Financial Development and Technology Diffusion*

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Abstract

We examine the extent to which financial market development impacts the diffusion of 16 major technologies, looking across 55 countries, from 1870 to 2000. We find that greater depth in financial markets leads to faster technology diffusion for more capital-intensive technologies, but only in periods closer to the invention of new technologies. In fact, we find no differential effect of financial depth on the diffusion of capital-intensive technologies in the late stages of diffusion or in late adopters. Our results are consistent with a view that local financial markets play a critical role in facilitating the process of experimentation that is required for the initial commercialization of technologies. This evidence also points to an important mechanism relating financial market development to technology diffusion and economic growth.

Key Words: banking, technology diffusion, experimentation, growth.

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1 Introduction

A central issue in the economics and finance literature is the extent to which financial market development drives economic growth across countries (e.g., Beck et al. 2000; Levine 1997; Levine et al. 2000). There is increasing evidence that better financing environments are associated with higher economic growth because they reduce financing constraints for entrepreneurs (Rajan and Zinglaes 1998; Gusio, Sapienza and Zinglaes 2004) and facilitate more efficient allocation of capital across investment opportunities in the real economy (e.g., King and Levine 1993a,b; Jayaratne and Strahan 1996; Rajan and Zingales 2003; Bertrand et al 2007). While the relationship between financial development and product market efficiency is well-documented, far less attention has been paid to the specific role that capital markets might play in the faster adoption and diffusion of new technologies. Technology adoption is believed to be a key channel through which productivity growth is achieved (Aghion and Howitt, 1992), and differences in the diffusion of new technologies has been found to explain a significant portion of the large cross-country differences in total factor productivity (Comin and Hobjin, 2010).

In this paper, we examine whether, and if so how, financial market contributes to technology diffusion. Examining this question requires data that both span a long period of time and are also comparable across countries. We combine a cross-country panel dataset spanning 16 general purpose technologies (such as electricity, railways, telephones and motor cars) over 50 countries and 130 years with data on financial market development over the same extended period of time. The long time span and extensive coverage across countries and technologies allows us to examine the diffusion of technology both within and across countries. A key challenge with such an analysis is untangling the extent to which an observed correlation between financial market development and technology diffusion is in fact causal. Our identification strategy therefore focuses on two types of cross sectional variation to understand the causal impact of financial development on technology diffusion. First, some of these technologies (such as the railroads or electricity generation) are significantly more capital intensive to commercialize than others (such as the ring spindles or radios) and hence more reliant on financial markets for their commercialization. By exploiting cross-technology variation in the reliance on financial markets, we therefore examine whether the *relative* rate of diffusion for more vs. less capital intensive technologies is greater in countries with deeper financial markets than in countries with less-well developed financial markets. Second, as we point out in greater detail below, commercializing technologies at their birth requires extensive experimentation by entrepreneurs, as the customers, business models, and even the way the technology will be used is often unknown. Indeed, there tends to be a consistent pattern of hundreds of new entrants into these nascent markets that is then followed by a shakeout as the technology matures and industry leaders emerge (Klepper, 1996, Klepper and Simons 2005). We exploit the fact that the governance required to commercialize new ventures in these early periods is much higher (and hence the need for well-developed local financial markets is much greater), compared to later stages of an industry's development when commercialization can more easily take place through arms length financing of larger well-established corporations. We therefore also examine the relative importance of financial development on the diffusion of technologies closer to their date of invention compared to when they are more established.

We find that deeper financial markets in a country accelerate technology diffusion of more capital intensive technologies. Importantly, however, this benefit of financial market depth is only present in the early stages of a technology's commercialization. These results are robust to the inclusion of important control variables as well as a stringent set of fixed effects. The difference in the importance of financial development for technology diffusion in the early and late stages of the technology's lifecycle is important in two respects. From an econometric standpoint, it reduces concerns about unobserved heterogeneity driving the results, as this would likely have a consistent effect at all stages of a technology's life. From a substantive perspective, these results highlight the important role of *domestic* capital markets in the diffusion of technologies in a country, particularly in the early stages of the technology's lifecycle. They are consistent with a view that in addition to reducing frictions, deeper financial markets play a critical role in facilitating the process of experimentation that is required for the adoption and diffusion of new technologies close to their date of invention. While this mechanism has been explored in the context of venture capital (Kortum and Lerner, 2000; Nanda and Rhodes-Kropf 2010, 2011; Kerr, Nanda and Rhodes-Kropf, 2014), it has not been examined in a larger cross-country setting and points to a new channel by which financial development affects economic growth.

The rest of the paper is is structured as follows. In Section 2, we use historical examples to outline the mechanisms through which we believe financial market development impacts the commercialization, and diffusion of new technologies. Section 3 relates these examples to the data and identification strategy used in our empirical analysis. Section 4 presents our main findings and robustness checks and Section 5 concludes.

2 Finance and the Commercialization of New Technologies

Startup firms play a central role in the commercialization of new technologies. While the role of startups in the emergence of more recent industries such as semiconductors, the internet and biotechnology is well known, historical accounts of the commercialization of the railways, motor cars and other new technologies also illustrate the important role of new firms. Indeed, Lamoreaux and Sokoloff (2007), writing about US innovation from the 1870s to the present day, highlight that startups have played a critical role in the development of cutting edge technologies for over a century. They point out that while individual inventors played a disproportionate role in commercializing their own innovations in the early and mid-1800s, the greater complexity and capital intensity of new technologies being commercialized from the late 1800s onwards drove an increasing amount of innovation to happen within the boundaries of new firms. For example, they write that "most of the firms that invested heavily in R&D facilities in the early twentieth century originated as entrepreneurial companies formed to exploit the discoveries of particular inventors. Perhaps the most famous [example of such an occurance is the case of] General Electric, formed from a merger of two core enterprises that had been organized by investors with the aim of commercializing the innovations of Thomas Edison and Elihu Thomson." (p14)

The increasing complexity and capital intensity of new technologies being developed across the world from the late 1800s onwards created a key role for the financial markets in helping to fund the commercialization of these innovations. In the context of the US economy, Lamoreaux and Sokoloff (2007) point out that: "by the late nineteenth century, it was clear to observers that technological change was a permanent feature of the industrial economy and that substantial returns could be obtained through investing in the development of frontier technologies. Railroads and telegraphy were perhaps the first grand-scale examples of industries created or revolutionalized by important inventions, but others such as electricity, telephones, steel, chemicals and automobiles soon followed. An interest in these sorts of opportunities grew, technologically creative entrepreneurs increasingly sought out investors (and vice versa) because the greater technical complexity and capital intensity of new technologies meant that effective programs of inventive activity and commercial exploration required more financial backing than before."

As is still true to this day with early stage investors, much of the inital financing for these startups "typically was raised informally from local backers, many of whom were personally acquinted with the inventors involved" (p.14) For example, Lowell was a hot bed of economic activity in the early nineteenth century and its growth, based on the textile industry and immigrant labor, was extraordinary. The Boston Associates (a group of rich investors who made their money in trade) provided finance for investment in the mills and they are often considered to be the pre-history of venture capital. Lamoreaux, Levenstein and Sokoloff (2007) provide a detailed study of Cleveland, Ohio, "a center of inventive activity in a remarkable number of important industries, including electric light and power, steel, petroleum, chemicals and automobiles". They find that while formal institutions such as banks and stock markets helped finance working capital for established firms, they did not play a central role in the creation of the new enterprises commercializing these technologies, but rather that venture capital was raised directly from wealthy invididuals "who bought substantial shares in the equity of new firms, held onto their investments for long periods of time and often played an important role in ongoing management". For example, George Eastman, the founder of the Eastman Kodak Company first founded the Eastman Dry Plate Company in 1881, with the backing of angel investor, Henry Strong, while the Ford Motor Company was founded in 1903 with investments from twelve local angel investors.

The active role played in the governance of new ventures seems particularly important early in the life of industries, when hundreds of new entrants are typically experimenting with the way in which the technology will be put to use. Gort and Klepper (1982) and Klepper and Simons (2005) have documented these patterns of entry across a wide range of industries, including in televisions and automobiles. For example, Klepper (2007) notes that while the motor car industry was dominted by just 9 firms by 1940, the industry was characterized by widespread experimentation in its early years, with over 270 automobile startups in the 1909. Klepper notes that "the growth of the industry was spurred by tremendous technological change. The original automobiles had low-power steam, electric or gasoline engines. They were buggy-like contraptions with engines under the body, tiller steering, chain transmissions, open bodies and hand-cranked starters". Some were designed for urban use while others were meant for rural settings. In fact, in many instances early in the life on a new technology, it was even unclear what the technology would be used for. Janeway (2012) notes that one of the early application of the telephone was to broadcast entertainment to the home. He writes that "in the first years of the 1890s, the Electrophone Company in London was offering concerts, opera, music hall variety and even church services by subscription; the entertainments were delivered to homes, hospitals and other venues via telephone". On the other hand, "point-to-point communication by wireless telegraphy served as the principal application of radio communications until the introduction of public broadcasting after the First World War"! Relatedly, Nye (1992) documents the several decade long search for commercially viable applications of electric power.

Our hypothesis is that much like is true with venture capital today (Kortum and Lerner, 2000; Samila and Sorenson, 2010) the depth of local financial markets and the ability of networks of wealthy local financiers to help commercialize these innovations was central to the rate and trajectory of the technology's diffusion. While the importance of financial markets in the commercialization and diffusion of new technologies over the past century has been documented in these detailed accounts of particular industries, regions or periods of time, it has not been studied in terms of a systematic role it might play in the rate of technology diffusion across countries. In this paper, therefore, we address this issue by asking the following question: do cross-country differences in financial market development help to explain differences in the degree to which new technologies are commercialized and diffuse across countries? This question is of particular relevance, as technology adoption is increasingly viewed as a key channel through which countries achieve economic growth, and hence may be an important (under-explored) mechanism linking financial market development to subsequent economic growth.

3 Data and Empirical Strategy

A key challenge to such a study is the availability of good data. Three important aspects of our data and analysis allow us to make headway on this question. First, our measures of technology diffusion come from the CHAT data set introduced in Comin and Hobijn (2004, 2010). This data set contains historical data on the adoption of several major technologies over the last 200 years across a large set of countries. We therefore construct panel data at the technology-country-year level, measuring the intensity with which each technology is used in each country over time. Table 1 lists the technologies we use. As can be seen from Table 1, the set of technologies cover a wide span of sectors and have played a major role in driving productivity and economic growth across time. Because of data availability constraints, we use different measures of diffusion for different technologies. Some technologies are measured as the share of capital that embodies the new technology (e.g. fraction of ring spindles). Other production technologies are measured either by the number of equipment units of the technology scaled by real GDP or by the output produced with the technology over real GDP. We discuss how we address this issue when outlining our empirical strategy below.

Second, we use the ratio of deposits in commercial and savings banks divided by GDP as our measure of financial market depth. The source for these data are Mitchell (2000) and Table 2 provides descriptive statistics on our measure of financial market depth. The depth of the banking sector is a useful proxy for several of the functions that financial markets provide (Levine, 1997). At the most basic level, bank deposits measure the degree to which savings are mobilized towards the availability of funds for credit. Better developed financial markets also reduce intermediation costs, facilitate risk management, as well as play a role in governance, all of which are critical factors for helping to commercialize new technologies.[1]

Third, we exploit fact that some technologies are more capital intensive than others and hence will need to depend more on external finance for their commercialization. In particular, since technologies that require large investments will be more inclined to incur such an investment

[1]We see bank deposits are a proxy for the overall level of financial development, not just that of the banking sector. For example, the degree of savings are a proxy for the extent to which angel investors or other financial intermediaries can deploy "risk capital" to finance new ventures. Nevertheless, it is also worth noting that there is growing evidence that banks play a (surprisingly) large role in directly financing innovation (e.g. Mann (2014), Chava et al (2013), Nanda and Nicholas (2014))

if they have access to sufficient capital at reasonable rates, we expect that financial market development will accelerate the diffusion of more capital-intensive technologies to a greater degree than those that are less capital-intensive. Note that, measuring the capital intensity of technologies, rather than industries, facilitates our analysis, since the capital intensity of technologies is a truly technological attribute and therefore it is likely to be more stable over time and across countries than the capital needs of the companies in an industry.

The classification of technologies according to their capital intensity is outlined in Table 1. Appendix 1 provides detail on the sources, measures and coverage of the different technologies. We consider that the more capital intensive technologies are railways, telegrams, telephones, electricity production, the production of steel with electric arc and blast oxygen furnaces, and cell-phone communications. The less capital intensive technologies are ring spindles, automatic looms, cars, trucks, tractors, radios, TVs, computers and MRI machines.

Our baseline econometric specification therefore takes the form:

$$y_{ict} = \eta_{it} + \phi_c \ + \beta_1 \mathbf{X}_{ct} + \beta_2 FIN_{ct} + \beta_3 (FIN_{ct} * DEP_i) + \varepsilon_{ict}. \tag{1}$$

where y_{ict} denotes our measure of the adoption of technology i in country c at time t. To allow for the fact that technologies follow different diffusion paths as well as to account for the fact that we measure different technologies using different units, we include a full set of technology-times-year fixed effects, denoted by η_{it} in our regression specification. Effectively these fixed effects imply that our dependent variable is the deviation of a country's adoption of a technology from the average adoption of that technology across countries in each period. Many of the concerns related to confounding factors in cross-country econometric studies are country–specific (and, to a first order, symmetrically affect the adoption of all kind of technologies). We therefore include country-fixed effects, denoted by ϕ_c, to control for other country-specific factors that might impact the rate of diffusion of technologies. $\mathbf{X}_{ct}$ is a vector of time-varying control variables such as income per capita, a country's stock of human capital, and the adoption of complementary technologies, that are also impact technology diffusion. FIN_{ct} is our time-varying measure of financial market depth across countries. Hence β_2 measures the relationship between financial market depth and country's relative rate of adoption of technologies.

Given concerns about endogeneity and omitted variables that may bias this relationship, our main coefficient of interest is β_3, which is the coefficient on the interaction between financial market depth and an indicator variable for whether a given technology is highly capital intensive to commercialize. It therefore measures a country's relative rate of adoption of more vs. less capital intensive technologies. Our identification hinges on the assumption that our indicator variable creates a substantive distinction between the capital needs required for the commercialization of new technologies, and furthermore, does not confound any other mechanism that may also cause these technologies to be grouped together and that happens to be the true driver of faster technology diffusion in deeper capital markets.

More specifically, three assumptions are necessary for the validity of our identification strategy. (i) Deposits to GDP ratio is a good measure of financial market development; (ii) financial market development is the only variable that affects differentially the diffusion of capital-intensive (vs. non-capital-intensive) technologies, and (iii) our classification of technologies truly captures their capital intensity and not something else that correlates with capital-intensity. Below we discuss the validity of these assumptions.

For all the variables used in our analysis, we compute five-year averages and use non-overlapping data in our regressions. Taking these five year averages increases the signal-to-noise ratio of our variables and, a priori, does not reduce much of the relevant variation in the data since both technology diffusion and financial market depth are relatively low frequency phenomena. In addition, since we are interested in understanding the determinants of the speed of diffusion of new technologies along the transition path, we censor the data for each technology at the year when the level of technologies across countries becomes stable.

4 Empirical Results

4.1 Basic Results

Table 3 reports the results from our baseline regression, using both the full sample and a subsample that only includes the countries in Europe and North America. As can be seen from column 1 of Table 3, the level of financial development is correlated with the speed of technology diffusion. More importantly, the association between financial market development and technology diffusion is larger for capital intensive technologies. Column 2 highlights that the correlation between the level of financial development and technology diffusion is mitigated, once we control for other time-varying covariates such as the level of human capital and the level of per capital GDP in the country. However, the interaction between our measure of financial development and the indicator for capital intensive technologies continues to be significant, and in fact increases in magnitude. Columns 3 and 4 highlight that the degree to which financial development matters for the faster diffusion of capital intensive technologies is particularly salient for countries with above median financial development over the period 1870-2000. In panel B of Table 3, we re-run the same regressions, but restricting the sample to countries in Europe and North America. The results continue to hold for this sub-sample of countries with more reliable and comprehensive data.

Thus far, we have shown that there is a significant positive association between the level of financial development and the differential diffusion of technologies that are capital intensive. We now discuss various hypotheses about the origin of this association with the hope that the discussion brings us closer to uncovering a causal link between financial development and technology diffusion. One concern that typically arises in cross-country empirical analysis is that of reverse causality. In our context, this means that our baseline results may not indicate that financial development fosters technology adoption but rather that technology adoption leads to the development of financial institutions. One formulation of this reversed mechanism is that technology adoption increases income, and in richer societies there is a higher supply of financial resources (in this case more deposits relative to GDP). Note however that this cannot be driving our estimates since our regressions control for per capita income. So the mechanism by which technology adoption fosters the development of financial markets cannot operate through income.

Alternatively, the adoption of capital-intensive technologies could lead to an increase in investment (for a given income) and that could in turn spur financial development. However, the total amount of investment involved in the adoption of our technologies is not necessarily correlated with their capital intensity. Take for example computers since the 1990s or cars since the 1920s. Though not very capital-intensive, investment in these capital goods represented a significant portion of total investment in the economy during these time periods. Hence, there is little reason to believe that it is precisely the adoption of capital intensive technologies what stimulates investment and, through this channel, the development of financial markets.

One way to study this reverse causality hypothesis more systematically is by allowing per capita income to affect differentially the diffusion of capital intensive technologies. The rationale for this strategy steams from the fact that investment-output ratios are highly correlated with income at high and medium term frequencies (see, e.g., Prescott, 1984 , and Klenow and Rodriguez-Clare, 1997). If this correlation is driven by the expansion of capital intensive industries, allowing for a differential effect of income on the diffusion of technologies in capital intensive industries should capture the reverse channel of technology diffusion on financial market development. Columns 5 and 6 of Table 3 implements this exercise. We observe that both for the full and the Europe and North America samples, per capita income is not differentially associated with the diffusion of capital intensive technologies. Furthermore, allowing for a differential effect of income on capital intensive technologies does not affect the significance of the differential association between financial development and the diffusion of capital intensive technologies.

4.2 Late vs. Early Stage of Technology's Lifecycle

To obtain a better understanding of the mechanism that drives our findings, we divide our sample between the early and the late stages of technology diffusion. We implement this division using two distinct criteria. First, we split our sample into periods before and after 50 years from the invention of a technology. Thus, for each technology and country, the early adoption period comprises the periods prior to the invention year plus 50, and the late adoption, the periods afterwards. Second, we use the estimates of the adoption lags for each technology-country pair from Comin and Hobjin (2010). We define the early adoption stage as the period between the invention of the technology and the median adoption date for all the countries in sample for that technology. The late adoption stage comprises the subsequent years. Table 4 outlines the invention dates, and technology lags from Comin and Hobjin (2010). Note that, a key difference between these two classifications is that in the first the length of the early adoption stage is the same across technologies, while in the second it varies. Also note that early adopting countries will tend to have their diffusion process split in both samples, with the early stage covering the initial observations and the late stage covering diffusion once the technology is more widespread worldwide.

Table 5 presents the results for the two diffusion stages. We find that financial market development affects the diffusion of technology only in the early stages of diffusion. This is true both for splits made using a cutoff of 50 years from the invention of all technologies as well as a more nuanced split based on the median adoption lag for each technology as outlined in Table 4. The lack of association between financial market development and the diffusion of capital-intensive technologies for late adopters is hard to reconcile with the reversed causation hypothesis. If adopting capital-intensive technologies caused the development of financial markets, why don't we see a similar association between these two variables for both early and late adopters? On the other hand, the fact that the effect is much more salient in the early stages of a technology's lifecycle highlights the particularly important role of domestic capital markets in the initial diffusion of technologies. One natural interpretation of this finding is that local financial market development may facilitate the experimentation required with helping to commercialize new technologies.

4.3 Omitted Variables

Aside from reverse causality, there may be concerns that an omitted variable that is correlated with our interaction term (i.e., financial development * capital intensity) may be driving technology diffusion. Next we argue that our findings are unlikely to be driven by the omission of a relevant variable and instead they are substantive. Many of the sources of omitted variable bias stem from factors that have been shown to predict long-term cross-country differences in development such as genetic diversity (Spolaore and Wacziarg, 2009, and Galor and Ashraf, 2013), culture (Guiso, Sapienza and Zingales, 2008, and Tabellini, 2009), geography (Sachs and Warner, 1995) and the quality of institutions (Acemoglu, Johnson and Robinson, 2001). However, they typically do not have predictive power over development measures at higher frequencies once we include country-fixed effects which control for persistent country-level characteristics as we do.

For an omitted variable to drive our findings, it would have to be correlated with financial development **and** affect differentially the diffusion of capital intensive technologies. This second requirement is unlikely to be true for most of the usual suspects in cross-country analyses. That is, the channels by which some factors are likely to affect technology diffusion are most likely roughly symmetric across technologies. Therefore, their effect on diffusion would not bias the estimated effect on diffusion of our interaction term.

Take for example the case of culture. According to Guiso, Sapienza and Zingales (2006), certain cultural traits may affect trust as well as preferences for thriftiness and fiscal redistribution. Ichino and Maggi (2000) also provide evidence that culture affects shirking at work. One could make the case that trust, good work-attitude, low taxes or low discount rates are factors that may enhance technology adoption. But there is little reason to believe that they asymmetrically affect different technologies.

Geography is another dimension that has been regularly invoked as a fundamental driver of cross-country differences in development. As with culture, certain geographical variables such as access to the sea, latitude, malaria prevalence, or climate are unlikely to affect differentially capital-intensive technologies. However, there are other geographical variables that in principle could have a differential effect on the diffusion of capital intensive technologies. Take for example country size. Since the diffusion of certain capital intensive technologies such as telephone lines or railways often require large sunk costs and lead to network externalities one could argue that larger countries may be more prone to adopting intensively these technologies than small countries. Similarly the ruggedness of the terrain may also affect the costs of setting up the networks involved in the diffusion of these capital intensive technologies.

All these geographical variables are arguably constant. Therefore, we could collectively capture their effect on technology diffusion by interacting the country fixed-effects with the capital intensity indicator. This set of dummy variables also captures any differential effect of other variables that are fixed at the country-level on the diffusion of capital-intensive technologies. Therefore, the dummies capture the potential effect of certain institutional traits such as property right protection or the rule of law that arguably are very persistent.

As can be seen from Table 6, the inclusion of the set of country-dummies interacted with our capital intensity indicator does not significantly alter our estimates of the effect of financial market development on technology diffusion. For the early-late split based on the 50 years cut-off, the estimated effect of financial development* capital intensity increases marginally, while for the split based on the country-technology adoption lags estimates of Comin and Hobijn, the effect declines slightly and remains significant at the 10% level for Europe and North America, although it does attenuate significantly for the full sample. Overall, our results suggest that fixed country-level characteristics that affect differentially the diffusion of capital-intensive technologies do not account for our findings.

What about other omitted variables that may change over time? To start exploring this question, note that our interactions between per capita income and capital intensity provides a first control for many omitted variables that tend to be correlated with income. For example, suppose capital-intensive technologies had different Engel curves than less capital-intensive technologies. Allowing the log of per capita income to have a differential effect on the adoption of capital-intensive technologies addresses this concern. The robustness of our results to including the interaction between income and capital intensity suggests that the differential effect of financial depth we identify is distinct from other channels that operate through proxies of development.

An alternative way to rule out biases from omitted variables is by exploring the robustness of our findings to controlling for some reasonable drivers of technology diffusion. Given the previous discussion, we start this exploration by controlling for the openness of political institutions. We use PolityII from the Polity Project as a measure of political openness. Table 6 shows that Polity is associated differentially with the diffusion of capital intensive technologies, the estimate of β_3 is robust to controlling for PolityII and for its interaction with capital intensity.

A second natural control is human capital. We measure human capital by the secondary enrollment rate.In the second column of Table 6 we observe no differential effect of human capital on the diffusion of capital-intensive technologies. As with political institutions, the differential effect of financial development on the diffusion of capital-intensive technologies is absolutely robust to adding human capital to the control set.

Another argument that could be made in this regard is that capital-intensive technologies may also benefit more from government involvement in the economy since this involvement may be directed towards building or financing the infrastructures required for these technologies to diffuse. If government investment in infrastructures was correlated with financial market development, omitting government investment measures would bias our estimates. Exploring this possibility is not easy due to the severe data limitations that exist when using government expenditure data in panels such as ours. Data for expenditure on infrastructure is not available for most countries. Even if we use some cruder measure such as the share of government expenditure in GDP, this data is not available for most countries before 1960. However, despite these data limitations, there are two exercises we can perform, that are reported in Table 7. We limit our sample to the European and North American countries and first show that the coefficients on our main variable of interest are not drastically different for the post-1960 period compared to the entire period from 1870-2000. In fact, the coefficients are somewhat smaller for the later period, when the government involvement in the economy was arguably greater. This observation suggests that the omission of government expenditure and its interaction with capital intensity are not likely to be driving our estimates of β_3. Second, we introduce two additional controls in our baseline regressions: the share of government expenditure in GDP and this share interacted with our measure of capital-intensity. As can be seen from Table 7, government expenditure is positively associated with the diffusion of technologies. However, government expenditure is not more associated with the diffusion of capital intensive than non-capital intensive technologies. Further, including these controls does not lead to a significant change in the magnitude or significance of the effect of financial development on technology diffusion. If anything, the magnitude goes up slightly. This is true both for specifications that include only country fixed effects as well as for those that use country x dependence fixed effects. Therefore, we conclude that the differential effect of financial development on the diffusion of capital-intensive technologies we have identified is very unlikely to be driven by the omission of other drivers of adoption that may affect differentially capital intensive technologies such as the quality of political institutions, human capital or government spending.

4.4 Alternative interpretations of the classification

An assumption we have explicitly made to identify the role of financial markets on technology diffusion is that the classification of technologies according to their capital-intensity does not proxy for other classifications of technologies. That is, that there is no omitted variable in the capital intensive classification.

A possible classification that is correlated with ours is based on whether the technologies are tradable. It is easy to see that all the technologies in the less capital-intensive group are traded, while some technologies in the more capital-intensive group such as KMs of railroad tracks laid, telegrams sent, telephones installed are non-traded. Tradable technologies are directly embodied in goods whose import may be easier when importers have access to credit. Therefore, if this is the channel by which financial development affects technology diffusion, we should observe a positive differential effect of financial development on the diffusion of tradable technologies vs. non-tradable ones. To the extent that tradability is associated with less capital intensity, we find the exact opposite. Therefore, this is clearly not the mechanism we have identified in our analysis.[2]

Finally, we have observed that though human capital tended to matter in the diffusion of technology (see Table III), we did not find that it mattered more for the diffusion of capital intensive technologies. This suggests, a priori, that our classification based on capital intensity does not capture the degree of complementarity with human capital of the technologies. Inspection of the classification supports this conclusion. Technologies whose operation require significant human capital, such as computers or MRI are in the less capital-intensive group.

The number of possible technology-classifications is extremely large and we cannot go through all of them. But given this evidence, we feel confident that our classification of technologies based on their capital intensity is not proxying for alternative classifications of technology. Furthermore, we hope to have convinced the reader that the differential effect that financial development has on the diffusion of capital-intensive technologies in the early stages of technology diffusion of the leading countries, is evidence of the importance of local access to financial markets by the companies that develop new products and services that embody the specific new technologies.

[2]Furthermore, there is no apparent reason why tradability should matter only in the initial stages of adoption.

5 Conclusions

Prior work looking at the role of financial market development in productivity and economic growth has largely focused on the role of better developed financial markets in allocating capital efficiently across investment opportunities. In this paper, we provide evidence for another key role played by well-developed financial markets: reducing the frictions associated with the adoption and the diffusion of new technologies. We use a panel dataset that covers the diffusion of 16 major technologies across 55 countries and 130 years to examine whether greater depth in the banking sector leads to faster diffusion of these new technologies.

Our results provide compelling evidence that banking sector depth facilitates the faster diffusion of more capital intensive technologies. This effect operates in the early stages of diffusion and in the early adopters of technology. In contrast, we find no differential effect of financial depth on the diffusion of capital-intensive technologies in the late stages of diffusion or in late adopters.

This evidence points to the importance of capital markets for the experimentation required to overcome the initial hurdles of adoption and diffusion. While this mechanism has been explored in the context of venture capital, it has not been examined as a driver of technology diffusion nor has it been studied in a broad cross-country setting. Our evidence points to a new mechanism relating financial development to economic growth.

Future work on this topic should explore why financial development does not seem to affect the diffusion of new technologies in developing countries or in developed economies at the later diffusion stages. One possibility is that the only relevant channel through which financial development affects technology diffusion is the one we have identified in this paper. Our findings are also consistent with an environment where financial development affects other mechanisms that impact technology diffusion in emerging countries but in opposite ways, so that the net effect is insignificant.

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Table 1: Description of Technologies Used

	Technology	Capital Intensity	Countries covered		Country-Years per technology	
			Full Sample	*Europe & N. Am*	*Full Sample*	*Europe & N. Am*
1	Railroad track	High	34	18	183	131
2	Telegram	High	35	17	275	156
3	Telephone	High	54	19	631	318
4	Electricity Production	High	53	18	628	285
5	Electric Arc Steel	High	47	18	291	165
6	Blast Furnace Steel	High	35	17	156	87
7	Cell Phones	High	53	19	137	59
8	Ring Spindle	Low	32	12	170	63
9	Loom	Low	46	18	81	20
10	Passenger Cars	Low	54	19	599	277
11	Trucks	Low	53	18	575	268
12	Tractors	Low	52	18	263	103
13	Radio	Low	54	18	518	212
14	TV	Low	55	19	422	167
15	Computers	Low	53	19	138	56
16	MRI machines	Low	23	18	59	51
	Total				5,126	2,418

Table 2: Bank Deposits / GDP

Year	Europe and N. America	Asia	South America	Africa
1870	0.15	0.26		
1875	0.22	0.24		
1880	0.20	0.30		
1885	0.28	0.13		
1890	0.29	0.14		
1895	0.37	0.23		
1900	0.39	0.17	0.20	
1905	0.46	0.16	0.48	
1910	0.48	0.14	0.38	0.10
1915	0.44	0.18	0.53	0.09
1920	0.42	0.15	0.69	0.09
1925	0.43	0.13	0.30	0.09
1930	0.52	0.20	0.32	0.11
1935	0.47	0.20	0.45	0.12
1940	0.51	0.32	0.36	0.14
1945	0.41	0.27	0.35	0.17
1950	0.31	0.17	0.25	0.12
1955	0.30	0.15	0.27	0.09
1960	0.31	0.12	0.21	0.10
1965	0.30	0.14	0.23	0.11
1970	0.30	0.14	0.26	0.12
1975	0.30	0.14	0.29	0.13
1980	0.28	0.15	0.21	0.15
1985	0.32	0.15	0.14	0.16
1990	0.34	0.18	0.12	0.17
1995	0.36	0.28	0.25	0.20

Notes: (1) All data is aggregated to 26 5year time periods spanning 1870-2000.

Europe & N. Am includes AUT, BEL, CAN, CHE, DEU, DNK, ESP, FIN, FRA, GBR, GRC, ITA, NLD, NOR, POL, PRT, RUS, SWE and USA

Asia includes AUS, CHN, IDN, IND, IRN, IRQ, ISR, JOR, JPN, KOR, LBY, MYS, NZL, PHL, SAU, THA and TUR

South America includes ARG, BRA, CHL, COL, MEX, URY and VEN

Africa includes EGY, ETH, GHA, KEN, MUS, NGA, SDN, TUN, UGA, ZAF, ZAM, ZMB and ZWE

Table 3: Financial Development and Technology Diffusion

1870-2000: Dependent Variable: Log Technology Diffusion per capita

Panel A: Full Sample

	Full Sample	*Full Sample*	*Above Median Bank Deposits / GDP*	*Below Median Bank Deposits / GDP*	*Above Median Bank Deposits / GDP*	*Below Median Bank Deposits / GDP*
Deposits/GDP X capital intensity	0.424***	0.508***	0.402*	0.135	0.441**	-0.866
	(0.120)	(0.110)	(0.210)	(2.220)	(0.187)	(2.162)
Deposits/GDP	0.340***	0.137	0.104	1.383	0.0800	1.735*
	(0.120)	(0.110)	(0.140)	(1.010)	(0.149)	(0.938)
Human Capital		0.172	0.387**	0.248	0.199	-0.0281
		(0.110)	(0.160)	(0.440)	(0.260)	(0.495)
GDP per Capita		1.176***	1.340***	1.169***	1.383***	1.120***
		(0.052)	(0.250)	(0.170)	(0.370)	(0.191)
Human Capital x capital intensity					0.447	0.628
					(0.409)	(0.414)
GDP per capita x capital intensity					-0.0726	0.199
					(0.312)	(0.196)
Technology X Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	5126	5126	3153	1973	3153	1973

Panel B: Europe and North America

	Full Sample	*Full Sample*	*Above Median Bank Deposits / GDP*	*Below Median Bank Deposits / GDP*	*Above Median Bank Deposits / GDP*	*Below Median Bank Deposits / GDP*
Deposits/GDP X capital intensity	0.643***	0.624***	1.225***	0.263	1.235***	0.118
	(0.130)	(0.120)	(0.260)	(0.550)	(0.262)	(0.490)
Deposits/GDP	0.0129	0.081	-0.347*	0.167	-0.327	0.239
	(0.120)	(0.110)	(0.170)	(0.250)	(0.195)	(0.257)
Human Capital		0.483***	0.511*	0.156	0.465	0.143
		(0.120)	(0.250)	(0.250)	(0.323)	(0.319)
GDP per Capita		1.031***	0.736*	1.225***	0.997**	1.115***
		(0.087)	(0.360)	(0.180)	(0.435)	(0.267)
Human Capital x capital intensity					0.0981	0.0398
					(0.303)	(0.347)
GDP per capita x capital intensity					-0.439	0.191
					(0.301)	(0.348)
Technology X Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Observations	2418	2418	1221	1197	1221	1197

Robust standard errors in parentheses, clustered by technology

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

Notes: (1) All data is aggregated to 26 5year time periods spanning 1870-2000.

(2) Main effect for capital intensity is absorbed by the technology-year fixed effects

Table 4: Invention Dates and Diffusion Lags across Technologies

	Technology	Invention Date	Median Diffusion Lags from Comin and Hobjin (2010)		Number of country-years of data within 50 years of invention	
			Full Sample	*Europe and North America*	*Full Sample*	*Europe and North America*
1	Railroad track	1825	*96*	*72*	*21*	*19*
2	Telegram	1835	*31*	*21*	*49*	*44*
3	Telephone	1875	*35*	*10*	*135*	*102*
4	Electricity Production	1882	46	20	100	74
5	Electric Arc Steel	1907	59	29	49	49
6	Blast Furnace Steel	1950	13	10	156	87
7	Cell Phones	1973	13	12	137	59
8	Ring Spindle	1779	111	78	-	-
9	Loom	1785	170	168	-	-
10	Passenger Cars	1885	36	30	118	79
11	Trucks	1885	30	26	112	73
12	Tractors	1903	57	71	-	-
13	Radio	1920	18	12	270	123
14	TV	1927	30	26	218	93
15	Personal Computers	1973	14	13	138	56
16	MRI machines	1977	5	5	59	51
	Total				1,562	909

Table 5: Early vs. Late in Technology's Lifecycle

1870-2000: Dependent Variable: Log Technology Diffusion per capita

Panel A: Using 50 years from invention as cutoff for "Early"

	Full Sample <50 years	*Full Sample >50 years*	*Europe & N. America <50 years*	*Europe & N. America >50 years*
Deposits/GDP X capital intensity	0.999***	-0.130	1.182***	0.401
	(0.290)	(0.390)	(0.340)	(0.250)
Deposits/GDP	-0.0767	0.437	-0.144	0.180
	(0.150)	(0.290)	(0.230)	(0.260)
Human Capital	0.104	0.022	0.802	0.419*
	(0.390)	(0.350)	(0.640)	(0.200)
GDP per Capita	1.401***	1.046***	1.017**	1.181***
	(0.290)	(0.230)	(0.400)	(0.370)
Human Capital x capital intensity	0.547	0.193	-0.153	-0.206*
	(0.480)	(0.360)	(0.630)	(0.110)
GDP per capita x capital intensity	-0.178	0.233	-0.482	0.072
	(0.340)	(0.210)	(0.350)	(0.370)
Technology X Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Observations	1,562	3,564	909	1509

Panel B: Using Comin and Hobjin (2000) Diffusion Lags for Technologies

	Full Sample < Median Adoption Time	*Full Sample > Median Adoption Time*	*Europe & N. Am < Median Adoption Time*	*Europe & N. Am> Median Adoption Time*
Deposits/GDP X capital intensity	1.056***	-0.304	1.137***	0.283
	(0.270)	(0.500)	(0.320)	(0.460)
Deposits/GDP	-0.153	0.519*	-0.539**	0.493
	(0.170)	(0.260)	(0.250)	(0.340)
Human Capital	(0.120)	0.026	0.537	0.267
	(0.260)	(0.450)	(0.380)	(0.240)
GDP per Capita	1.267***	1.082***	1.695***	0.804***
	(0.420)	(0.170)	(0.480)	(0.190)
Human Capital x capital intensity	0.466	-0.0551	-0.365	0.468
	(0.340)	(0.420)	(0.390)	(0.410)
GDP per capita x capital intensity	-0.314	0.221	-0.720	0.008
	(0.300)	(0.160)	(0.420)	(0.260)
Technology X Year FE	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes
Observations	2413	2713	1201	1217

Robust standard errors in parentheses, clustered by technology

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

Notes: (1) All data is aggregated to 26 5year time periods spanning 1870-2000.

(2) Main effect for capital intensity is absorbed by the technology-year fixed effects

Table 6: Robustness Checks: Country x Dependence Fixed Effects

1870-2000: Dependent Variable: Log Technology Diffusion per capita

Panel A: Using 50 years from invention as cutoff for "Early"

	Full Sample <50 years	*Full Sample >50 years*	*Europe & N. America <50 years*	*Europe & N. America >50 years*
Deposits/GDP X capital intensity	0.870*	-0.0664	1.017*	-0.100
	(0.467)	(0.294)	(0.500)	(0.320)
Deposits/GDP	-0.00195	0.543***	-0.0625	0.507*
	(0.261)	(0.132)	(0.245)	(0.239)
Human Capital	0.371	0.151	1.009	0.554*
	(0.409)	(0.289)	(0.685)	(0.300)
GDP per Capita	1.425***	0.894***	1.357***	1.158***
	(0.276)	(0.254)	(0.336)	(0.361)
Political Institutions	0.0172	0.0137	0.0320**	0.0208
	(0.0152)	(0.00806)	(0.0139)	(0.0132)
Human Capital x capital intensity	-0.174	-0.110	-0.757	-0.323
	(0.640)	(0.471)	(0.828)	(0.341)
GDP per capita x capital intensity	-0.351	0.174	-1.049	0.127
	-0.00791	0.000160	-0.0218	-0.0103
Political instututions x capital intensity	(0.0169)	(0.00932)	(0.0156)	(0.0148)
Technology X Year FE	Yes	Yes	Yes	Yes
Country X Capital Intensity FE	Yes	Yes	Yes	Yes
Observations	1,464	3,280	868	1,465

Panel B: Using Comin and Hobjin (2000) Diffusion Lags for Technologies

	Full Sample < Median Adoption Time	*Full Sample > Median Adoption Time*	*Europe & N. Am < Median Adoption Time*	*Europe & N. Am> Median Adoption Time*
Deposits/GDP X capital intensity	0.416	0.499	0.626*	-0.0446
	(0.292)	(0.287)	(0.327)	(0.434)
Deposits/GDP	0.221	0.172**	-0.267	0.699**
	(0.150)	(0.0632)	(0.244)	(0.322)
Human Capital	0.102	0.132	0.662	0.237
	(0.333)	(0.497)	(0.434)	(0.292)
GDP per Capita	1.055**	0.797***	1.427***	0.849***
	(0.465)	(0.175)	(0.415)	(0.158)
Political Institutions	0.0386***	0.00747	0.0437**	0.0258**
	(0.00823)	(0.00797)	(0.0202)	(0.0112)
Human Capital x capital intensity	0.140	-0.637	-0.602	0.283
	(0.362)	(0.692)	(0.450)	(0.386)
GDP per capita x capital intensity	-0.0603	0.392	-0.474	-0.182
	-0.0231*	0.00401	-0.0133	-0.0224
Political instututions x capital intensity	(0.0120)	(0.0110)	(0.0224)	(0.0130)
Technology X Year FE	Yes	Yes	Yes	Yes
Country X Capital Intensity FE	Yes	Yes	Yes	Yes
Observations	2,293	2,451	1,138	1,195

Robust standard errors in parentheses, clustered by technology

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

Notes: (1) All data is aggregated to 26 5year time periods spanning 1870-2000.

(2) Main effect for capital intensity is absorbed by the technology-year fixed effects

Table 7: Robustness Checks: Government Expenditure

1870-2000: Dependent Variable: Log Technology Diffusion per capita

	Europe and North America	*Europe and North America - Post 1960*		*Europe and North America*	*Europe and North America - Post 1960*	
Deposits/GDP X capital intensity	0.711***	0.465**	0.474**	0.305	0.228*	0.265*
	(0.230)	(0.160)	(0.190)	(0.220)	(0.120)	(0.130)
Deposits/GDP	0.051	-0.093	-0.017	0.270	-0.027	0.052
	(0.160)	(0.120)	(0.130)	(0.180)	(0.110)	(0.110)
Human Capital	0.547*	-0.049	-0.045	0.635	0.073	0.095
	(0.280)	(0.180)	(0.210)	(0.360)	(0.130)	(0.130)
GDP per Capita	1.117***	0.850***	0.894***	1.512***	0.751**	0.845**
	(0.310)	(0.220)	(0.250)	(0.270)	(0.340)	(0.400)
Human Capital x capital intensity	-0.156	0.214	0.315	-0.390	-0.069	0.003
	(0.240)	(0.150)	(0.210)	(0.390)	(0.350)	(0.410)
GDP per capita x capital intensity	-0.146	0.147	0.158	-0.567	0.455	0.291
	(0.290)	(0.270)	(0.290)	(0.340)	(0.510)	(0.530)
Government Expenditure			0.032***			0.028***
			(0.008)			(0.009)
Gov Expenditure x capital intensity			-0.008			0.011
			(0.011)			(0.015)
Technology X Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Country FE	Yes	Yes	Yes	Yes	Yes	Yes
Country X Capital Intensity FE	No	No	No	Yes	Yes	Yes
Observations	2418	1333	1239	2418	1333	1239

Robust standard errors in parentheses, clustered by technology

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

Notes: (1) All data is aggregated to 26 5year time periods spanning 1870-2000.

(2) Main effect for capital intensity is absorbed by the technology-year fixed effects

Appendix

Capital Intensive Technologies

Railroads: Establishing a rail network was extremely capital-intensive. Comin and Hobjin (2009) cite work that estimated the cost of the Union Pacific Railroad to be $32,000 per mile and note that a railroad in England that was constructed in the 1820's and ran from Liverpool to Manchester in England cost $187,495 per mile. Janeway (2012) notes that in the peak years of the US railroad boom of the 1850s, expenditures on the construction of railroads amounted to $100 million per year.

Telegram: Telegrams required a complex wired network, often built along railroad tracks. Construction of the New York to Erie line was projected in 1848 to cost 250$ per mile for the first wire and an additional 100$ for each wire after that (Thompson, 1947). In 1850, there were about four thousand miles of wire in operation in the United Kingdom. The quality of the lines in the United Kingdom was higher than in the United States. This emphasis in quality led to higher construction costs. In some cases these amounted to $600 per mile. The first transatlantic cable from Newfoundland to Valentia, Ireland was laid in 1859, at a cost of $1.2 million.

Telephone– Similar to telegrams, setting up the telephone lines necessary for telephonic communication was very costly. By 1888, the American Bell Company had contracted telephone lines with 26,038 miles of wire, which covered a distance of approximately twenty times less than the actual wire length. These lines cost approximately 2,200,000 or 84$ per mile of wire (Rhodes, 1929)

Electricity Production- Thomas Edison is famously credited with the creation of the light bulb. Not long after his invention the United States began to see a demand for electric power. On September 4th of 1882 Thomas Edison opened the Pearl Street Station and in doing so created the first feasible alternative to gas lighting. The small structure in lower Manhattan is estimated to have cost upwards of $300,000 for its initial construction. Electric power stations were extremely capital intensive (Janeway, 2012).

Electric Arc Steel – Alcoa is typically credited with the first electric arc steel plant. In the construction of the pilot plant that began in 1888 the founders invested an estimated 20,000 dollars for construction. While the price of an electric arc furnace has decreased relatively over time the initial undertakings to get a plant started were incredibly capital intensive (Alcoa 2013).

Basic Oxygen Steel– The basic oxygen process developed outside of traditional "big steel" environment. It was developed and refined by a single man, Swiss engineer Robert Durrer, and commercialized by two small steel companies. Most basic Oxygen Steel Shops contain at least two furnaces. Dr. Schroeder of G.E. Process Automation Studies estimated the cost of a standard two shop furnace to be approximately $600,000 in 1968.

Cell Phones– The first cell phone, the DynaTAC (by Motorola) retailed at $3,900 in 1983 and was an additional 50 cents a minute to talk on. The steep price paid by consumers for the first cell phones are nothing in comparison to the sunk costs in the construction of the hundreds of cell towers across the United States. The entire process took close to 10 years to produce and an estimated $100 million in towers and research (Wolpin 2014).

Less Capital Intensive Technologies

Ring Spindle– The first mule was invented in a home in 1779 by a 26-year-old boy (Walton, 1925); similarly, the second mule was erected in a loft above a schoolhouse (French, 1862). The small, unsophisticated settings for the construction of these first mules indicate that producing mules required small sunk costs.

Loom– In William Radcliffe's personal narrative on the creation of the power loom, he cites that many of his British purchasers were paying just pounds 20 per machine. These were in the very first years of production (Radcliffe 1828).

Passenger Cars and Trucks– Lawrence Selzer (1928) documented that local financial networks played a role in the development of the automobile industry. He noted that "individual financiers made sporadic investments in automobile enterprises from time to time, but the organized fixed capital markets, until very recently, played a relatively small role in financing the expansion. O'Sullivan (2007) notes the example of Ford motor company, that raised only $28,000 in external finance, was profitable from the start and hence financed its expansion through internal cash flows.

Tractors– The Fordson was the first tractor to be produced at a large commercial scale. It was sold for just $750 in 1917 (Pripps and Morland 1993). In the early 20's as more competitors entered the market prices dropped even lower and some Fordson were sold for as cheap as $395 (Beemer and Peterson 1997).

Radio: The total cost of setting up a "modest" radio station was only around $50,000 (Archer, 1938).

TV– By 1939 one could purchase the Andrea Radio "sharp focus" 5-inch television for just $189. Even to purchase a top of the line 12-inch RCA Victor console consumers only had to spend $600.

Computers (1973) – The Altair 8800 was the first personal computer for sale in 1974. It cost just $397 to purchase. The engineer who helped create it, Ed Roberts, did not anticipate its huge success as many hobbyists wanted to purchase a personal computer for such a low price (Groeger 2005).