Do Inventions Drive Firm Growth?

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Abstract: *R&D generates two outputs: inventions and knowledge. While the prevailing view is that inventions drive growth, a fundamental assumption behind patent policy as well as growth theory, is that knowledge accumulation drives growth. While the distinction between inventions and knowledge may be inconsequential at the economy-level, it becomes important at the firm level, because firms can outsource their R&D. When they do so, inventions and knowledge are no longer co-located: inventions accrue to the funding firm, but knowledge accumulates at the performing firm. Thus R&D outsourcing presents both the need and the means to determine whether inventions or knowledge drives growth. I characterize the output elasticity of firms' internal R&D and outsourced R&D. By comparing the two, I find that inventions comprise 0.8% of growth from R&D, while knowledge accumulation comprises 99.2%. Beyond the theoretical contribution that growth from R&D stems from knowledge accumulation rather than inventions, this research has practical implications as well. It suggests that the six-fold increase in R&D outsourcing has contributed to the decline in firms' R&D productivity and nominal GDP growth. Thus, it may be possible to restore R&D productivity and economic growth by gradually bringing outsourced R&D back inside the funding firm.*

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I. Introduction

Innovation is the primary driver of growth at the firm-level, and in aggregate, at the economy-level (Solow, 1957). While a common view is that inventions fuel this growth, Romer's (1990) theory linking R&D to growth suggests instead that inventions are incidental. Rather, what fuels growth is the knowledge accumulated as a byproduct of the inventive process.

That R&D generates two outputs was recognized long before Romer. In fact, the distinction between the invention and the knowledge byproduct forms the basis of patent law. Patents, whose earliest use dates to the 14^{th} century (Malchup 1958), provide temporary property rights to an invention, in exchange for full disclosure of the knowledge underpinning the invention. The logic is that unless an inventor has the ability to appropriate returns from an invention, there will be less invention, and accordingly less knowledge production. Because nations benefit more from the knowledge, than they lose from temporary monopolies, they are willing to offer patents as an incentive for inventors to innovate.

Romer's theory is at the macro-economic level. However, it's foundation, the production function, is inherently a firm-level construct. Accordingly, the theory should hold at the firm-level. In particular, firm growth should be driven by knowledge accumulation, rather than by inventions. I test that proposition.

On its face, the proposition seems to make a meaningless distinction between knowledge and inventions, since the two are co-produced. In the case of firms, however, the distinction may be meaningful. For any given project, firms choose whether to conduct their R&D internally or outsource it to other organizations. When projects are executed internally, both the inventions and the knowledge accumulation accrue to the funding firm. When projects are outsourced, however, only the inventions accrue to the funding firm. The knowledge accumulates at the performing firm. Thus, the phenomenon of outsourcing creates both the need to examine the distinction between inventions and knowledge accumulation, as well as the opportunity to do so.

Using data from the National Science Foundation (NSF) survey of industrial R&D (SIRD), which represents all for-profit R&D-performing companies in the U.S., I separately characterize the output elasticity of internal R&D and outsourced R&D at the funding firm. Each elasticity captures the percentage increase in revenues from a 1% change in that form of R&D—thus its growth contribution. The elasticity of internal R&D should capture the growth contributions from both inventions and knowledge accumulation, since with internal R&D the funding firm obtains both. The elasticity of outsourced R&D should capture the growth contribution from inventions alone, since when outsourcing R&D, the funding firm obtains the inventions, but not the knowledge accumulation. Accordingly, the difference in elasticity between internal R&D and outsourced R&D captures the growth contribution from accumulated knowledge.

Results reveals that the mean elasticity of outsourced R&D for the SIRD sample is 0.001, as compared to a mean of 0.128 for internal R&D. Thus a 10% increase in outsourced R&D yields essentially no growth for the funding firm, whereas a 10% increase in internal R&D increases top-line growth of 1.3%. Efforts to account for endogeneity in outsourcing decisions, indicate that neither firm quality nor project quality explains the lower elasticity of outsourced R&D. Thus, growth appears to be fueled by knowledge accumulation rather than inventions.

In addition to this theoretical implication, the results have practical implications as well. Outsourced R&D as share of total R&D has increased almost six-fold over the past 30 years, from 2.2% of firms' R&D in 1984 to 12.5% in 2014 (Figure 1). This increase coincides with a

31% decrease in R&D productivity, and a 61% decrease in nominal GDP growth over the same period (Figure 2). Thus, much of the decline in R&D productivity and GDP growth may stem from the reallocation of R&D away from internal execution to outsourcing. If so, then restoring prior allocations of internal R&D may help restore R&D productivity and revive GDP growth.

[Insert Figures 1 and 2 About Here]

This paper proceeds as follows. First, I review Romer's theory of growth from R&D and derive firm-level implications. Next, I review the literature on R&D outsourcing. Third, I outline the empirical approach. Fourth, I present results and robustness checks. Finally, I discuss implications.

II. Theory

The theoretical and empirical link between technological change and growth was established by Solow (1957). In a growth accounting exercise, he found that increases in capital and labor, together with improvements in human capital, only explained 37% of U.S. growth. The vast majority of growth was unexplained. Solow attributed this 63% "residual" to technological change, and articulated a theory in which knowledge, which accumulated over time, was added to the aggregate production function. While he was silent on where knowledge came from, it was taken to be exogenous.

Romer (1990) preserved Solow's link between technological change and growth in explaining why labor elasticity increased ten-fold over the 20th century: "*The raw materials that we use have not changed, but as a result of trial-and-error experimentation, refinement, and scientific investigation, the instructions that we follow for combining raw materials have become vastly more sophisticated"* (1990: S72). Romer's contribution to growth theory is endogenizing technological change, such that it arises from purposeful investment in R&D that responds to market incentives. The R&D investment produces both "designs" (inventions) and knowledge. The key distinction between the two outputs is that inventions are excludable, while knowledge is non-rival—it can be used repeatedly at no cost.

Romer's model comprises three sectors: 1) a research sector that uses human capital, H, (formal education plus on-the-job training) and the existing stock of knowledge, A, to produce new knowledge and designs, 2) an intermediate goods sector that uses the designs to manufacture producer durables, K, and 3) a final goods sector that uses human capital and physical capital, and the producer durables to produce final output.

In equilibrium, output, Y, and capital, K, grow at the same rate, which is driven by the growth in knowledge, A. Knowledge growth, $\dot{\boldsymbol{A}}$, is determined by the amount of human capital in the research sector, H_A, the productivity of that human capital, δ, and the current level of knowledge, A:

(1) $$\dot{A} = \delta H_A A$$

Firm-level implications

Romer's theory pertains to the macro-economy. However, it's foundation, the production function, is inherently a firm-level construct. Accordingly, his theory and propositions should hold at the firm-level. If so, firm growth should be driven by cumulative knowledge, rather than by inventions.

On its face, the proposition seems to make a meaningless distinction between inventions and knowledge, since at the economy-level the two are jointly held. In the case of firms however, the distinction between inventions and knowledge may be important, because inventions and knowledge may not be co-located. Romer's mechanics rest on an assumption that because knowledge is non-rival, it is equally accessible to all researchers at all times. However, we know that knowledge is sticky (Szulanski 1996), and that its diffusion decreases with distance (Allen 1977). Recognition of this stickiness helps explain why firms cluster near technological leaders (Shaver and Flyer 2000). Since knowledge is sticky, it may be more accessible to those involved in its creation, than to others. If so, whether a firm conducts R&D internally or outsources it should matter. When it is conducted internally, both inventions and knowledge accrue at the funding firm. When R&D is outsourced however, inventions accrue to the funding firm, but the knowledge accumulates at the performing firm.

Accordingly, the phenomenon of R&D outsourcing creates both the need to test whether inventions or knowledge drive growth, as well as the opportunity to do so. If inventions alone fuel growth, then the elasticity of both forms of R&D should be equivalent, since in both cases the funding firm obtains the inventions. Moreover either elasticity will capture the growth contribution from invention. Conversely, if knowledge accumulation alone fuels growth, then outsourced R&D should have an elasticity of zero, since the funding firm obtains the invention, but not the knowledge accumulation, and the elasticity of internal R&D will capture the growth contribution from knowledge accumulation. If both inventions and knowledge accumulation contribute to growth (and there are no complementarities), then the elasticity of internal R&D minus that of outsourced R&D will capture the growth contribution from knowledge accumulation, as shown in the mapping in Table 1.

[Insert Table 1 About Here]

III. Prior Research on Outsourced R&D

Prior research has examined R&D outsourcing, but not for this purpose. One stream within that literature examines the outsourcing decision, a second stream examines outcomes from R&D outsourcing, while a third stream examines whether internal R&D and outsourced R&D are substitutes or complements. Because this literature focuses on the invention output rather than the knowledge output, we also discuss a related literature on knowledge accumulation in operations outsourcing.

An interesting study in the first stream combining theory and empirics, builds a model of the decision to outsource research to universities (Lacetera 2009). The key wedge in the model is arrival of a new project with higher value than an ongoing research project. The firm wants flexibility to switch to the new project, and outsourcing is assumed to make switching more difficult. The outsourcing decision is therefore a function of the probability of a new project's emergence and the expected return of the new project relative to the primary project. Under the model's assumptions, firms prefer outsourcing when projects have a) shorter duration (lower likelihood of new project arrival), or b) broader applicability (less value in switching). Lacetera's data is research contracts, which by definition, are outsourced, so he can't test the propositions directly. Rather, he examines terms of the research contracts to see if they are directionally consistent with the model's propositions, which they are. Firms require greater control and termination rights as project duration increases.

Another study in the decision stream is Higgins and Rodriguez (2006), which examines pharmaceutical firms "outsourcing" R&D through acquisitions of biotechnology firms. While this definition of outsourcing doesn't match the NSF definition employed here "*others outside* *your company performed R&D funded by your company*", the motives are similar. The authors find that acquisitions increase with a "desperation index", that captures the quality of a pharmaceutical firm's pipeline. That is, when firms lack drugs at the front-end of their pipeline, they acquire firms with drug candidates. The authors also look at outcomes from these acquisitions, and find that abnormal stock returns for the acquirer increase with the desperation index, and with the relatedness of the firms' therapeutic classes. Thus the market believes that acquisitions create value when they fill pipeline gaps. While this study is helpful for understanding outsourcing motives, it is less relevant for the question of whether inventions or knowledge drive firm growth, since in the acquisition form of outsourcing, the acquirer obtains both the inventions and the accumulated knowledge of the target.

The second stream of prior literature examines the consequences of R&D outsourcing. In addition to the Higgins and Rodriguez study showing the impact of acquisitions on firms' market value, are a handful of studies examining the impact of outsourcing on innovation. In general, the data utilized in these studies are cross-sectional and the measures are coarse: both the outsourcing variable and the innovation variable are binary: did the firm outsource (yes/no)? did the firm introduce an innovation (yes/no)? Bertrand and Mol (2013) in a study of French firms, found foreign outsourcing is significant in predicting product innovation. Similarly, Rodriguez and Nieto (2016) in a study of small to medium enterprises (SME) in Spain, found that R&D outsourced to foreign firms is significant in predicting sales growth and innovation. In a more recent study, Garcia-Vega and Huergo (2019) examine the impact of outsourced R&D on the likelihood of innovating among Spanish firms, and also find that outsourcing increases innovation. However, given that the intent of R&D, whether internal or outsourced, is to produce innovations, the results from these studies are not surprising. Their value here is support for the premise that R&D outsourcing produces inventions (one of the two outputs of R&D).

The third stream of literature on R&D outsourcing considers whether internal R&D and outsourced R&D are complements or substitutes. This is relevant, since the implicit assumption in the empirical approach here are that the two are substitutes. If the two are complements, then the elasticity of internal R&D minus that for outsourced R&D will overstate the growth contribution from knowledge accumulation. The first of these studies, Cassiman and Veugelers (2006), looks at the complementarities between internal R&D and external R&D, where external R&D includes licensing, take-over (acquiring the entire firm), hiring away personnel, and R&D outsourcing. They find that R&D productivity (measured as the percentage of sales from products introduced in the past three years) was higher for firms who did both internal R&D and external R&D than for those who did either, suggesting the internal R&D and external R&D are complements. However, the productivity of firms who did neither was also higher than that for firms who did either. Thus, it is difficult to draw conclusions. In a later study, Teirlinck, Durmont and Spithoven (2010) look at the impact of R&D outsourcing on R&D inputs. They find that R&D employment intensity decreases in R&D outsourcing. Thus, they conclude that R&D outsourcing appears to substitute for internal R&D, which is consistent with the implicit assumption here.

Collectively, the literature on R&D outsourcing to date, focuses on invention from R&D, and finds 1) that firms outsource R&D when they lack internal resources to generate inventions, or when they require flexibility to terminate invention projects, 2) that outsourcing generates inventions, providing support for the first of R&D's two outputs, and 3) that outsourcing appears to be a substitute for internal R&D, supporting an assumption for the empirical approach. However, the literature appears to be silent on the second output of R&D (knowledge accumulation). Fortunately, a related literature on operations outsourcing addresses implications for knowledge accumulation.

The underlying argument in Clark, Huckman and Staats (2013) is that specialized service providers, which aggregate over a large number of related projects, accumulate knowledge at a faster rate than firms who perform a service internally. Accordingly, the specialized providers should have higher quality and lower cost per project than a firm which internalizes the services. Rather than examining the funding firm (as the R&D outsourcing literature did), the authors examine the service providers. Looking at radiological services and measuring learning within service providers, they find that learning increases with experience levels and concentration (same customer in the same domain). Thus this study supports the assumption that knowledge accumulates at the performing organization.

A converse of Clark et al, looks at the relationship between outsourcing and knowledge accumulation at the funding firm. The key hypothesis in Mayer, Somaya and Williamson (2012) is that the likelihood of outsourcing projects decreases with the level of relevant cumulative experience from prior internal projects. Looking in the context of legal expertise for patent filings, the authors find that the probability of outsourcing decreases in the level of cumulative internal experience, but increases with prior related outsourcing. Thus, this study, like Clark et al, is consistent with the proposition that knowledge accumulates at the performing organization. Moreover, it suggests that knowledge fails to accumulate at the funding firm, when work is outsourced.

In summary, the R&D outsourcing literature focuses on the invention output of R&D, thus it doesn't address the proposition here, that firm growth is driven by knowledge accumulation. It does however help with the assumptions here that a) outsourcing produces inventions, and b) outsourcing is a substitute for internal R&D. Thus, a useful complement to the R&D outsourcing literature is the literature on operations outsourcing, which provides support for the assumption that knowledge accumulation occurs at the performing organization, rather than the funding organization. Jointly the two sets of literature support the assumptions here, that R&D produces both inventions and knowledge accumulation, and that knowledge accumulation occurs in the performing organization rather than the funding firm. However, they don't address the question of whether inventions or knowledge accumulation drives growth. That is the goal of the current study.

IV. Empirical Approach

I test whether inventions or knowledge accumulation drive growth, by exploiting the phenomenon of R&D outsourcing. While for internal R&D, both inventions and cumulative knowledge will be co-located at the funding firm, for outsourced R&D, inventions will belong to the funding firm, but knowledge will accumulate at the performing organization. Accordingly, I separately characterize the elasticity of internal R&D and outsourced R&D for the funding firm. If inventions alone fuel growth, then the elasticity of both forms of R&D should be equivalent, since in both cases the funding firm obtains the inventions. Moreover either elasticity will capture the growth contribution from invention. Conversely, if knowledge accumulation alone fuels growth, then outsourced R&D should have an elasticity of zero, and the elasticity of internal R&D will capture the growth contribution from knowledge accumulation. If both inventions and knowledge accumulation contribute to growth (and there are no complementarities), then the elasticity of internal R&D minus that of outsourced R&D will capture the growth contribution from knowledge accumulation.

To estimate the elasticity of the funding firm's R&D, I model a production function in which internal R&D and outsourced R&D are treated as distinct inputs. Following this, I test whether the effects of R&D outsourcing are true treatment effects, or merely artifacts of who outsources and what they outsource.

Data and variables

Data for the study come from the NSF Survey of Industrial Research and Development (SIRD). The SIRD is an annual survey of US firms conducting R&D. The data was collected through a joint partnership between the sponsoring agency, the NSF, and the Census Bureau from 1957 to 2007 (though microdata is only available from 1972 forward)[1]. Accordingly, access to the data requires sworn status with the Census.

The SIRD addresses the industry component of the NSF mandate "…to provide a central clearinghouse for the collection, interpretation, and analysis of data on scientific and engineering resources and to provide a source of information for policy formulation by other agencies of the Federal government" (NSF Act of 1950, as amended; 42 U.S.C. 1862). To my knowledge, the SIRD (and its successor, the Business Innovation and Research and Development Survey) provide the only large-scale longitudinal data of U.S. firms' R&D expenditures decomposed into its constituent elements. Moreover, because SIRD data is collected by the U.S. Census, firms are legally required to respond. Accordingly, the survey enjoys a significantly higher response rate than most other surveys.

The SIRD is gathered from a sample intended to represent all for-profit R&D-performing companies, either publicly or privately held. (See Foster and Grimm 2010 for details). The

[1] As of 2008, the SIRD was substantially redesigned and renamed the Business Research and Development and Innovation Survey (BRDIS).

sampling methodology comprises a census of all firms whose R&D expenditure exceeds one million dollars, and a random sample of firms with smaller budgets. In order to minimize the burden of completing the survey, the SIRD collects some data each year, and other data in alternating years. The data collected annually include: domestic sales, domestic employment, number of scientists/engineers, and total domestic R&D expenditures by source of funding (Federal R&D funds versus company R&D funds), horizon (basic research, applied research, and development), and location (internal, outsourced within US, conducted by foreign entities).[2] The data collected in alternating years adds: total R&D costs decomposed by type (wages and salaries of R&D personnel, costs of materials, depreciation on R&D property and equipment, and other costs). For R&D conducted internally, the survey also includes distribution across the 50 states and the District of Columbia.

I construct a variable *internal R&D,* by summing three SIRD variables (basic research, *brtot*, applied research, *ardtot*, development, *devtot*). Other variables include: US outsourced R&D, *outuscomp*, foreign R&D, *foreign*, domestic revenues, *dns*, and the number of full-time equivalent employees*, dne*. *Outuscomp* is the response to the question, "*If others outside your company performed R&D funded by your company, what was the cost of the R&D performed in the 50 United States and D.C. during < prior year>? Include payments for R&D projects, contracts, or services performed for your company by contractors, suppliers, grantees, educational institutions, or other organizations*." *Foreign* is the response to the question, *"If your company funded R&D performed outside the 50 United States and D.C. during <prior year>, what was the cost? (Please report costs of R&D performed by subsidiaries, affiliates, or others*)." *Foreign* is therefore a composite measure that combines outsourced R&D and internal

[2] https://www.nsf.gov/statistics/srvyindustry/surveys/srvyindustry_rd1ai_2007.pdf

R&D, so long as it is conducted outside the US. While we can't use it to assess outsourced R&D, we include it to ensure all R&D inputs are captured. A statistical summary of these variables is presented in Table 2.

[Insert Table 2 About Here]

To test whether growth from R&D is driven by inventions versus knowledge accumulation, I decompose R&D investment into its three SIRD constituents, *Internal R&D* (*R_{it}*), *Outsourced R&D* (*O_{it}*) and *Foreign R&D* (*F_{it}*). I treat them as separate inputs to the firms' production function (Equation 2). This allows me to derive the output elasticities for each form of R&D. The coefficient γ_{ri} captures the output elasticity for internal R&D, while γ_{oi} and γ_{fi} capture the output elasticities of R&D outsourced within the US, and R&D performed by foreign entities, respectively. Each elasticity captures the percentage increase in revenues from a 1% increase in that form of R&D, when other inputs and their elasticities are held constant.

(2) $$Y = A_{i,} L_{i,t}^{\beta_i} R_{i,t-1}^{\gamma r_i} O_{i,t-1}^{\gamma o_i} F_{i,t-1}^{\gamma f_i} S_{i,t-1}^{\delta_i} e_{i,t}$$

I estimate the firm-level elasticities in Equation 3 using a random coefficients model (RCM) that includes a firm fixed effect, A_i, as well as firm-specific elasticities for all inputs. Importantly, if indeed the firm-specific terms are significant, a fixed effects model produces biased estimates.[3]

The translation of equation 2 into an RCM is given in equation 3, where the $\beta\_$ and β_i

[3] Note that a central assumption of RCM is that the β_i terms are uncorrelated with the regressors. This is of particular concern in production function estimation, since firms should allocate more resources to inputs that are more productive. Interestingly, over the period we examine, the covariance between R&D and its elasticity is insignificant: -.0002(.9799). Cooper, Knott and Yang (2022) Appendix compares RCM to other efforts to control for simultaneity in R&D production functions.

represent the direct effect and the firm-specific error, respectively for each of the exponents in equation 1, e.g., $(\beta_2 + \beta_{2i})$ corresponds to γ_{ri} in equation 2. This estimation is a natural extension of the approach in Knott (2008).

(3) $$\ln Y_{it} = (\beta_0 + \beta_{0i}) + (\beta_1 + \beta_{1i}) \ln L_{it} + (\beta_2 + \beta_{2i}) \ln R_{it-1} + (\beta_3 + \beta_{3i}) \ln O_{i,t-1} + (\beta_4 + \beta_{4i}) \ln F_{i,t-1} + (\beta_5 + \beta_{5i}) \ln S_{it-1} + \varepsilon_{it}$$

Firm level data items used to estimate equation 3, include (in $MM unless otherwise stated): *revenues* (Y_{it}), *labor* as full-time equivalent employees (L_{it}), in units of 1000, and *Internal R&D* (R_{it}), *Outsourced R&D* (O_{it}) and *Foreign R&D* (F_{it}). From these primary data, I calculate firm-specific *spillovers* (S_{it}), a "free input" in equations 2 and 3. I follow Knott, Posen and Wu (2009) in computing *spillovers* as the sum of the differences in knowledge between focal firm *i* and rival firm *j* for all firms in the four digit SIC industry with more knowledge (R&D) than the focal firm (Equation 4). Knott et al find this functional form better matches empirical outcomes than either pooled spillovers (all firms in an industry share knowledge equally), or a leader distance form (a firm's spillover pool equals its distance from the frontier firm).

(4) $$S_{it} = \sum_{j \neq i} R_{jt} - R_{it} \ \forall \ R_{jt} \geq R_{it}$$

I lag each of the knowledge inputs (*R,O,F* and *S*) one year. This follows the approach in Cooper, Knott and Yang (2022). As documented in Cooper, et al, tests with alternative lags reveal that one-year and two-year lags were equally significant. Beyond two-year lags, the coefficients on R&D became increasingly less significant. Of one-year and two-year lags, one-year is favored because it allows for more observations.

I require all firms to have a minimum of six years of non-missing data for all variables other than *Outsourced R&D* (O_{it}) and *Foreign R&D* (F_{it}). If a firm-year observation for either of these variables is missing, I assign a value of zero. I delete observations with any other missing values in equation 3. I perform random coefficients estimation of Equation 3 to generate the firm specific errors, β_i. While these are not directly estimated, I form best linear unbiased predictions (BLUPs) of them using post estimation. I then define the output elasticities of *Internal R&D* (R_{it}), *Outsourced R&D* (O_{it}) and *Foreign R&D* (F_{it}) as the sum of $(\beta_2 + \beta_{2i})$ $(\beta_3 + \beta_{3i})$ and $(\beta_4 + \beta_{4i})$, respectively.

Note that SIRD does not collect data on capital or advertising, thus this estimation suffers from omitted variables. To gauge the impact of the omitted variables, I conducted a parallel analysis outside the Census. I utilized Compustat data to generate estimates of γ_i in a version of Equation 1 where all three types of R&D (internal, outsourced and foreign) are summed to form a single R&D variable. This is necessary, because in the public domain (the source for Compustat), firms only report topline R&D. I then compare these estimates to ones from an equivalent production function which has been expanded to include capital and advertising. The comparison indicated the R&D elasticities from the two approaches were correlated at 92%.

V. Results

Results from estimation of equation 3 are presented in Table 3. Model 1 presents results for the full period over which SIRD has all variables (1983 to 2000).[4] The model indicates that the output elasticity of internal R&D is 0.128, whereas the elasticity of outsourced R&D is precisely estimated near zero (0.001) (The 95% confidence interval is -0.003 to 0.005). This means a 10% increase in internal R&D increases revenues 1.3%, whereas a 10% increase in outsourced R&D yields essentially no increase in revenues. The elasticity of foreign R&D is

[4] Prior to 1983 not all SIRD variables were available all years; post 2000 some variable definitions changed

0.008, suggesting that foreign R&D is largely outsourcing to foreign firms, rather than internal R&D performed by foreign subsidiaries, however the data don't allow us to distinguish between the two forms of foreign R&D. These results are robust to the exclusion of interorganizational spillovers (Model 2).

Thus the main results are consistent with the proposition that knowledge accumulation is the main driver of growth from R&D. Inventions contribute 0.8% (0.001/0.129) of firm growth from R&D, while knowledge accumulation contributes 99.2%, at least for this sample over this period.

[Insert Table 3 About Here]

Endogeneity: Firm quality

While the results in Table 3 are consistent with the proposition that knowledge accumulation is the principal driver of growth from R&D, an important question is whether the estimate for outsourced R&D reflects a treatment effect (due to outsourcing itself), or merely an artifact of who outsources (firm quality) or what is outsourced (project quality). Building a model of the outsourcing decision to address the firm quality question requires some understanding of why firms outsource. The explanations in the prior literature discussion were that the performing firm had resources the funding firm lacked, or that outsourcing enhanced flexibility. To determine if there were other rationale which the literature missed, I conducted interviews with R&D managers. Those interviews surfaced some additional motives for outsourcing. Generally, they varied with top-level R&D strategy rather than industry mandate (in less than 5% of industries is it the case that all firms outsource). At one end of the outsourcing spectrum, firms outsource only to universities and government labs (as in Lacatera

2009). They do this to gain access to basic research as well as to identify potential employees. In the middle of the spectrum, firms outsource under special circumstances. For example, they use outsourcing as a flexible substitute for internal hiring when future demand is uncertain; they outsource activities where they permanently expect to operate below efficient scale (as in Clark et al and Mayer et al); or they outsource activities not viewed to add value, such as pharmaceutical firms outsourcing FDA trials to contract research organizations, (CRO)s. At the other end of the spectrum, firms outsource all "non-core" R&D activities.

The SIRD did not collect data on the destination for outsourced R&D. However, these data were collected in its successor, the Business R&D and Innovation Survey (BRDIS). A report of BRDIS data (Morris and Shackelford 2014) indicates 3.4% of outsourcing is to universities, 81.3% is to companies, and the remaining 15.2% is to government agencies and other organizations. This partitioning of outsourced R&D between companies and labs mimics the long-run partitioning of industrial R&D into research versus development: Over the period 1953 to 2018, development comprised 76.5% of R&D.[5] Thus, the vast majority of outsourcing appears to be development, suggesting it conforms to rationale in the middle and extreme ends of the spectrum, where outsourcing substitutes for internal R&D rather than providing access to specialized knowledge.

I employ these insights to construct a two-stage treatment model of the impact of outsourcing, where the first stage models the firm's decision to outsource, and the second stage models the treatment effect of that choice on internal R&D elasticity. This approach is similar in spirit to Higgins and Rodriguez (2006) who examine the impact of pharmaceutical pipelines (their desperation index) on the likelihood of acquiring a target firm, then separately examine the

[5] Table 3 - National Center for Science and Engineering Statistics
ncses.nsf.gov › data-tables › tables › nsf20307-tab003 (retrieved January 21, 2021)

impact of acquisitions on abnormal stock market returns. Whereas Higgins and Rodriguez model the two stages separately, my principal concern is isolating the treatment effect. Thus, I combine the causes and consequences in a two-stage model.

To estimate the first stage, I construct a variable, *neverout*, which takes on the value 0 if the firm has ever outsourced, and takes on the value 1 otherwise. I test all variables in SIRD consistent with prior accounts of the outsource decision. However, because of the limited number of variables in SIRD (the survey only asks 15 questions, one of which is contact information), no first stage model was able to explain more than 5% of the variance in *neverout*. Despite this limitation, the treatment model (Table 4) yields interesting results.

[Insert Table 4 About Here]

Looking first at Stage 1, only two factors are significant in explaining outsourcing—*Basic research* and *foreign R&D*. *Basic research* decreases the likelihood a firm has ever outsourced, while *foreign R&D* increases the likelihood a firm has outsourced. The *foreign R&D* result in unsurprising in that the variable includes outsourcing to foreign entities.

Looking next at the treatment regression which captures the impact of outsourcing on *internal R&D elasticity.* If the quality of firms who outsource drives the lower elasticity of outsourcing, the coefficient for *neverout* should be significant in the second stage model of internal R&D elasticity. This "treatment effect" would mean that firms who outsource have lower internal R&D elasticity. Table 4 indicates that's not the case. The coefficient on *neverout* in model 1 is precisely estimated at 0.000 (the 95% confidence interval is -0.002 to +0.002). This implies that outsourcing firms are of the same quality as non-outsourcing firms (have the same internal R&D elasticity).

Endogeneity: Project quality.

While firm quality doesn't appear responsible for the outsourcing result, it is still possible the lower elasticity of outsourced R&D is driven by project quality/importance—firms outsource their lower quality or less important projects, preferring to allocate their scarce internal resources to the most important projects. To investigate that, I employ a dynamic difference in difference (DiD) approach to estimate how the internal R&D elasticity of outsourcing firms compares to that for non-outsourcing firms in the years leading up to and following the year they first outsource. If firms are merely outsourcing their lower quality or less important R&D projects, their internal elasticity should increase immediately after they shunt those projects to outsourcing. Figure 3 indicates that doesn't happen. In fact, the mean coefficient prior to outsourcing (0.0006) is actually marginally higher than post-outsourcing (0.0000). Thus, it appears unlikely project quality/importance is driving the lower elasticity of outsourcing. [6]

[Insert Figure 3 About Here]

Test of estimate differences over time

Given that the main test, as well as tests addressing endogeneity concerns, support the proposition that growth from R&D is driven by knowledge accumulation rather than invention, it appears that the six-fold increase in R&D outsourcing may be at least partially responsible for the declines in R&D productivity and GDP growth in Figure 2. If the increase is completely responsible for the declines, we should see that the elasticity of both forms of R&D (internal and outsourced) have remained constant over the period of the decline. If however, firms' R&D productivity has declined for other reasons, we should see decline in the elasticity of internal R&D.

[6] Note that this test assumes that firms are siphoning outsourced projects from the pool of internal R&D projects. If we make an alternative assumption, that firms are maintaining their prior internal pool, while outsourcing new projects of entirely different quality, this test is not helpful. However, given that outsourced R&D is growing faster than total R&D, it appears more likely that the outsourced projects are drawn from the evolving internal pool.

I test that by partitioning the SIRD data into three periods, and re-estimating the production function for each period (Table 3: Models 3-5). This partitioning increases the coefficient on outsourced R&D relative to the full sample (Model 1), because firms who aren't active for all years of each window drop out. For these subsamples, the corresponding growth contributions from invention are 6.6% (0.008/0.122), 6.0% (0.006/0.100) and 7.1% (0.009/0.127) of the total contribution from R&D. Thus, while these coefficients are higher than in the full sample (0.8%), they support the main result that knowledge accumulation is the primary driver of growth from R&D.

More importantly, the results indicate the elasticities for all three components of R&D are fairly stable over time. There is no statistical difference in coefficients from model 3 to model 5 for any R&D component. Thus, firms appear not to have gotten worse at any element of R&D. Rather, the aggregate decline in R&D elasticity appears to stem from reallocation of R&D from internal execution to outsourcing.

VI. Discussion

R&D generates two outputs, inventions and knowledge. While the prevailing view is that inventions drive growth, in Romer's (1990) theory, and in the foundations of patent policy, it is knowledge accumulation that drives growth. The distinction between inventions and knowledge accumulation is inconsequential at the macro-level, since both accrue within the economy. The distinction may become important at the firm level, however, because firms can outsource their R&D. When they do so, inventions and knowledge accumulation are no longer co-located. Inventions belong to the funding firm, while knowledge accumulates at the performing organization. Thus the phenomenon of R&D outsourcing presents both the need to determine whether inventions or knowledge accumulation drives growth, as well as the opportunity to conduct the test.

Accordingly, I test whether invention or knowledge accumulation drives growth by separately characterizing the output elasticity of internal R&D and outsourced R&D. I find that while the elasticity of internal R&D is 0.128, that for outsourced R&D is 0.001. These elasticities translate into the growth contributions from each output of R&D. Since outsourcing provides only inventions to funding firms, inventions contribute 0.8% of the growth from R&D. Since internal R&D provides both inventions and knowledge accumulation to funding firms, knowledge accumulation contribute 99.2% of the growth from R&D, at least over this time period, and for the full sample.

Efforts to control for endogeneity in the outsourcing decisions indicate that neither firm quality nor project quality are responsible for the lower elasticity of outsourced R&D. Results which partition the sample into three periods are consistent with the main results, but raise the contribution of invention from 0.8% to up to 7.1% of the growth from R&D.

Beyond the theoretical contribution that growth from R&D stems principally from knowledge accumulation rather than inventions, this research has practical implications as well. It explains how the six-fold increase in R&D outsourcing has contributed to the decline in firms' R&D elasticity and nominal GDP growth. Funding firms have foregone an increasing amount of knowledge accumulation from their R&D.

Moreover, the fact that knowledge, rather than inventions, drives growth from R&D helps explains why R&D outsourcing, once begun, grew six-fold, as well as why firms persist with it. Once a firm begins outsourcing its R&D, it foregoes internal knowledge accumulation, while increasing knowledge accumulation of the performing organization. Accordingly, capability of the funding firm deteriorates over time, while capability of the performing firm increases over time. Thus R&D outsourcing becomes increasingly more attractive over time, just as Mayer et al observed with services outsourcing.

The fact that much of the decline in R&D elasticity can be explained by outsourced R&D is actually encouraging. It implies that firms have not gotten worse at R&D, they are just doing less of it themselves. Thus, it may be possible to restore R&D elasticity and economic growth fairly simply—by gradually bringing outsourced R&D back inside the funding firm.

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TABLE 1. Mapping Elasticities of Internal and Outsourced R&D onto Growth Contributions from Inventions and Knowledge Accumulation

	Invention	Knowledge Accumulation
Internal R&D	Funding Firm	Funding Firm
Outsourced R&D	Funding Firm	Performing Organization
Growth contribution	Elasticity of either	Elasticity of Internal R&D - Elasticity of Outsourced R&D

TABLE 2. NSF Survey of Industrial R&D (SIRD) Data

28500 Firm-year Observations (3500 firms)

	Mean	Std.Dev.	1	2	3	4	5	6
1.ln(revenue)	10.89	2.28	1.00					
2.ln(scientists)	2.82	1.93	0.53	1.00				
3.ln(employees)	6.20	2.00	0.92	0.76	1.00			
4.ln(InternalRD)	7.73	2.46	0.63	0.91	0.71	1.00		
5.ln(outUS)	5.45	2.47	0.29	0.54	0.33	0.63	1.00	
6.ln(foreign)	7.27	2.29	0.44	0.62	0.49	0.64	0.51	1.00

TABLE 3. Decomposing R&D elasticity

Random coefficients estimation	(1)	(2)	(3)	(4)	(5)
Dependent variable: ln(Revenues)*Yit*	1983-2000	1983-2000	1983-1988	1989-1994	1995-2000
ln(employees) *(Lit)*	**0.841**	**0.843**	**0.885**	**0.867**	**0.921**
	0.006	0.006	0.018	0.015	0.023
ln(internalR&D) *(Rit-1)*	**0.128**	**0.126**	**0.114**	**0.094**	**0.108**
	0.004	0.004	0.015	0.010	0.011
ln(outsource R&D) *(Ot-1)*	0.001	0.002	**0.008**	**0.006**	**0.009**
	0.002	0.002	0.003	0.003	0.004
ln(foreignR&D) *(Fit-1)*	**0.008**	**0.007**	0.003	0.004	0.000
	0.002	0.002	0.004	0.004	0.003
ln(spillovers) *(Sit-1)*	**0.004**		0.003	-0.005	-0.008
	0.001		0.002	0.002	0.002
Constant	**4.872**	**4.915**	**4.487**	**5.210**	**4.931**
	0.049	0.047	0.147	0.113	0.123
Log-likelihood	-25911	-26195	-2094	-5019	-3902
Wald chi2	23438	24022	3939	5649	8292
prob>chi2	0	0	0	0	0
Observations*	28500	28500	2500	5000	5000
Firms*	3500	3500	500	1000	1000

*Rounded to nearest 500 by the Census to preserve anonymity

Std errors below coefficients

Coefficients in bold significant at 0.05

TABLE 4. Treatment test of firm quality

Treatment regression Dependent variable: Internal RQ	
ln(employees)	0.000
	0.000
Scientist ratio (dns/dne)	**0.006**
	0.001
Scientist cost (totcost/dns)	**0.000**
	0.000
Neverout	0.000
	0.001
Constant	**0.093**
	0.001
wald chi2	40.46
prob>chi2	0
stage 1 neverout	
Basic percent (brtot/rdtotown)	**0.511**
	0.122
Applied percent (ardtot/rdtotown)	-0.186
	0.124
Foreign percent (outforeign/RDtrue)	**-1.330**
	0.215
Federal percent (fedtot/Rdtrue)	0.194
	0.164
Constant	**0.857**
	0.078
/ath rho	0.030
/lnsigma	-4.548
rho	0.030
sigma	0.010
lambda	0.000
prob>chi2	0.690
Observations*	6000
Firms*	500

*Rounded to nearest 500 by the Census to preserve anonymity
Std errors below coefficients
Coefficients in bold significant at 0.05

FIGURE 1. Share of Industrial R&D contracted to other organizations

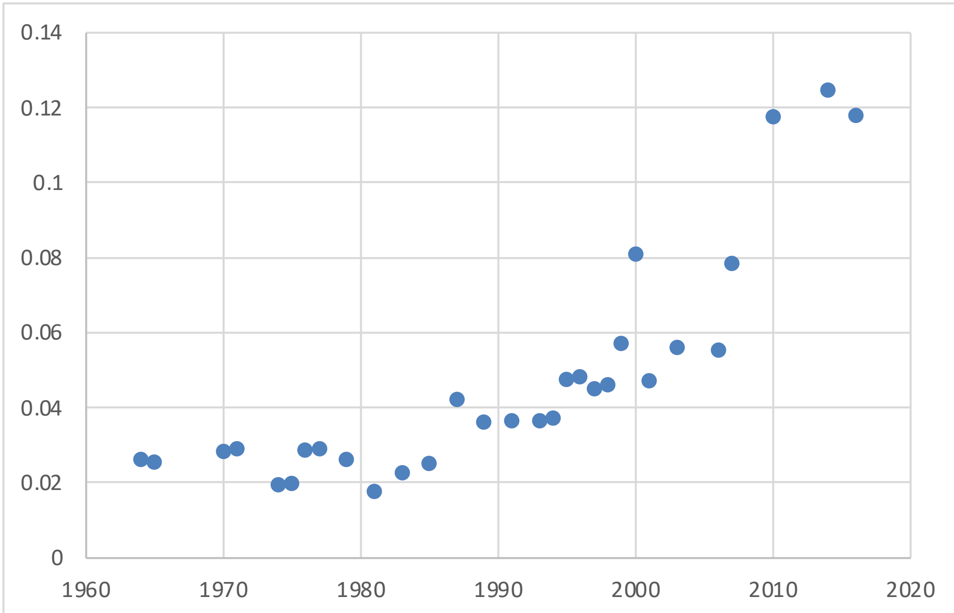

FIGURE 2. R&D Elasticity (RQ) and Nominal GDP Growth (Historical)

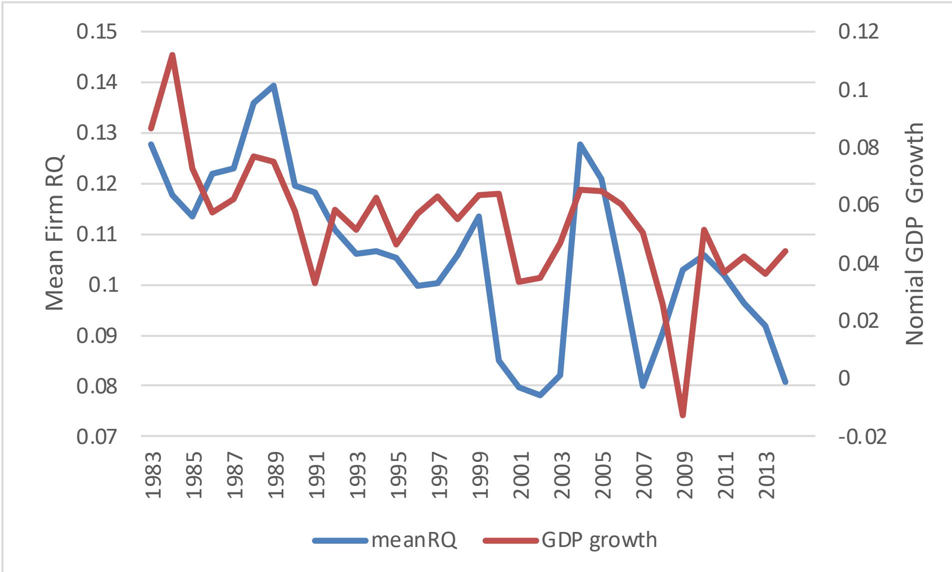

FIGURE 3. Test of Project Quality