside the firm (Cummings and Knott 2018). We discuss each in turn.

Decentralization. Cummings (2018) documents a 34% decrease in the level of R&D centralization, which he operationalizes as the extent to which a firm's patents emerge from locations other than its dominant one. He finds that decentralization is associated with significantly lower patent intensity and RQ (the output elasticity of R&D (Knott 2008)). Other work obtains similar results for the impact of decentralization, but doesn't track the trend toward decentralization. Argyres and Silverman (2004) for example, show that decentralized R&D (measured via survey responses regarding the centralization of both the conduct of R&D and its funding decisions) is less broad (technical range of backward citations) and less impactful (number of forward citations). Similarly, Arora, Belenzon and Ruis (2011) using a centralization measure of whether patents are associated with the company name or that of a subsidiary, obtain results similar to those of Argyres and Silverman. Knott (2017) in correlations of RQ with the Argyres and Silverman's centralization measure as well as the Arora et al's centralization measure finds that firms with decentralized R&D have 40-60% lower RQ than firms with centralized R&D. The inferred mechanism is that decentralization leads to R&D which serves divisions rather than the entire firm, and therefore is less generative.

Outsourced R&D. Knott (2016) utilizes data from the National Science Foundation (NSF) Survey of Industrial Research and Development (SIRD), to document a 20-fold increase in the prevalence of "outsourced R&D" –R&D funded by the focal firm but performed by an outside firm. In addition, the paper finds that the output elasticity of outsourced R&D is zero, while the mean output elasticity of internal R&D is 0.13. These results suggest that firms' R&D productivity decreases linearly in the extent of outsourced R&D. While the paper doesn't isolate why outsourced R&D has zero elasticity, it offers a number of plausible explanations: 1) firms lose the spillovers from one project to the next (because the knowledge is being accumulated

outside), 2) relatedly funding firms lose the opportunity to redeploy the technology for other purposes if it fails in its initial purpose, and 3) because the R&D is performed outside, the funding firm lacks the expertise to implement its results, and so is less likely to derive economic benefit from it.

Outside CEOs. While not an R&D practice per se, Cummings and Knott (2018) document a 67% increase in the rate at which CEOs are hired from outside the firm. They speculate, then test, the hypothesis that R&D capability erodes under outside CEOs (because they lack expertise to direct R&D). They find that RQ decays with each year of an outside CEO's tenure. To support their conjecture this decay stems from lack of expertise, they find there is less decay in the presence of related expertise, e.g., if the CEO is from the same industry. In follow-on work, Kluppel and Cummings (2019) explore what outside CEOs do differently that might explain the decay. They find that rather than changing the technological direction of R&D (which they expected), outside CEOs seem to enter autopilot—not changing direction at all. Thus, the decay in RQ may reflect failure to recognize and/or respond to new opportunity.

Taken together this emerging research suggests that firms in aggregate have substantially changed the organization and conduct of their R&D, and that the newer forms of organization and conduct are associated with significantly lower R&D productivity. This research not only supports the view that firms have gotten worse at R&D, it identifies specific ways in which it has gotten worse, and points to things firms could do to restore their R&D productivity.

V. Discussion

Romer's (1990) theory of growth from R&D generates a "scale effects" prediction that growth should increase in the level of scientific labor. However recent empirical evidence conflicts with that: scientific labor has been increasing, while GDP growth has been declining. Thus the implied productivity from R&D has been declining.

The leading explanation for the decline is that R&D has gotten harder (Jones 1995, Gordon 2016). This implies both that growth from R&D is essentially exogenous and ultimately that growth from R&D will converge to zero. We proposed an alternative explanation for the decline that preserves expectations from endogenous growth—that firms are getting worse at R&D.

We tested a structural model of Jones theory that the decline in R&D productivity is due to fishing out and externalities. While we found support for externalities, we failed to find support for fishing out. In addition to this primary test, we conducted a supplementary test of R&D getting harder, by examining what happens to *maximum IdeaTFP* over time. We found that while *maximum IdeaTFP* decreased within industries over time (consistent with prior within-domain tests in Bloom et al), it increases over time when looking across the economy. This result suggests that as opportunities decay, firms create new industries with greater opportunity. This regeneration is consistent with stylized facts from a number of disciplines: logistic curves (sociology of science), technological trajectories (evolution economics), and S Curves (management practice), as well as with Schumpeter's (1942) creative destruction.

Finally, while we don't empirically test whether firms are getting worse at R&D, we first show that firms' IdeaTFP decreases in the age of their primary industry—suggesting that one behavior responsible for the decline in research productivity is failure to exit industries optimally. We then review recent empirical literature that identifies three widespread changes in firms' R&D organization and practices and links that to lower productivity: decentralizing R&D, outsourcing R&D, and hiring outside CEOs.

These results have important as well as optimistic implications. First, they reinforce endogenous theory, and accordingly the expectation of steady-state growth from R&D. However, the results also suggest to achieve that growth, firms need to restore their prior levels of R&D productivity. Accordingly, important areas of research are understanding why firms R&D productivity has declined, and determining how much of that is reversible.

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TABLE 1. Test of Jones' Theory (kept the 2019 table with my IdeaTFP)

	1	2	3	4	5	6
Dependent Variable: IdeaTFP						
ln(R&D)	-0.1888***	-0.1347***	-0.1857***	-0.1311***	-0.2028***	-0.1707***
	-0.0197	-0.0064	-0.0205	-0.0063	-0.0212	-0.0108
ln(Knowledge_average)	-0.0038	-0.0111				
	-0.0063	-0.0088				
ln(Knowledge_citation)			-0.0105	-0.0069		
			-0.0069	-0.011		
ln(Knowledge_sum)					0.0188***	0.0392***
					-0.0036	-0.0061
Constant	0.8525***	0.7392***	0.8979***	0.6845***	0.6511***	0.3139***
	-0.094	-0.0707	-0.0963	-0.0869	-0.0597	-0.0363
Observations	10455	10669	10162	10383	10455	10669
R-squared	0.6979	0.2555	0.6996	0.2512	0.6991	0.2651
Firm FE	YES	NO	YES	NO	YES	NO
Year FE	YES	YES	YES	YES	YES	YES

Standard errors are in parenthesis

**** p<0.01, ** p<0.05, * p<0.1*

TABLE 2. Test Decline in Maximum IdeaTFP

	1	2	3	4	5
	OLS	FE	FE	FE	FE
Dependent variable: maxIdeaTFP		1 digit SIC	2 digit SIC	3 digit SIC	4 digit SIC
Year	**0.5682**	0.0133	-0.0057	**-0.0182**	**-0.0207**
	0.4350	0.0449	0.0305	0.0086	0.0064
Industry effects		included	included	included	included
Constant	1111.8	-24.970	12.036	36.766	41.601
	864.9	89.127	60.751	17.167	12.845
R-squared	0.0538				
Adjusted R-squared	0.0223				
within		0.0068	0.0018	0.0710	0.1092
between		0.1976	0.0800	0.0615	0.0265
overall		0.0060	0.0276	0.0406	0.0307
observations	32	59	218	606	795
groups (sic)		10	40	105	143

TABLE 3. Impact of industry age on R&D productivity

	2
	Firm FE
Dependent variable	Idea TFP
Industry age (4 digit sic)	**-0.0179**
	0.0021
Constant	**0.6376**
	0.0366
R-squared	
within	0.0113
between	0.0055
overall	0.0068
observations	14157
groups (sic)	1498
robust standard errors clustered by firms	

FIGURE 1. Empirical Evidence Regarding Scale Effects Prediction