Fibonacci, Pacioli, and the Slow Diffusion of Knowledge

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Abstract

In 1202, Fibonacci introduced Arabic numerals and the basic principles of arithmetic to the West, but it was not until 1494, when Pacioli published a book that translated Fibonacci's ideas into the vernacular, that Arabic numerals and the basic principles of arithmetic began to have an effect on the practical world of business. In economics, we typically assume that agents have state-of-the-art knowledge, but the example of Fibonacci and Pacioli suggests that knowledge may diffuse slowly. This paper tests the assumption of state-of-the-art knowledge against the alternative of slow diffusion. The tests are based on panel data on the consequential decisions of highly sophisticated agents. We find strong evidence for slow diffusion of knowledge.

Keywords: state-of-the-art knowledge assumption, slow diffusion of knowledge, investment, risk, asset pricing models

JEL codes: E22, G31, G32

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Leonardo da Pisa, better known as Fibonacci, was a widely traveled Italian merchant who grew up on the coast of what is now Algeria. As a youngster, he was enthralled by the Arabic numbers used by local merchants. In his 1202 book *Liber Abaci*, Fibonacci introduced Arabic numerals and the basic principles of arithmetic to the West. This represented a huge intellectual breakthrough. If you doubt this, try doing addition and subtraction, let alone long division, with Roman numerals, the prevailing numerical system in Western Europe at the time.

Eventually returning to Italy, Fibonacci became a celebrated mathematician among the academics of the day. Interestingly, however, Roman numerals continued to dominate in the business world.

In the 1460s, while Luca Pacioli, a Franciscan monk, was working in Venice, he discovered a copy of Fibonacci's *Liber Abaci*. Because he had worked six years as a merchant's assistant, Pacioli was able to recognize the importance of the book for the practical world of business. In 1486, Pacioli was appointed professor of mathematics in Perugia. Perhaps fortunately, he had a falling out with the authorities at the monastery in Perugia that led him to return to his hometown of Sansepolcro. Free from his teaching responsibilities, he devoted himself to writing a book that would bring together all that was known of mathematics in the Europe of his day.

Pacioli's summary of contemporary mathematical knowledge appeared in 1494 under the title *Summa de arithmetica, geometria, proportioni, et proportionalita*. Chapters 1-7 of Volume 1 are devoted to Arabic numerals and the basic principles of arithmetic. Chapter 8 covers algebra. Chapter 9 is devoted to practical business applications, including the first systematic written treatment of double-entry bookkeeping, the contribution for which Pacioli is best remembered today (at least among accountants, for whom this is the seminal intellectual event).

There are two key differences between Fibonacci's *Liber Abaci* and Pacioli's *Summa*, despite the fact that the intellectual content of Pacioli's chapters on Arabic numerals and the basic principles of arithmetic follow Fibonacci's book very closely. First, the *Summa* was printed, rather than handwritten. The dramatic decrease in cost made it possible for merchants to buy the book. Second, Pacioli wrote almost all of his book in the vernacular, making it accessible to business people.[1]

[1] For a lively account of Pacioli's life, see Gleeson-White (2012).

In economics, we typically assume that agents have state-of-the-art knowledge. In other words, we assume that agents behave according to the latest thinking of economists, as embodied in the model. For example, models of fixed investment typically make an assumption about the asset pricing model used by agents, since asset pricing affects the discount rate used by the firm. In Section 4 of his classic *Econometrica* paper, Hayashi (1982, p. 221) assumes a constant equity risk premium of 4%.

As of the early 1980s, the state-of-the-art technique for calculating the firm's discount rate in corporate finance was the weighted-average cost of capital:

$$\tilde{r}_{WACC} = \tilde{r}^{DEBT}\left(1-\tau\right)\lambda + \tilde{r}^{EQUITY}\left(1-\lambda\right),$$

where $\tilde{r}^{WACC}$ is the weighted-average cost of capital, $\tilde{r}^{DEBT}$ is the inerest rate on the firm's debt, τ is the marginal corporate income tax rate, $\tilde{r}^{EQUITY}$ is the expected rate of return on the firm's equity, and λ is the leverage ratio. This equation is taken directly from Brealey and Myers (1984), a leading corporate finance textbook. In their influential *Econometrica* paper, Abel and Blanchard (1986) use a weighted-average cost of capital to calculate the discount factor, with two different assumptions about the equity share (0.5and 0.3). By the mid 1980s, the assumption of a constant equity premium was beginning to look empirically tenuous. This is reflected in the fact that Abel and Blanchard (1986), unlike Hayashi (1982), do not assume a fixed equity premium.

From the 1960s, the Capital Asset Pricing Model (CAPM) was the dominant cross-sectional asset pricing model.[2] This is reflected in leading financial economics textbooks of the time. For example, "Part Three: Risk" of Brealey and Myers (1984) is overwhelmingly devoted to the CAPM. In discussing a firm's investment decisions, these textbooks typically advocated using the weighted-average cost of capital to calculate the discount rate, with $\tilde{r}^{EQUITY}$ based on the CAPM.

The first serious empirical rejections of key implications of the CAPM began to appear in the late 1970s and early 1980s.[3] In the early 1990s, Fama and French (1992) provided what many

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[2] Evidence supportive of the CAPM was provided by a number of influential early tests including Black, Jensen, and Scholes (1972), Fama and MacBeth (1973), and Blume and Friend (1973).

[3] See, e.g., Basu (1977), Banz (1981), and DeBondt and Thaler (1985).

in the literature regarded as the death blow for the CAPM. Fama and French (1993) introduced a competing asset pricing model, the Fama-French three-factor model, that fits the data much better than the CAPM.[4] Over time, the evidence against the CAPM – and in favour of the Fama-French three-factor model has penetrated financial economics textbooks. For example, Brealey and Myers (2003) explains risk primarily in terms of the CAPM but devotes three pages (p. 208 – 210) to the Fama-French three-factor model.

Many models introduce some new idea about how the world works. For example, Fama and French (1993) introduced a new cross-sectional asset pricing model. Models typically assume that agents are endowed with full knowledge of the model and have always behaved in the way described in the model. In other words, economic models often assume that agents are endowed with state-of-the-art knowledge. For example, Fama and French (1993) attempt to explain returns over their full sample on the basis of their new asset pricing model.

The state-of-the-art knowledge assumption is very appealing. It fits naturally with rational expectations. It may help to make a model more mathematically elegant. It may help the theorist to avoid internal inconsistency. On the other hand, the state-of-the-art knowledge assumption may sometimes be too strong. A new idea may begin in the academic world of economics and only gradually begin to influence how agents behave in the real world.

In the 20th and 21st centuries, with the printing press and electronic media, we might expect knowledge to diffuse much faster than in the days of Fibonacci. Perhaps the Internet will make the diffusion of knowledge almost instantaneous, but the example of Fibonacci and Pacioli suggests otherwise. It was only when Pacioli made Fibonacci's academic work accessible to the practical business world that the use of Arabic numerals and the basic principles of arithmetic began to have an impact.

In this paper, we test the state-of-the-art knowledge assumption using actual business decisions about capital expenditures. We do this by estimating the investment Euler equation on firm-level panel data.[5] Our objective is to determine whether firms use the current state-of-the-art

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[4] For a skeptical view of the tests that have contributed to the dominance of the Fama-French three-factor model, see Lewellen, Nagel, and Shanken (2010).

[5] Our Euler equation specification closely follows the classic paper in the literature, Whited (1992). Specialists in corporate finance or business fixed investment might quibble that we do not include all the possible subsequent bells and whistles. Frankly, it seemed cleaner to base our work on the classic paper in the literature, and, based on this specification, the data speak clearly on the central issue. A possible topic for future research would be to explore whether issues such as stock price misvaluation or non-convexities in adjustment costs affect our results, but, although we are sympathetic to the potential empirical relevance of these issues, we are skeptical that this would be

cross-sectional asset pricing model, the Fama-French three-factor model, in making investment decisions. An alternative possibility is that firm managers make investment decisions based on the knowledge that was current at a formative stage in their life, perhaps when they got their MBA or took a relevant economics or finance course. The latter possibility would be consistent with the provocative ideas and empirical results in Malmendier and Nagel (2011). An appealing feature of our approach is that it uses consequential decisions of sophisticated agents (i.e., investment decisions by the managers of publicly traded firms) to address the issue.

The paper is organized as follows. Since this paper is not primarily aimed at economists who specialize in either the theory of business fixed investment or the empirical methods that are used to study investment, Section 1 provides an intuitive explanation of the investment Euler equation. Section 2 formally derives the empirical specification, which closely follows the classic investment Euler equation paper, Whited (1992). Section 3 describes the US panel data. Section 4 tests whether firms use the CAPM to make their investment decisions (specifically, whether $\tilde{r}^{EQUITY}$ is calculated using the CAPM). Section 5 tests whether firms use the current state-of-the-art cross-sectional asset pricing model, the Fama-French three-factor model, to make their investment decisions. Section 6 provides two types of robustness checks. Section 7 briefly summarizes the main results and their implications.

1. An Intuitive Explanation of the Euler Equation

A simple, intuitive way to understand the investment Euler equation is to start from the Net Present Value (NPV) rule: Accept all investment projects with positive net present value. Mathematically, we could write the NPV rule as:

$$\left(\sum_{t=1}^{\infty}\left(\frac{1}{1+r}\right)^{t} CF_t\right) - MC_0 \geq 0, \quad (1)$$

where the current year is 0, r is the firm's cost of capital, CF_t is the cash flow generated by an investment project at time t, and MC_0 is the marginal cost of the investment. To derive the investment Euler equation from the NPV rule, let's assume that the firm accepts all investment projects with positive NPV, so that the inequality in (1) holds with equality for the marginal investment project. We can then rewrite the NPV rule as:

a fruitful research topic. These issues are discussed further in Section 6, where we consider two main robustness checks.

$$MC_0 = \left(\frac{1}{1+r}\right)CF_1 + \left(\sum_{t=2}^{\infty}\left(\frac{1}{1+r}\right)^t CF_t\right). \quad (2)$$

The same NPV rule applies next year. In order to include the same terms in the summation, multiply the NPV rule for next year by $1/(1+r)$:

$$\left(\frac{1}{1+r}\right)MC_1 = \left(\frac{1}{1+r}\right)^2 CF_2 + \left(\frac{1}{1+r}\right)\left(\sum_{t=3}^{\infty}\left(\frac{1}{1+r}\right)^{t-1} CF_t\right) = \left(\sum_{t=2}^{\infty}\left(\frac{1}{1+r}\right)^t CF_t\right). \quad (3)$$

By subtracting (3) from (2) and rearranging, we obtain the investment Euler equation:

$$MC_0 = \left(\frac{1}{1+r}\right)\left(CF_1 + MC_1\right). \quad (4)$$

In words, the investment Euler equation says that the firm chooses investment to equate the marginal benefits and marginal costs. The marginal cost of investment is MC_0. There are two marginal benefits. First, the investment generates additional cash flow of CF_1 next year. Second, the firm doesn't need to make the investment MC_1 next year. Because the benefits occur next year, they are discounted using the firm's cost of capital.[6]

The investment Euler equation has now been used in empirical studies in finance and economics for many years. Shapiro (1986) and Whited (1992) were pioneering studies. Other important early papers include Hubbard and Kashyap (1992) and Bond and Meghir (1994). Some previous work has focused on finance constraints, including Hubbard, Kashyap, and Whited (1995), Ng and Schaller (1996), Love (2003), and Whited and Wu (2006), but a wider variety of issues have been examined, such as investment adjustment costs [Whited (1998)], corporate governance [Chirinko and Schaller (2004)], and the role of non-convex costs of adjustment [Chirinko and Schaller (2009)].

2. A Formal Derivation of the Investment Euler Equation

Whited (1992) and others have shown how to go from the firm's problem (of optimally choosing investment) to a specification that can be empirically estimated. This section and the Technical Appendix are included to make the details of the specification and estimation explicit -- and to show the link with the intuitive explanation in Section 1.

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[6] For another approach to linking the NPV rule with the investment Euler equation, see Chirinko and Schaller (2004).

Assume the objective of the firm is to maximize its value, V_0, as of period 0:

$$V_0 = E_0 \sum_{t=1}^{\infty} \left(\prod_{j=0}^{t-1} \beta_j \right) d_t \, , \tag{5}$$

where E_0 is the expectations operator conditional on information available at time 0, β_j is the discount factor at time t, and d_t is dividends. The firm faces a capital accumulation constraint that

$$K_t = (1-\delta) K_{t-1} + I_t \, , \tag{6}$$

where K_t is the capital stock at the end of period t, δ is the depreciation rate, and I_t is investment. The firm also faces a non-negativity constraint on dividends,

$$d_t \geq 0 \;\; \forall t \, , \tag{7}$$

with d_t defined as

$$\left(\Pi\left(K_{t-1}, L_t\right) - G\left(I_t, K_{t-1}\right) - w_t L_t \right) - p_t^I I_t + B_t - \left(1 + r_{t-1}\right) B_{t-1} , \tag{8}$$

where $\Pi\left(K_{t-1}, L_t\right)$ is the revenue function, L_t is variable inputs, and w_t and p_t^I are the real relative (i.e., relative to the price of output) price of variable inputs and investment goods, respectively. It is assumed that capital is costly to adjust, and $G\left(I_t, K_{t-1}\right)$ is a linear homogenous function in I and K. The firm pays r_{t-1}, the cost of capital, on the stock of one-period external finance outstanding at the end of period $t-1$ and issues an amount B_t of new external finance each period, subject to the transversality condition that

$$\lim_{T \to \infty} \left(\prod_{t=0}^{T-1} \beta_t \right) B_T = 0 . \tag{9}$$

Let λ_t^K and λ_t^d be the Lagrange multipliers on capital accumulation and the non-negativity constrain on dividends, respectively. Let H_x denote the partial derivative of the function H with respect to x. The first order conditions for capital, investment, and debt are, respectively:

$$E_t\left[-\lambda_t^K+\left(1+\lambda_{t+1}^d\right)\beta_t\left(\Pi_K\left(K_t,L_{t+1}\right)-G_K\left(I_{t+1},K_t\right)\right)+\beta_t\left(1-\delta\right)\lambda_{t+1}^K\right]=0, \tag{10}$$

$$\lambda_t^K=\left(1+\lambda_t^d\right)\left(p_t^I+G_I\left(I_t,K_{t-1}\right)\right), \tag{11}$$

$$\left(1+\lambda_t^d\right)-E_t\left[\left(1+\lambda_{t+1}^d\right)\beta_t\left(1+r_t\right)\right]=0. \tag{12}$$

If the constraint in equation (7) does not bind, then $\lambda_t^d=0$ and $\beta_t=1/\left(1+r_t\right)$.[7] In other words, the discount rate is equal to the firm's cost of capital. In this case, the first order conditions imply the following investment Euler equation:

$$\begin{aligned}&E_t[-\left(p_t^I+G_I\left(I_t,K_{t-1}\right)\right)\\&+\frac{1}{1+r_t}\left(\Pi_K\left(K_t,L_{t+1}\right)-G_K\left(I_{t+1},K_t\right)+\left(1-\delta\right)\left(p_{t+1}^I+G_I\left(I_{t+1},K_t\right)\right)\right)]=0\end{aligned} \tag{13}$$

This has the same form as the Euler equation derived in Section 1, using the NPV rule with:

$$MC_t=p_t^I+G_I\left(I_t,K_{t-1}\right), \tag{14}$$

$$MC_{t+1}=\left(1-\delta\right)\left(p_{t+1}^I+G_I\left(I_{t+1},K_t\right)\right), \tag{15}$$

$$CF_{t+1}=\Pi_K\left(K_t,L_{t+1}\right)-G_K\left(I_{t+1},K_t\right). \tag{16}$$

Equation (14) reflects the fact that there are two components of the marginal cost of investing -- the price of buying one more unit of investment goods and the marginal adjustment cost of installing one more unit. If the firm buys one unit of capital this year, it will only have $\left(1-\delta\right)$ units of capital next year, due to depreciation. Equation (15) reflects this fact. Equation (16) shows that there are two components to the cash flow benefit of an additional unit of capital. The first is the marginal increase in revenue Π_K. The second is the marginal reduction in adjustment costs due to an additional unit of capital G_K.

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[7] If the constraint binds, then $\beta_t=E_t\left[\left(1/\left(1+r_t\right)\right)\left(\left(1+\lambda_t^d\right)/\left(1+\lambda_{t+1}^d\right)\right)\right]$ and the discount rate reflects both the firm's cost of capital and the constraint.

In the empirical work, we multiply equation (13) by $\left(1+r_t\right)$ to obtain:

$$E_t[-\left(p_t^I+G_I\left(I_t,K_{t-1}\right)\right)\left(1+r_t\right) \\ +\left(\Pi_K\left(K_t,L_{t+1}\right)-G_K\left(I_{t+1},K_t\right)+\left(1-\delta\right)\left(p_{t+1}^I+G_I\left(I_{t+1},K_t\right)\right)\right)]=0 . \qquad (13')$$

The advantage, for purposes of estimation, is that r_t enters less nonlinearly; i.e., as $\left(1+r_t\right)$, rather than $\left[1/\left(1+r_t\right)\right]$. The Technical Appendix provides the empirical specifications for G_I and $\Pi_K - G_K$, incorporates the effect of taxes, and describes how equation (13') is estimated.

3. Dataset

The panel data consists of U.S. firms for the period 1980-2001, with data drawn from CompuStat, CRSP, and various sources of industry and aggregate data.[8] Details are provided in the Data Appendix.

The baseline cost of capital is a weighted-average cost of capital

$$\tilde{r}_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)\tilde{r}_{f,t}^{EQUITY} , \quad (17)$$

where λ_s is the sector-specific leverage ratio, τ_t is the corporate tax rate, $\tilde{r}_t^{DEBT}$ is the cost of debt, and $\tilde{r}_{f,t}^{EQUITY}$ is the cost of equity capital.[9] In some of the empirical work, we allow for differences between the baseline cost of capital $\tilde{r}$ and the actual discount rate r by omitting the risk adjustment in $\tilde{r}_{f,t}^{EQUITY}$ and adding terms that allow us to estimate the effect of risk, as discussed in subsequent sections.

The depreciation rate is allowed to vary across industries and over time and is based on BEA data. The relative price of investment is the ratio of the price of investment to the price of output. The industry-specific implicit price deflators are taken from the BEA; the relative price series is adjusted for corporate income taxes. In order to reduce noise in the data due to mergers, acquisitions, or other corporate events that lead to significant accounting changes, we trim the

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[8] Our sample ends in 2001 because of a data issue. The data on the present value of depreciation allowances were provided by Dale Jorgenson. In general, it might be reasonable to use cruder data than that provided by Dale Jorgenson in estimating investment Euler equations, but, because our focus here is on estimation of the firm's discount rate, it seems advisable to use the best possible data, even if this shortens the sample.

[9] In order to avoid cluttering the notation, the text of the paper abstracts from the distinction between real and nominal variables in the cost of capital. Precise details are provided in the Data Appendix, particularly Sections A and F.

3% tails of the following variables: $SALES_t / K_{t-1}$, $COST_t / K_{t-1}$, and I_t / K_{t-1}, where $SALES$ is Net Sales (CompuStat item 12), variable costs ($COST$) are the sum of the Cost of Goods Sold (CompuStat item 41) and Selling, General, and Administrative Expense (CompuStat item 189; when this item is not reported, it is set to zero.), and I is capital expenditures (CompuStat item 128).

Table I presents summary statistics. Median market capitalization is about $90 million. As is typically the case with firm-level data, mean size is much larger – about $1.5 billion. The median ratio of investment to the capital stock is 0.097. There are some differences between firms depending on their asset pricing model betas, but the differences are generally not dramatic. One exception is SMB beta, where median market capitalization is about five times as large for firms with low SMB beta as for firms with high SMB beta.

4. Do CAPM Betas Affect the Discount Rate?

Suppose we want to test whether the CAPM affects the discount rate. We can begin by calculating the weighted average cost of capital according to the standard textbook formula, with one exception. In the standard textbook formula, the equity cost of capital for firm f under the CAPM is $\tilde{r}_f^{EQUITY} = \tilde{r}^F + \beta_f^{CAPM} \mu^{EMR}$, where $\tilde{r}^F$ is the risk-free rate, β_f^{CAPM} is the firm's CAPM beta, and μ^{EMR} is the mean excess market return. By setting $\beta_f^{CAPM} = 0$ for all firms, we can construct the cost of equity capital without the CAPM (i.e., set the cost of equity capital equal to the risk-free rate). We can then test whether firms with higher CAPM betas use a higher discount rate. To do this, we divide the sample into high-β^{CAPM} and low-β^{CAPM} firms, specifying the cost of capital as $\tilde{r}_f = \tilde{r}_f^{NRA} + \theta_{CAPM} \Gamma_f^{High\beta^{CAPM}}$, where $\tilde{r}_f^{NRA}$ is the No-Risk-Adjustment cost of capital, $\Gamma_f^{High\beta^{CAPM}}$ is an indicator variable (equal to 1 if firm f has a CAPM beta above the median, 0 otherwise), and θ_{CAPM} is the estimated coefficient on $\Gamma_f^{High\beta^{CAPM}}$.[10] In other words, the cost of capital is specified as:

[10] Dividing the sample into high-β^{CAPM} and low-β^{CAPM} firms has two advantages compared to specifying the cost of equity capital as a linear function of beta. First, using categorical variables is more robust to the possibility of noise in the betas. Second, a regression with categorical variables can detect a relationship between the cost of equity capital and beta, even if the relationship is nonlinear. Later in this section, we also estimate a linear specification.

$$\tilde{r}_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)\tilde{r}_t^{F} + \theta_{CAPM}\Gamma_f^{High\beta^{CAPM}} . \quad (17')$$

The coefficient θ_{CAPM} measures how much higher the discount rate is for a firm with a CAPM beta above the median. Substituting the detailed specification of the cost of capital into equation (13'), we obtain

$$\begin{aligned} &E_t[-\left(p_t^I + G_I\left(I_t, K_{t-1}\right)\right)\left(1+\lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)\tilde{r}_t^{F} + \theta_{CAPM}\Gamma_f^{High\beta^{CAPM}}\right) \\ &+\left(\Pi_K\left(K_t, L_{t+1}\right) - G_K\left(I_{t+1}, K_t\right) + \left(1-\delta\right)\left(p_{t+1}^I + G_I\left(I_{t+1}, K_t\right)\right)\right)] = 0 \end{aligned} . \quad (13'')$$

Table II provides evidence that the CAPM beta affects the discount rate. The discount rate is 0.060 (i.e., 600 basis points) higher for firms with a CAPM beta above the median. This effect is precisely estimated and significant at the 1% level. The standard error of the estimate is 80 basis points, implying a t-statistic of 7.5.

Besides the estimate of θ_{CAPM}, Table II reports some general information about the Euler equation. The J statistic is the Hansen J statistic for testing overidentifying restrictions, which provides a useful check for the overall specification of the model. A large value of the J statistic implies that a model is misspecified. The J statistic in Table II is small. The p-value is 0.590, so the Euler equation specification is not rejected.

The parameter ζ captures the combined effects of non-constant returns to scale in production and imperfect competition in output markets. The estimated value of 0.841 is consistent with decreasing returns to scale and some degree of imperfect competition. The parameter α determines marginal adjustment costs, while $G_I[I_t, K_{t-1}]$ is the marginal adjustment cost and $G_{II}[I_t, K_{t-1}]$ is the curvature of the adjustment cost function. Both marginal adjustment costs and the curvature of the adjustment cost function are positive, which is economically sensible. N is the number of firm/year observations. The sample is reasonably large, with more than 40,000 firm-year observations.

Table III provides further evidence on how tight the relationship is between the CAPM beta and the discount rate by dividing firms more finely. In Panel A, firms are divided into quintiles based on their CAPM beta. Firms in the upper CAPM beta quintiles use significantly higher discount rates. Firms with the lowest CAPM beta have the lowest discount rates. From the lowest quintile to the highest, each successive quintile has a higher discount rate. Panel B divides firms into deciles based on their CAPM betas. Again, there is a strong positive relationship between the discount rate and the CAPM beta.

As an additional check, Panel C of Table III specifies the cost of equity capital as a linear function of CAPM beta,

$$\tilde{r}_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)\tilde{r}_t^{F} + \gamma_{CAPM}\beta_f^{CAPM}, \qquad (17'')$$

where γ_{CAPM} is the coefficient on β_f^{CAPM}. The estimate of γ_{CAPM} is positive, economically important (with an estimated value of 600 basis points for γ_{CAPM}), and statistically significant.

Tables II and III show that discount rates are strongly linked to CAPM betas. What about the quantitative magnitude of the effect of CAPM beta on the equity discount rate? Do firms set the equity discount rate in line with the CAPM? To address this question, we can use the estimated effects of CAPM beta (specifically, the estimates of $\theta_{\text{BOTTOM QUINTILE}}$ and $\theta_{\text{TOP QUINTILE}}$ from Table III), together with the risk-free rate and the leverage ratio, to calculate the estimated equity discount rate $\hat{r}_{f,t}^{EQUITY}$.[11] The difference in the mean of estimated excess equity discount rates ($\hat{r}_{f,t}^{EQUITY} - r_t^F$) between firms in the top and bottom beta quintiles is 14.3%. Using the mean beta for the firms in the top and bottom beta quintiles, respectively, the difference in expected excess returns under CAPM is 15.1%. Based on the estimated Euler equation, firms are adjusting the equity discount rate roughly in line with the CAPM.

The results in Tables II and III provide strong support for Graham and Harvey (2001). In their survey, 73.5% of respondents reported that they always or almost always use the CAPM. Graham and Harvey (2001) argue that the respondents to their survey are representative of US firms. This is consistent with empirical results in the tables.

5. Do Fama-French Betas Affect the Discount Rate?

We use a similar approach to test whether the Fama-French three-factor model betas affect the discount rate. We start with a cost of capital in which the equity component is based on the riskless interest rate and then add indicator variables for firms that have Fama-French betas that are above the median

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[11] Section E of the Data Appendix provides a more detailed description of the calculation of $\hat{r}_{f,t}^{EQUITY}$, the estimated equity discount rate.

$$r_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)r_t^F + \theta_{EMR}\Gamma_f^{High\beta EMR} + \theta_{SMB}\Gamma_f^{High\beta SMB} + \theta_{HML}\Gamma_f^{High\beta HML}, \quad (22)$$

where $\Gamma_f^{High\beta EMR} = 1$ if $\beta_f^{EMR} > Median[\beta_f^{EMR}]$, $\Gamma_f^{High\beta SMB} = 1$ if $\beta_f^{SMB} > Median[\beta_f^{SMB}]$, and $\Gamma_f^{High\beta HML} = 1$ if $\beta_f^{HML} > Median[\beta_f^{HML}]$ and $\theta_{EMR}, \theta_{SMB}$, and θ_{HML} are the estimated coefficients on the corresponding Γ. The results are presented in Table V. The market beta enters positively and significantly and the HML beta enters negatively and significantly. In contrast, the coefficient on the indicator variables for above-median SMB beta is close to zero and insignificant.

Since the previous section provides evidence that the CAPM beta affects the discount rate, an interesting question is whether the Fama-French betas have an incremental effect on the discount rate, above and beyond the CAPM beta. To test this, we estimate a specification in which the baseline discount rate includes the CAPM risk adjustment. We then add indicator variables for SMB beta above the median and HML beta above the median, so the specification of the cost of capital is

$$r_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)\left(r^F + \beta_f^{CAPM}\mu^{EMR}\right) + \theta_{SMB}\Gamma_f^{High\beta SMB} + \theta_{HML}\Gamma_f^{High\beta HML}. \quad (23)$$

The results are presented in the second column of Table V. When the baseline discount rate includes the CAPM risk adjustment, the HML beta no longer has significant explanatory power for discount rates.

6. Robustness Checks

The Fama-French three-factor model is generally regarded as the current state-of-the-art cross-sectional asset pricing model. In our first robustness check, we consider two other cross-sectional asset pricing models that have been somewhat influential in the recent asset pricing literature – Carhart (1997) and Campbell-Vuolteenaho (2004). Although these models tend to be less frequently mentioned in corporate finance textbooks, it is conceivable that CFOs or Corporate Treasurers are highly sophisticated and consider these models superior to the Fama-French three-factor model. Our second robustness check involves the specification of the Euler equation. The specification described in Section 2 follows the classic investment Euler equation paper, Whited (1992), very closely. The subsequent investment Euler equation literature has considered a variety of additional elements, including stock market misvaluation, corporate governance problems, non-convex costs of adjustment, and endogenous finance constraints.[12] (The last of these three arises in models of corporate savings, since firms in these models endogenously choose their cash holdings in an effort to avoid costly external finance.) We are sympathetic to the empirical relevance of all of these refinements of the classic Whited (1992) model but skeptical that they would change our results, because the data speak so clearly about the asset pricing model that is being used by firms. However, in our second robustness check, we examine whether our results change if we alter the specification to allow for finance constraints as modeled by Whited (1992).

6.1 Other Asset Pricing Models

The Carhart (1997) model adds momentum as an additional factor to the Fama-French three-factor model. A large number of empirical studies suggest that momentum plays a role in determining returns. To test whether firms base their discount rate on the Carhart model, we begin with a baseline cost of capital that includes no risk adjustment and add indicator variables for Carhart betas above the median:

$$r_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)r_t^F + \theta_{EMR}\Gamma_f^{High\beta EMR} + \theta_{SMB}\Gamma_f^{High\beta SMB} + \theta_{HML}\Gamma_f^{High\beta HML} + \theta_{MOM}\Gamma_f^{MOM}, \tag{24}$$

where $\Gamma_f^{MOM} = 1$ if $\beta_f^{MOM} > Median[\beta_f^{MOM}]$.[13] The momentum beta, however, appears to have little effect on the discount rate. The estimated coefficient is close to zero and statistically insignificant, as shown in Table VI.

When momentum is incorporated into the asset pricing model, it changes the estimated betas on the factors in the Fama-French three-factor model. This has little effect on the discount rate results, however. The market and HML betas continue to enter significantly when the baseline discount rate includes no risk adjustment.

We also consider a baseline cost of capital that includes the CAPM risk adjustment:

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[12] See Chirinko and Schaller (1996, 2001) on the effect of stock market misvaluation on the investment Euler equation; Chirinko and Schaller (2004) on the implications of corporate governance problems; Chirinko and Schaller (2009) on non-convex costs of adjustment; and Riddick and Whited (2009), Bolton, Chen, and Wang (2011, 2012), and Bolton, Schaller, and Wang (2013) on endogenous finance constraints.

[13] Strictly speaking, the asset pricing model in our empirical specification is the Fama-French three-factor model plus momentum, since we obtain the momentum variable from Ken French's website (as described in Section B of the Data Appendix), rather than using Carhart's original momentum variable.

$$
\begin{aligned}
r_{f,t} = {} & \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)\left(r^F + \beta_f^{CAPM}\mu^{EMR}\right) \\
& + \theta_{EMR}\Gamma_f^{EMR} + \theta_{SMB}\Gamma_f^{SMB} + \theta_{HML}\Gamma_f^{HML} + \theta_{MOM}\Gamma_f^{MOM}
\end{aligned}
\quad . \qquad (25)
$$

When the baseline discount rate includes the CAPM risk adjustment, none of the Carhart betas enters significantly.

Campbell and Vuolteenaho (2004) propose a cross-sectional asset pricing model that is more tightly tied to finance theory. Their "good beta/bad beta" model can be derived from the Intertemporal CAPM. If the risk prices associated with cash flow beta ("good beta") and discount rate beta ("bad beta") are equal, their model reduces to the conventional CAPM. They provide evidence that the conventional CAPM fits the cross-sectional asset pricing data fairly well for the early period (1926-1962) but breaks down in the modern period (1962-2001), when the risk prices on cash flow and discount rate beta diverge.

The Intertemporal CAPM on which the Campbell-Vuolteenaho model is based predicts that the risk price of cash flow beta should be equal to the coefficient of relative risk aversion times the variance of the market return. The variance of the market return must be positive, and the coefficient of relative risk aversion is normally believed to be positive, so the model predicts that cash flow beta should have a positive risk price. Empirically, Campbell and Vuolteenaho (2004) obtain positive estimates of the risk price on cash flow beta.

We again begin with a baseline cost of capital that includes no risk adjustment:

$$
r_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)r_t^F + \theta_{CF}\Gamma_f^{CF} + \theta_{DR}\Gamma_f^{DR}, \qquad (26)
$$

where $\Gamma_f^{CF} = 1$ if $\beta_f^{CF} > Median[\beta_f^{CF}]$, $\Gamma_f^{DR} = 1$ if $\beta_f^{DR} > Median[\beta_f^{DR}]$, and β_f^{CF} and β_f^{DR} are the Campbell-Vuolteenaho cash flow and discount rate betas for firm f. The first column of Table VII shows that the Campbell-Vuolteenaho cash flow beta enters with the wrong sign.

In the second column, we report results for a baseline cost of capital that includes the CAPM risk adjustment:

$$
r_{f,t} = \lambda_s(1-\tau_t)\tilde{r}_t^{DEBT} + (1-\lambda_s)\left(r^F + \beta_f^{CAPM}\mu^{EMR}\right) + \theta_{CF}\Gamma_f^{CF} + \theta_{DR}\Gamma_f^{DR}, \qquad (27)
$$

Once the baseline discount rate includes the CAPM risk adjustment, the coefficient on discount rate beta is close to zero (and statistically insignificant). The Campbell-Vuolteenaho cash flow beta continues to enter with the wrong sign. This parallels the results in Tables V and VI, in which the CAPM risk adjustment eliminates the significance of all other betas.

6.2 Finance Constraints

Table VII tests whether CAPM betas still affect the discount rate if we control for finance constraints. We focus on measures of finance constraints that have been widely used in the literature – Kaplan and Zingales (1997) and Whited and Wu (2006). In the first column, an indicator variable is included in the specification for observations with a Whited-Wu index above the median (WW). In the second column, a similar indicator variable is included for observations with a Kaplan-Zingales index above the median (KZ).

Table VIII tests whether our earlier result – that firms do not use the Fama-French model – continues to hold if such we control for finance constraints. The first and second columns of Table VIII are similar to the first column of Table IV; the baseline specification includes no risk adjustment, and we include coefficients that test whether the Fama-French betas affect the discount rate. The first and second columns use the Whited-Wu and Kaplan-Zingales indexes, respectively. The third and fourth columns of Table VIII are similar to the second column of Table IV; the baseline specification includes the CAPM risk adjustment, and we test whether the Fama-French betas have an incremental effect on the discount rate (after controlling for CAPM).

7. Conclusion

The data speaks clearly on whether firms use the current state-of-the-art cross-sectional asset pricing model, the Fama-French three-factor model, or a model that is now widely believed by academics in the field of asset pricing to have been decisively rejected, the CAPM. There is strong evidence that firms use the CAPM in making their investment decisions, rather than the Fama-French three-factor model.

Our starting point is an investment Euler equation in which the trade-off between this year and next year is determined by a discount factor calculated using the standard weighted-average cost of capital formula described in corporate finance textbooks. The special feature of our formula is that it <u>tests</u> whether the risk factors specified by a given asset pricing model affect the discount rate. To implement the test, we calculate firm-level betas. The discount rate for firms with high CAPM betas (above the median) is 600 basis points higher than for firms with low CAPM betas. When we divide firms into quintiles by CAPM beta, the test for equal coefficients is overwhelmingly rejected. The p-value is 0.000. The discount rate is monotonically increasing in the CAPM beta, as shown in Table III.

The data are not so kind to the idea that firms use the Fama- French three-factor model in making their investment decisions. When we allow the discount rate to depend on the Fama-French betas, the market beta enters significantly and with the expected sign. In contrast, the coefficient on the HML beta is negative, and the coefficient on the SMB beta is insignificant. When we use an Euler equation specification in which the baseline discount rate already incorporates the CAPM, none of the Fama-French betas have a significant coefficient.

The empirical results cast doubt on the state-of-the-art knowledge assumption, a common assumption in economic models. Instead, the results suggest that knowledge diffuses slowly, especially from the academic world to the general public. The results are especially striking because they are not based on anomalies at the household level, where it is easy to imagine that knowledge diffuses more slowly. Instead, they come from publicly traded firms that typically have many employees, often including senior staff with professional training in finance.

The empirical results in this paper are supportive of Malmendier and Nagel (2011), who argue that agents tend to be strongly influenced by experiences in their formative years. The data suggest that managers use the asset pricing model that was dominant at the time they received their professional training.

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Technical Appendix

The empirical Euler equation incorporates the effect of taxes:

$$-\Big(\big(1-itc_t-z_t\big)\tilde{p}^I_{f,t}+(1-\tau_t)G_I\big[I_{f,t},K_{f,t-1}\big]\Big)\big(1+\tilde{r}_{f,t}+\psi+\theta\Gamma_{f,t-1}\big)+(1-\tau_t)(\Pi_{K,f,t}-G_{K,f,t})$$
$$+\big(1-\delta_{f,t+1}\big)\big(1-itc_{t+1}-z_{t+1}\big)\tilde{p}^I_{f,t+1}+\big(1-\delta_{f,t+1}\big)(1-\tau_{t+1})G_I\big[I_{f,t+1},K_{f,t}\big]=u_{f,t+1} \quad \text{(TA-1)}$$

where itc_t is the investment tax credit rate, z_t, is the present value of depreciation allowances per dollar of investment spending, $\tilde{p}^I_{f,t}$ is the relative price of capital goods $p^I_{f,t}/p^Y_{f,t}$, $p^I_{f,t}$ is the price of capital goods, $p^Y_{f,t}$ is the price of output, and τ_t is the marginal corporate income tax rate. All variables with cross-sectional variation are denoted with an *f* subscript. The variable $\tilde{r}_{f,t}$ is the baseline cost of capital. In some specifications, this includes an adjustment for risk. In other specifications, the baseline cost of capital excludes an adjustment for risk. $\Gamma_{f,t-1}$ is an indicator variable for firms that fall into a particular category; e.g., $\Gamma^{High\beta^{CAPM}}_{f,t-1}=1$ if the CAPM beta for firm f is above the median, 0 otherwise. The parameter θ measures the effect of $\Gamma_{f,t-1}$ on the discount rate; e.g., the amount by which the discount rate is greater for firms that have CAPM beta above the median. (When firms are divided into more than two categories, e.g., CAPM beta quintiles, $\Gamma_{f,t-1}$ is a vector of indicator variables and θ is the corresponding vector of coefficients on each indicator variable.) The error term $u_{f,t+1}$ arises when we replace the expected values of variables dated t+1 with their realized values. We have added a time subscript to δ because we allow for time-varying depreciation rates, as described in the Data Appendix. The parameter ψ captures the effects of unmodeled factors that affect the discount rate and are common to all firms.

We assume that the marginal adjustment cost function $G_I\big[I_{f,t},K_{f,t-1}\big]$ depends on the investment/capital ratio. We use the following first-order Taylor approximation,

$$G_I\big[I_{f,t},K_{f,t-1}\big]=\alpha\frac{I_{f,t}}{K_{f,t-1}}. \quad \text{(TA-2)}$$

The marginal revenue product of capital $\Pi_{K,f,t}-G_{K,f,t}$ depends on the underlying production and adjustment cost functions and product market characteristics. The production function is assumed to be homogeneous of degree (1+ξ), where ξ is not necessarily equal to zero. Product markets may be imperfectly competitive, and the demand schedule has a constant elasticity of μ ≥ 0. Using Euler's Theorem on Homogeneous Functions, we obtain the following specification for the marginal revenue product of capital,

$$\begin{aligned}\Pi_{K,f,t} - G_{K,f,t} = \zeta * \left(SALES_{f,t} / K_{f,t-1}\right) - \left(COST_{f,t} / K_{f,t-1}\right) \\ + G_I\left[I_{f,t}, K_{f,t-1}\right] * \left(I_{f,t} / K_{f,t-1}\right)\end{aligned}, \qquad \text{(TA-3)}$$

where $(SALES_{f,t} / K_{f,t-1})$ and $\left(COST_{f,t} / K_{f,t-1}\right)$ are sales revenues and variable costs, respectively, divided by the beginning-of-period capital stock, $G_I\left[I_{f,t}, K_{f,t-1}\right]$ is defined in equation (TA-2), and $\zeta \equiv (1+\xi)(1-\mu)$, thus capturing the combined effects of non-constant returns to scale and imperfect competition. Decreasing returns to scale and/or non-competitive product markets imply that $\zeta < 1$.

The main empirical results are based on the Euler equation (TA-1) estimated by GMM with the following instruments: $(1-\tau_{t-1})(SALES_{f,t-1} / K_{f,t-2})$, $(1-\tau_{t-1})(I_{f,t-1} / K_{f,t-2})$, $(1-\tau_{t-1})(1+\tilde{r}_{f,t-1})$, $(1-itc_{t-1} - z_{t-1})\tilde{p}^I_{f,t-1}$, and an indicator variable ($\Gamma_{f,t-1}$) identifying a class of observations.[14]

[14] Andrews and Lu (2001) discuss the role of the J statistic in detecting correlation between the instruments and unobserved fixed effects in the error term (which, if present, could lead to inconsistent parameter estimates). As shown in Table II, the J statistic for the model provides no evidence of such a correlation (and the model fits better without first differencing to remove fixed effects, perhaps because of the stronger link between instruments and Euler equation variables in levels), so we do not first difference the model. Other studies, using slightly different specifications and data, find that first differencing can be useful in estimating Euler equations.

Data appendix (Supplementary Appendix)

The primary data source is CompuStat with additional information obtained from CRSP and various sources of industry and aggregate data. In order to compensate for noise in the data due to mergers, acquisitions, or other corporate events that lead to significant accounting changes, we use 3% trimming of the upper and lower tails for SALES/K, COST/K, and I/K, where I is investment (capital expenditures) and K is the firm's capital stock.

A. *The Cost of Capital*

The baseline (real) cost of capital is defined as follows,

$$\tilde{r}_{f,t} = ((1+\tilde{r}_{f,t}^{NOM}) / (1+\pi_{s,t}^{e})) - 1.0. \tag{A-1}$$

The construction of the equity risk premium is described in the next section. The components of $\tilde{r}_{f,t}$ are defined and constructed as follows,

$\tilde{r}_{f,t}^{NOM}$	=	Nominal cost of capital
	=	$\lambda_s (1-\tau_t)\ \tilde{r}_{t}^{NOM,DEBT} + (1-\lambda_s)\ \tilde{r}_{f,t}^{NOM,EQUITY}$.
$\tilde{r}_{t}^{NOM,DEBT}$	=	Nominal corporate bond rate (Moody's Seasoned Baa Corporate Bond Yield)
$\tilde{r}_{f,t}^{NOM,EQUITY}$	=	Nominal, short-term, risk-adjusted cost of equity capital for firm *f*.
	=	$r_t^{NOM,F} + \sigma_f^{NOM}$
$r_t^{NOM,F}$	=	Nominal, one-year, risk-free rate (One-Year Treasury Constant Maturity Rate)
$\pi_{s,t}^{e}$	=	Sector-specific capital goods price inflation rate from t to t+1.[15]
σ_f^{NOM}	=	Equity risk premium for firm *f* (nominal).
τ_t	=	Marginal rate of corporate income taxation.
λ_s	=	Sector-specific leverage ratio calculated as the mean of book debt for the sector divided by the mean of (book debt + book equity) for the sector.

B. The Equity Risk Premium

[15] For 2002, the inflation rate for nonresidential fixed investment was used for $\pi_{s,t}^{e}$ for 2001.

In the case of no risk adjustment we set the equity risk premium, σ_f^{NOM}, equal to zero. In the case of risk adjustment based on the CAPM, the equity risk premium is defined by

$$\sigma_f^{NOM} = \beta_f \mu^{EMR} \tag{B-1}$$

where μ^{EMR} denotes the sample mean of EMR_t, which is the excess market return (value-weighted market return minus the risk-free rate). We calculate the CAPM betas by estimating the regression

$$EFR_{f,t} = \alpha_f + \beta_f EMR_t + \varepsilon_{f,t} \tag{B-2}$$

for each firm *f* over monthly data for January 1955 through December 2001 (or the largest subset of this sample for which data is available for firm *f*). $EFR_{f,t}$ is the excess firm return (the monthly return of firm *f* minus the risk free rate), and EMR_t is as defined above.

We calculate the Fama-French three-factor model betas by estimating the regression

$$EFR_{f,t} = \alpha_f + \beta_f^{EMR} EMR_t + \beta_f^{SMB} SMB_t + \beta_f^{HML} HML_t + \varepsilon_{f,t} \tag{B-3}$$

for each firm *f* over the same sample as described above. SMB_t is the size risk factor (average return on three small portfolios minus the average return on three big portfolios), and HML_t is the book-to-market risk factor (average return on two value portfolios minus the average return on two growth portfolios).

We calculate the Carhart model betas by estimating the regression

$$EFR_{f,t} = \alpha_f + \beta_f^{EMR} EMR_t + \beta_f^{SMB} SMB_t + \beta_f^{HML} HML_t + \beta_f^{MOM} MOM_t + \varepsilon_{f,t} \tag{B-4}$$

for each firm *f* over the same sample as described above. MOM_t is the momentum risk factor. We use six value-weight portfolios formed on size and prior (2-12) returns to construct MOM_t. The portfolios, which are formed monthly, are the intersections of 2 portfolios formed on size (market equity, ME) and 3 portfolios formed on prior (2-12) return. The monthly size breakpoint is the median NYSE market equity. The monthly prior (2-12) return breakpoints are the 30th and 70th NYSE percentiles. MOM_t is the average return on the two high prior return portfolios minus the average return on the two low prior return portfolios: MOM_t = 0.5 (Small High + Big High) - 0.5 (Small Low + Big Low).

The risk-free rate is the one-month treasury bill rate. EMR, SMB, HML, MOM and the risk free rate are taken from Kenneth French's website.[16] The monthly firm returns are taken from the CRSP database.

We calculate the Campbell-Vuolteenaho cash flow and discount rate betas as follows:

$$\begin{aligned} \hat{\beta}_f^{CF} &= \frac{\mathrm{Cov}(EFR_{f,t}, \hat{N}_t^{CF})}{\mathrm{Var}(\hat{N}_t^{CF} - \hat{N}_t^{DR})} + \frac{\mathrm{Cov}(EFR_{f,t}, \hat{N}_{t-1}^{CF})}{\mathrm{Var}(\hat{N}_t^{CF} - \hat{N}_t^{DR})} \\ \hat{\beta}_f^{DR} &= \frac{\mathrm{Cov}(EFR_{f,t}, -\hat{N}_t^{DR})}{\mathrm{Var}(\hat{N}_t^{CF} - \hat{N}_t^{DR})} + \frac{\mathrm{Cov}(EFR_{f,t}, -\hat{N}_{t-1}^{DR})}{\mathrm{Var}(\hat{N}_t^{CF} - \hat{N}_t^{DR})} \end{aligned} \tag{B-5}$$

where Cov and Var denote the sample covariance and variance functions, respectively, $\hat{N}_t^{CF}$ is the cash flow news function[17] and $\hat{N}_t^{DR}$ is the discount rate news function.

[16] Available as "Fama/French Factors" at: http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data_library.html
[17] The news factors are available in this data set, provided on the AER website: http://www.e-aer.org/data/dec04_data_campbell.zip

C. Capital Stock and Investment Flows

For the first observation for firm *f*, the capital stock is based on the net plant (*NPLANT*), the nominal book value of net property, plant, and equipment (CompuStat item 8). To convert this to real terms, we divide by the sector-specific price index for investment (p^I). Since book value is not adjusted for changes in the value of capital goods purchased in the past, we adjust the initial capital stock using a sector-specific adjustment factor (*AF*):

$$K_{f,t_0^f} = \frac{NPLANT_{f,t_0^f}}{p^I_{s,t_0^f}} \; AF_s \qquad \text{(C-1)}$$

where s is a sector index (for firm *f*'s sector) and t_0^f is the year of the first observation for firm f.

Failure to adjust book value affects the initial value of the capital stock, but has a geometrically decreasing impact on the measured capital stock over time. After 15 years, the initial value effect is negligible. We use this fact to construct the adjustment factor for the initial value of the capital stock. For sector *s*, *AF* is the ratio of the mean unadjusted capital stock for firms of age 15 or greater to the mean of what the unadjusted capital stock would have been measured as, if t equaled t_0^f (i.e., if the current year were the firm's first year in the sample). In effect, *AF* is the ratio of the true capital stock to the unadjusted initial value.

For subsequent observations, a standard perpetual inventory method is used to construct the capital stock,

$$K_{f,t+1} = (1-\delta_{s,t})K_{f,t} + \frac{KCHG_{f,t+1}}{p^I_{s,t+1}} \qquad \text{(C-2)}$$

where δ is the depreciation rate, *KCHG* is gross additions to the firm's capital stock and, in this Data Appendix, the capital stock is dated at the end of the period. The firm reports the additions in nominal terms, so we divide by p^I to convert to real terms.

In the standard case, *KCHG* is gross investment (*GI*), which is capital expenditures in the firm's financial statements (CompuStat item 128). CompuStat does not always have reliable data for the additions to the capital stock associated with large acquisitions. We use a modified version of the algorithm of Chirinko, Fazzari, and Meyer (1999) to adjust *KCHG* for acquisitions and divestitures. In the case of a substantial acquisition, we can use accounting identities to derive a more accurate measure of the additions to the capital stock,

$$DGPLANT_{f,t} = GI_{f,t} + ACQUIS_{f,t} - RETIRE_{f,t} \qquad \text{(C-3)}$$

where $DGPLANT_t$ is the change in *GPLANT* from the end of year t-1 to the end of year t and $GPLANT_t$ is gross property, plant, and equipment (CompuStat item 7), *ACQUIS* is acquisitions, and *RETIRE* is retirements of capital stock (CompuStat item 184). (When data on *RETIRE* is missing, we assume that the reason is that firms do not report any retirements in their financial statements, and we therefore assign a value of 0 to *RETIRE* for these observations.) We use the following screen to identify cases where there has been a substantial acquisition. If

$$\frac{DGPLANT_{f,t} - GI_{f,t}}{GPLANT_{f,t-1}} > 0.1 \qquad \text{(C-4)}$$

then we calculate the gross change in the capital stock as

$$KCHG_t = DGPLANT_t + RETIRE_t \qquad \text{(C-5)}$$

We also account for substantial divestitures, using the following screen. If

$$\frac{DGPLANT_{f,t} + RETIRE_{f,t}}{GPLANT_{f,t-1}} < -0.1 \quad \text{(C-6)}$$

we calculate the change in the capital stock as

$$KCHG_{f,t} = DNPLANT_{f,t} + \delta K_{f,t-1} p^{I}_{s,t} \quad \text{(C-7)}$$

where *DNPLANT* is the change in *NPLANT* (as defined above).[18] Because *NPLANT* in the firm's financial statements will deduct depreciation (as well as accounting for the divestiture), depreciation must be added to *KCHG* to avoid deducting depreciation twice.

If $GPLANT_{f,t-1}$ is missing (or equal to zero) or $DGPLANT_{f,t}$ is missing, it is not feasible to use these screens, and we set *KCHG* equal to *GI*.

In some cases, there is a data gap for a particular firm. In this case, we treat the first new observation for that firm in the same way as we would if it were the initial observation. This avoids any potential sample selection bias that would result from dropping firms with gaps in their data.

Investment (*I*) is defined by *KCHG*.

We construct sector-specific, time-varying depreciation rates using data from the BEA. Specifically,

$$\delta_{s,t} = \frac{D\$_{s,1996} DQUANT_{s,t}}{K\$_{s,1996} KQUANT_{s,t}} \quad \text{(C-8)}$$

where *D*\$ is current-cost depreciation of private fixed assets by sector (BEA, Table 3.4ES), *DQUANT* is the chain-type quantity index of depreciation of private fixed assets by sector (BEA, Table 3.5ES), *K*\$ is the current cost net stock of private fixed assets by sector (as defined above), and *KQUANT* is the chain-type quantity index of the net stock of private fixed assets by sector (BEA, Table 3.2ES).

We construct the sector-specific price index for new investment goods using BEA data:

$$p^{I}_{s,t} = \frac{100(I\$_{s,t} / I\$_{s,1996})}{IQUANT_{s,t}} \quad \text{(C-9)}$$

where *I*\$ is historical-cost investment in private fixed assets by sector (BEA, Table 3.7ES) and IQUANT is the chain-type quantity index of investment in private fixed assets by sector (BEA, Table 3.8ES).

D. The Tax-adjusted relative price of investment goods

The variable $p^{Y}_{s,t}$ is the sector-specific price index for output defined as the implicit price deflator for Gross Domestic Product by industry produced by the BEA (normalized to 1 in 1996).

Where variables are available at a monthly or quarterly frequency, we take the average for the calendar year. The investment tax credit rates (itc_t) are drawn from Pechman (1987, p.160-161). Because the investment tax credit applies only to equipment, the investment tax

[18] To see this result, start with the perpetual inventory equation.

$$K_t = I_t + (1-\delta)K_{t-1}$$

$$K_t - K_{t-1} + \delta K_{t-1} = I_t$$

Now, put the previous equation in nominal terms.

$$[K_t - K_{t-1}]p^I_t + \delta K_{t-1} p^I_t = I_t p^I_t$$

$$DNPLANT_t + \delta K_{t-1} p^I_t = I_t p^I_t = KCHG_t$$

credit for structures is zero; we multiply the statutory ITC rate for each year by the ratio of equipment investment to the sum of structures and equipment investment for that year. The present value of depreciation allowances (z_t) – for non-residential equipment and structures, respectively – were provided by Dale Jorgenson. To calculate z_t, we took the weighted sum of Jorgenson's z's for equipment and structures, where the weights are the share of equipment investment and the share of structures investment (for a given year) in nominal gross private non-residential investment in fixed assets from the Bureau of Economic Analysis (Table 1IHI, where equipment investment is referred to as equipment and software).

E. Estimated Equity Discount Rate

Section 4b reports statistics based on the estimated equity discount rate $\hat{r}_{f,t}^{EQUITY}$. Here we explain the background. In order to flexibly estimate the effect of CAPM beta on the firm's discount rate, we omit the CAPM risk adjustment to the equity cost of capital (i.e., $\sigma_f^{NOM} = \beta_f \mu^{EMR}$, as shown in equation (B-1) above) and add to the empirical specification of the firm's discount rate a vector of indicator variables (e.g., for firms with CAPM beta in the bottom quintile, second quintile, etc.) multiplied by a vector of coefficients. The vector of indicator variables for firm f is denoted by $\Gamma_{f,t-1}$ and the vector of estimated coefficients is denoted $\hat{\theta}$.

The general expression for the nominal weighted average cost of capital is:

$$\tilde{r}_{f,t}^{NOM} = \lambda_s(1-\tau_t)\tilde{r}_t^{NOM,DEBT} + (1-\lambda_s)\tilde{r}_{f,t}^{NOM,EQUITY}, \tag{F-1}$$

where

$$\tilde{r}_{f,t}^{NOM,EQUITY} = r_t^{NOM,F} + \sigma_f^{NOM}, \tag{F-2}$$

and σ_f^{NOM} is the nominal equity risk premium for firm f. The variables in the Euler equation are expressed in real terms (i.e., in constant 1996 dollars). We omit the CAPM risk adjustment by setting $\sigma_f^{NOM} = 0$ and convert $\tilde{r}_{f,t}^{NOM}$ from nominal to real terms using equation (A-1) to obtain the real baseline cost of capital with no risk adjustment:

$$\tilde{r}_{f,t}^{NRA} = \frac{1+\lambda_s(1-\tau_t)\tilde{r}_t^{NOM,DEBT} + (1-\lambda_s)r_t^{NOM,F}}{1+\pi_{s,t}^e} - 1. \tag{F-3}$$

Equation (TA-1) in the Technical Appendix shows that the discount rate in the Euler equation is specified as $\tilde{r}_t + \psi + \theta\Gamma_{t-1}$, where the parameter ψ captures the effects of unmodeled factors that affect the discount rate and are common to all firms.[19] The estimated discount rate from the Euler equation is therefore:

$$\hat{r}_{f,t} = \tilde{r}_{f,t}^{NRA} + \hat{\psi} + \hat{\theta}\Gamma_{f,t-1}. \tag{F-4}$$

If the risk adjustment had been included in (F-3), we would have had

[19] When we group firms into quintiles by CAPM beta, for example, we do not include an indicator variable for the middle quintile, so $\tilde{r}_{f,t}^{NRA} + \hat{\psi}$ can be interpreted as the estimated discount rate for the middle quintile.

$$\tilde{r}_{f,t} = \frac{1+\lambda_s(1-\tau_t)\tilde{r}_t^{NOM,DEBT} + (1-\lambda_s)\left(r_t^{NOM,F} + \sigma_f^{NOM}\right)}{1+\pi_{s,t}^e} - 1$$
$$= \tilde{r}_{f,t}^{NRA} + \frac{(1-\lambda_s)\sigma_f^{NOM}}{1+\pi_{s,t}^e}. \tag{F-5}$$

Thus $\hat{\psi} + \hat{\theta}\Gamma_{f,t-1}$ corresponds to $(1-\lambda_s)\sigma_f^{NOM} / \left(1+\pi_{s,t}^e\right)$, so the estimated nominal equity risk premium is:

$$\sigma_f^{NOM} = \frac{1+\pi_{s,t}^e}{(1-\lambda_s)}\left(\hat{\psi} + \hat{\theta}\Gamma_{f,t-1}\right), \tag{F-6}$$

and the estimated nominal equity discount rate is:

$$\hat{r}_{f,t}^{EQUITY} = r_t^{NOM,F} + \sigma_f^{NOM}$$
$$= r_t^{NOM,F} + \frac{1+\pi_{s,t}^e}{(1-\lambda_s)}\left(\hat{\psi} + \hat{\theta}\Gamma_{f,t-1}\right). \tag{F-7}$$

Table I
Summary Statistics

		Investment (I/K)	Size (ME)	Book-to-Market (BE/ME)	Sales (SALES/K)	Costs (COSTS/K)	Leverage (λ_s)	CAPM β
All observations		0.097 (0.146) [0.156]	90.44 (1490.29) [9210.95]	0.620 (0.746) [1.647]	2.169 (3.023) [2.872]	1.965 (2.773) [2.671]	0.413 (0.412) [0.089]	1.045 (1.079) [0.510]
CAPM beta	Low	0.088 (0.128) [0.136]	79.07 (1808.12) [9072.90]	0.669 (0.828) [0.811]	2.088 (2.867) [2.747]	1.853 (2.616) [2.582]	0.419 (0.421) [0.088]	0.811 (0.745) [0.298]
	High	0.112 (0.169) [0.176]	103.45 (1086.76) [9368.02]	0.561 (0.641) [2.303]	2.299 (3.220) [3.012]	2.142 (2.972) [2.767]	0.413 (0.401) [0.090]	1.389 (1.503) [0.394]
SMB beta (Fama-French)	Low	0.098 (0.142) [0.148]	216.07 (2427.07) [11920.79]	0.604 (0.730) [1.747]	2.064 (2.880) [2.798]	1.809 (2.584) [2.580]	0.419 (0.420) [0.087]	0.955 (0.974) [0.462]
	High	0.096 (0.151) [0.167]	41.84 (203.875) [1830.09]	0.643 (0.766) [1.498]	2.321 (3.218) [2.959]	2.204 (3.033) [2.771]	0.409 (0.401) [0.091]	1.188 (1.223) [0.536]
HML beta (Fama-French)	Low	0.113 (0.166) [0.170]	80.22 (2073.76) [12084.61]	0.533 (0.672) [0.707]	2.315 (3.265) [3.035]	2.131 (3.005) [2.805]	0.372 (0.396) [0.090]	1.191 (1.223) [0.573]
	High	0.086 (0.130) [0.142]	98.30 (1030.76) [6014.19]	0.692 (0.804) [2.109]	2.045 (2.833) [2.722]	1.837 (2.591) [2.546]	0.421 (0.425) [0.086]	0.964 (0.966) [0.420]
Momentum beta (Carhart)	Low	0.102 (0.153) [0.162]	95.26 (1064.68) [7784.47]	0.622 (0.727) [2.171]	2.349 (3.232) [2.961]	2.179 (2.976) [2.753]	0.413 (0.414) [0.089]	1.094 (1.132) [0.518]
	High	0.093 (0.139) [0.150]	85.29 (1933.96) [10475.36]	0.617 (0.765) [0.790]	2.004 (2.805) [2.759]	1.783 (2.561) [2.565]	0.413 (0.410) [0.089]	0.988 (1.024) [0.495]
Cash flow beta (Campbell-Vuolteenaho)	Low	0.106 (0.157) [0.164]	92.22 (2343.14) [12943.43]	0.547 (0.692) [0.709]	2.348 (3.212) [2.958]	2.129 (2.942) [2.741]	0.413 (0.408) [0.088]	0.985 (1.050) [0.547]
	High	0.089 (0.136) [0.149]	88.83 (727.25) [3103.32]	0.686 (0.794) [2.165]	2.014 (2.853) [2.781]	1.844 (2.622) [2.597]	0.413 (0.416) [0.090]	1.090 (1.104) [0.472]
Discount rate beta (Campbell-Vuolteenaho)	Low	0.088 (0.130) [0.139]	110.31 (1824.66) [8858.27]	0.656 (0.797) [1.737]	2.017 (2.800) [2.719]	1.792 (2.537) [2.533]	0.419 (0.422) [0.087]	0.868 (0.831) [0.364]
	High	0.114 (0.170) [0.176]	71.64 (984.256) [9698.76]	0.566 (0.669) [1.497]	2.446 (3.361) [3.058]	2.299 (3.130) [2.830]	0.405 (0.397) [0.090]	1.389 (1.454) [0.467]

Each cell reports the median, (mean), and [standard deviation] of the listed variable. “Low” and “High” refer respectively to below and above the median of the corresponding beta. I/K denotes the investment/capital stock ratio, ME is market equity in millions of (1996) dollars, and BE is book equity. Sales and costs are real and normalized by the capital stock.

Table II
Does the CAPM Beta Affect the Discount Rate?
CAPM Beta Above the Median

θ_{CAPM}	0.060 *** (0.008)
ζ	0.841 *** (0.073)
α	128.767 * (75.441)
J	0.290 [0.590]
$G_I[I_t, K_t]$	12.488
$G_{II}[I_t, K_t]$	1.694
N	41369

The parameter θ_{CAPM} is the estimated amount by which the discount rate is higher for a firm with a CAPM beta above the median, when the baseline cost of capital includes no adjustment for risk. An estimate of 0.060 means 6% (600 basis points). The estimates are based on the capital expenditures in two subsequent years, where the firm chooses the trade-off between the costs and benefits in each year, using a standard NPV rule. (See Sections 2 and the Technical Appendix for details.) Standard errors are in parentheses under the parameter estimate (and account for both heteroscedasticity and serial correlation). The parameter ζ captures the combined effects of non-constant returns to scale in production and imperfect competition in output markets. The parameter α determines marginal adjustment costs, while $G_I[I_t, K_{t-1}]$ is the marginal adjustment cost and $G_{II}[I_t, K_{t-1}]$ is the curvature of the adjustment cost function (both evaluated at the median of the arguments). The J statistic is a generic specification test, the Hansen J statistic for testing overidentifying restrictions (with p-values in brackets). N is the number of observations. Equation (TA-1) in the Technical Appendix presents the specification of the Euler equation on which the parameter estimates are based. GMM estimation is used with lagged values of tax-adjusted sales/K (capital stock), I (capital expenditures)/K, $1+r$ (cost of capital), the relative price of capital goods, and Γ (indicator variable for selected observations) as instruments. In this table, the indicator variable Γ equals 1 if a firm has a CAPM beta above the median, 0 otherwise. In subsequent tables, the corresponding definition of the indicator variable is shown in the table heading, as in this table. See the Technical Appendix for the functional form assumptions for the marginal revenue product and marginal adjustment costs and the Data Appendix for additional information about the data.

Table III
Does the CAPM Beta Affect the Discount Rate?
Quintiles, Deciles, and Parametric Estimate

Panel A: CAPM beta quintiles

$\theta_{BOTTOM\ QUINTILE}$	-0.013 (0.015)
$\theta_{2nd\ QUINTILE}$	-0.002 (0.010)
$\theta_{4th\ QUINTILE}$	0.051 *** (0.011)
$\theta_{TOP\ QUINTILE}$	0.085 *** (0.014)
Test of equality of θ	68.301 *** [0.000]
N	41369

The parameter "$\theta_{TOP\ QUINTILE}$" is the estimated amount by which the discount rate for a firm with a CAPM beta in the top 20% exceeds the discount rate for a firm with a CAPM beta in the middle 20%, when the baseline cost of capital includes no adjustment for risk. See the notes under Panel B for additional details.

Panel B: CAPM beta deciles

$\theta_{\text{BOTTOM DECILE}}$	-0.004 (0.027)
$\theta_{\text{2nd DECILE}}$	0.004 (0.018)
$\theta_{\text{3rd DECILE}}$	0.009 (0.014)
$\theta_{\text{4th DECILE}}$	0.018 (0.013)
$\theta_{\text{6th DECILE}}$	0.032 ** (0.014)
$\theta_{\text{7th DECILE}}$	0.044 *** (0.014)
$\theta_{\text{8th DECILE}}$	0.092 *** (0.015)
$\theta_{\text{9th DECILE}}$	0.088 *** (0.016)
$\theta_{\text{TOP DECILE}}$	0.129 *** (0.025)
Test of equality of θ	84.979 *** [0.000]
N	41369

The parameter "$\theta_{\text{TOP DECILE}}$" is the estimated amount by which the discount rate for a firm with a CAPM beta in the top decile exceeds the discount rate for a firm with a CAPM beta in the fifth decile, when the baseline cost of capital includes no adjustment for risk. An estimate of 0.060 means 6% (600 basis points). Standard errors are in parentheses (and account for both heteroscedasticity and serial correlation). The row labeled "Test of equality of θ" reports the Wald statistic for a test of the null hypothesis that all the θ_x are the same (with p-value in brackets). See the notes under Table II for additional information about the specification, estimation, and data.

Panel C: Equity Discount Rate as a Linear Function of CAPM Beta

γ_{CAPM}	0.060*** (0.007)
N	41369

The parameter γ_{CAPM} is the coefficient on CAPM beta, based on including $\gamma_{CAPM}\beta_f^{CAPM}$ in the empirical specification of the discount rate. An estimate of 0.060 means 6% (600 basis points). Standard errors are in parentheses (and account for both heteroscedasticity and serial correlation). See the notes under Table II for additional information about the specification, estimation, and data.

Table IV
Do the Fama-French Betas Affect the Discount Rate?

	Baseline Cost of Capital Includes No Risk Adjustment	Baseline Cost of Capital Includes CAPM Risk Adjustment
θ_{EMR}	0.052 *** (0.008)	--
θ_{SMB}	0.007 (0.009)	-0.002 (0.009)
θ_{HML}	-0.037 *** (0.008)	-0.014 * (0.008)
N	41369	41369

The parameters θ_{EMR} , θ_{SMB}, and θ_{HML} are the estimated amounts by which the discount rate is higher for a firm with Fama-French EMR beta, SMB beta, and HML beta above the median, respectively. An estimate of 0.040 means 4% (400 basis points). Standard errors are in parentheses (and account for both heteroscedasticity and serial correlation). See the notes under Table II for additional information about specification, estimation, and data.

Table V
Do the Carhart Betas Affect the Discount Rate?

	Baseline Cost of Capital Includes No Risk Adjustment	Baseline Cost of Capital Includes CAPM Risk Adjustment
θ_{EMR}	0.048*** (0.008)	--
θ_{SMB}	0.005 (0.009)	-0.005 (0.009)
θ_{HML}	-0.034*** (0.008)	-0.011 (0.008)
θ_{MOM}	0.001 (0.008)	-0.001 (0.008)
N	41369	41369

The parameters θ_{EMR}, θ_{SMB}, θ_{HML}, and θ_{MOM} are the estimated amounts by which the discount rate is higher for a firm with Carhart EMR beta, SMB beta, HML beta, and momentum beta above the median, respectively. An estimate of 0.040 means 4% (400 basis points). Standard errors are in parentheses (and account for both heteroscedasticity and serial correlation). See the notes under Table II for additional information about specification, estimation, and data.

Table VI
Do the Campbell-Vuolteenaho Betas Affect the Discount Rate?

	Baseline Cost of Capital Includes No Risk Adjustment	Baseline Cost of Capital Includes CAPM Risk Adjustment
θ_{CF}	-0.024*** (0.008)	-0.025*** (0.008)
θ_{DR}	0.036*** (0.008)	0.004 (0.008)
N	41369	41369

The parameters θ_{CF} and θ_{DR} are the estimated amounts by which the discount rate is higher for a firm with Campbell-Vuolteenaho cash flow beta and discount rate beta above the median, respectively. An estimate of 0.040 means 4% (400 basis points). Standard errors are in parentheses (and account for both heteroscedasticity and serial correlation). See the notes under Table II for additional information about specification, estimation, and data.