

External Finance, Firm R&D and Economic Growth

Qiushi Huang^{*†*}

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Abstract

This paper proposes that there exists a two-way interaction between a firm's R&D investment and its external financing: on the one hand, external financing facilitates R&D investments; on the other hand, higher R&D investments expand the technology frontier and render existing capital obsolete, which leads to lower collateral value, and hence, decreases a firm's ability to secure external financing. I provide empirical evidence for the proposed channel. In aggregate, this two-way interaction may manifest itself as a trade-off between growth (R&D) and financial stability (short-term debt): higher R&D investments resulted from additional credit supply shortens the debt maturity in the economy and hence increases its reliance on the use of short-term debt, which subsequently increases the economy's vulnerability to adverse credit shocks.

^{*}Kellogg School of Management. Email: q-huang@kellogg.northwestern.edu.

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1 Introduction

Technological innovation is a key determinant of economic growth ([Solow \(1957\)](#)), and there is a growing consensus that well-functioning credit markets play an important role in driving economic growth by alleviating capital misallocation problem. Another critical channel through which credit market might impact technological innovation is by financing innovation directly. Regarding this channel, one may ask, how does an additional supply of credit contribute to economic growth by financing firm-level R&D investment? If the decision is made to stimulate the economy with additional credit supply, how much additional innovation should be expected as a result? Would an additional supply of credit undermine the financial stability of the economy?

Much literature on the real impact of financial frictions focuses on physical investment¹. In contrast to physical investment, R&D investment differs in that its outcome is usually highly uncertain and intangible, and thus is not as collateralizable as physical investment.

In this paper, I propose that there exists another major difference between physical investment and R&D: a two-way interaction between R&D and firm's external financing capacity. On the one hand, external financing facilitates R&D investment. On the other hand, to the extent that technology is usually embodied in physical capital, R&D investment extends the technology frontier and renders existing capital obsolete, in turn lowering the firm's collateral value and, hence, its ability to secure external financing. To develop my argument, I first build a theoretical model to illustrate this two-way interaction. I then provide evidence that support the proposed obsolescence channel.

I consider an industry consisting of heterogeneous firms. In the model, a firm is a collection of production lines in which it has invested in the past. All of a firm's production lines produce the same products and generate profits, but with varying degrees of efficiency. Firms may invest in both physical capital (production lines) and R&D. Physical investment increases firms' capital stock for production. R&D investment expands the technological frontier in which firms are later able to invest, thereby improving their future productivity.

¹For instance, the sensitivity of investment to cash flow literature that is started by [Fazzari et al. \(1988\)](#), and its critique by [Rajan and Zingales \(1998\)](#). Most of the research on financial constraints following the debate between two papers has focused on physical investment.

The financial market in the model is characterized by two main frictions. First, due to limited commitment, firms are required to pledge physical capital in order to engage in external borrowing². Second, when firms borrow, they are required to pay a proportional cost³. There are two degrees of freedom in a firm's financing policy: the amount a firm borrows and the maturity of its external financing. A firm maximizes its value by optimally choosing both its physical investment and R&D investment, as well as how it manages the level and maturity of its external financing.

There are two main results in my analysis. First, R&D intensive firms tend to feature assets that depreciate comparatively quickly. The capital obsolescence rate (depreciation rate) is a weighted average of industry level innovation and firm level innovation, with the weight on the firm-level innovation being the inverse of the elasticity of substitution of firms' products.

To interpret this result, first note that the depreciation rate depends on the firm level innovation because each firm operates as a monopoly on its own production line. As a result, a new production line imposes a downward pressure on the existing products' profits. Second, the obsolescence rate is also a function of industry level innovation, for the following reason. Due to technological advancement, the average marginal product of capital is increasing over time. At the same time, the total labor supply remains fixed. Since capital and labor are not perfect substitutes, in equilibrium, the marginal product of labor increases over time. Hence, wage rate has to rise proportionally to equilibrate the labor market. The weights on these two forces depend on how much monopolistic power the firm has. This power itself is dependent upon the substitutability of the firm's products. As the economy grows, profits for installed capital decline while the overall labor cost rises. Inevitably, capital that demonstrates a lower marginal product will become obsolete when its profit falls below its associated labor cost. The main assumptions that drive this result are that technological progress needs to be embodied in the new capital and that capital and labor are not perfect substitute.

²See [Rampini and Viswanathan \(2010, 2013\)](#) for its application in corporate finance and [Gertler and Kiyotaki \(2015\)](#); [Buera and Moll \(2015\)](#); [Jermann and Quadrini \(2012\)](#) for its implications in macroeconomics literature.

³For example, if the firm issues public debt, this can be considered as a one-time issuance costs.

My second result is that R&D-intensive firms tend to rely more than other firms do on short-term external financing. Given the fact that collateral is required for external borrowing, assets are subject to a greater obsolescence discount when they are pledged as collateral for longer-term borrowing. Additionally, the obsolescence discount is higher for assets that depreciate quickly. However, short-term financing is subject to frequent rollover, a situation that also increases its overall financing costs. As a result, there exists a trade-off in the maturity choice: long-term external financing features a lower rollover cost, since firms are not often forced to renegotiate outstanding debt. Short-term debt, however, is subject to a lower obsolescence discount, and hence provides higher liquidity when firms are collateral constrained. Since the obsolescence discount is greater for R&D-intensive firms, and since rollover costs are the same for all firms, R&D-intensive firms with assets that depreciate more quickly tend to make use of short-term borrowing, while firms with assets that depreciate more slowly tend to engage in long-term borrowing.

To study the impact of additional credit supply, I have calibrated the model to match the key moments in the data. The parameters governing the obsolescence process were calibrated to match (1) the negative correlation between R&D investment and the degree of a firm's leverage and (2) the negative correlation between R&D investment and a firm's debt maturity. I then changed the collateralizability parameter that controls the amount of credit available in the economy as a whole, in order to study the impact of credit supply.

The model shows that despite the two-way interaction that exists between finance and innovation, an additional supply of credit is still conducive to R&D investment. More importantly, the two-way interaction that exists between R&D and debt finance manifests itself as a trade-off between growth and financial stability, in the following sense: higher R&D investment resulted from additional credit supply shortens the average asset maturity. Because of credit market frictions, the average amount of debt maturity in the economy as a whole is shortened. Hence, the economy is more reliant on the use of short-term debt, which subsequently increases the vulnerability of tech sectors to adverse credit shocks.

To summarize, the model shows that higher R&D investment leads to assets depreciating more quickly, a development which subsequently lowers a firm's collateral value and ability to secure external financing. The following facts are consistent with the model's predictions.

First, at both the firm-level and industry-level, the capital depreciation rate is positively related to R&D intensity. The industry-level data is from Bureau of Economic Analysis fixed assets tables and the firm-level data is from Compustat. In addition, incomplete contract theory suggests that creditors are more likely to agree to lend if they can recover more value from liquidation, which predicts that R&D intensity is negatively related to firm leverage and R&D intensity is negatively related to debt maturity ⁴. These predictions are confirmed in the data.

Finally, to understand whether the proposed obsolescence risk is indeed a concern for firms and creditors, I augment the analysis above that based on accounting variables with direct text evidence from companies' 10-K filings. I find that the frequency of the occurrence of obsolete-related words (obsolete, obsolescence) is positive correlated with firm level R&D intensity, after controlling industry fixed effects. This suggests that R&D intensive firms are more concerned with obsolescence risks than non-R&D-intensive firms. Additionally, 10-Ks from several commercial banks explicitly reveal their concern that that collateral might not be sufficiently valuable due to technological obsolescence. Collectively, these facts suggest that there exists a cause-effect relationship between R&D investment and debt capacity, and that this relationship is likely due to higher technological obsolescence associated with R&D investment.

Literature. This paper relates to several strands of literature. The first is a set of theoretical papers that studies models of limited commitment on various subjects such as financial constraints ([Albuquerque and Hopenhayn \(2004\)](#)), macroeconomic dynamics ([Cooley, Marimon, and Quadrini \(2004\)](#); [Jermann and Quadrini \(2007\)](#)), physical investment ([Lorenzoni and Walentin \(2007\)](#)), risk management ([Rampini and Viswanathan \(2010\)](#)) and capital structure ([Rampini and Viswanathan \(2013\)](#)). My model is closely related to [Rampini and Viswanathan \(2013\)](#), but my paper differs in its focus on the impact of R&D investment. In

⁴Liquidation value is of central importance for financial decisions when contracts are incomplete. In particular, debt contracts allow the creditor to seize the debtor's assets when the latter fails to make a promised payment. Since the debtor cannot commit to not withdraw his human capital from the project ([Hart and Moore \(1994\)](#)), or to not divert cash flows to himself ([Aghion and Bolton \(1992\)](#)), creditors are more likely agree to lend if the debt is secured by the project's assets. See also, [Williamson \(1988\)](#), and [Shleifer and Vishny \(1992\)](#)

particular, I show that, because of the problem of obsolescence inherent in the advancement of technology, the collateral constraints that arise from the problem of limited commitment may influence R&D investment in the economy as a whole.

My paper also relates to the growing literature that studies how external financing affects corporate innovation. The seminal paper [Brown, Fazzari, and Petersen \(2009\)](#) document that firms seem to face particular challenges associated with financing R&D. Although early research on capital structure and innovation pointed strongly against the role of banks (and debt) in financing innovation⁵, subsequent work seem to suggest a growing evidence that bank finance is an important source of capital for firms engaged in innovation. Specifically, [Chava, Oettl, Subramanian, and Subramanian \(2013\)](#) find that the US banking deregulations over the 1980s had a measurable effect on innovation, particular by firms who would have been more likely to be financially constrained. [Robb and Robinson \(2012\)](#) show that external bank finance is an important source of startup capital⁶. My paper contributes to this discussion by showing that innovation can also affect firms' external finance capacity, since innovation renders existing capital obsolete, and lowers those firms collateral value.

My paper contributes to the study of debt maturity in the finance literature. On the bank loan market, [Mian and Santos \(2018\)](#) show that creditworthy firms actively manage the maturity of their syndicated loans. [Xu \(2017\)](#) focuses on the public corporate bond market. Theoretically, [He and Milbradt \(2016\)](#) studies endogenous debt maturity dynamics in the Leland framework. [Arellano and Ramanarayanan \(2012\)](#) provide a quantitative model in which the the sovereign country can manage its debt maturity structure and leverage. My contribution is in showing that debt maturity decisions may also be affected by technological innovation, a channel that is absent from the literature.

Finally, my paper relates to the strand of macroeconomic research that adds financial factors to macroeconomic models. Along this line of research, including [Gertler and Kiyotaki \(2015\)](#); [Buera and Moll \(2015\)](#); [Jermann and Quadrini \(2012\)](#), assumes a maximum leverage constraint as a parsimonious way to model financial frictions. My paper adopts the same

⁵See [Hall and Lerner \(2014\)](#) for an extensive discussion

⁶For paper that emphasize the role of bank finance in facilitating innovation, see also [Nanda and Nicholas \(2014\)](#); [Mann \(2018\)](#); [Hsu, Tian, and Xu \(2014\)](#)

assumption, but enriches the financial side of these models by allowing firms to choose a maturity structure of external financing. Therefore, borrowers may choose both the level and maturity of external financing. In doing so, my model contributes to this literature by showing that there might be a trade-off between finance and growth. Higher R&D investments lead to faster economic growth, but it also extends the technology frontier and shortens existing asset maturity. Because of credit market frictions, the average debt maturity as a whole is also lower. So the economy has a higher reliance on the use of short-term debt, which subsequently increases the vulnerability of tech-sectors to adverse credit shocks.

Layout. The paper is organized as follows. In Section 2, I build a model to illustrate the two-way interaction between R&D investment and firm’s financing capacity. In Section 3, I solve the model and discuss its properties. In section 4, I provide empirical evidence for the proposed obsolescence channel. Section 5 concludes.

2 Model

In this section, I start by giving a micro-foundation for how physical capital depreciates, and how the rate of depreciation depends on both firm-level and industry level innovation. This is illustrated in a standard Schumpeterian growth model that features quality ladders and creative destruction.

Then I show that the firms’ optimization problem can be studied in a reduced form model where deprecation rates are determined by their innovation intensity. And I investigate the relation between external finance and firms’ investment.

2.1 The Micro-foundation of Capital Depreciation

2.1.1 Environment

Consider the following discrete time economy. Individuals consume a unique final good $Y(t)$. The final good is produced by labor and a continuum of intermediate goods $j \in [0, 1]$ with the following production technology

$$Y(t) = \frac{1}{1-\eta} \left[\int_0^1 x(j, t|q)^{1-\eta} dj \right] \quad (1)$$

$q(j)$ is the highest quality in variety j . $x(j, t|q)$ is the quality-adjusted quantity of variety j at time t . Mapping the model to the real life, one can think of each variety as a different type of product. For example, say i is the computer processor and j is computer RAM.

For each intermediate product j , goods with different quality are perfect substitute after they are quality adjusted. For example, one unit of computer RAM with quality 2 (2GB of memory) will be treated the same as two units of computer RAM with quality 1 (1GB memory). Different varieties are not perfect substitutes, and $\eta = \frac{1}{\sigma}$ captures the extent to which they are substitutable where σ is the elasticity of substitution. That is, $x(j, t|q) = \sum_{i=0,1,\dots,t} x_i q_i$.

2.1.2 Demand Curve and Final Good Sector

The final good producer maximizes profits, using a set of differentiated goods $x(j)$ as input and takes their prices as given. Each of the differentiated input $x(j)$ is produced by a monopolist $j \in (0, 1)$ who charges p_j for each quality-adjusted unit it sells. One can think of each monopolist as a different brand of product, and that the representative household demands all of the brands. In such environment, the final good producer will demand more of the lower priced intermediates goods which will push firms to compete in the price per quality-adjusted unit.

The final good producer has no saving technology and thus needs to optimize period-by-period. The problem of the final good producer is

$$\max_{x_j} \left\{ \frac{1}{1-\eta} \left[\int_0^1 x(j, t|q)^{1-\eta} dj \right] - \sum p_j x_j \right\} \quad (2)$$

First order condition of 2 gives the demand curve (price per unit of quality of that intermediate good).

$$p_i(q, x) = x_i^{-\eta} \quad (3)$$

2.1.3 Firms' Production Function

The definition of a firm A firm $j \in (0, 1)$ is a collection of capital invested in the specific production line $j \in [0, 1]$. That is, a firm can only operate on production line j and it excludes the possibility of multi-production firms ⁷. Each capital has a technology index $q_{i,j,t}$ where i is the technology, j is the intermediate good index and t is the time at which the capital is installed. A firm at j is indeed represented by $\{[k_{0,q_0}, k_{1,q_1}, k_{2,q_2}, \dots, k_{t,q_t}], [q_0, q_1, q_2, \dots, q_t]\}$ where k_{t,q_t} is the capital installed at t with technology $q_{i,t}$ (the intermediate good index j is omitted for $q_{i,t}$ as a firm is only operating on one production line).

Capital level Production The production function at the capital level is Leontief:

$$y = q_t \min\{k, l\}$$

where q_t is the technology at which the capital is installed, k is the amount of capital and l is the labor associated with operating this capital. That is, for each unit of k_{t,q_t} , it produces q_t unit of output using one unit of labor, so the production function for this capital k_{t,q_t} is . One unit of labor costs wage w . Therefore, the profits associated with one unit of capital k_{t,q_t} is

$$q_t k - w k \tag{4}$$

Next we aggregate the profits from the capital level to the firm level.

⁷For example, [Akcigit and Kerr \(2010\)](#)

Firm Level Production The profit of a firm is the total sales minus the total production costs, over all the vintage capital $i \in I$ of firm j :

$$\pi = \underbrace{p(q, x)x}_{\text{total sale}} - w_0 \underbrace{\sum_{i \in I} k_i}_{\text{total cost}} \quad (5)$$

$$= x^{1-\eta} - w_0 \sum_i k_i \quad (6)$$

$$= \left\{ \left(\sum_i k_i q_i \right)^{1-\eta} - w_0 \sum_i k_i \right\} \quad (7)$$

The summation is over all the technology index in the past $i \in I$ for this variety j . I is the set of technology index for the firm's current capital stock.

Proposition 1 A firm's production can be written as

$$\frac{\pi}{\tilde{q}^{1-\eta}} = Ak^\nu - w_0 k \quad (8)$$

where $A = \bar{q}^{1-\eta}$ is firm's productivity, w_0 is the wage rate, and k is a firm's capital stock. \tilde{q} is the industry level productivity that is defined as

$$\tilde{q}^{\frac{1-\eta}{\eta}} = \int_{j \in (0,1)} \bar{q}(j)^{\frac{1-\eta}{\eta}} dj \quad (9)$$

Proof: see appendix [A](#).

2.1.4 Aggregate Innovation Rate

We now examine the growth rate of the economy along the balanced growth path. The average productivity of capital in the economy is given by total production divided by total capital stock:

$$\overline{MPK} = \frac{\int_0^1 (\bar{q}(j) k_j^r)^{1-\eta} dj}{\int_0^1 k_j^r dj} \quad (10)$$

$$= \int_0^1 x(j)^{1-\eta} dj \propto Y(t) \quad (11)$$

Here we use the fact that the total labor demand in the economy is one unit. Since the fundamental production is Leontief, there is no redundant supply for either capital or labor factor, and the total quantity for capital is also one unit. The Leontief production function also implies that the wage rate w should be growing at the same rate as the average marginal product of capital $\tilde{q}^{1-\eta}$. In appendix A we verify that the growth rate along the balanced growth path is indeed $\tilde{q}^{1-\eta}$.

2.1.5 Capital Obsolescence

In the long run, the efficiency of capital production is increasing. But the price per unit of quality given by is falling. Therefore, once a unit of capital is installed, its life-span is limited as the variable cost associated with using it with – the labor cost of one unit of labor – will eventually exceed the profit it generates. Once its operating cost exceeds its profit flow, it will be out of operation and we call it *complete obsolete*.

The value of one unit of the capital installed at technology q_i is determined by the sum of discounted cash flow it would generate in the future, which is

$$\begin{aligned} v_i &= \sum_t \left(\frac{1}{1+r} \right)^t \{ p(k^r \bar{q}(j)) q_i - w_t \} \\ &= \sum_t \left(\frac{1}{1+r} \right)^t \{ \underbrace{(k_t^e q(j))^{-\eta}}_{\text{Firm Level}} q_i - \underbrace{w_t}_{\text{Industry Level}} \} \end{aligned} \quad (12)$$

The cash flow is decreasing over time for two reasons. First, the labor cost w_t is rising, as the average marginal product of labor is rising. Second, the profit per unit of quality $(k^e q(j))^{-\eta}$ is shrinking, for the products generated by the new capital impose a downward pressure on the existing product. The first has to do with industry-level innovation and the second is related to firm-level innvation.

These two forces are operating on different rates:

- Profit is shrinking at the rate of $q(j)^\eta$
- Labor cost is rising at the rate of $\tilde{q}(j)^{1-\eta}$

The weights on these two forces depend on the elasticity of substitution $\sigma = \frac{1}{\eta}$

- If η is close to zero, meaning that varieties are substitutable, then more obsolescence is coming from industry-level – this makes sense because they are close to perfect substitute so what happens in other production lines matter a lot for the firm.
- On the other hand, if η is close to one, meaning that those varieties are not substitutable and the monopoly power is high. This means that the new product affect old product mainly through the profit channel.

Definition A capital is *completely obsolete* if its operating cost exceeds its profit flow, so its operational value is negative.

The equation that determines *completely obsolete* capital is

$$(k^r \bar{q}(j))^{-\eta} \underline{q}_t - w_t > 0 \quad (13)$$

Which is

$$\underline{q}_t > w_t (k^r \bar{q}(j))^\eta = w_0 (\tilde{q}^{1-\eta}) (k_j^r)^\eta (\bar{q}(j)^\eta) \quad (14)$$

Proposition 2 In equilibrium, the obsolescence rate is proportional to an weighted average of firm level innovation and industry level innovation. The weight on industry level innovation is equal to the inverse of elasticity of substitution. That is:

$$\delta \propto \eta \gamma z_j + (1 - \eta) \gamma \bar{z} \quad (15)$$

where

$$z_j = \Delta \log \tilde{q}(j) \quad (16)$$

$$\bar{z} = \Delta \log \tilde{q} \quad (17)$$

Proof: take log on both sides of 14, assuming that we are in steady state so k^r is a constant, we have:

$$\log \underline{q}_t > c_0 + \underbrace{\eta \log \bar{q}(j)}_{\text{Firm level}} + \underbrace{(1 - \eta) \log \tilde{q}}_{\text{Industry Level}} \quad (18)$$

18 shows that the cash flow of an installed capital decreases proportionally to $\eta \log \bar{q}(j) + (1 - \eta) \log \tilde{q}$, which is a linear combination of the industry level innovation and a firm level innovation. More importantly, the weights on these two levels of innovations are the inverse of elasticity of substitution within this industry. Indeed, the RHS of 18 provides a threshold for which the capital technology is too costly to operate. Thus, the speed at which it grows is related to the obsolescence rate:

$$\delta_j \propto \Delta \{c_0 + \eta \log \bar{q}(j) + (1 - \eta) \log \tilde{q}\} = \eta \Delta \log \bar{q}(j) + (1 - \eta) \Delta \log \tilde{q} \quad (19)$$

If we assume γ to be the constant proportional factor, then we can write the above relationship as

$$\delta_j = \eta \gamma \underbrace{\Delta \log \bar{q}(j)}_{\text{firm-level innovation}} + (1 - \eta) \gamma \underbrace{\Delta \log \tilde{q}}_{\text{industry-level innovation}} \quad (20)$$

$$= \eta \gamma z_j + (1 - \eta) \gamma \bar{z} \quad (21)$$

QED.

This result is intuitive and provides a foundation for the reduced form relation between R&D and capital depreciation. Again, when η is close to zero, meaning that varieties are substitutable, then firms' products are close to perfect substitute so what happens in other production lines have a large impact on the firm. If, on the other hand, η is close to one, meaning that those varieties are not substitutable. The firm is operating in a more monopolistic environment and the industry-level pressure is small. However, because of this monopolistic power, the price effect due to new product is high. The cash flow is shrinking mostly because of the downward pressure imposed by the new product.

2.1.6 Firm's Investment and R&D

Until now the technology index for firm j is given: $\{q_i\}, i \in I$. In this section we endogenized it. Consider a firm operating at a intermediate good production line $j \in [0, 1]$. A firm with frontier technology $q(j)$ and effective capital stock k^e can invest in research and development. The outcome of R&D is a technology index $q' > q(j)$ that will be available for firm to invest in the next period.

The R&D production function is

$$A_x(r, k) = x_i \left(\frac{r}{k^r} \right)^c \quad (22)$$

$$r = \frac{R}{\tilde{q}^{1-\eta}} \quad (23)$$

and

$$\frac{q'}{q(j)} = A_x(R, k) + 1 \quad (24)$$

Where x is the firm's level characteristic that measures the efficiency of R&D investment. x takes two possible values: x_L, x_H and $x_L < x_H$. A firm's R&D ability is determined upon the entry of the firm. After the entry, its R&D efficiency is fixed.

The firm can also invest in physical capital in a technology that is available. Investing in capital with different technologies are equally costly. Therefore, a firm would optimally choose to invest in the frontier technology. That is, by investing in I amount of real capital today, the firm needs to spend $Iq(j)$ and the firm's quality-adjusted capital stock is increased by $Iq(j)$.

The Dynamics of Capital Stock Note that each period, we have

$$(k^r)' = k^r(1 - \delta_r) + i \quad (25)$$

$$(k^e)' = k^e(1 - \delta_e) + i \quad (26)$$

$$i = \frac{I}{\tilde{q}^{1-\eta}} \quad (27)$$

Recall that k^r is the physical units of the firm's capital stock and k^e is the quality-adjusted effective unit of the capital stock. δ_r is the obsolete rate of physical capital, it is positive because some vintage capital will be completely obsolete each period. δ_e denotes the effective rate of capital obsolete, which depends on both the firm level innovation and the industry level innovation.

2.2 Model with Financial Market

In this section, we allow firms to have access to financial market and study the two-way interaction between R&D investment and external finance.

2.2.1 Technology

By Proposition 1, a firm i that starts business at time t with capital stock $k_{i,t}$ uses the production technology

$$W(A_{i,t}, k_{i,t}) = A_{i,t}k_{i,t}^\nu - w_0k_{i,t} \quad (28)$$

Where $A_{i,t}$ is the firm productivity, $k_{i,t}$ is the capital stock. The first term $A_{i,t}k_{i,t}^\nu$ represents the revenue of the firm. The second term $w_0k_{i,t}$ encapsulates the variable cost associated with the production process, and it is assumed to be linear in capital stock.

This production function implies that revenue is increasing in both productivity A and physical capital stock k . The former could be improved by R&D investment, and the later accumulates over time because of physical capital investment, thus providing the firms with incentives to invest in both physical capital and R&D.

(1) R&D Investment The firm-level innovation in the current period z_i is assumed to be a function of the scaled R&D investment:

$$z_i(R, K) = x_i\left(\frac{R}{K}\right)^c + \epsilon \quad (29)$$

where x_i is the exogenous, firm-specific R&D ability, R is the R&D investment and k is the physical capital stock. $\epsilon \in N(0, v^2)$ is a random variable that corresponds to the uncertainty in innovation(cites here). In the previous section, we show that the dynamics of productivity is given by

$$\log A_{i,t} = \log A_{i,t-1} + a_1 z_i - a_2 \quad (30)$$

Where $A_{i,t}$ is the firm's productivity in the current period and $A_{i,t-1}$ is the productivity in the last period. a_1 and a_2 are parameters in the model. This functional form implies that higher R&D investment is associated with higher productivity in the next period.

(2) Physical Capital Investment A firm can invest in physical capital. The physical capital accumulation is standard

$$k_{i,t+1} = k_{i,t}(1 - \delta_{i,t}) + i_{i,t} \quad (31)$$

We assume that capital investment is irreversible $i \geq 0$ so that physical capital is eligible for long-term collateral. The capital depreciation rate δ is determined by an weighted average of firm level innovation and industry level innovation.

2.2.2 Financial Market

The entrepreneur can obtain external financing by entering the financial market, which are shaped by two important assumptions. First, the external financing capacity is determined by the collateral value of the firm. Second, there is a fixed cost for borrowing from the financial market.

The timing of events is as follows. When the firm starts at time t , it has an initial capital stock k_t and receives a draw from the distribution of the productivity shock, which in turn is determined by the R&D investment in the last period. It then decides whether to borrowing from the financial market in the current period. If the firm obtains additional external finance this period, it pays a fixed cost F . Then the firm invests, pays out dividends, and makes payments to the lender as required. At the beginning of the next period, the firm can

choose whether or not to renege the contract after observing the current-period profits. If the firm does not renege, the firm continues.

An entrepreneur with physical capital k can pledge the physical capital as collateral for external financing. The entrepreneur can choose both the maturity M and the amount of repayment D_M of the financial contracts. For such a contract, the collateral constraint is

$$D_M \leq \theta \underbrace{k_M}_{\text{collateral}} \quad (32)$$

Where k_M is the value of the collateral at the maturity. The parameter θ can be thought of as the degree of credit rationing or credit supply in the economy, with $\theta = 0$ corresponding to zero credit supply and $\theta = \infty$ corresponding to zero credit rationing.

Lenders in the economy have deep pockets and discount the future at rate $\frac{1}{1+r} \in (\beta, 1)$. These lenders are competitive and require an expected return $1+r$. Lenders understand that borrowers may default, in which case the lenders can seize the collateral. The assumption that firms are less patient than lenders is standard in the literature, and it implies that external financing matters in the long run. That is, firms are never completely unconstrained and thus financing policy is uniquely determined for all firms.

2.2.3 Collateral Constraint and Maturity

The value of the collateral determines the capacity of the external financing. In this part we examine how the collateral value is affected by the innovation rate and the maturity of the contract.

First, when a firm pledges capital stock k as collateral, the value of the collateral at the maturity M is given by

$$k_M = k(1 - \delta)^M \quad (33)$$

Where δ is the depreciation rate. And the collateral constraint can be written as

$$D_M \leq \theta k(1 - \delta)^M \quad (34)$$

Since the collateral needs to be of sufficient value in the event of default, fast-depreciation assets with higher δ will be of relatively less value than those with lower depreciation. According to the collateral constraint 34, it means that for the same amount of capital stock today, firms that own assets with higher depreciation rate δ have lower financing capacity. Similarly, long-term contracts discount the collateral value more than the short-term contracts, keeping everything else the same.

Second, notice that these collateral constraints need to be hold for all the outstanding contracts. That is, for each M , the capital of the firm needs to satisfy 34. On the firm level, all the pledged capital should not exceed the total capital stock of the firm. Therefore, we have

$$\begin{aligned}
D_1 &\leq \theta k^1 (1 - \delta) \\
D_2 &\leq \theta k^2 (1 - \delta)^2 \\
&\dots \\
D_M &\leq \theta k^M (1 - \delta)^M \\
&\dots \\
\sum_{i=1}^{\infty} k^i &\leq K
\end{aligned}$$

Where k^i is the capital associated with contract with maturity i , and K is the total capital stock of the firm. In the data, we only observe K and D_i at the firm level, and these constraints can be written as

$$\sum_i \frac{D_i}{\theta(1 - \delta)^i} \leq K \tag{35}$$

For computational reason, we restrict the maturity set to two choices $\{D_1, D_2\}$: one-period contracts that feature the short-term liability in the economy, and two-period contracts that correspond to the long-term contract. This modeling approach is closely related to a variety of methods that have been adopted in the literature.

2.3 Entry, Exit and Industry Dynamics

In the model, the external financing is fully collateralized. The only risk that a firm faces is the exogenous exiting probability ξ . Due to law of large numbers, in each period, a measure ζ of firms is eliminated from the economy. Once a firm dies, it is replaced with a new firm so that a stationary equilibrium is obtained. Each new firm owns physical capital k_0 and its innovation ability is drawn from the distribution $x \in F(x)$.

The aggregate innovation is an industry variable. In the appendix A, we show that the relationship between industry-level innovation and firm level innovation can be written as

$$\bar{z}^{1-\frac{1}{\sigma}} = \int_{i \in (0,1)} (z_i)^{1-\frac{1}{\sigma}} di \quad (36)$$

Which is a standard aggregate formula in Dixit-Stiglitz framework. subsectionFirm's Problem The firm's problem can be written recursively as the problem of maximizing the discounted expected value of future dividends by choosing the current dividend d , physical capital investment I , R&D investment R , short-term debt D'_1 , long-term debt D'_2 , given current state $S = \{A, k, D_1, D_2, W\}$ where W is the current profit.

$$V_x(A, k, D_1, D_2, W) = \max_{\{d, I, R, D'_1, D'_2\}} d + \beta \mathbb{E}V(A', k', D'_1, D'_2, W') \quad (37)$$

subject to budget constraints for the current and next period:

$$d + I + R + D_1 = W + \sum_{v=1,2} \frac{(D'_v - D_{v+1} - F(1+r)^v) \mathbb{1}_{D'_v > D_{v+1}}}{(1+r)^v} \quad (38)$$

$$W' = Ak^\nu - w_0 k \quad (39)$$

the collateral constraints:

$$\sum_{v=1,2} \frac{D'_v}{(1-\delta)^v} \leq \theta k \quad (40)$$

the states in the next period are determined by

$$k' = (1 - \delta)k + I; I \geq 0 \quad (41)$$

$$A' = x\left(\frac{R}{k}\right)^c + \epsilon \quad (42)$$

The capital depreciation rate is proportional to an weighted average of firm-level innovation and industry-level innovation:

$$\delta = \left(\frac{1}{\sigma}\hat{A}_i + \left(1 - \frac{1}{\sigma}\right)\bar{A}\right)\gamma \quad (43)$$

where γ is a scaling factor, σ is the elasticity of substitution and the industry-level innovation is given by

$$\bar{A} = \int_{i \in (0,1)} (A'_i)^{1-\frac{1}{\sigma}} di \quad (44)$$

2.4 Equilibrium

Let $s = (A, k, D_1, D_2, W, x)$ be the state vector for an individual in our economy. From the decision rules that solve the maximization problem, we can derive a transition function that provides the probability distribution of s' conditional on s .

A stationary equilibrium is given by dividend policy $d(s)$, physical investment policy $I(s)$, R&D investment policy $R(x)$ and financing policies $D'_{1,2}(s)$; and a constant distribution of people over the state variables s , $m(s)$, such that, given r , w_0 , and θ , the following conditions hold:

- The functions $d(s)$, $I(s)$, $R(x)$, $D'_{1,2}(s)$ solve the maximization problem described above.
- The distribution m^* is the invariant distribution for the economy.

3 Solution

In this section, we discuss the solution to the model and its properties.

3.1 Parameter Choices and Calibration

The model is solved numerically. Each period is one year. Entrepreneurs discount factor is set to be 0.92, in line with dynamic corporate finance literature. The risk-free rate is set to be $r = 0.04$. The exit rate is set to be 0.04, corresponding to an average firm life of 25 years.

I set the curvature of production function as $\nu = 0.65$. In our model, the curvature of the production function is closely linked to the elasticity of substitution between industry products. According to our derivation in proposition 1, this implies the industry has an elasticity of substitution of $\frac{1}{1-\nu} = 3.0$. The persistence of productivity $\rho = 0.65$ and its volatility $\sigma = 0.2$. The wage rate is set to $w_0 = 0.1$. And the base of depreciation rate $\delta_0 = 0.12$ ⁸.

The important parameters in our model are the sensitivity of depreciation to R&D investment, as well as the collateralizability of the physical capital θ . As a benchmark case, I choose the collateralizability θ to match the average leverage ratio for firms that have positive R&D in Compustat.

I calibrate the parameters for financing costs and R&D investment to match the following moments : (1) the correlation between R&D to asset ratio and firms' leverage, and (2) the correlation between R&D to assets ratio and firms' maturity. If the financing costs F is high, firms will choose to shorten their debt maturity. This obtains a collateralizability of $\theta = 0.3$, a fixed cost $F = 0.2$, and the curvature of R&D investment function $c = 0.2$.

Figure 1 shows a sample path of firm dynamics under these parameters. It shows that after a firm's entry, it has to go through a number of financial constrained periods before it reaches the area in which it start paying out dividend.

⁸The base deprecation rate is slightly higher because my focus is on the firms that engage in research and development.

3.2 Optimal Financing Policies

Previously we have shown that the depreciation rate is affected by both the firm-level innovation and the industry-level innovation. In this section we consider how the innovation rate affects firms' financing choices through its impact on the depreciation rate.

R&D Investment and Firm Leverage First, we discuss its impact on the levels of external finance. Notice that firms with higher depreciation rate δ have lower total collateral value $\sum_i k^i (1 - \delta)^i$ and therefore lower capacity for external financing. In the context of debt financing, this generates two predictions on the level of external finance:

- (1) innovation-intensive firms are expected to borrow less
- (2) high-tech industries are expected to have lower leverage

R&D and Firm's Debt Maturity We now turn to the maturity structure of external finance. According to the borrowing constraint, a financially constrained firm that aims to maximize the liquidity gains in the current period should borrow at the short-term. In fact, in the absence of fixed cost of initiating contracts, any long-term contracts can be equivalently implemented by a sequence of short-term contracts, as shown in [Rampini and Viswanathan \(2013\)](#). As a result, every firm should use one-period contracts and rollover every period to maximize the financing capacity. That is, there is no cross-sectional variation in the debt maturity structure.

With the fixed cost, however, firms have incentive to borrow long-term to lower the frequency of paying this cost. In the context of debt contracts, firms borrow long-term to reduce the rollover costs. The optimal maturity structure should balance the trade-off between liquidity gains and rollover costs.

Next consider how depreciation rate affects the maturity choice. Note that for M-period contract, the collateral value needs to be discounted by a factor of $(1 - \delta)^M$. Short-term contracts, relative to long-term contracts, get discounted less in the collateral value, thereby providing a higher upfront liquidity gains. Moreover, the liquidity gains from using short-term contracts is increasing in the depreciation rate δ . Intuitively, when the capital depre-

ciation rate is high, it is more optimal to borrow short-term against it. On the other hand, the benefit associated with using long-term contract is the rollover cost, which is not varying across different firms. As a result, firms with faster-depreciation assets tend to borrow more short-term. This implies that

- innovation-intensive firms are expected to borrow more at the short-term
- high-tech industries are expected to have more short-term liabilities

Taken together, this section argues that higher obsolescence rate resulting from innovation leads to lower leverage and shorter maturity, at both the firm level and industry level. That is,

- R&D intensity is negatively correlated with firm leverage.
- R&D intensity is negatively correlated with debt maturity.

For each industry, I calculate the following variables: (1) average R&D intensity is the ratio of R&D expenditure to total assets (2) average leverage is the ratio of debt levels to the total assets. Figure 2 presents the industry level result. It shows that R&D intensive industries such as Business Service, Business Equipment, Medical Equipment and Electrical Equipment are characterized by lower leverage and the usage of short-term debt, which are consistent with our theoretical predictions. After controlling the industry fixed effects, I find that on the firm level, firm leverage and debt maturity are negatively correlated with firm level R&D intensity.

3.3 The Impact of Additional Credit Supply

In the model, the credit supply in the economy is controlled by the collateralizability parameter θ . Intuitively, the higher the θ , the more credit will be available for a firm with the same amount of collateral. To study the effect of credit supply to R&D investment, for each value of θ I simulate an industry consisting of 10000 firms. At the steady state, I calculate the average R&D to capital stock ratio, the external finance to capital ratio (leverage) and the average maturity.

Figure 3 plots how R&D ratio varies with different level of credit supply. In the presence of financial frictions, firms are constrained for a certain number of time before they start paying out dividends. Once the collateral constrained is loosened, constrained firms increase their R&D investment.

In the model, constrained firms will naturally want to borrow more with higher collateralizability θ . They also reach the unconstrained area with a shorter time. In fact, in the absence of financing constraints, they will reach the dividend paying state in one period. Figure 4 shows that the average leverage ratio is increasing in the credit supply θ .

The additional credit supply fuels more R&D investment, so the obsolescence rate in the economy rises, which lowers the value of collateral and hence the financing capacity of firms. Especially, the obsolescence discount is particularly high for long-term borrowing. Figure 5 shows that when credit supply leads to higher R&D investment, there will be more short-term borrowing in the economy. To the extent that short-term debt is more sensitive to adverse credit shock relative to long-term debt, the economy's higher reliance on the use of short term might undermine its financial stability.

So far we have illustrated the theoretical reasoning for why R&D investment is associated with the use of short term assets and hence the short term debt. Next we ask whether this mechanism can be observed in the data.

4 Empirical Evidence

This section presents evidence that R&D investments are associated with the use of short term assets. We start by the fact unlike physical investment, R&D has become highly concentrated in the high-tech industries. The high-tech industries are defined as follows:

- SIC 28: Pharmaceutical
- SIC 35: Industrial Equipment
- SIC 36: Electronic Equipment
- SIC 37: Transportation Equipment

- SIC 38: Instruments
- SIC 737: Computer-Related Service

Figure 6 plots physical and R&D investment in billions of 2000 dollars for all publicly traded firms listed in Compustat from 2006 to 2012. Several facts stand out. First, the high-tech sectors account for almost 80% of the total R&D, but they invest relatively less in physical capital. Second, during the recent credit crisis, there has been a large drop in aggregate R&D and physical investment. Therefore, high-tech sectors should be the major focus for understanding the R&D investment in the economy. The rest of the empirical analysis focuses exclusively on the firms in high-tech sectors.

4.1 BEA Tables

I use BEA fixed assets table from 1975-2015 to show the industry level correlation between R&D expenditure and the depreciation rate of physical assets. Fixed asset data are available in three categories: structures, equipment and intellectual property (which includes software: R&D; and expenditures for entertainment, literary, and artistic originals). Since our mechanism works through the embodiment of technology and most technology are embodied in the equipments, I expect to observe a positive correlation between intellectual property investment (proxy for R&D) and the depreciate rate of equipment (proxy for physical capital depreciation rate). The breakdown of asset classes allows us to examine whether my conjecture is reflected in the data.

Figure 7 shows a positive cross-sectional correlation between the rate of intellectual property investment and equipment depreciation rate. Each dot represents an industry over the entire span of the dataset, and the size of a dot is proportional to the average R&D investment. The industry classification is 3-digit NAICS. It shows that industries that have higher intellectual investment rate are associated with higher equipment depreciation rate, which is consistent with the theory. Figure 8 replicates this relationship in the time-series data. Each dot represents a year in the data. Thus, the positive correlation between intellectual property investment and equipment depreciation rate can be found in both cross-sectional data and time-series data.

4.2 Compustat

Next, I confirm this industry-level positive correlation using accounting variables in Compustat. Firms in Compustat report research and development expense XRD, book value of physical capital PPEGT, total asset AT and depreciation DP. The R&D intensity is defined as R&D expenditure over total assets $\frac{XRD}{AT}$, and the proxy for asset maturity is defined as book value of physical capital divided by the depreciation $\frac{PPEGT}{DP}$ (Guedes and Opler (1996)). For each industry in Fama-French categories, I calculate the average R&D intensity and average asset maturity.

Figure 11 confirms that R&D intensive industries are associated with lower asset maturity. This relationship is robust to different industry classification: upper panel is for FF49; middle panel is for FF30 and the lower panel is for FF17. The high-tech sectors are concentrated at the lower right corner of each graph, which is consistent with the theoretical prediction.

The firm level accounting variables in Compustat allow me to further test this relationship at the firm level. After controlling for industry fixed effect, we still find a negative correlation between R&D intensity and the proxy for asset maturity. Table 1 presents the BEA and Compustat results. Column (1) shows that the univariate relation between industry level equipment depreciation rate and intellectual property investment rate is positive and statistically significant. In Column (2), I control for industry fixed effects; the coefficient illustrates the correlation between the proxy of asset maturity and the R&D intensity.

4.3 Evidence from 10Ks

In this section I document evidence of the obsolescence channel through 10-K filings of public traded companies in the United States. The obsolescence channel consists of two parts: (1) firms that are R&D intensive are subject to higher obsolescence risks and (2) The supply side of credit takes the obsolescence risks into consideration for credit lending. To do so, I download all filings of Form 10-K from 1994 - 2007. Appendix B provides details on the data processing.

4.3.1 Anecdotal Evidence from Firms' 10Ks

The importance of debt financing and technological obsolescence get reflected in various reports.

- From 10-K filed by ADVANCED MICRO DEVICES, INC (semiconductor industry) for the fiscal year ended December 26, 2015: debt financing is important for innovation.
“We regularly assess markets for external financing opportunities, including debt and equity financing. Additional debt or equity financing may not be available when needed or, if available, may not be available on satisfactory terms. The health of the credit markets may adversely impact our ability to obtain financing when needed. Any downgrades from credit rating agencies such as Moody’s or Standard & Poor’s may adversely impact our ability to obtain external financing or the terms of such financing. In July 2015, Moody’s lowered our corporate credit rating to Caa1 from B3 and our senior unsecured debt rating to Caa2 from Caa1. Furthermore, in October 2015, Standard & Poor’s lowered our corporate credit rating to CCC+ from B- and our senior unsecured debt rating to CCC from B-. Credit agency downgrades or concerns regarding our credit worthiness may impact relationships with our suppliers, who may limit our credit lines. Our inability to obtain needed financing or to generate sufficient cash from operations may require us to abandon projects or curtail planned investments in research and development or other strategic initiatives. If we curtail planned investments in research and development or abandon projects, our products may fail to remain competitive and our business would be materially adversely affected.”
- From the same report: *“:Factors that may result in excess or obsolete inventory, which could result in write-downs of the value of our inventory, a reduction in the average selling price or a reduction in our gross margin include: ...” a higher incidence of inventory obsolescence because of rapidly changing technology and customer requirements...*
- From 10-Q filed 1/27/2016 by APPLE INC(AAPL): Obsolescence Risk
“Although the Company believes its provisions related to inventory, capital assets, inventory prepayments and other assets and purchase commitments are currently adequate, no assurance can be given that the Company will not incur additional related

charges given the rapid and unpredictable pace of product obsolescence in the industries in which the Company competes.”

- From 10-Q filed 5/6/2016 by SOCKET MOBILE, INC. (SCKT): Technological obsolescence
“Our handheld computers are designed with wireless LAN (802.11 b/g/n) and Bluetooth connectivity for use with applications that do not require phones. Due to the technical obsolescence of key components, we have announced end of life for this product family and are expected to exhaust supplies during 2016.”

4.3.2 Perceived Obsolescence Risks: Firms’ Side

Since the frequency of obsolete-related-words to some extent reflects firms’ concern about this particular risk, I examine the relationship between R&D intensity and the perceived obsolescence risk by merging the Compustat Data with frequency data from 10-K filings.

Figure 12 shows that R&D intensive industries are associated with higher frequency of obsolete-related-words, suggesting the perceived obsolescence risk is correlated with R&D intensity. Table 1, column (3) controls the industry fixed effects and shows that on the firm level, the frequency of occurrence of obsolete-related-words is positive correlated with R&D intensity calculated from the Compustat.

4.3.3 Perceived Obsolescence Risk: Bank’s Side

Several banks explicitly mention the following in their 10-Ks:

“Although commercial business loans are often collateralized by real estate, equipment, inventory, accounts receivable or other business assets, the liquidation of collateral in the event of a borrower default is often not a sufficient source of repayment because accounts receivable may be uncollectible and inventories and equipment may be obsolete or of limited use, among other things.”

The above quote suggests that banks not only require collateral for credit lending, but are also aware of the risk that collateral may be less valuable because of the technological obsolescence when it needs to be liquidated. Evidently, lenders such as banks take this obsolescence factor into account consideration. As a result, the collateral value of equipment

and inventory is subject to the obsolescence risk, which has been shown to be associated with firm and industry level R&D intensity.

5 Conclusion

The empirical and theoretical results in this paper point to an important two-way interaction between a firm's R&D and its external financing: on the one hand, external financing facilitates R&D investment; on the other hand, higher R&D investment extends the technology frontier and renders existing capital obsolete, a development that leads to lower collateral value, and hence, decreases a firm's ability to secure external financing.

This two-way interaction on the firm level might manifest itself on the aggregate level as a trade-off between economic growth and financial stability. If banks stimulate the economy with an additional supply of credit, R&D investment increases, and the capital depreciation rate rises. According to the theory, the average debt maturity falls, so the economy will rely more heavily on the use of short-term debt, thereby undermining the financial stability of the economy.

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Appendices

A Proofs of Propositions

A.1 Proof of Proposition 1

To further simplify the production function we use the following notations:

$$k^r = \sum_i k_i \quad (45)$$

$$\bar{q}(j) = \frac{\sum_i k_i q_i}{\sum_i k_i} \quad (46)$$

$$k^e = \frac{\sum_i k_i q_i}{q(j)} \quad (47)$$

$$k^r \bar{q}(j) = k^e q(j) = \sum_i k_i q_i \quad (48)$$

k^r is the total amount of capital the firm have accumulated in the past, without quality adjustment. $\bar{q}(j)$ is the average capital quality for firm j , which by definition is equal to the total amount of quality-adjusted capital divided by total amount of capital. k^e is the quality-adjusted capital stock, and the unit is in terms of the frontier technology $q(j)$. 48 gives the identities that these quantities have to hold. Using 45–48, the firm's profit can be simplified to:

$$\pi = \bar{q}(j)^{1-\eta} (k^r)^{1-\eta} - w k^r \quad (49)$$

We define the industry average capital quality to be

$$\tilde{q}^{\frac{1-\eta}{\eta}} = \int_{j \in (0,1)} \bar{q}(j)^{\frac{1-\eta}{\eta}} dj \quad (50)$$

and make a guess that $w = w_0 \tilde{q}^{1-\eta}$. That is, the wage is growing at the rate $\tilde{q}^{1-\eta}$. In section A.2, we will verify that the wage and the economy are indeed growing at this rate. With

this guess, we have

$$\pi = \left(\left(\frac{\bar{q}(j)}{\tilde{q}} \right)^{1-\eta} (k^r)^{1-\eta} - w_0 k^r \right) \tilde{q}^{1-\eta} \quad (51)$$

Let us denote $A_{j,t} = \left(\frac{\bar{q}(j)}{\tilde{q}} \right)_t^{1-\eta}$, then

$$\log A_{j,t} = (1-\eta)(\log \bar{q}(j)_t - \log \tilde{q}_t) \quad (52)$$

$$= (1-\eta)(\log \bar{q}(j)_{t-1} - \log \tilde{q}_{t-1} + \Delta \log \bar{q}(j) - \Delta \log \tilde{q}) \quad (53)$$

$$= \log A_{j,t-1} + (1-\eta)(\Delta \log \bar{q}(j) - \Delta \log \tilde{q}) \quad (54)$$

It means that the log of firm-level productivity is equal to the past productivity plus the technology innovation today minus the industry-level innovation today. If we denote firm-level innovation and industry-level innovation as

$$z_j = \Delta \log \bar{q}(j) \quad (55)$$

$$\bar{z} = \Delta \log \tilde{q} \quad (56)$$

then the dynamics of productivity can be written as

$$\log A_{j,t} = \log A_{j,t-1} + (1-\eta)(z_j - \bar{z}) \quad (57)$$

Denote

$$k = k^r \quad (58)$$

$$\nu = 1 - \eta \quad (59)$$

and the production function can be simplified to

$$\frac{\pi}{\tilde{q}^{1-\eta}} = A k^\nu - w_0 k \quad (60)$$

QED.

A.2 Verifying the Aggregate Innovation Rate

Optimal Capital Stock The profit function can also be written as:

$$\pi = q(j) \left\{ (k^e q(j))^{-\eta} - \frac{w}{\bar{q}(j)} \right\} k^e \quad (61)$$

$$= q(j)^{1-\eta} \left\{ (k^e)^{-\eta} - \frac{w_0 \tilde{q}^{1-\eta} q(j)^\eta}{\bar{q}(j)} \right\} k^e \quad (62)$$

If we define

$$\hat{q} = \left(\frac{\bar{q}(j)}{\tilde{q}} \right)^{1-\eta} \left(\frac{\bar{q}(j)}{q(j)} \right)^\eta \quad (63)$$

The profit becomes

$$\pi = q(j)^{1-\eta} \left\{ (k^e)^{-\eta} - \frac{w_0}{\hat{q}} \right\} k^e \quad (64)$$

FOC of 64 (with respect to k^e) gives the optimal amount of effective capital stock

$$k^{e*} = \left(\frac{1-\eta}{w_0} \right)^{\frac{1}{\eta}} \frac{\bar{q}}{q} \left(\frac{\bar{q}}{\tilde{q}} \right)^{\frac{1-\eta}{\eta}} \quad (65)$$

and the real amount of capital stock

$$k^r = \left(\frac{1-\eta}{w_0} \right)^{\frac{1}{\eta}} \left(\frac{\bar{q}}{\tilde{q}} \right)^{\frac{1-\eta}{\eta}} \quad (66)$$

Therefore the total intermediate good on j is:

$$x^* = q k^{e*} = \left(\frac{1-\eta}{w_0} \right)^{\frac{1}{\eta}} \bar{q} \left(\frac{\bar{q}}{\tilde{q}} \right)^{\frac{1-\eta}{\eta}} \quad (67)$$

Note that the first term $(\frac{1-\eta}{w_0})^{\frac{1}{\eta}}$ is a constant. Without the loss of generality we normalized the first term by assuming that $w_0 = 1 - \eta$ ⁹ and we have

$$k^r = (\frac{\bar{q}}{\tilde{q}})^{\frac{1-\eta}{\eta}} \quad (68)$$

$$x^* = \bar{q}(\frac{\bar{q}}{\tilde{q}})^{\frac{1-\eta}{\eta}} \quad (69)$$

Combining 67 and 1, the aggregate output is:

$$Y(t) = (\frac{1-\eta}{w_0})^{\frac{1-\eta}{\eta}} \int_{i \in [0,1]} \frac{\bar{q}(i)^{\frac{1-\eta}{\eta}}}{\tilde{q}^{\frac{(1-\eta)^2}{\eta}}} di \quad (70)$$

$$= (\frac{1-\eta}{w_0})^{\frac{1-\eta}{\eta}} \int_{i \in [0,1]} \bar{q}(i)^{\frac{1-\eta}{\eta}} di \frac{1}{\tilde{q}^{\frac{(1-\eta)^2}{\eta}}} \quad (71)$$

$$= (\frac{1-\eta}{w_0})^{\frac{1-\eta}{\eta}} \frac{\tilde{q}^{\frac{1-\eta}{\eta}}}{\tilde{q}^{\frac{(1-\eta)^2}{\eta}}} \quad (72)$$

$$= (\frac{1-\eta}{w_0})^{\frac{1-\eta}{\eta}} \tilde{q}^{1-\eta} \quad (73)$$

This again validates that along the balanced growth path the growing at the rate is $\tilde{q}^{1-\eta}$.

In fact, on the Balanced-Growth-Path (BGP), everything is growing but at the same time the economy is effectively static. The aggregate output in the economy is growing:

$$Y(t) = (\frac{1-\eta}{w_0})^{\frac{1-\eta}{\eta}} \tilde{q}^{1-\eta} \quad (74)$$

and the rate $\tilde{q}^{1-\eta}$ is given its definition 50.

⁹This normalization ensures that the total number of capital in the economy is one unit. Otherwise, the total number of capital in the economy is a constant $(\frac{1-\eta}{w_0})^{\frac{1}{\eta}}$.

B Empirical Appendix

Accounting Rules in Compustat According to General Accepted Accounting Principles (GAAP), the depreciation rate is calculated as

$$DP = \frac{\text{Purchased Cost} - \text{Estimated Salvage Value}}{\text{Estimated Useful Life}} \quad (75)$$

The numerator is the difference between the purchased cost and the estimated salvage value, and the denominator is the estimated useful life. The firms have discretion over changing the estimated useful life and the salvage value. In fact, they are instructed to do so, at least annually. The Chapter 30.76 of the Financial Accounting Manual for Federal Reserve Banks writes:

“The depreciation rate should be based on the expected unique useful life to the Reserve Bank, taking into account such factors as probable technological obsolescence and projected capacity limitations consistent with the Bank’s long-range procurement plans, industry information, and improvements. The salvage value assigned to an asset should reflect the Reserve Bank’s expected recovery upon sale or trade-in of the asset. Assessments of the useful life and salvage value of all assets, excluding building but including Building Improvements, and Building Machinery and Equipment should be reviewed annually, at a minimum.”

Although the Federal Reserve Banks provide a table for the estimated useful life and estimated salvage value for different asset classes, the above quote shows that firms are instructed to adjust the depreciation rate taking into account the effect of technological obsolescence. Indeed, the Harvard Business School case “Depreciation at Delta Air Lines: The ‘Fresh Start’.” is about the fact that Delta Air Lines has changed its assumptions about aircraft lifespan (estimated useful life) and residual values (salvage value) four times in the last thirty years. Therefore, firms indeed exercise the options of adjusting the depreciation rate of their assets.

It is also important to notice that financial accounting (Compustat variables) is different from tax accounting. The later has to strictly follow the IRS accounting rule. In the tax accounting, firms have no discretion over changing the depreciation rate of assets.

Asset Composition Or Obsolescence?

The discussion of accounting rules and the fact that Delta Airlines had changed its depreciation rates many times in the past precludes the possibility that the documented causal effect of R&D investment on the capital depreciation rate is merely due to the asset composition effect. Common sense informs us that the effect is likely a combination of both the asset composition effect and the obsolescence effect. That is, higher R&D increases the technological obsolescence so that firms adjust the estimated useful life and estimated salvage values, and the depreciation rate rises. On the other hand, the R&D investment is associated with the purchase of short term assets such as computers and high-tech equipments, and as a result the average asset depreciation rate rises.

It should be noted that these two explanations for the empirical results do not contradict each other. The table of the depreciation rates has already taken into account of the technological obsolescence when the table was made. Put differently, the fact that the expected useful life of asset A (e.g., a computer) in the table is shorter than asset B (e.g. a chair) is mostly likely because asset A has a higher technological obsolescence.

To more credibly show that high-tech industries are likely to experience higher technological obsolescence, I turn to the 10-K filings of the public traded firms.

B.1 Evidence From Textual Analysis

In this section I document evidence of the obsolescence channel through 10-K filings of public traded companies in the United States. To do so, I download all filings of Form 10-K from 1994 - 2007.

B.1.1 Preprocessing.

After obtaining all the filings, I preprocess each document following standard procedures. The goal is to make the textual analysis more precise by reducing unnecessary noise in the text. It involves two stages, the first is essentially cleaning each filing document of extraneous materials. A substantial portion of an EDGAR text filing's content consists of HTML code, embedded pdf's, jpg's and other artifacts not typically of interest. Some large file exceed 400MB in size. The stage one is mainly designed to take care of those large files and exclude

the extraneous information associated with graphics and pdf. Stage two process is mostly concerned with reorganizing data in a format that is conducive to subsequent analysis.

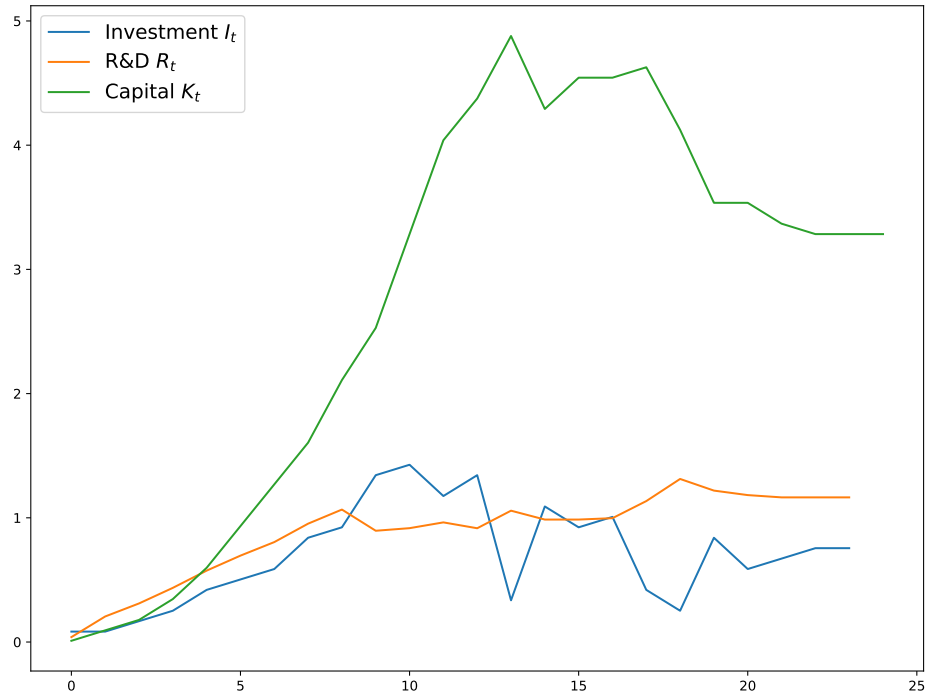
B.1.2 The difference between Tech-Sectors and Non-Tech-Sectors

The first step is to understand how the 10k filings for high-tech firms differ from the rest. To this end, I calculate the frequency of occurrence of the following words: obsolete, collateral, technology, credit as a fraction of the total document length, and then compare them across two sectors.

Figure 14 plots the average length of document in tech and non-tech sectors. It shows that the total length of the 10K documents is comparable in these two different sectors. Next I calculate the frequency of words related to credit, innovation, collateral, technology, and obsolescence. Credit ratio is defined as $\frac{\# \text{ credit and } \# \text{ debt}}{\text{total length of the document}}$. The numerator is the frequency of occurrence of word “credit/debt” in the filings scaled up by 10^3 , and the denominator is the total length of the document. The other ratios are defined in the same way. Figure 20 gives an overview of the distinction between tech sectors and non-tech sectors. Tech sectors are characterized by the more frequent use of words obsolete, technology, innovation, and less frequent use of the words credit and collateral. This result is consistent with the notion that tech-firms are associated with higher level of obsolescence risks and less usage of credit.

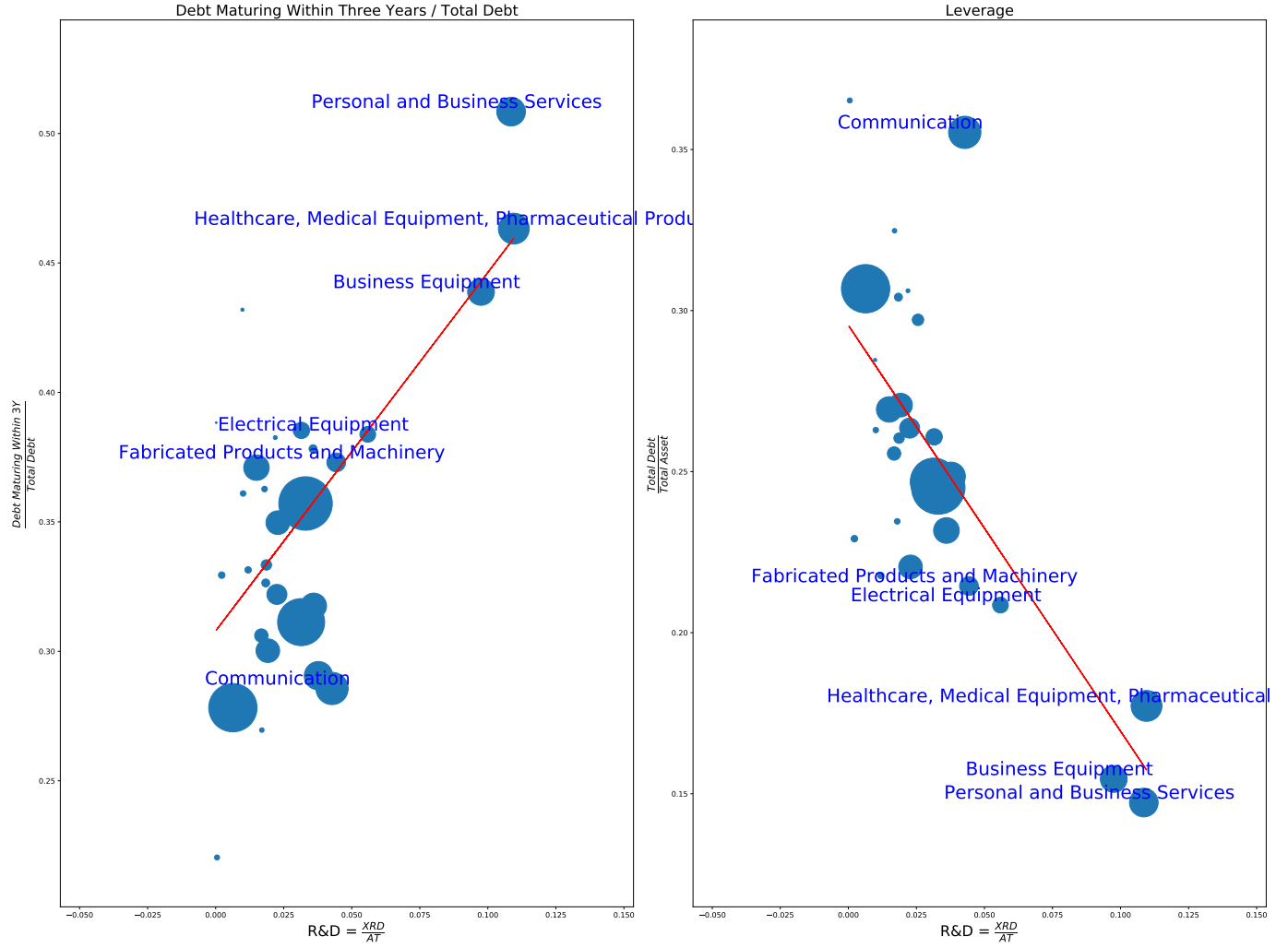
C Figures

Figure 1: One Sample Path of Firm Dynamics



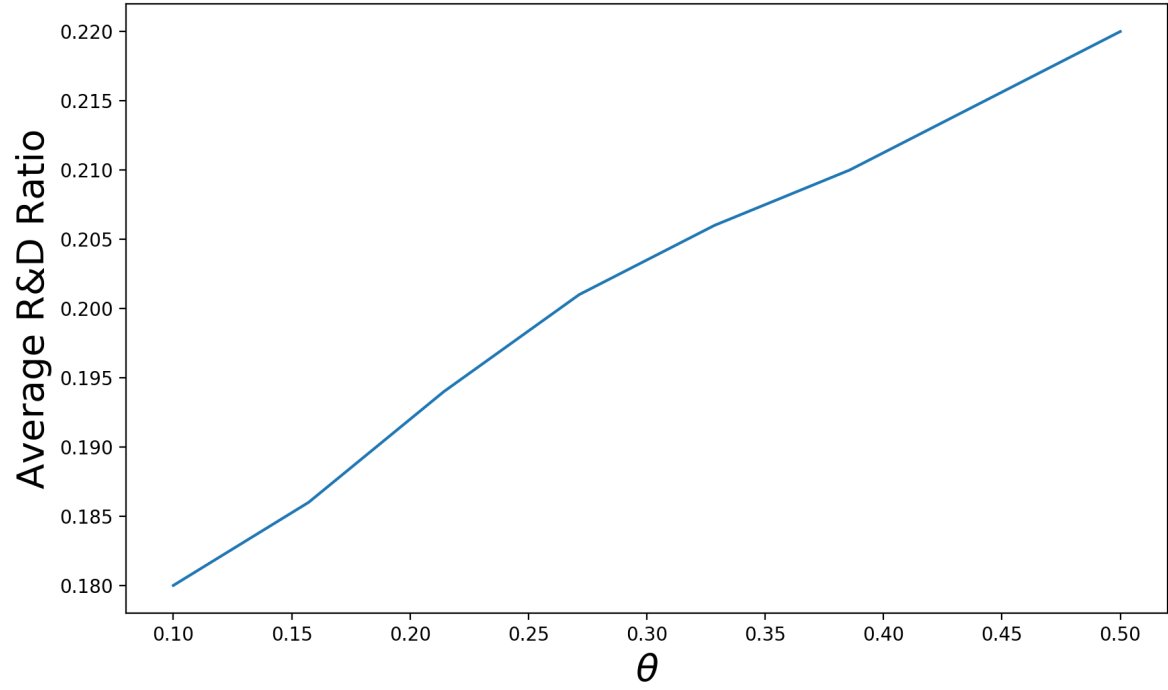
Notes: The figure plots one sample path from the simulation. The green line plots the capital stock of the firm, the orange line the R&D investment and the blue line, physical investment.

Figure 2: Maturity and Leverage with R&D intensity



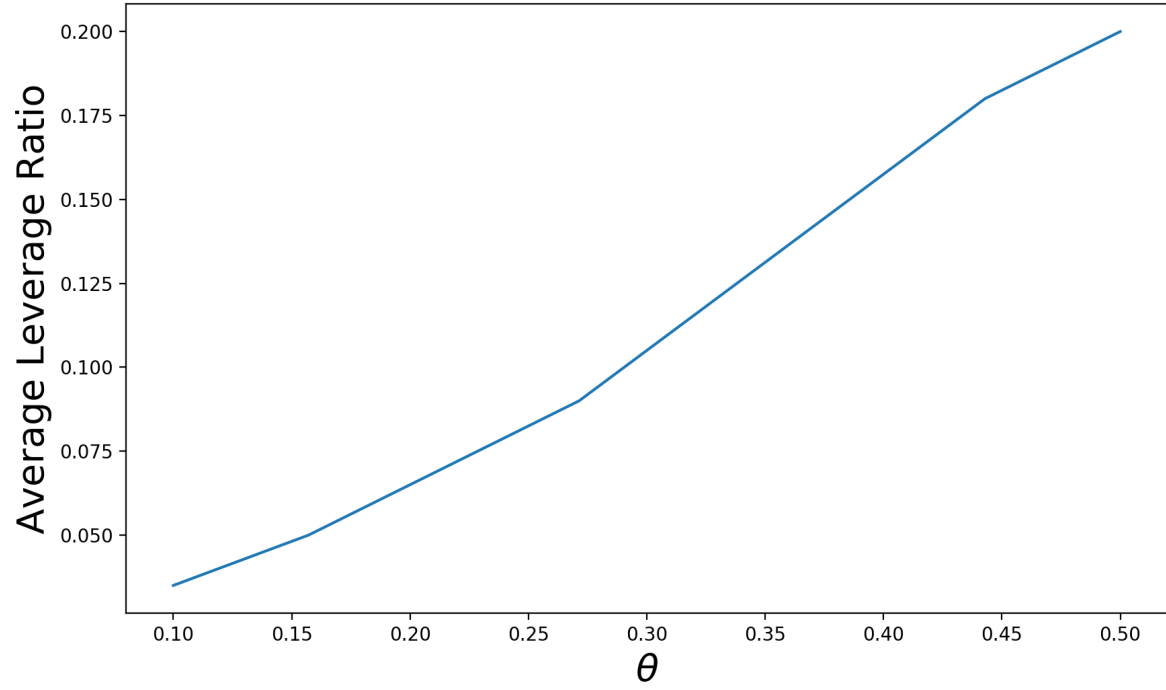
Notes: The figure plots how the average maturity and leverage vary across different industries. The maturity is plotted on the left panel and the right panel leverage. The x-axis is the R&D intensity measured by $\frac{XRD}{AT}$. A firm's debt maturity is measured by the fraction of debt maturing in three years. A firm's leverage is measured by the ratio of its total debt over its total asset.

Figure 3: Simulation: Average R&D Ratio with Credit Supply



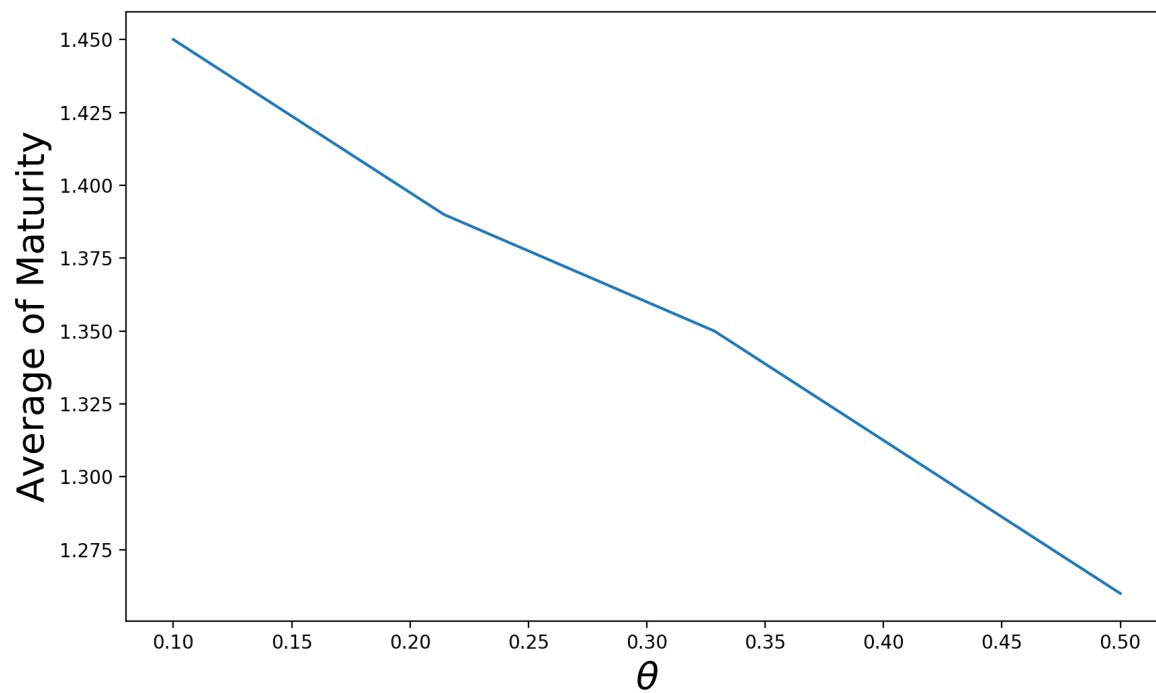
Notes: The figure plots how the average R&D ratio varies with the collateralizability θ . The y-axis is the average of R&D investment to capital stock.

Figure 4: Simulation: Average Leverage Ratio with Credit Supply



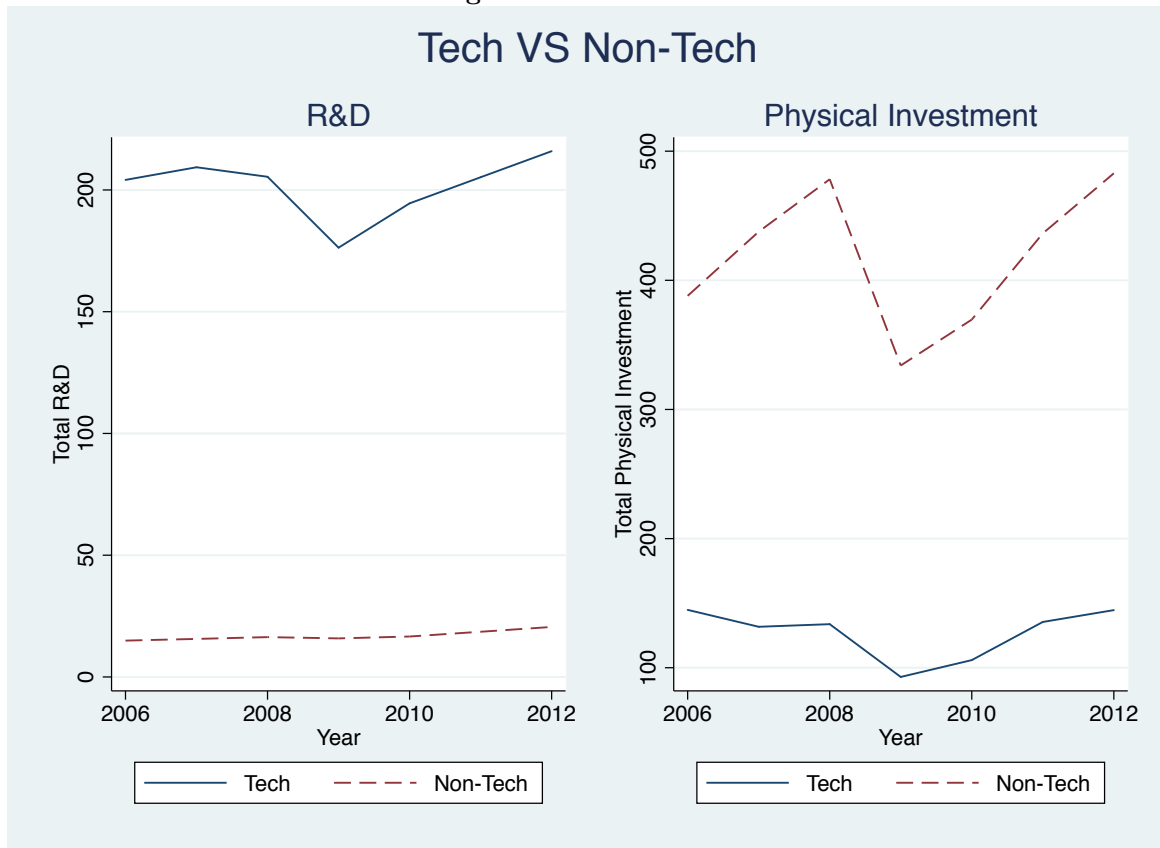
Notes: The figure plots how the average leverage ratio varies with the collateralizability θ . The y-axis is the average of the ratio of external finance to capital stock.

Figure 5: Simulation: Average Debt Maturity with Credit Supply



Notes: The figure plots how the average maturity varies with the collateralizability θ . The y-axis is the average of maturity in the economy.

Figure 6: Tech VS Non Tech



**Figure 7: BEA: Cross-Section relationship
Equipment Depreciation and IP Investment**

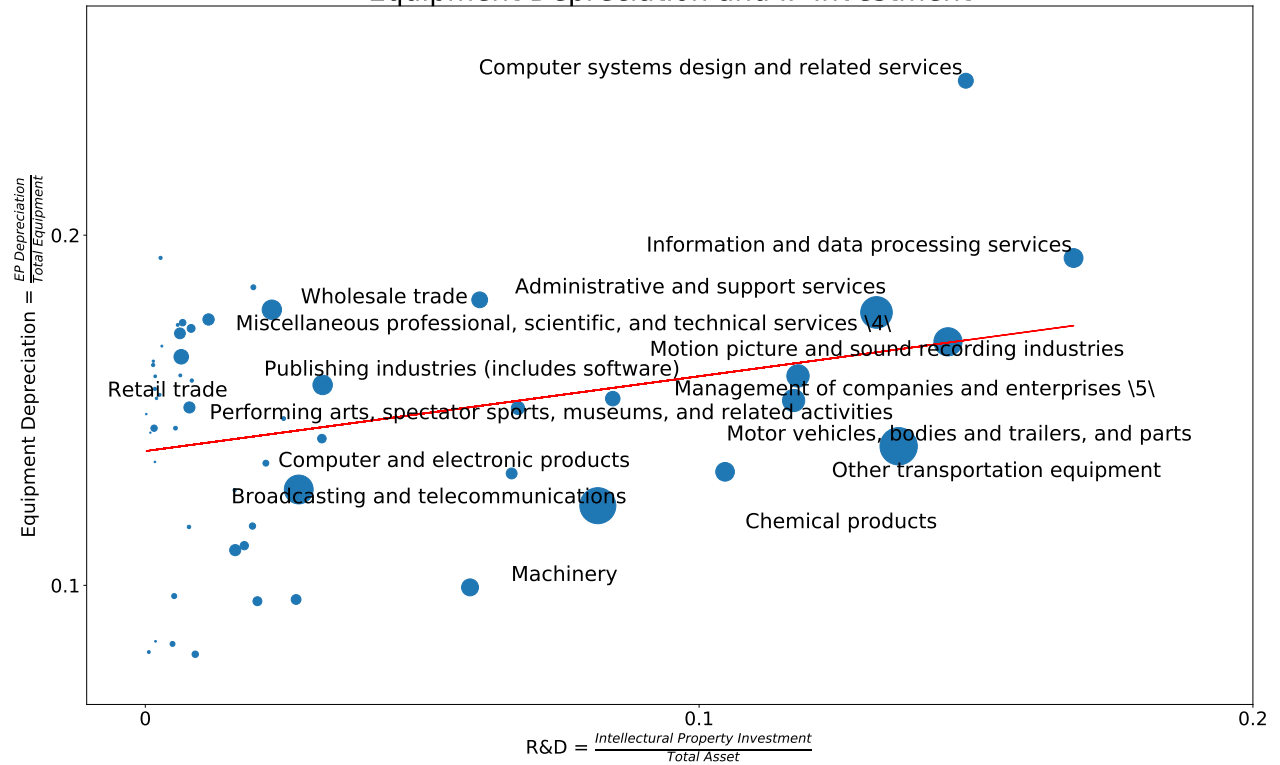


Figure 8: BEA: Time-series relationship

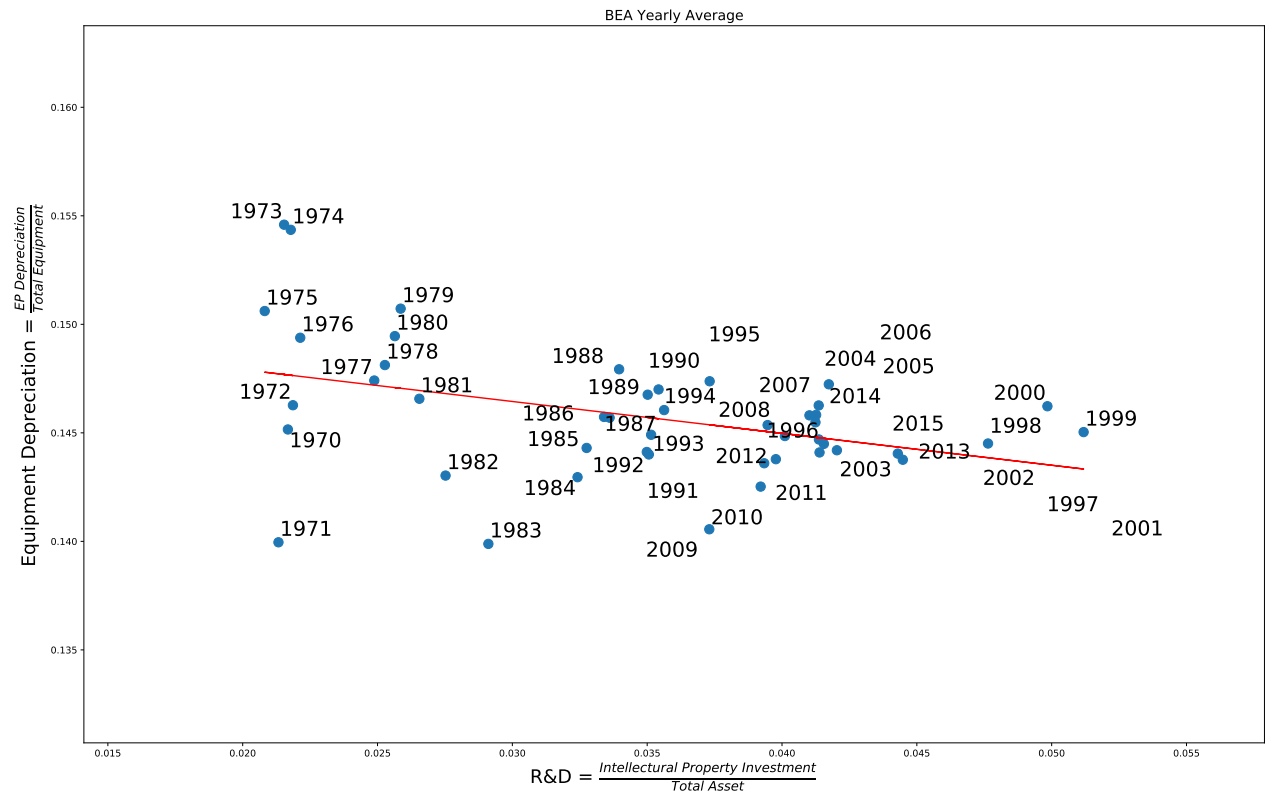


Figure 9: Compustat FF Cross Section
Asset Maturity $PPEGT/DP$ and R&D FF49

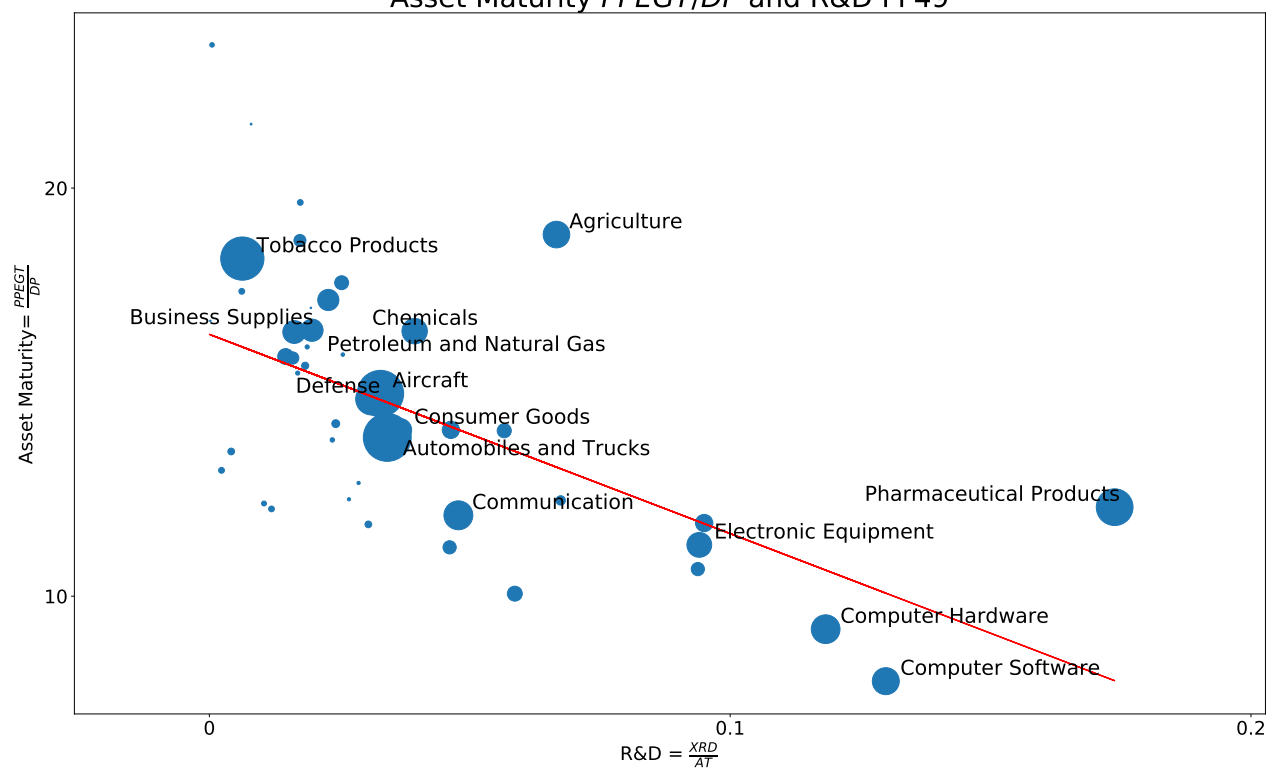


Figure 10: Compustat FF Cross Section
Asset Maturity $PPEGT/DP$ and R&D FF30

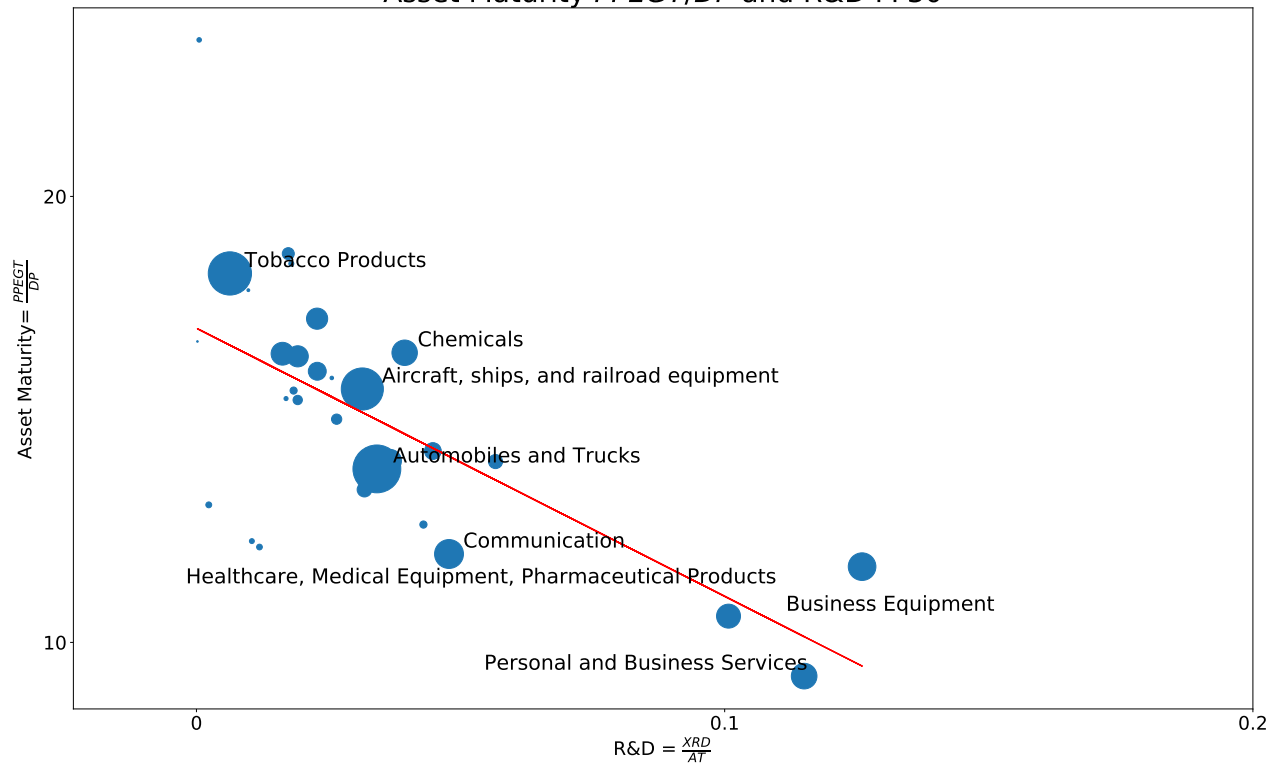


Figure 11: Compustat FF Cross Section
Asset Maturity $PPEGT/DP$ and R&D FF17

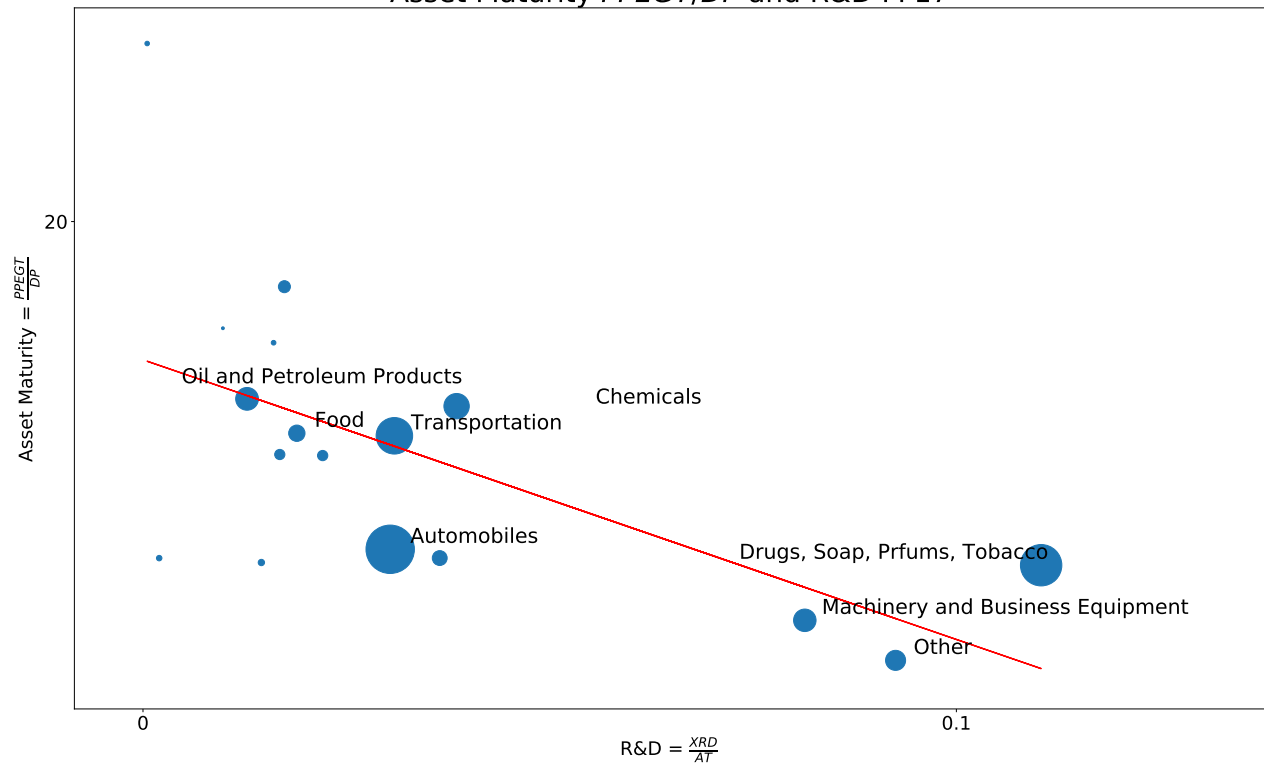


Figure 12: 10K Filings
Frequency of Obsolete-Related-Words and R&D

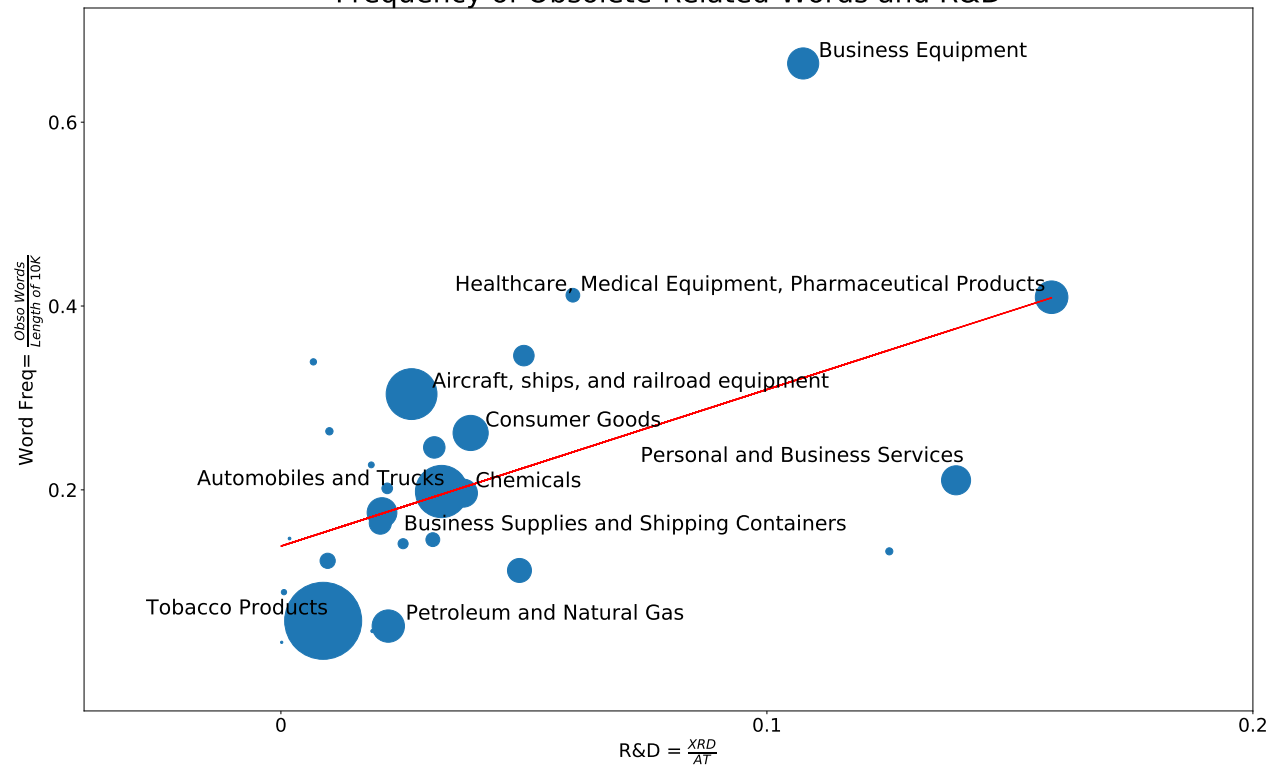


Figure 13: Accounting Rule

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Depreciation at Delta Air Lines: The "Fresh Start"

by **William J. Bruns Jr.**

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Abstract

In estimating depreciation for accounting purposes, Delta Air Lines has changed its assumptions about aircraft lifespan and residual values four times in the last thirty years or so. In the most recent changes, Delta adopted fair value accounting as part of its fresh start emergence from bankruptcy. Each of these policy changes has affected future asset values as well as present and future income. Students should organize their case analysis around three types of questions: (1) the estimated life cycle of commercial passenger airplanes; (2) the uses of financial reports, including the purpose of depreciation in reporting on assets and periodic income; and (3) alternative procedures for reporting asset book values and income that might better serve users of financial reports.

Keywords: Accounting Policies; Accounting Procedures; Depreciation; Bankruptcy; Cost Accounting; Financial Reporting; Insolvency and Bankruptcy; Policy; Air Transportation Industry



Figure 14: Total Word Count: Tech VS NonTech

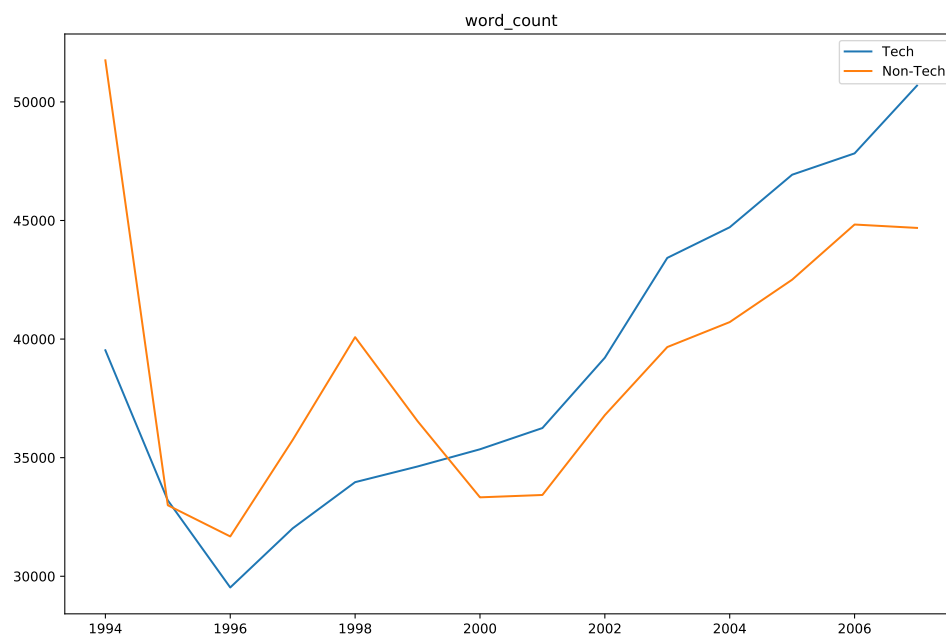
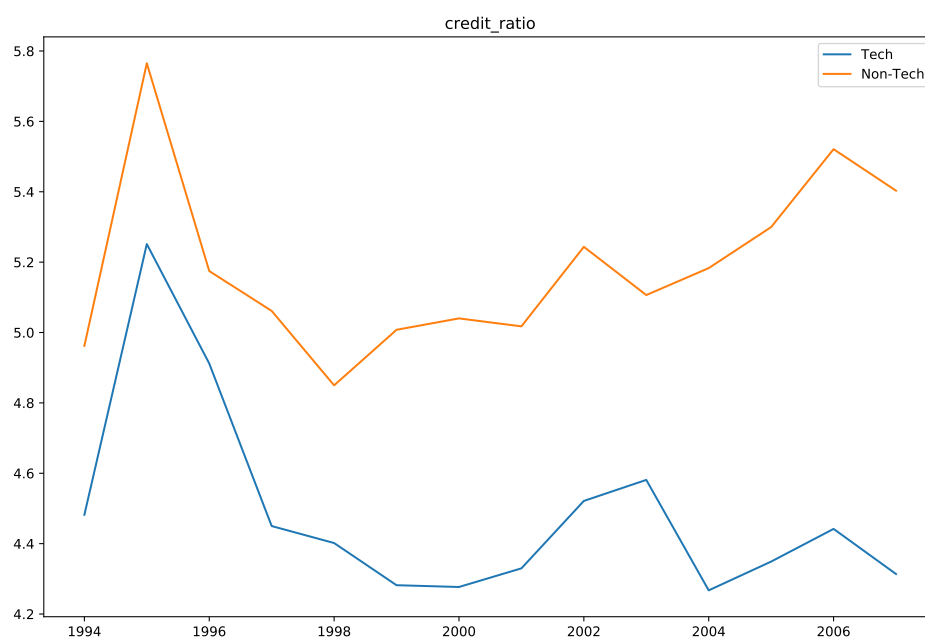


Figure 15: Word Frequency of Credit: Tech Vs NonTech



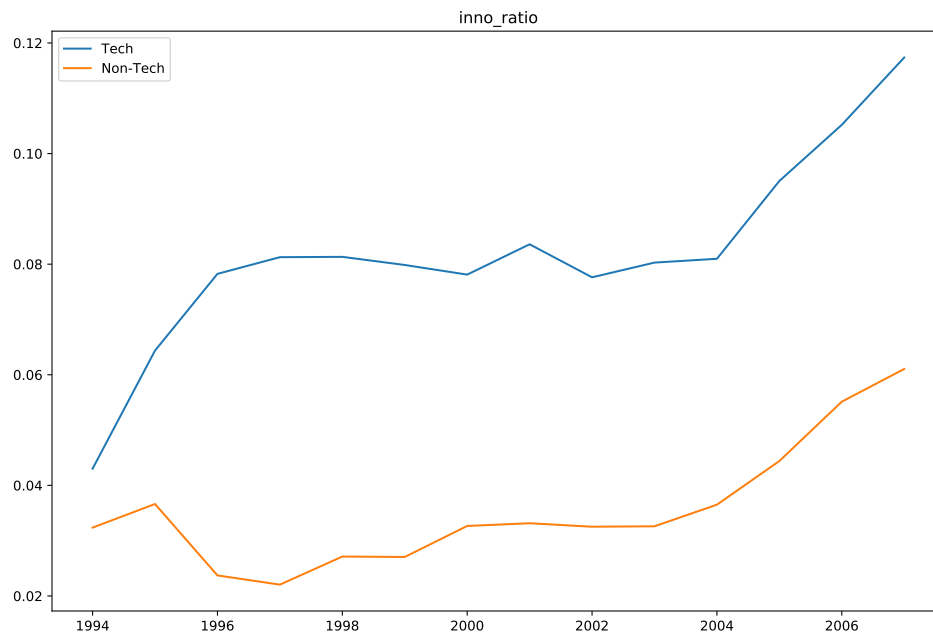


Figure 16: Word Frequency of Innovation: Tech Vs NonTech



Figure 17: Word Frequency of Collateral: Tech Vs NonTech

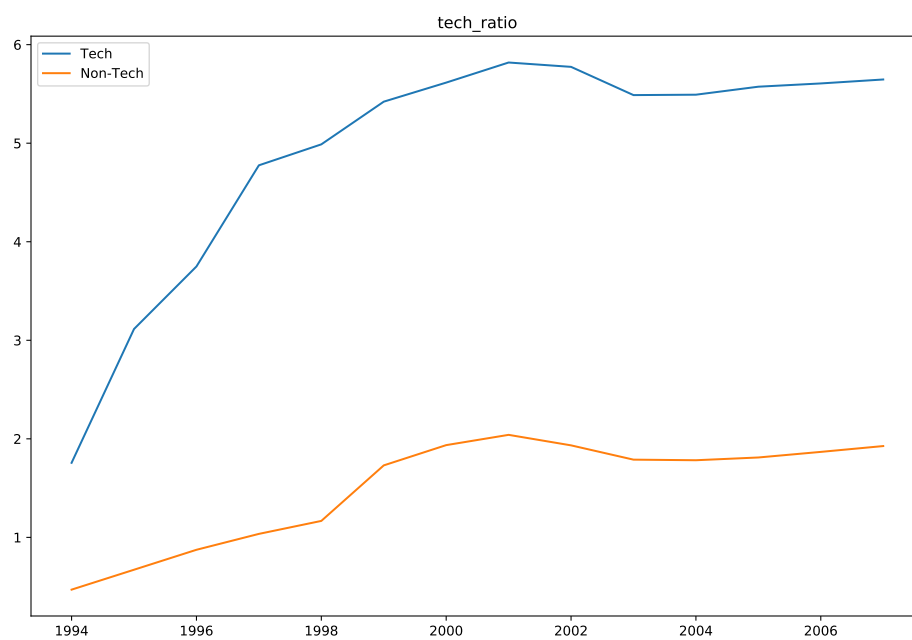


Figure 18: Word Frequency of Technology: Tech Vs NonTech

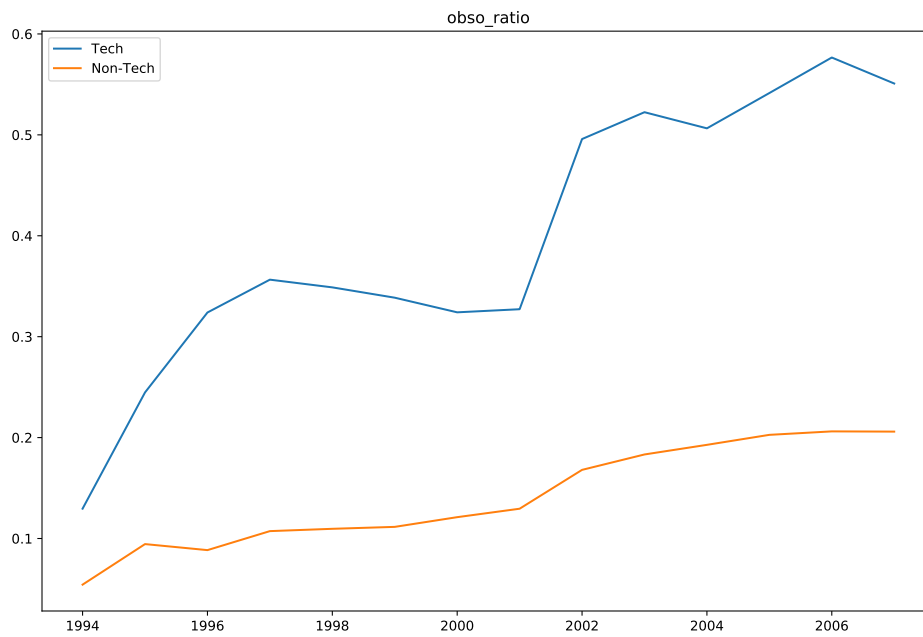


Figure 19: Word Frequency of Obsolescence: Tech Vs NonTech

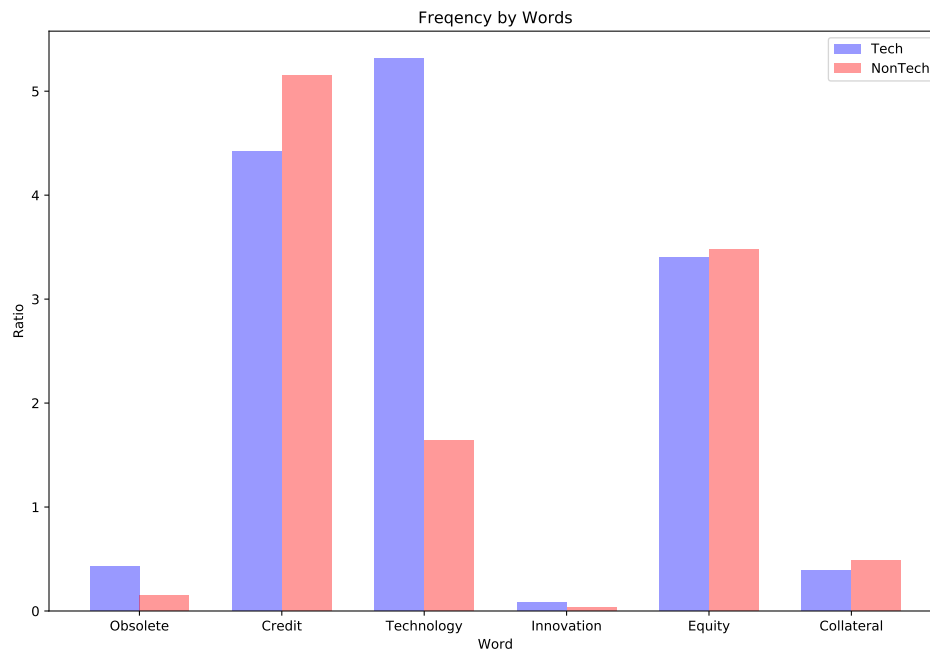


Figure 20: Frequency of Words by Sectors: Tech VS NonTech

Tables

Table 1: Correlation between R&D and Obsolescence

VARIABLES	(1) BEA DP	(2) COMPUSTAT PPEGT/DP	(3) 10K Obsolete Freq
rdratio_bea	0.349*** (0.0166)		
rdratio_compustat		-10.37*** (0.252)	0.137*** (0.0360)
Constant	0.121*** (0.00173)	11.95*** (0.0262)	0.373*** (0.00505)
Observations	799	64,894	17,438
R-squared	0.357	0.312	0.153
Industry FE	No	YES	YES
Standard errors in parentheses			
*** p<0.01, ** p<0.05, * p<0.1			