The Value of Firm Communication for Innovation: Evidence from the Adoption of Communication Technologies*

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Abstract

Innovation is a company-wide endeavor that requires the combination of knowledge inputs from workers with different specializations. Thus, problems in the internal communication of large corporations hinder their innovation capacity. In this article, I show how a reduction in communication costs, coming from the adoption of new communication technologies, helps large firms to achieve higher levels of innovation. I find the increase in innovation is more pronounced for firms with widely dispersed site locations, firms in low competition sectors and firms with low innovation in the past. Moreover, using information on the economic value of innovations, I find better communication is most effective in increasing the number of high-value innovations. Finally, I find a positive response of firm productivity to increases in innovation. I interpret the results as evidence of the impact of new technologies in overcoming limitations in the internal organization of large corporations, potentially increasing their competitive strength as a result.

Keywords: ICT, innovation, firm communication, firm productivity.
JEL codes: O31, O32, D22

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1 Introduction

Small firms have been considered to be responsible for a disproportionate share of significant innovations in the past. Quoting Holmstrom (1989): "The causal evidence suggests the hypothesis that large firms are at comparative disadvantage in managing truly innovative research". However, the patterns of innovation in the last decades reveal a striking increase in patenting concentration by market leaders and large firms (Akcigit and Ates (2019b)). This increase in innovation can be welfare improving if large firms were innovating too little in the past. But it can also have profound implications for market competition and business dynamism by increasing large firms' market power and discouraging new entries. To understand the consequences and address possible negative externalities of this change in innovation is necessary, first, to find out the reasons behind it.

In this paper I present an explanation based on an increase in the innovation capacity of large firms. I show how improvements in communication within the firm driven by technology adoption allow large firms to be more innovative. Because the ability to transmit information among workers is central to the innovation process, firms experiencing improvements in communication are able to increase their levels of innovation. To empirically examine this hypothesis I exploit information on the adoption of corporate intranets, i.e. private computer networks primarily intended to reduce communication costs and facilitate the access to information in the environment of an organization[1]. Using an original panel dataset of US corporations from 1988 to 2002 with plant-level information, I find that intranet adoption increases firm patent counts, citation-weighted patents and dollar-weighted patents. The effect of intranet adoption is larger in increasing the number of high economic value patents, and for firms with more impediments to communicate, less incentives to innovate and lower innovation in the past. Moreover, I find that the increase in innovation translates in an increase in firm productivity. I confirm the results are robust to endogeneity concerns in the adoption of intranets by using an instrumental variable identification exploiting variation in historical expertise with network technologies across locations.

Innovation requires coordinating efforts and inputs from workers with different specializations. Because of their different fields of expertise, these workers are likely to be spread across different teams and divisions of an organization. Moreover, the idiosyncratic and unpredictable nature of innovation hinders the possibility of coordinating innovation activities by standardizing processes and letting employees stick to some pre-agreed plan, as it is usually done in production and routine tasks[2]. Communication among workers thus becomes crucial to coordinate all relevant knowledge that is dispersed across the firm. Reduction in communication

[1]A more detailed discussion of the main features and functionalities of intranets is presented in Appendix A.

[2]According to March and Simon (1958): "The type of coordination used in the organization is a function of the extent to which the situation is standardized. (...)We may label coordination based on pre-established schedules coordination by plan, and coordination that involves transmission of new information coordination by feedback. The more stable and predictable the situation, the greater the reliance on coordination by plan."

cost will help alleviate coordination problems and will result in higher innovation levels. This is especially relevant for large firms, where it is necessary to coordinate an increasing number of agents with more narrowly-defined tasks and knowledge[3].

The data on the adoption of intranets comes from the private sector data source Harte-Hanks. This is a plant level panel dataset with annual information on the stock of technology, which probably represents the richest source of historical information to study firm's Information and Communication Technology adoption (ICT hereafter)[4]. Because firms in my sample are large corporations with many sites, I measure firm's intranet adoption each year as the share of firm sites that have adopted intranet by that moment in time. The point of reference for the commercial diffusion of intranets is the year 1995 (see Forman et al. (2012) and Scott (1998)). However, because of its non-commercial origins, many intranet technologies were quite mature by this time and were quickly adopted by firms. By exploiting variation in the adoption of intranet both across firms and over time, I can estimate its effect on innovation measured as the number of successful patents applied by a firm in a given year.

The main empirical challenge for identification of the causal effect of better communication on innovation is the possible existence of firm-specific transitory shocks to innovation that can be correlated with the adoption decision. To address this concern, first, I perform a series of robustness checks to show that the effects are not driven by simultaneous increases in firm R&D investment, capital investment or other investments in communication technologies, like the internet, that are not directly intended to improve internal communication. Second, I construct an interacted instrument that exploits differences across firms in the costs to adopt intranets when these became commercially available. This instrument combines two sources of variation: (i) changes in availability of intranet technologies over time; and (ii) cross-sectional variation in familiarity and expertise with network technologies in the regions where firms are located - some regions were more familiar with intranet-type technologies because of the existence of a connection to an early computer network (Bitnet) used by the research community of a local university. Because decisions about the connection to this type of predecessor networks were taken years before the commercialization of intranets, the instrument should affect the costs and propensity of intranet adoption and should remain exogenous to firm-specific transitory shocks to innovation as argued in Forman et al. (2012),.

The heterogeneous effects of intranet adoption provide further evidence on how improvement in communication of a firm impacts its innovation capacity. The increase in innovation is larger for firms with more widely dispersed site locations, firms with low levels of innovation in the past and firms that operate in low competition sectors. This result shows that improvement

[3]The saliency of this trade-off between specialization and communication in large organizations was previously studied by Becker and Murphy (1992), Bolton and Dewatripont (1994), Garicano (2000)).

[4]Some influential articles such as Bresnahan et al. (2002), Brynjolfsson and Hitt (2003), and Bloom et al. (2016) have used this dataset to measure hardware utilization. I focus on the adoption of network communication technologies, a much less explored component of these data.

in communication is more effective in fostering innovation in firms that face greater barriers and incentives to innovate. Using information on the economic value of each patent, I find that intranet adoption is most effective in increasing the generation of high-value patents. By contrast, it does not affect more intensively the generation of innovations of higher scientific quality, as proxied by the number of citations received by a patent. This result is consistent with intranets improving communication not within the research team, but between the research team and other firm departments with different specializations. As a result, the pure scientific quality of innovation is not affected, but the new information flowing between the research department and other parts of the firm is specially valuable to identify profitable innovation ideas and to attune them to consumer preferences and market opportunities.

Finally, I study the effects of intranet adoption and innovation increases on firm productivity. I identify a positive response of firm productivity to increases in innovation. Thus, better communication is indirectly affecting productivity by increasing firm's innovation. This positive impact of innovation on productivity has also been documented in other settings (Crépon et al. (1998) and Doraszelski and Jaumandreu (2013)). By contrast, I find no direct contribution of intranet adoption to firm productivity. Production tasks are predictable and can be coordinated ex-ante by standardized processes. As a result, the direct impact of improved communication on productivity is of second-order importance.

This article provides empirical evidence on the importance of internal firm communication for innovation activities and shows how ICTs can foster innovation by alleviating communication problems. Previously, Forman and Zeebroeck (2012) and Agrawal and Goldfarb (2008) showed how better communication between different research teams raises their probability of collaboration in joint projects[5]. My results go one step further than the current literature by showing how better communication can not only raise collaboration among researchers but increase innovation at the organization level. This work also adds to the understanding of the effects of ICT investments on firm productivity. It shows that one of the channels through which ICT investment impacts firm productivity is by increasing firm innovation. This result complements previous works studying the role of ICT as a General Purpose Technology acting as a complement of other factors such as firm decentralization (Bloom et al. (2014)); managerial skills (Bloom et al. (2012)) and human capital (Autor et al. (2003) and Akerman et al. (2015)). Finally, the results in this article contribute to explain the existence of large and persistent differences in productivity levels across businesses (Syverson (2011)), which are closely connected to other highly relevant phenomena like the rise in large firms' market power and decreases in business dynamism documented for the last decades (De Loecker and Eeckhout (2017) and

[5]There are also a number of articles showing the existence of a positive correlation between better communication and innovation. For instance, Jensen et al. (2007) demonstrate for a sample of Danish firms how those excelling in innovation count with a good system of internal communication and transmission of tacit knowledge. Mansfield and Wagner (1975) shows how a closer integration of the departments of marketing and R&D increases the probabilities of commercialization of technologically successful projects.

Akcigit and Ates (2019a)).

The rest of the article is organized as follows. Section 2 describes the data. Section 3 explains the identification strategy. Section 4 presents and discusses the results, and Section 5 concludes.

2 Data

To implement the empirical analysis I use three different datasets. First, I obtain information on the adoption of intranets and other ICTs from Harte Hanks Technology database. Second, I use the Kogan et al. (2017) patent dataset which contains information on firm assignee and year of application for each patent. Finally, I complement this with firm productivity estimates and other control variables obtained from Compustat.

2.1 ICT data

I use the Computer Intelligence Technology Database (CiTDB), a plant level ICT panel produced by the information company Harte-Hanks (hereinafter HH). Since the late 1980s HH has collected IT data in order to sell it to large producers and suppliers of IT products that use it to target their sales efforts. This exerts strong market discipline on the data quality, as major inaccuracies are likely to be picked up by HH's customers. HH surveys establishments annually on a rolling basis obtaining information of the firm IT stock. The CiTDB contains detailed hardware, equipment, and software information at the plant level, which probably represents the richest source of historical information on IT adoption.

In this work I focus on studying the effects of intranet adoption. To do so, my sample covers the years previous to intranet commercialization, which started in 1995, and the years of its diffusion. Furthermore, my data have information on intranet adoption not for every year but for every other year. In order to accommodate these two requirements, my sample includes all alternative years from 1988 to 2002, giving a total of 8 firm-year observations. Because HH information is disaggregated at the plant level but patent and accounting information are available only at the firm level, I aggregate intranet adoption at the firm level by calculating the percentage share of firm plants reporting to have adopted intranet at a given year. This is my main measure of firm intranet adoption[6]. Because intranets start their commercial diffusion in 1995, intranet adoption for 1994 and prior years can be considered to be zero (Forman et al. (2012) and Scott (1998) adopt this same approach).

My sample is restricted to large corporations because until the late 1990's HH surveyed only firms in the Fortune 1000 list. This is, in general, a limitation to obtain generalized

[6] I show that results do not change by using alternative measures of intranet adoption.

conclusions on the effects of technology adoption on firm outcomes (Draca et al., 2006). However, the results are still highly important because (i) firm internal communication problems are greater in large firms than in small ones; and (ii) big corporations are responsible for a very large share of R&D investment and innovation[7].

2.2 Patent data

I measure firm innovation by the number of successful patents applied by a firm in a given year. Patents constitute the best available measure of firm innovation outcomes, include interesting technical information, and they are extensively used in the Economic literature. I use a new patent dataset constructed by Kogan et al. (2017). This is an extension of the NBER Patent-citation dataset containing all patents granted by the US Patent and Trademark Office (USTPO) from 1926 to 2010 and all citations received by each patent. It further includes a new measure of the economic value of each patent. This value is estimated by exploiting movements in stock market prices following the day that a patent is issued to a firm.

2.3 Compustat data

Compustat North America is a database of U.S. and Canadian fundamental and market information on more than 24,000 active and inactive publicly held companies. It is a near census of publicly traded firms, providing thousands of annual reports. First, I use Compustat (Fundamental Annuals) information on sales, number of employees, capital, investment, and consumption of intermediate inputs I obtain firm productivity estimates. Appendix C contains a more detailed explanation of the variables used and the estimation procedure. Second, I also use Compustat to retrieve information on the levels of annual R&D investment reported by firms[8].

2.4 Matching of datasets

To use all the above information, it was necessary to match firms in the three different datasets. I started by matching patent data to Compustat information. Patent assignees in Kogan et al. (2017) database are identified by CRSP permno number. Using a bridge dataset linking CRSP and Compustat firm identifiers I can directly connect patent assignees to Compustat firms. Matching HH firm information with the two other datasets was a more complicated task. HH does not provide firm identifiers that link firms in HH to other commonly used databases. As a result, I had to resort to string matching algorithms in order to match firms by their names. The details of this matching process are explained in detail in Appendix B.

[7]Firms in the sample are responsible for approximately 25% of total R&D investment carried out in the US during the sample years (source: https://www.aaas.org/page/historical-trends-federal-rd).

[8]The US Statement of Financial Accounting Standards No.2 (SFAS 2) requires US firms to disclose in their financial statements material R&D expenditures.

2.5 Descriptive statistics

Once firms in the three datasets are matched, I construct a balanced panel of firms including all even years between 1988 and 2002. To do so, I drop firms that are not fully covered by Compustat or HH in all these years. Moreover, I drop firms that are not granted any patent over the sample years as in a Poisson fixed effects regression they do not provide any variation in the estimation. This is a widespread practice in the literature and has no implications for the consistency of the estimates. A more thorough explanation of the reasons for this will be presented in the next section.

My final data is a balanced panel of 348 firms. On average, I have information on intranet adoption for 37 establishments per firm. Table 1 presents some characteristics of these firms in more detail. As mentioned above, these are large firms, which is reflected in the high levels of employment (35,000 employees on average with a firm-year maximum of 1.4 million workers), capital (2,942 million USD on average), and sales (9,485 million USD). The sample covers close to 10% of the total US labor force and around 33% of total sales by US public firms. It is also interesting to highlight the high variation across firms in all these dimensions. This dispersion is even more pronounced in innovation-related variables. Some firms consistently invest heavily in R&D and generate many dozens or even hundreds of patents every year, whereas, in other cases, innovation is a more sporadic and less intense activity.

As mentioned above, I define the level of intranet adoption for a firm in a given year as the percentage share of firm sites that have adopted intranet at that point in time. To identify the effect of intranet adoption on patenting, I exploit both variation over time in intranet penetration and across firms in each year. Figure 1 shows the different levels of intranet penetration for each of the years. Before the year 1996 adoption is 0 for all firms. In 1996, almost 75% of the firms had adopted intranet in at least one site. However, in most of the firms penetration of intranet is still low with high levels of dispersion (average adoption of 10.2% with standard deviation of 11.5%). This timid diffusion in the beginning was followed by a rapid expansion in subsequent years (average adoption of 27% in 1998 and 44.7% in 2000) that slows down to reach 55% in 2002. This pattern is consistent with the well-known "S" shape observed in the diffusion process of many other innovations (Griliches (1957)). Interestingly, as the level of intranet diffusion increased, so too did the dispersion in penetration across firms (around 20% standard deviation for the years 1998, 2000, and 2002).

A number of reasons can account for the apparently puzzling fact that different establishments of the same firm adopt intranet at different moments in time[9]. The main reason is probably the existence of significant geographical variation in the local availability and costs of Internet and intranet's connectivity during the late 1990s (see Forman et al. (2005)). This was especially important for intranet implementation, as it usually requires high-speed con-

[9]For a comprehensive analysis of this issue refer to Forman et al. (2012).

nectivity and not all locations counted with this service over this period. Another reason to mention is that control about IT decisions in firms is often decentralized (see Sambamurthy and Zmud (1999); McElheran (2011)). As a result, IT investment decisions may ignore potential complementarities arising from coordinated investments.

Finally, Figure 2 captures the different trends in patenting over time for those firms adopting intranet more intensively (strong adopters) and those others doing it less intensively (weak adopters). Because treatment in this context is not a binary variable as in many other economic settings, it is not obvious how to define who is treated and non-treated. I consider as strong adopters those firms that are above the median of intranet adoption for all years between 1996 and 2002 (98 firms). Figure 2 shows for each year in the sample the average number of patents generated by a firm in each of the two groups. This graph shows that (1) there exists an increasing trend in patenting over time for all firms in the sample; (2) both strong intranet adopters and weak intranet adopters present parallel trends in patenting growth for years before 1994; and (3) there is a pronounced acceleration in patenting after 1994 for strong intranet adopters coinciding with the diffusion of intranets.

3 Empirical Identification

3.1 Estimation Strategy

Following a literature initiated by Hausman et al. (1984), I consider a firm patent production function in which I include intranet adoption as one of the determinants of patenting. Because the dependent variable, number of successful patent applications, is a count variable with overdispersion and many zeros, I use Poisson-based econometric models and estimation methods (see Cameron and Trivedi (2013)). Then, assuming that the patent process follows a Poisson distribution, the expected number of patents for firm j at year t has the following exponential functional form[10]

$$E[pat_{jt}|Intranet_{jt}, \mathbf{x_{jt}}, \eta_j] = \lambda_{jt} = exp(\alpha\ Intranet_{jt} + \beta\ \mathbf{x_{jt}} + \eta_j + \delta_t) \tag{1}$$

where η_j is a firm fixed effect and $\mathbf{x_{jt}}$ includes time-varying controls such as R&D investment, number of employees, and year fixed effects. Coefficients of this model should be interpreted as semielasticities. Therefore, α is the semielasticity of patenting with respect to $Intranet_{jt}$. Because I include firm fixed effects, all firm time-invariant characteristics are going to be subsumed and not individually identified. In order to estimate this model by Poisson regression it

[10]The variable $Intranet_{jt}$ constitutes a measure of intranet penetration in firm j at year t. As argued in Bresnahan et al. (1996), intranets require little adoption or coinvention to be used successfully. Considering also that most patents are applied at an early stage in the innovation process (Pakes (1986)), I focus on short-run changes in innovation driven by intranet adoption.

is necessary to make an assumption of strict exogeneity. Thus, estimates may be inconsistent if regressors are predetermined (e.g., if past shocks to patenting affect R&D investment or intranet adoption in the future).

One big advantage of using Poisson fixed effects regression is that, in contrast with many other non-linear panel data estimators, there is no incidental parameter problem. Even in a short panel (T fixed) with $n \to \infty$ one can consistently estimate α given that the conditional mean function is multiplicative in the fixed effect. Similar to the transformation used in the linear fixed effects regression, the fixed effects can be eliminated by using a conditional MLE. Some algebra leads to the simple moment condition

$$\sum_{j=1}^{n} \sum_{t=1}^{T} x_{jt} \left(pat_{jt} - \frac{\lambda_{jt}}{\overline{\lambda_j}} \, \overline{pat_j} \right) = 0 \tag{2}$$

This moment condition reveals an issue: observations with $pat_{jt} = 0$ for all T make no contribution to the estimation of α and β. Thus, it is better to drop them out of the sample. As commented on above, this is a common practice in the innovation literature (see for instance Aghion et al. (2013)) and, as shown by Blundell et al. (2002) it has no implications for the consistency of the estimates.

3.2 Identification Issues

The most basic concern to consider for the identification of the effect of intranet on patenting is a potential selection based on firm characteristics. This would be the case if firms with better or worse innovation capacity were the ones adopting intranets more intensively. Then, the estimated effect of intranet may just be a spurious correlation due to omitted firm characteristics. Using panel fixed effect estimation I control for all firm permanent characteristics and, as a result, concerns about time-invariant endogeneity are solved.

Adopting this approach, the identification strategy exploits variation over time and across firms in the adoption of intranet to estimate its effects on innovation. In other words, given that different firms are adopting intranets with different intensities at different times, I exploit changes in patenting for those firms adopting intranets more intensively at a given moment in time to identify intranet's effect on innovation. This identification strategy hinges on the existence of parallel trends in the propensity to patent for strong intranet adopters and weak adopters in the absence of intranet adoption (after controlling for observable time-varying factors). This may fail if there are firm-specific unobservable transitory shocks that simultaneously affect firm patenting and adoption of intranets. Throughout the results section, I present a series of robustness checks and IV estimations that support the rejection of this hypothesis and favor a causal interpretation of the estimates.

4 Results

This section is structured in three subsections. Subsection 1 reports the baseline results for the effect of intranet adoption on innovation, together with robustness specifications and instrumental variable estimates. Subsections 2 analyzes the heterogeneous effects of intranet adoption for the generation of different types of innovations and for different innovating firms. Subsection 3 presents results about the effects of innovation on firm productivity.

4.1 The Effects of Intranet Adoption on Innovation

Baseline Results

The baseline results are based on a Poisson regression of the number of successful patents applied by firm j in year t on the level of intranet penetration and different sets of control variables (see equation 1). The first column of Table 2 shows a positive and significant estimate on the effect of intranet when I control only for year fixed effects. Further controlling for firm fixed effects, in column 2 the estimated effect of intranet adoption on patenting is still significant at the 1% level although smaller in magnitude.

In column 3 I include as controls the contemporaneous level and the first lag of R&D investment. R&D is the most immediate input for innovation and including it as a regressor will partially capture innovation productivity shocks. Because patents tend to be applied at an early stage of the innovation process (Pakes (1986)), including the contemporaneous level and the first lag of R&D is the best way to capture firm-specific transitory shocks to innovation[11]. Later, I will show how the results do not change by including further lags of R&D or using alternative measures as R&D stock. I also control for firm size by including the number of firm employees as a regressor. Earlier studies including Lanjouw and Lerner (1996) and Lerner (1995) point out that firm size has an effect on innovation due to the presence of economies of scale in the innovation process. It can also be the case that changes in firm size capture variation in unobserved variables affecting innovation incentives, such as firms' perspectives about the future. The inclusion of these controls reduces the size of the effect of intranet by more than one third. The magnitude of the estimated effect implies that a 10 percentage point increase in intranet penetration is associated with a 5.6% increase in patenting once changes in R&D investment and firm size are controlled for.

Following some of the seminal works on the literature of patent production function estimation (Hausman et al. (1984); Hall et al. (1986); etc), in column 4 I include as controls the contemporaneous level and the first four lags of R&D investment. Including these extra lags has minimal consequences in the estimated effect of intranet adoption. Moreover, because

[11]Hall and Ziedonis (2001) and Forman and Zeebroeck (2012) among others adopt a similar approach and control for the contemporaneous level of R&D investment.

of the high autocorrelation in firm R&D investment levels, only the first and last of the years included as controls become significant, which is a common result in the literature.

In column 5 I regress by OLS the level of R&D investment in year t on the contemporaneous level of intranet penetration including firm and year fixed effects. The positive coefficient estimate indicates that intranet adoption affects patenting in two ways. First, it impacts patenting in a direct way by increasing the production of patents once R&D investments are controlled for. Second, it fosters patenting in an indirect way by prompting an increase in R&D investment that in turn will result in more patenting. Consistent with this double channel, the coefficient on the effect of intranet on patenting is larger when R&D investments are not controlled for (see column 2).

Robustness Analysis

It is well known that whereas some patents have a very strong innovative content others represent minor advances. Using simple patent counts can then underestimate or overestimate the importance of innovations. As a result, it could be the case that the higher number of patents firms generate when they adopt intranets represents marginal innovations with a negligible innovative content and the total amount of generated innovation does not change. In order to tackle this problem, the literature has proposed using information on the number of forward citations received by a patent as a proxy for its quality, radicalism, or innovative content (see Hall et al. (2005)). In column 1 of Table 3, I weight patents by an adjusted measure of the number of forward citations received [12]. Doing this, I have to drop five firms that did not receive any citation for any of the patents they obtained during the sample period. The point estimate for the effect of intranet on citation-weighted patents is significant and a bit larger in size than in the baseline regression.

However, it is still possible that some patents represent a breakthrough for a firm despite having low innovative content, or the other way around. Kogan et al. (2017) provide an estimate of the private value of a patent by exploiting movements in stock prices. They further confirm that this new measure is a useful proxy for the value of patents, showing that it is more associated with creative destruction and is more strongly related to firm growth than citation-weighted patent counts. The dependent variable in column 2 is the number of patents generated by the firm in a given year weighted by the adjusted economic value of each patent[13]. The effect

[12] I divide the number of citations received by a patent by the average number of citations of all patents that were issued in the same year. Making this adjustment corrects for the different time spans during which different patents applied for in the same year were able to receive citations. For instance, consider two patents applied for in the year 2000. One of them is granted in 2001 whereas the other is granted in 2005. In my data I have information on citations received until 2010. As a result, patents granted in 2001 were able to receive citations during 9 years whereas patents granted in 2005 could do so only for 5 years. Independently of their qualities, it is likely the case that the patent granted in 2001 received a higher number of citations. Normalizing patent counts by the average number of citations received by patents granted in the same year partially corrects for this problem (see Lerner and Seru (2017) for a monograph on these issues).

[13] I divide again the economic value of a patent by the average of the patent economic values of all the patents

of intranet on this adjusted measure of patent counts is positive and significant. It is also interesting to notice that in contrast to simple patent counts and patents weighted by citations, firm changes in R&D investment do not seem to have strong explanatory power in this case. This is an issue probably worthy of further investigation.

Columns 3 to 8, check the robustness of the results to omitted variable bias presenting different specifications with extra added control variables and using different definitions of the variables of interest. In the next section I will resort to instrumental variables estimation to further address this concern.

Column 3 shows how results are robust to changes in the way in which firm's intranet adoption is measured. I construct the variable $Weighted\ intranet_{j,t}$ as the share of establishments adopting intranet in which each site is weighted by its number of employees. The effects remain positive and significant at the 5% level.

Column 4 includes a dummy equal to one when at least one establishment of the firm reports having adopted intranet. One source of concern is that when a firm decides to intensify its innovation strategy one of the things they do, together with many other possible initiatives, is to start the implementation of an intranet. As a result, the intranet dummy variable (but not the level of intranet penetration) should be positively biased if it is the decision to initiate the deployment of the intranet what correlates with other firm policies intended to increase innovation. This does not seem to be the case as the dummy variable is not significant and coefficients on the rest of the variables remain similar in magnitude.

Given that intranets can be adopted as part of a wider modernization strategy of the firm one would like to control for other types of investment decisions that can potentially drive the results. More specifically, because the deployment of intranets and Internet was contemporaneous, it could be the case that the effect of the two is being confounded. Moreover, the purpose of each of them is very different; whereas intranets mainly improve internal firm communication, the main effect of the Internet is to facilitate external communication[14]. Therefore, they can both potentially foster innovation but through very different channels that I would like to disentangle. I construct the variable $Internet_{j,t}$ as the percentage share of firm establishments reporting to use the Internet for research. Column 5 shows how its effect on patenting is non-significant and the coefficient on intranet becomes somewhat larger in size and significant at the 1% level. Controlling more generally for Internet adoption or for capital installed at the firm, results remain unchanged.

that were issued in the same year. This corrects for differences in stock market situation at the time when a patent is granted. Consider again two patents applied for in the year 2002. One of them is issued in 2004, when stock markets were in a good situation and the other in 2008 when stock markets were at a minimum. Independently of the quality of the patents, it is likely that the estimated economic value of the patent granted in 2004 is higher. Dividing by the corresponding average value of patents granted in the same year we partially correct for this problem.

[14]Because the Internet at this time was still at an early stage, those firms reporting to use the Internet for research were basically using it to obtain information about their competitors, markets, or new products.

In column 6 I control for an alternative measure of R&D investment. Following Hall and Hayashi (1989) and Klette (1994), I construct a measure of the stock of R&D investment using a permanent inventory method (see Appendix C for a more detailed explanation). The effect of intranet on patenting is perfectly robust to this alternative measure of R&D investment.

Despite the robustness of the results obtained so far, one could still be concerned about the possible existence of firm-specific trends on patenting correlating with the adoption of intranets. To address this concern, I introduce different time trends for different types of firms to confirm that those omitted variables are not driving my results. In column 7 I include time trends for different quartiles of "firm's innovative capacity" that I proxy in the following way. Following Blundell et al. (1999), I construct the variable $Patent\ stock_{j,t}$ using a permanent inventory method (assuming a 15% yearly depreciation rate) and use the value of this variable at the beginning of the sample to proxy for firm's innovative capacity. For instance, if it were the case that less innovative firms are increasing their innovation capacity and, for some reason, these are also the firms that are adopting intranets more intensively, by controlling for these trends the endogeneity problem would be solved. Column 7 shows how the effect of intranets seems to be robust to this form of endogeneity. In column 8 I include different time trends for firms that operate in digital sectors. During the '90s there is a high expansion in the digital sectors. At the same time, it is likely that firms operating in digital sectors are adopting intranets more intensively. Column 8 shows the effect of intranet adoption on patenting is robust to controlling for these time trends. Controlling for year-specific dummies instead of time trends the results in columns 7 and 8 remain unchanged.

Instrumental Variable Estimation

To further address the concerns of omitted variable bias, in Table 4 I present results of instrumental variable control function estimation (see Wooldridge (2015)) exploiting exogenous variations in the costs of intranet adoption. Under exogeneity of intranet adoption, the following moment condition holds

$$E[e^{v_{jt}}|Intranet_{jt}, \mathbf{x_{jt}}, \eta_j, \delta_t] = 1 \tag{3}$$

where v_{jt} is the error term associated with equation (1). This moment condition is not valid if $Intranet_{jt}$ is endogenous. I assume that $Intranet_{jt}$ satisfies the following linear reduced form where z_{jt} is the instrument

$$Intranet_{jt} = \mu_j + \psi_t + \pi\ z_{jt} + \gamma\ \mathbf{x_{jt}} + u_{jt} \tag{4}$$

and the following moment condition holds

$$E[u_{jt}|z_{jt}, \mathbf{x_{jt}}, \mu_j, \psi_t] = 0 \tag{5}$$

As a result, controlling in (1) for $\rho(u_{jt})$, a non-parametric function of u_{jt}, should be enough to remove the endogeneity bias. I proceed in a two step estimation, estimating first equation (4) and controlling for a polynomial series expansion of the estimated residual in equation (1). In conclusion, I use the following extended moment condition in which a simple test for exogeneity of $Intranet_{jt}$ can be conducted by checking the significance of $\rho(u_{jt})$

$$E[pat_{jt}|Intranet_{jt}, \mathbf{x_{jt}}, \eta_j, \delta_t, u_{jt}] = \lambda_{jt} = exp(\alpha \ Intranet_{jt} + \beta \ \mathbf{x_{jt}} + \eta_j + \delta_t + \rho(u_{jt})) \quad (6)$$

As I have just shown, after controlling for $\rho(u_{jt})$, $Intranet_{jt}$ becomes exogenous in (6). Thus, I can introduce interactions between $Intranet_{jt}$ and other exogenous variables once $\rho(u_{jt})$ is controlled for. This is exactly the strategy I follow to study the existence of heterogeneous returns to intranet adoption for different types of firms.

The instrument I use is the product between the average number of Bitnet local connections (Bitnet nodes) per firm establishments and the number of Internet Service Providers (ISPs) operating in the US in a given year. The average number of local Bitnet nodes per firm site is intended to capture cross-sectional variation in knowledge and expertise on intranet technologies. Bitnet was an early computer network for the research community in US universities. Its first link was created in 1981 between the Universities of CUNY and Yale, and it had become the largest academic network in the US by the end of the 1980s. Bitnet supported interactive transmission of files and email between users based on protocols similar to the TCP/IP later used for the internet and intranets. Because of this, increases in this variable will capture improvements in local expertise with network technologies. Forman (2005) and Forman et al. (2008) argue that availability of local knowledge about IT and network technologies lowered the costs of adoption of Internet and intranets to firms. Following this rationale, other articles such as Forman et al. (2012) and Forman and Zeebroeck (2012) use the number of local nodes of Arpanet (another computer network predecessor of the Internet) to instrument for Internet adoption. Because decisions about the connection to Bitnet are taken at a time before the commercialization of intranets, one should not expect local changes on current economic activity to correlate with them. Figure 2 shows the distribution of Bitnet nodes across US counties. There exists a higher concentration of nodes along the coasts but, in general, one can see a relatively high dispersion across the country.

Because the average number of local connections to Bitnet is going to provide only variation in the cross-section of firms but not over time, I interact average number of Bitnet nodes per firm with the number of ISPs operating in the US at a given point in time. ISPs provide the technology to connect computers to networks and the internet. I obtain data on the number of ISPs from Boardwatch Magazine, a magazine specialized on the Internet that during the 1990s and early 2000s included a directory of ISPs advertisements that constitutes the most comprehensive list of the number of operating ISPs. Changes in the number of ISPs appearing in Boardwatch Magazine have been considered in other works to be a good barometer of the growth of the commercial internet access market (see Stranger and Greenstein (2007)). Before 1995 there were very few ISPs in the country but the number grew exponentially from mid-1995 on with the Internet's commercialization. The number of ISPs went from 1400 in the year 1996 to 7200 in the year 2002. I will consider the number of ISPs to be zero for 1994 and previous years (although probably there was a small number of them, around 30).

In conclusion, my instrument captures variation in local knowledge about network technologies and the availability of these network technologies over time. Thus, increases in the instrument correspond to exogenous reductions in the costs of adoption of intranet technologies that should affect its adoption. By contrast, one should not expect it to affect firm innovation through any other channel. A possible threat to this exclusion restriction would be the existence of different economic trends contemporaneous with the adoption of intranets across regions with more or fewer connections to Bitnet [15]. However, as argued by Forman et al. (2012), because these are historical decisions and there is relative high dispersion of Bitnet nodes across different regions, this variable is unlikely to be correlated with economic activity over our sample period.

Despite the impossibility to empirically check the validity of the exclusion restriction, I can perform a test for the presence of different trends in patenting across firms in regions with more or less Bitnet nodes in the years before intranet diffusion (1988 to 1994 in my sample). If the exclusion restrictions holds, then being in a region with more Bitnet nodes should not affect patenting but through its effect on intranet adoption. Therefore, I should not be able to find any impact of Bitnet nodes on patenting in the years before intranet commercialization. To do this, I regress the number of firm patents on a time trend and a time trend squared interacted with the variable $Bitnet\ nodes_j$ whilst controlling for year and firm FE. The two trend variables are jointly and individually insignificant (p-value of 0.279 for the joint significance). This result is consistent with the validity of the instrumental variable identification.

The first column of Table 4 shows the first-stage regression of intranet adoption on the instrument and controls. The effect of the instrument on intranet adoption is positive and significant (F-statistic of 38.52). Furthermore, this first-stage specification captures 79.9% of the within-firm variation in intranet adoption. Column 2 reports the second stage; a Poisson FE regression of number of patents on intranet, controls, and a polynomial series expansion of the residual from the first stage (the residual and the residual squared). The effect of intranet on patenting is positive and significant at the 5% level. Its size is larger than in the baseline regression, perhaps due to the existence of heterogeneous returns to intranet adoption. If firms located in counties with more Bitnet nodes have higher returns to intranet adoption - because there is more knowledge about the technology and its implementation is going to be more efficient - then the local average treatment effect can be expected to be greater than the average

[15] For analysis of possible endogeneity concerns when using an interacted instrument in panel regression see Christian et al. (2017).

treatment effect. This implies that although the instrument affects innovation only through its impact on intranet adoption, the returns to intranet adoption are largest for those firms whose adoption decision is most strongly affected by the instrument. Despite the coefficient increase, the residual control function is not significant (p-value of 0.138 for the joint significance of the residual and the residual squared) so the null hypothesis of intranet adoption being exogenous cannot be rejected. This increase in the IV estimates is in the same order of magnitude as results in other papers relying on very similar identification strategies for the effects of communication technologies (Forman et al. (2012) and Forman and Zeebroeck (2012)).

In the remaining of columns, I report second-stage estimates for different specifications. I do not present first-stage estimates, but in each column I include the corresponding F-statistics. In column 3 I show the second stage of a regression including all four first lags of R&D investment (the control function version of table 2 column 4). The effect of intranet remains positive and we do not reject the exogeneity of intranet adoption (p-value of 0.164 for the residual control function).

In column 4, instead of using the interacted variable $Bitnet\ nodes_j * ISPs_t$ to instrument intranet adoption, I use $Bitnet\ nodes_j$ interacted with a different dummy for each of the years 1996, 1998, 2000 and 2002. This allows for more flexible heterogeneous impacts on the effects of the instrument over time. As a result, I have four IVs to instrument intranet adoption. This identification exploits only cross-sectional variation in the costs of intranet adoption for each of the years in which intranet is commercially available, which is the exact same strategy used in Forman and Zeebroeck (2012). Because now I use four IVs that exploit the same variation as the original one, the F-statistic goes down to 11. Apart from this expected change, the rest of the coefficient estimates remain basically unchanged.

Columns 5 and 6 report the second stages for the adjusted versions of patent counts: patents weighted by forward citations and patents weighted by their economic value (the control function version of Table 3 columns 1 and 2). The effect of intranet on patenting is significant in both cases but, for the case of patents weighted by their economic value, exogeneity of intranet adoption is rejected. Column 7 presents an OLS IV regression of R&D investment on intranet adoption (the IV version of Table 2 column 5). The effect of intranet adoption is significant only at the 10% level in this case.

In conclusion, the IV results seem to confirm the existence of a positive causal impact of better communication on firm innovation. One further concern to take into account is whether the pathway between intranet adoption and innovation is mediated only by improved communication. It could be the case that as a result of better communication the firm decides to make other complementary investments that also have an impact on innovation capacity. I do not consider this a serious concern for two reasons. First, because I have already controlled for some of the main candidates for complementary investments such as increases in R&D investment, capital investment or investments in other technologies; and none of them are completely driving the effects. Second, and more importantly, because even if improvements in communication trigger other investments and organizational changes, my estimates would still be capturing the total effect of better communication on innovation. Decomposing this total effect into the different channels that explain it would be a natural next step. In the next sections I am able to provide some evidence about the mechanisms driving the effects, but further research would be necessary to provide a complete answer to this.

4.2 Heterogeneous Effects

This section disentangles some of the mechanisms for the positive effect of better firm communication on innovation by analyzing the heterogeneous effects of intranet adoption on the generation of different types of innovations and for different innovating firms.

Heterogeneous Effects by Type of Innovation

I start by analyzing if better firm communication affects the capacity to generate high and low-quality patents in different ways. I will measure quality both in terms of the economic and scientific value of a patent. In column 1 of Table 5 I check the effect of intranet adoption on the number of high economic value patents (patents that are above the median of the economic value of all patents applied in a given year)[16]. In column 2 I do the same for the number of patents below the median of economic value. The effect of intranet adoption is highly significant and large in magnitude for the number of high-value patents, whereas it is insignificant for the case of low-value patents.

In column 3 I check the effect of intranet for number of patents generated by a firm that are above the median of forward adjusted citations by application year. These can be considered highly innovative patents. In column 4 I do the same for patents below the median. I find a similar positive effect of intranet adoption for both types of patent qualities. Columns 5 to 8 contain the same specifications as columns 1 to 4 but instrumenting for the variable intranet.

These results are consistent with the company-wide character of innovation. In order to innovate, it is necessary to combine the scientific knowledge of the research team with information about a wide variety of issues such as consumer tastes, market competition and opportunities, firm's production capacity, or firm's business strategy. Whereas the scientific knowledge of the firm is concentrated in the research division, information about the rest of factors is most likely dispersed across different divisions. As a result, an improvement in internal communication between divisions has no effect on the scientific quality of innovations. By contrast, it has a strong impact on the ability to target the most profitable fields for innovation

[16] Because in the original sample there are some firms that did not obtain any patent above the median of economic value over the sample period, these firms have to be dropped in the regression.

and shape innovation ideas to be in line with consumer tastes, firm capacities, and market opportunities.

Heterogeneous Effects by Firm Type

The effect of intranet adoption fostering innovation should be greater for firms with higher barriers to communication. In this section I show that firms with greater geographical dispersion in their firm's site locations, firms with lower levels of innovation in the past, and firms operating in less competitive markets experience higher increases in innovation as a result of intranet adoption.

Firms with greater geographical dispersion are more likely to have their different plants operating as information silos in the absence of a good system of communication. The lack of interaction between researchers and workers of other departments will handicap innovation capacity. An improvement in communication capacity will bring greater increases in innovation for these firms. To empirically test this hypothesis, I calculate the average distance between each of the firm sites and the firm headquarters (weighting each site by its number of workers). Using this information I construct the variable $Intranet_{j,t} * High\ dispersion_j$, where $High\ dispersion_j$ is a dummy equal to one if firm j is in the top quartile of geographical dispersion. Column 1 of Table 6 reports the estimates on both intranet adoption and the interaction term. The coefficient of $Intranet_{j,t}$ remains positive although a little smaller in magnitude. $Intranet_{j,t} * High\ dispersion_j$ is also positive and significant at the 5% level. In column 4 I report IV estimations by including a residual control function obtained from a first-stage regression of $Intranet_{j,t}$ on $BitnetNodes * NumberISPs$ and controls. Both terms remain positive and significant and the control function is non-significant (p-value of 0.334).

The next two results show how the effect of intranet is larger for firms and sectors with larger barriers and incentives to innovate. First, I show the effect of intranet is larger for firms that have innovated less in the past. To proxy for the previous level of innovation I use the variable $Patent\ Stock$ introduced above and constructed using a perpetual inventory method following Blundell et al. (1999). Then, I create the variable $Intranet_{jt} * Low\ innovation_j$ in which $Low\ innovation_j$ is a dummy equal to 1 if firm j is in the bottom quartile of $Patent\ Stock$ in 1994, just before the diffusion of intranets. Following the same strategy as in the previous case, in column 2 I regress patent counts on $Intranet_{jt}$ and the interacted term. In column 5 I further include the control function. Both terms are positive and significant, confirming the hypothesis that the effect of intranet on patenting is greater for firms with lower initial levels of innovation. I interpret this as evidence that the effect of an improvement in firm communication is larger for firms with stronger barriers to innovation.

In column 3 I show the effect of intranet is also larger for firms operating in less competitive sectors. Less competitive markets have been proved to have lower incentives for innovation (Vives (2008)) and tend to have lower levels of innovation in practice (Geroski et al. (1995); Nickell (1996); and Blundell et al. (1999)[17]). To determine competition level in the sector in which a firm operates I calculate the average of the Herfindahl Index at the two-digit SIC code over the years in my sample. With this information, I construct the variable $Intranet_{jt} * Low\ competition_j$ in the same way as before. I consider that firm j is in a low competition sector if it is in the lowest quartile of the competition variable (which corresponds to being in the highest quartile of the average of the Herfindahl Index over the sample years). In column 3 I report the results of the reduced form regression including both intranet and the interaction term. Column 6 adds the control function. The positive estimates on the effect of both variables confirm that the effect of intranet in stimulating innovation is more intense for firms in sectors with lower incentives for innovation.

4.3 Effects on Productivity

This section examines the effect of intranet adoption on firm productivity. The robust positive impact of intranet adoption on diverse measures of innovation has been documented throughout the article. As a result, and given the extensive literature connecting firm innovation with productivity increases, there is reason to believe that intranet adoption may have affected productivity through a double channel. First, it can do so by improving workers' coordination in production tasks. Second, it can also have an indirect impact on productivity through the increase it generates in firm's innovation.

To empirically study this question I obtain productivity estimates that I regress on intranet adoption and different measures of firm's innovation stock. First, I use labor productivity measured as the log of sales over number of employees. Second, I employ the method of Levinsohn and Petrin (2003) to calculate firm's TFP. Using this method I am able to account for the existence of other intermediate inputs such as capital and materials and the endogeneity in input levels. One should bear in mind, however, the possible issues pointed by the literature in the use of these structural estimation methods. I obtain firm's TFP estimates using the whole sample of Compustat firms where I estimate production functions at the two-digit SIC level. Appendix D contains a more detailed explanation of the estimation procedure.

In Table 7 column 1, I regress labor productivity on firm intranet adoption and the log of firm patent stock. I further include firm fixed effects, year fixed effects, and industry time-trends (at the two-digit SIC level). The effect of patent stock on labor productivity is positive and significant, whereas there is no significant direct impact of intranet adoption. To confirm the robustness of this finding, in columns 2 and 3 I use alternative measures of innovation stock: the stock of patents weighted by citations and the stock of patents weighted

[17] Aghion et al. (2005) rationalize this empirical result in a model showing that net profits from innovation are smaller for firms operating in markets with lower competition. They further point out that innovation rents can also decrease in very competitive markets due to the stronger effect of Schumpeterian creative destruction.

by their estimated economic value. Columns 4 to 6 repeat the same regressions but using as a dependent variable firm's TFP estimates. In all cases, the effect of innovation stock is positive, whereas the estimated direct impact of intranet adoption remains insignificant. Finally, column 7 and 8 show how results do not change by instrumenting for intranet adoption using $BitnetNodes_j * NumberISP_t$.

In light of these results, one can conclude the non-significant direct contribution of intranet adoption to firm productivity. This is consistent with communication being less critical to ensure the coordination of workers in routine tasks. By contrast, the increase in innovation fostered by intranet adoption has a strong connection with posterior increments in firm productivity.

5 Conclusions

This article studies the role of firm internal communication on innovation and productivity. I provide evidence that problems in the internal communication of large firms can limit their innovation capacity. I also show how the adoption of communication technologies can alleviate this problem. I find that the effect of technology adoption is larger for firms with higher geographical dispersion and for firms in low competition sectors and low innovation in the past. I also find evidence that the improvement in communication generated by technology adoption is especially effective in increasing the number of high economic value patents. However, it does not affect the scientific quality of innovation. I interpret this as an evidence that a reduction in the costs to transfer knowledge across firm boundaries improves the capacity to identify more profitable innovation ideas and tailor innovations to consumer tastes and market opportunities. Finally, I show how better communication has an indirect impact on productivity through the increase in innovation. I find no evidence of a direct effect of better communication on productivity. This is consistent with the view of ICTs as a General Purpose Technology affecting productivity indirectly by inducing other changes in the firm.

Innovation is claimed to be the engine of growth and therefore it is crucial to understand its determinants. However, most of the innovation literature has focused on studying firm and market incentives for innovation, neglecting a systematic empirical analysis of firm innovation capacity. This article helps to fill this gap by showing evidence of (i) the importance of firm organizational capacity for innovation activities; and (ii) how technologies can help to overcome limitations in organizational capacity and, as a result, raise innovation. These results should serve to inform the design of more effective government policies promoting innovation and help firms to conceive better innovation strategies. They also provide a possible explanation for the changes in competition and market dynamics observed over the last decades. Improvements in internal organization coming from technology adoption can be one of the factors behind the rise in large firms' market power and reductions in business dynamism documented in other works. These are issues of crucial importance for market regulation and policy design. I hope this paper helps to shed some light and stimulate future work in these areas.

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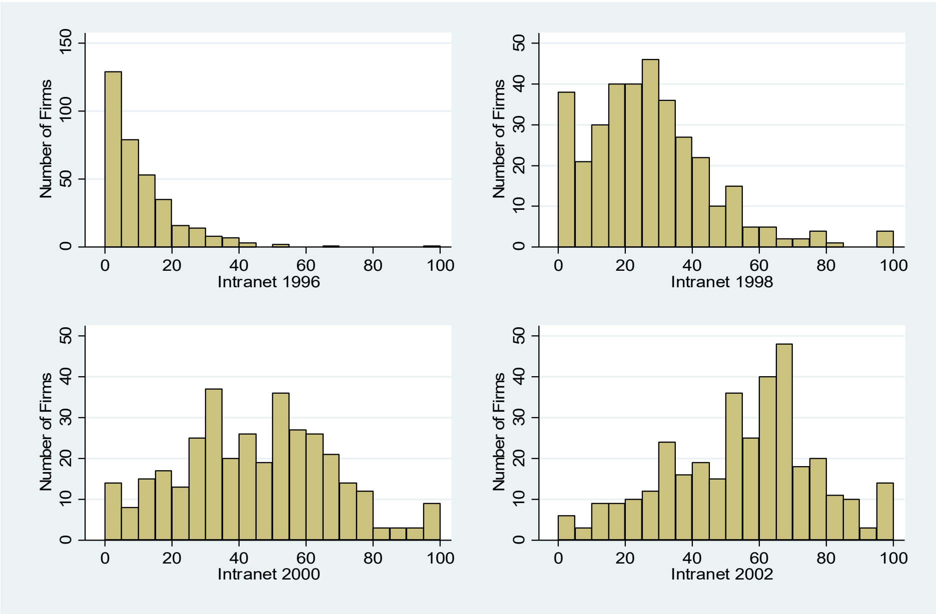
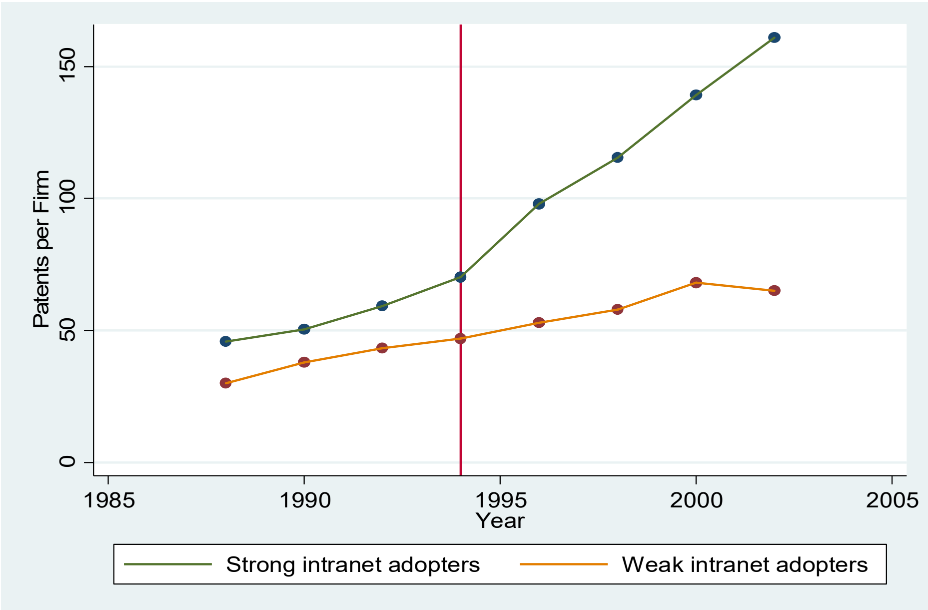
Figure 1: Levels of Intranet Penetration



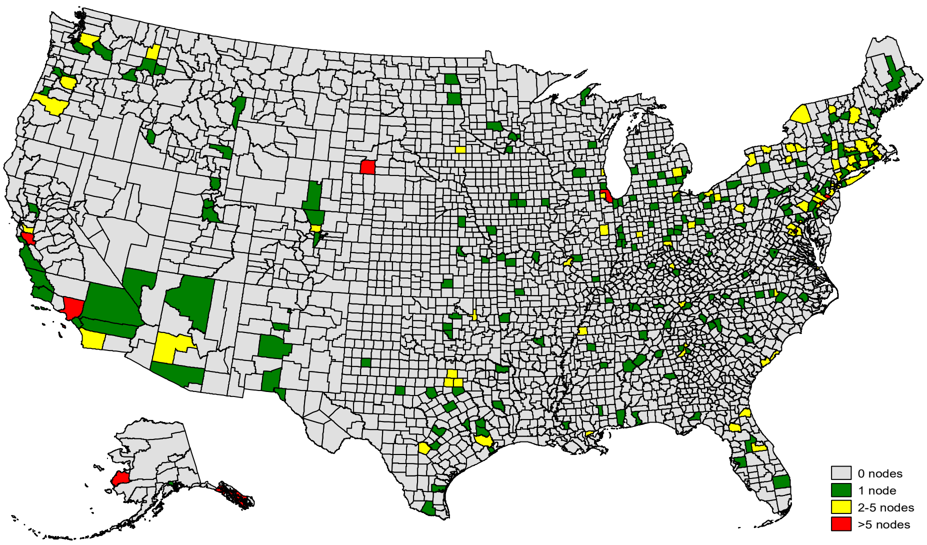
Notes: These graphs show the number of firms in each level of intranet adoption for the years 1996, 1998, 2000, and 2002. Intranet adoption is measured as the percentage share of firm sites having adopted intranet. The horizontal axis shows the different levels of intranet adoption and the vertical axis the number of firms in the corresponding bin of intranet adoption. Source: CiDB Harte Hanks.

Figure 2: Trends in patenting for different levels of intranet adoption



Notes: This graph shows the different trends in patenting over time for those firms adopting intranet more intensively (strong adopters) and those doing it less intensively (weak adopters). Strong adopters are those firms that are above the median of intranet adoption in all years after 1994. Intranet adoption starts in 1994 (marked in red). The vertical axis shows the average number of patents per year for firms in each group. Source: CiDB Harte Hanks.

Figure 3 : Distribution of Bitnet nodes across US counties



Notes: This figure shows the number of nodes of the Bitnet network in each county of the US. Source: Agrawal and Goldfarb (2008)

Table 1: Descriptive Statistics

	Observ.	Mean	Std. Dev.	Median	Min	Max
Employees	2784	35777	83024	11500	50	1400000
Capital (million USD)	2784	2942	7439	710	1	10958
Sales (million USD)	2784	9485	21967	2967	4	28847
R&D (million USD)	2784	228	761	15	0	957
Patents	2784	62	226	4	0	439

Notes: Data on total firm number of employees, capital, sales, and R&D investment are obtained from Compustat. Capital is calculated using a permanent inventory method. Data on number of patents is obtained from Kogan et al (2017) dataset. The sample comprises 348 firms for all even years between 1988 and 2002.

Table 2: Baseline Results

	(1)	(2)	(3)	(4)	(5)
	Patents	Patents	Patents	Patents	R&D
Intranet	0.0162***	0.00831***	0.00565**	0.00517**	3.310**
	(0.000145)	(0.00304)	(0.00234)	(0.00229)	(1.284)
Log R&D$_t$			0.0981**	0.101**	
			(0.0461)	(0.0431)	
Log R&D$_{t-1}$			0.05940	-0.00001	
			(0.0612)	(0.0482)	
Log R&D$_{t-2}$				0.00488	
				(0.0539)	
Log R&D$_{t-3}$				-0.02660	
				(0.054)	
Log R&D$_{t-4}$				0.109**	
				(0.0447)	
Employees			0.00317***	0.00310***	1.385
			(0.00119)	(0.00114)	(1.001)
Observations	2784	2784	2784	2784	2784
Number of firms	348	348	348	348	348
Year FE	Yes	Yes	Yes	Yes	Yes
Firm FE	No	Yes	Yes	Yes	Yes

Notes: *** denotes significance at 1%, ** at 5%, and * at 10%. The dependent variable Patents is a count of number of granted patents applied by a firm in a given year. Intranet adoption is measured as the percentage share of firm sites having adopted intranet. Coefficients are from Poisson regressions with standard errors clustered by firm (in parentheses)

Table 3: Robustness Analysis

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	Citation weight	Dollar weight	Patents	Patents	Patents	Patents	Patents	Patents
Intranet	0.00663**	0.00728**		0.00701**	0.00657***	0.00521**	0.00477**	0.00566**
	(0.00262)	(0.0034)		(0.00281)	(0.00234)	(0.00228)	(0.00206)	(0.0023)
Weighted intranet			0.00296**					
			(0.00124)					
Dummy intranet > 0				-0.307				
				(0.189)				
Internet					-0.00354			
					(0.00332)			
Log R&D$_t$	0.114*	0.0878	0.102**	0.0961**	0.0962**		0.116***	0.101**
	(0.0655)	(0.0839)	(0.0475)	(0.0454)	(0.0465)		(0.0438)	(0.0473)
Log R&D$_{t-1}$	0.0522	0.00567	0.0615	0.0576	0.0592		0.0304	0.0648
	(0.0593)	(0.0366)	(0.0613)	(0.0609)	(0.0603)		(0.0461)	(0.0551)
Log R&D Stock						0.111**		
						(0.0533)		
Employees	0.00248*	0.00332**	0.00320***	0.00308**	0.00319***	0.00308***	0.00298***	0.00324***
	(0.00135)	(0.00163)	(0.00119)	(0.0012)	(0.00119)	(0.00113)	(0.00114)	(0.0012)
Observations	2744	2784	2784	2784	2784	2784	2784	2784
Number of firms	343	348	348	348	348	348	348	348
Firm and Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Trends for innovation groups	No	No	No	No	No	No	Yes	No
Trends for digital sectors	No	No	No	No	No	No	No	Yes

Notes: *** denotes significance at 1%, ** at 5%, and * at 10%.Patents weighted by citations is a count of number of granted patents applied by a firm in a given year weighted by an adjusted measure of number of forward citations received by each patent. Patents weighted by dollars is a count of number of granted patents applied by a firm in a given year weighted by an adjusted measure of the economic value of each patent estimated by Kogan et al (2017). Intranet adoption is measured as the ratio of firm sites having adopted intranet. Weighted intranet is measured as the ratio of firm sites having adopted intranet weighting each site by its number of employees. Dummy Intranet is a dummy taking the value of one if at least one firm site has adopted intranet. Internet adoption is measured as the ratio of firm sites having adopted Internet. R&D stock is constructed using a perpetual inventory method. Coefficients are from Poisson regressions with standard errors clustered by firm (in parentheses).

Table 4: IV Estimation

	(1) Intranet	(2) Patents	(3) Patents	(4) Patents	(5) Citation w.	(6) Dollar w.	(7) R&D
Intranet		0.0256**	0.0239**	0.0272**	0.0265**	0.0262**	10.35*
		0.0108	0.0107	(0.0109)	0.0118	0.012	5.988
Bitnet nodes$_j$ * ISPs$_t$	0.000792***						
	(0.000128)						
Log R&D$_t$	0.0564	0.0875**	0.0915**	0.0866**	0.102*	0.0699	
	(0.316)	(0.0426)	(0.0403)	(0.0424)	(0.0599)	(0.0743)	
Log R&D$_{t-1}$	0.00448	0.0571	0.0104	0.0569	0.0464	0.00629	
	(0.29)	(0.0599)	(0.0468)	(0.0599)	(0.0565)	(0.0356)	
Log R&D$_{t-2}$			-0.000238				
			(0.0521)				
Log R&D$_{t-3}$			-0.03				
			(0.0538)				
Log R&D$_{t-4}$			0.0965**				
			(0.0423)				
Employees	-0.0259**	0.00394***	0.00383***	0.00400***	0.00325**	0.00412**	1.58
	(0.0121)	(0.00131)	(0.00126)	(0.00132)	(0.00146)	(0.00166)	(0.980)
Observations	2784	2784	2784	2784	2744	2784	2784
Number of firms	348	348	348	348	343	348	348
Firm and Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Interacted IV	Yes	Yes	Yes	No	Yes	Yes	Yes
p-value CF		0.138	0.164	0.126	0.179	0.0043	
F-stat 1st stage	38.52	38.52	37.44	11	38.52	38.52	37.37

Notes: *** denotes significance at 1%, ** at 5%, and * at 10%. Patents is a count of number of granted patents applied by a firm in a given year. Patents weighted by citations is a count of number of granted patents weighted by an adjusted measure of number of forward citations received by each patent. Patents weighted by dollars is a count of number of granted patents weighted by an adjusted measure of the economic value of each patent estimated byKogan et al (2017). Intranet adoption is measured as the share of firm sites having adopted intranet. Coefficients in column 1 come from an OLS regression with standard errors clustered by firm (in parentheses). In columns 2 to 6, coefficients are from Poisson regressions with standard errors clustered by firm (in parentheses). They include a second-order polynomial series expansion of the estimated error term in the first stage. Coefficients in column 6 come from an OLS regression in which Intranet is instrumented and standard errors are clustered by firm.

Table 5: Heteregeneous Effects I

	Poisson	Poisson	Poisson	Poisson	IV	IV	IV	IV
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
	High Value	Low Value	High Citations	Low Citations	High Value	Low Value	High Citations	Low Citations
Intranet	0.0115***	0.00243	0.00581**	0.00528**	0.0297**	0.025	0.0244**	0.0291**
	(0.00314)	(0.00227)	(0.00256)	(0.00246)	(0.0142)	(0.022)	(0.0104)	(0.0124)
Log R&D$_t$	0.132*	0.127	0.0990**	0.0964*	0.129*	0.0692	0.0884**	0.0849*
	(0.0757)	(0.14)	(0.0487)	(0.052)	(0.0744)	(0.101)	(0.0449)	(0.0488)
Log R&D$_{t-1}$	0.0426	0.181	0.0458	0.0845	0.0356	0.186	0.0428	0.0853
	(0.0678)	(0.158)	(0.0577)	(0.0735)	(0.0661)	(0.146)	(0.0562)	(0.0728)
Employees	0.00203	0.000925	0.00283**	0.00380***	0.00257	0.00283	0.00355***	0.00473***
	(0.00225)	(0.00371)	(0.00121)	(0.00111)	(0.00222)	(0.0043)	(0.00133)	(0.00127)
Observations	2288	1872	2576	2576	2288	1872	2576	2576
Number of firms	286	234	322	322	286	234	322	322
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
p-value CF					0.26	0.0842	0.193	0.0554
F-stat 1st stage					38.52	38.52	38.52	38.52

Notes: *** denotes significance at 1%, ** at 5%, and * at 10%. Patents High Value is a count of number of patents above the median of the economic value of patents generated in a given year. Patent Low Value is the same for patents below the median. Patents High Citations is a count of number of patents above the median of forward citations per year. Patent Low Citations is the same for patents below the median. Intranet adoption is measured as the ratio of firm sites having adopted intranet. Coefficients are from Poisson regressions with standard errors clustered by firm (in parentheses). In the control function regressions (cols 5-8) I control for a second-order polynomial expansion of the residual estimated in a first-stage regression of Intranet on Bitnet nodes$_j$ * ISPs$_t$ and controls. The p-value on the significance of the control function is reported in the table.

Table 6: Heteregeneous Effects II

	Poisson	Poisson	Poisson	IV	IV	IV
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**
	Patents	Patents	Patents	Patents	Patents	Patents
Intranet	0.00391**	0.00564**	0.00499**	0.0217*	0.0257**	0.0228**
	(0.00178)	(0.00234)	(0.00198)	(0.0127)	(0.0108)	(0.0114)
Intranet * High Dispersion	0.00572**			0.00561**		
	(0.00258)			(0.00269)		
Intranet * Low Innovation		0.0178***			0.0187***	
		(0.00611)			(0.00598)	
Intranet * Low Competition			0.00666**			0.00633**
			(0.00263)			(0.00288)
Log R&D$_t$	0.101**	0.0983**	0.106**	0.0908**	0.0877**	0.0955**
	(0.0483)	(0.0462)	(0.05)	(0.0445)	(0.0427)	(0.0462)
Log R&D$_{t-1}$	0.0732	0.0592	0.0656	0.0716	0.0568	0.0637
	(0.0661)	(0.0612)	(0.0656)	(0.065)	(0.0598)	(0.0645)
Employees	0.00314**	0.00317***	0.00295**	0.00383***	0.00394***	0.00365**
	(0.0013)	(0.00119)	(0.00137)	(0.00142)	(0.00131)	(0.00149)
Observations	2784	2784	2784	2784	2784	2784
Number of firms	348	348	348	348	348	348
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes
p-value CF				0.334	0.137	0.274
F-stat 1st stage				38.52	38.52	38.52

Notes: *** denotes significance at 1%, ** at 5%, and * at 10%.The dependent variable Patents is a count of number of granted patents applied by a firm in a given year. Intranet adoption is measured as the share of firm sites having adopted intranet. High Distance is a dummy equal to one if a firm is in the top quartile of geographical firm dispersion. Low Innovation is a dummy equal to 1 if a firm is in the bottom quartile of patent stock in 1994, just before the diffusion of intranets. Low Competition is dummy equal to 1 if a firm is in the bottom quartile of sector competition. Coefficients are from Poisson regressions with standard errors clustered by firm (in parentheses). In the control function regressions I control for a second-order polynomial expansion of the residual estimated in a first-stage regression of Intranet on Bitnet nodes$_j$ * ISPs$_t$ and controls. The p-value on the significance of the control function is reported in the table.

Table 7: Effects on Productivity

	OLS	OLS	OLS	OLS	OLS	OLS	IV	IV
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
	Labor Prod	Labor Prod	Labor Prod	TFP	TFP	TFP	Labor Prod	TFP
Intranet	0.000975	0.000941	0.000901	0.000828	0.000786	0.000732	0.000826	-0.000418
	(0.000619)	(0.000614)	(0.000621)	(0.00059)	(0.000586)	(0.000586)	(0.0018)	(0.00236)
Patent Stock	0.0325**			0.0413***			0.0327***	0.0432***
	(0.0163)			(0.0146)			(0.00898)	(0.0153)
Patent Stock Citations		0.0339**			0.0431***			
		(0.0167)			(0.014)			
Patent Stock Dollars			0.0491***			0.0629***		
			(0.0122)			(0.011)		
Observations	2784	2784	2784	2784	2784	2784	2784	2784
Number of firms	348	348	348	348	348	348	348	348
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Firm FE	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Industry-specific trends	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
F-stat 1st stage							34.6	34.6

Notes: *** denotes significance at 1%, ** at 5%, and * at 10%. The dependent variable in column 1 is labor productivity measured as the log of the ratio of sales over number of employees. Columns 2 to 5 use as a dependent variable an estimate of firm TFP obtained from production function estimation by the methods of Levinshon and Petrin (2003) at the two-digit SIC industry level. Intranet adoption is measured as the share of firm sites having adopted intranet. Patent Stock is a measure of the stock of patents generated by the firm applying a perpetual inventory method. Patent Stock Citations is a measure of the stock of patents applying a perpetual inventory method and weighting each patent by the number of forward citations received. Patent Stock Dollars weights each patent by an estimate of a patent economic value obtained from Kogan et al (2007). Controls for firm and year fixed effects and time-industry trends for two-digit SIC industries are included too. Regression in column 5 instruments Intranet using Bitnet nodes$_j$ * ISPs$_t$. Coefficients are from an OLS regressions with standard errors clustered by firm (in parentheses).

Appendix

Appendix A: Intranet Technology

Intranets are formally defined as the application of Internet technology for a prescribed community of users, typically members of an organization. Internet technology standards and protocols are employed but access is restricted by means of passwords, encryption, and firewalls. Internet and intranet technologies were developed for academic and governmental use in the early 1960s. However, the rise of the commercial Internet and intranets did not take place until the mid-90's. Because of its non-commercial origins, many intranet technologies were already quite mature by this time and could be applied immediately to organizational needs. At the time of its commercial diffusion, intranets already included a wide variety of applications and functionalities such as videoconferencing, collaboration tools, access to repositories of information located in other parts of the firm, and applications to search for subject matter experts within the organization. As a result, they were fastly adopted by firms (e.g., Forman (2005); Forman et al. (2002)). By contrast, more sophisticated technologies like the ones necessary to conduct Internet transactions required more time to be implemented.

Intranets are built and maintained for information storage and retrieval but mainly for enhancing information flow and communications within an organization. This provided firms with opportunities to create new knowledge and innovate. Numerous case studies highlighting the importance of intranets for fostering innovation can be found in the Business and Information Systems literature (see Scott (1998); Boersma and Kingma (2006)). I bring here three illustrative examples.

> Scientists at the Met Office (the UK's national weather service) *"use an intranet as a discussion forum for ongoing research projects. Staff are able to access each other's webpages to catch up with their colleges research and there are news groups for individual Departments and for special scientific interest groups"*.
>
> A manager in the engineering division of Jaguar (a car manufacturer) claims *"The intranet will allow our engineers to work in what seems to them to be the obvious and natural way. The logic is to ensure that all information is available to the people who need it and that they can access it easily"*.
>
> Olivetti Group (an IT manufacturer) reports to *"use a virtual laboratory to link their main sites and labs worldwide so that researchers access the largest possible amount of current information(...). In an R&D environment the free exchange of information and ideas is a powerful catalyst of innovation"*. Furthermore, *"if a problem has already been solved by one employee we can find about it intermediately and avoid duplicating efforts. Before the web there was no central repository of*

information so researchers often spent time looking for information that was already available in-house".

Appendix B: Matching of Datasets

In order to conduct the empirical analysis, I needed to match firm information in three different datasets: the patent dataset, Compustat and HH technology dataset. Matching patent assignees to Compustat firms was not specially difficult. Kogan et al. (2017) already contains a link between patent assignees and CRSP firms. This type of work is specially complicated due to inconsistencies in how firm names are listed in patent records. They can contain spelling variations, typographical errors or the name of a subsidiary firm (for example, IBM can be found with more than 100 different names). Then, using a bridge dataset between CRSP and Compustat I am able to connect patent assignees to Compustat firms.

The second step consisted on matching HH firms to Compustat firms. Because of the absence of a common firm identifier in both datasets I had to resort to string matching algorithms. In my matching strategy, I prioritized minimizing the number of false positives over the number of false negatives. As a result, I did a good job preventing wrong matches at the cost of probably losing a number of observations. I started by cleaning firm names getting rid of words like "Corp", "Incorporated", "L.S.", etc. Then, I matched firms in both datasets with the exact same name. The number of false negative cases using only this conservative matching mechanism is too big. For instance, I did not find a match in cases as obvious as "International Business Machines" and "Internat Business Machines". To solve this type of problematic cases, I resorted to string matching algorithms. I used different algorithms to reduce as much as possible the number of false positives. Furthermore, I dropped provisional matches that did not coincide in at least one the following pieces of information: firm's phone number, firm's web page or firm's stock market ticker symbol. Finally, I conducted a manual inspection checking in detail any suspicious candidate match. These were a handful of double match cases between firm subsidiaries and parent firms. I did some online research to discover which was the correct match and if this was not clear I dropped the observation.

Appendix C: Variable Definitions

In this section I describe the main variables used in the empirical analysis coming from Harte Hanks Technology Dataset, the patent dataset of Kogan et al. (2017) and Compustat North American Fundamental Annuals. More details about the definition of some of these variables can be found in İmrohoroğlu and Tüzel (2014).

- **Employees**. The number of employees was taken directly from Compustat (Compustat variable EMP). No adjustments were made to this figure.

- **Investment**. Value of current investment in capital goods calculated as the difference between capital expenditures (Compustat variable CAPX) and funds received for the sale of capital (Compustat variable SPPE) and deflated to prices of 2009.

- **Capital**. Capital stock is calculated using a perpetual inventory method where the value of capital stock in year t is equal to undepreciated capital in year t-1 plus investment $K_t = K_{t-1}(1-\delta)+I_t$. For K_0 I use the total book value of capital reported by Compustat (Compustat variable PPENT) deflated to prices of 2009. When available, I use 1983 as the first year to start constructing the series. Otherwise, I use the first available year in Compustat. I assume a yearly depreciation of 0.15.

- **Output**. Total net sales as reported by Compustat (Compustat variable SALE) deflated to prices of 2009.

- **Materials**. Materials was calculated by subtracting labor expenses form total expense and deflating this to prices of 2009. I calculate labor expenses as the product of the average total compensation per worker in a given year (using data from the BLS) and the number of workers reported in Compustat. Total expenses was computed as the difference between Operating Income Before Depreciation (Compustat variable OIBDP) and sales (Compustat variable SALE).

- **R&D investment**. Research and Development expenses as reported in Compustat (variable XRD) deflated to prices of 2009. Investment is measured in thousands of dollars. When I have to take the natural logarithm of R&D investment, as this can be zero for some years, I take the natural logarithm of R&D plus one.

- **R&D stock**. Constructed applying a perpetual inventory method to R&D investment using a yearly depreciation of 0.15.

- **Intranet**. Percentage share of firm sites reporting to have adopted intranet in a given year.

- **Weighted Intranet**. Percentage share of firm sites reporting to have adopted intranet in a given year weighted by their size (number of employees).

- **Internet**. Percentage share of firm sites reporting to have adopted internet in a given year.

- **Patents**. Number of granted patents applied by a firm in a given year.

- **Patent stock**. Constructed using a perpetual inventory method with a yearly depreciation of 0.15. When I have to take the natural logarithm of this variable, as its value can be zero, I take the natural logarithm of Patent stock plus one.

Appendix D: TFP Estimation

I follow the method of Levinsohn and Petrin (2003) to estimate firm-level TFP. This approach tries to address the problem that inputs are choice variables made by the firm to maximize profits, and hence will often depend on unobservable productivity shocks. LP uses assumptions about the information set of the firm at the time of making input decisions.

To see this, consider the following Cobb-Douglass production function

$$y_{it} = \beta_0 + \beta_l l_{it} + \beta_m m_{it} + \beta_k k_{it} + u_{it} \tag{7}$$

Where y_{it} is the logarithm of output of firm i at time t, and correspondingly, l_{it}, m_{it}, and k_{it} are the firm's (log of) labor, materials and capital inputs. Wlog, assume that $u_{it} = \omega_{it} + \epsilon_{it}$ where ω_{it} and ϵ_{it} are unobserved by the econometrician, whereas the firm can observe ω_{it} at time t. The term ϵ_{it} could be capturing unpredictable shocks, whereas ω_{it} can be interpreted as firm productivity. If ω_{it} is known to the firm, the optimal labor and materials input choice will be a function of ω_{it}, and simple OLS estimation will suffer from simultaneity bias.

LP uses firm's consumption of intermediates inputs (materials) to invert the productivity shock ω_{it} and control for it in the estimation. Assuming the productivity shock follows a markov process, i.e.

$$p(\omega_{i,t+1}|I_{i,t}) = p(\omega_{i,t+1}|\omega_{i,t}) \tag{8}$$

where $I_{i,t}$ is firm i's information set at t (which includes current and pasts ω_{it}'s). Notice this is not just an assumption on the stochastic process governing ω_{it} but an assumption on firms information set at various points in time. The next important assumption is that labor and materials are fully flexible inputs decided by the firm at t once ω_{it} is observed, whereas the level of capital for period t has to be made at $t-1$ when uncertainty about $\omega_{i,t}$ is not resolved for the firm yet. As a result, the level of intermediate inputs at t is a function of k_t and ω_{it},

$$m_{i,t} = h(\omega_{it}, k_{it}). \tag{9}$$

Under some conditions (9) can be inverted to obtain

$$\omega_{i,t} = h^{-1}(m_{it}, k_{it}) \tag{10}$$

This implies the productivity shock can be written as a function of variables that are observed by the econometric and, therefore solving the endogeneity problem.