R&D Dynamics and Corporate Cash

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Abstract

Innovative firms hold substantial cash reserves. Potential explanations in the literature for this phenomenon include R&D adjustment costs, financial frictions, knowledge spillover, innovation uncertainty, and market competition. We build a parsimonious industry equilibrium model of firms that incorporates all of the cited explanations and determines which factors are the most important for understanding the cash policy of innovative firms. We find that R&D adjustment costs have a relatively small effect on cash holdings, while financial frictions, knowledge spillover, and market competition matter if they are eliminated. Innovation uncertainty has the strongest effect and matters at the margin.

1   Introduction

Innovative firms in the United States hold massive cash reserves. During the 2000s, high-tech firms' average cash-to-assets ratio and cash-to-sales ratio were 1.4 times and 6.7 times higher, respectively, than those of non-high-tech firms. The staggering cash reserves maintained by high-tech firms are conjectured to be one of the main factors responsible for the economy's sluggish recovery from the Great Recession, and raise concerns about possible underinvestment and/or cash hoarding.[1] Given these concerns and the key role of R&D in productivity and economic growth, identifying the major underlying determinant(s) of high-tech firms' cash stocks is crucial.

The fact that innovative firms hold substantially more cash is evidenced by the significant positive correlation between R&D expenditures and cash holdings observed by Bates et al. (2009). While a number of key R&D features—R&D adjustment costs, financial frictions, knowledge spillover, innovation uncertainty, and market competition—have been examined to explain this well-documented pattern, the quantitative importance of some of these factors remains unexplored.[2] Evaluating the role of each factor is necessary because it helps answer important policy questions. For example, we can determine whether cash reserves are maintained for rational reasons, and identify effective tools the government can use to reduce cash holdings if firms are in fact holding too much cash.

Moreover, each of these factors has been studied in the absence of others, which is potentially problematic because it may bias their respective contribution and provide a misleading picture of how each mechanism influences cash decisions. For instance, if there is a high correlation between R&D adjustment costs and financial frictions, only including

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[1]See, for instance, "Corporate Hoarding and the Slow Recovery," by Paul Krugman, *The New York Times*, February 8, 2013.

[2]In addition to the factors mentioned above, Foley et al. (2007) also link the high cash holdings with tax policy. They find that multinationals facing higher repatriation taxes tend to store more cash. We compare the average cash ratios for high-tech firms with and without foreign income. Interestingly, multinational high-tech firms tend to have lower cash-to-assets and cash-to-sales ratios than their counterparts: 0.33 versus 0.40 and 0.76 versus 1.90, respectively. As such, abstracting from the tax-based explanation in this paper has only minor impacts on conclusions.

one of these factors in a model will tend to overstate the relative importance of the included factor. In our paper, we address these issues by quantifying the role of possible factors in explaining the remarkably high cash stocks within a unified framework.

Unlike most of the previous empirical studies that use proxies for unobservable or immeasurable R&D features and perform empirical tests on their effects, we introduce a structural model to extract information on those features from firms' R&D and cash choices, and systematically investigate and quantify their effects. Specifically, we build a dynamic industry equilibrium model of R&D and cash with endogenous entry and exit. In the model, firms compete by selling a homogeneous good in the market and invest in R&D to improve their competitive positions. The capital market is assumed to be imperfect, so firms have no access to debt financing due to prohibitive collateralization of R&D; they can, however, borrow funds through costly external equity issuance (Brown et al., 2009; Hall and Lerner, 2010; Hall et al., 2015). Firms face costs of equity inflow (equity issuance) and equity outflow (dividend distribution). This generates a precautionary motive for holding cash, even though firms are risk neutral (Zhao, 2016). That is, to avoid external financing costs in case of a liquidity shortage, firms accumulate internal funds.

The model captures five key features of R&D investment and allows a horserace to take place between them to explain the high correlation between R&D and cash. The first is R&D adjustment costs, implied by the observed high persistence of within-firm R&D expenditures across time. Next is the severity of financial frictions innovative firms face, caused by the non-collaterability of R&D and information asymmetry between firms and investors. The third is knowledge spillover, which has important implications for firms' R&D efforts. Fourth, R&D projects are risky because they entail a high degree of uncertainty. Finally, R&D-intensive firms potentially face great market competition and operate in sectors in which fortunes can reverse quickly, described by more elastic product demand and entry pressure. We incorporate all of these features into a parsimonious model and use structural parameters to characterize them. It should be noted that most of these factors

are difficult, if not impossible, to observe directly; and even if they are observed, the effects can be hard to disentangle empirically.

To examine the model's quantitative implications for cash and R&D policies, we first uncover model parameters from firms' R&D and cash behavior and validate our model by demonstrating its ability to match relevant data moments. We then use the structural estimates obtained to assess how each key R&D characteristic affects cash and R&D choices jointly. Each characteristic is encapsulated by one or more estimated parameters. The estimation produces the following results. First, on the "global margin," financial frictions, knowledge spillover, innovation uncertainty, and market competition are essential for understanding innovative firms' cash holdings. The absence of any one of these features will result in a low cash ratio and a low R&D-cash correlation, and generate patterns inconsistent with empirical observations. This finding likely explains why many researchers have determined that one or more of these R&D-related features are important. However, this finding also implies that none of these features is more important than the others on the global margin, where they are shut down alternately. To reiterate, the horserace suggests that all of these elements are necessary to generate the high correlation between R&D and cash—and in fact, it makes little sense to compare the relative importance of each element on the global margin.

However, on the "local margin," where we perform small local parameter perturbations, only innovation uncertainty makes significant contributions to the R&D-cash correlation. This is likely the factor that real-world firms monitor closely in determining their R&D and cash policies. Surprisingly, R&D adjustment costs play a relatively small role in generating cash holdings, contrary to the common belief among academic researchers. Adjustment costs have a less important impact than the other factors, because the absence of adjustment costs only affects the real price of investment—and thus the level of R&D expenditures. As long as financial frictions and cash flow uncertainty are present, cash will be valuable regardless of the magnitude of adjustment costs.

We also examine the policy implications of our model. First, we find significant R&D underinvestment caused by knowledge spillover, but no support for that caused by financial frictions. This finding suggests that the existence of cash holdings largely eliminates the underinvestment problem caused by imperfect capital markets, and policy instruments that aim to address the market failures generated by knowledge externalities should be used. Second, the Trump administration's planned corporate income tax cut should boost R&D investment at a modest rate and increase dividend payouts significantly, but is unlikely to reduce firms' cash reserves.

Lastly, we use the validated model to estimate the value of innovative firms' cash holdings and speak to the question of whether underinvestment and/or cash hoarding exists. We find that a temporary 10% reduction in cash holdings causes a 1% drop in average firm value, mainly through temporary dividend cuts by financially flexible firms. On the other hand, a permanent elimination of cash holdings reduces steady-state average firm value by 10.5%, and this loss in real firm value arises from a significant increase in equity financing raised by financially distressed firms. Therefore, innovative firms' cash reserves are induced by rational behavior.

This paper contributes in three ways. First, it contributes to the literature of corporate cash management by systematically analyzing the implications of unique features of R&D for the well-documented R&D-cash correlation. A number of features have been studied in the literature to explain the comovement: R&D adjustment costs (Brown and Petersen, 2011), financial frictions generated by the non-collaterability of R&D (Falato et al., 2013), knowledge spillover (Qiu and Wan, 2015), innovation uncertainty (Lyandres and Palazzo, 2014), and market competition (Ma et al., 2014; Lyandres and Palazzo, 2016). However, little is known about their relative quantitative importance in explaining the *level* of the remarkably high cash ratios of innovative firms, which is the main concern regarding corporate cash holdings. Furthermore, these factors have been examined in isolation, and this may cause erroneous conclusions to be reached. We determine in our study that some

results from previous work are overturned once all the features are analyzed jointly. For instance, we find a relatively minor role for R&D adjustment costs in innovative firms' cash holdings. We also find non-monotonic impacts of innovation uncertainty, and a rather different channel through which knowledge spillover affects cash policies. Finally, financial frictions and market competition have little effect on the local margin, contrary to popular belief. All these findings to our knowledge are new.

Second, this paper contributes to the literature on R&D by studying R&D decisions, cash holdings, and financial frictions within a unified framework. A large literature addresses the role of financial frictions in R&D investments in the absence of internal cash stocks.[3] However, in response to financial frictions, firms will endogenously choose to accumulate cash, which has important implications for the R&D-financial friction relationship. As such, the inclusion of cash choices in the model helps to generate important insights overlooked in previous studies and, more importantly, is necessary for a full understanding of the role of financial frictions in R&D and their long-term effects on productivity.

Third, the paper explicitly models R&D *flow* adjustment costs and sheds light on their nature. As emphasized by previous studies, R&D adjustment costs can be quite different in nature and magnitude from physical capital adjustment costs, and this difference has important policy implications (Bloom, 2007; Hall and Lerner, 2010; Brown et al., 2012). We infer the magnitude of R&D adjustment costs from the observed corporate R&D choices, and find that firms on average face a modest linear adjustment cost but a substantial convex adjustment cost. To our knowledge, no structural estimates of R&D flow adjustment costs are available in the literature. Our estimate, therefore, provides a reference for future quantitative studies concerning R&D.

The remainder of the paper is structured as follows. Section 2 presents additional empirical evidence on the positive R&D-cash correlation. Section 3 lays out a dynamic industry equilibrium model of R&D and cash with endogenous entry and exit. Section 4

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[3]Hall et al. (2015) give a comprehensive review of the available literature on the relationship between R&D and financial constraints.

reports the estimation results of the model, and Section 5 concludes.

2 Positive Correlation between R&D and Cash

There is a rich literature that provides supportive empirical evidence on the strong relationship between firms' R&D investment and cash balances. In this section, we introduce additional evidence to the ongoing discussion by demonstrating the distributional changes in cash holdings across different R&D intensities.

We sort firms into 10 groups on the basis of their R&D-to-sales ratios and derive the distribution of cash-to-sales ratios in each of these groups. Specifically, for each year, we compute the ranges of R&D-to-sales and cash-to-sales ratios, respectively, and divide them evenly into 10 equally spaced intervals. For each of the 10 R&D groups, we calculate the percentage of firms that fall in each of the 10 cash-to-sales intervals. We repeat this process for each year and compute the average across time. The sample includes all Compustat nonfinancial nonutility firms in the 2000s with positive total assets and sales and non-missing R&D expenditures. Both cash and R&D ratios are winsorized at the top 5% and bottom 1%.

[Figure 1 about here.]

Figure 1 plots the results. The top panels represent the groups with the lowest and second-lowest R&D intensity, while the bottom two show the groups with the second-highest and highest R&D intensity. Clearly, as R&D spending intensifies, the distribution of cash ratios has a longer and fatter right tail—that is, more and more firms have high cash ratios. This implies a strong positive correlation between R&D spending and cash holdings, which is consistent with the conclusions of previous studies. The same patterns are found for the 1980s and 1990s; results are available on request.

In the following sections, we present a parsimonious model featuring the key properties of R&D investment to rationalize the stylized fact of this positive R&D-cash correlation

and identify the main contributors.

3 Model

In this section, we consider an industry equilibrium model of corporate R&D investment and cash holdings that introduces R&D into an otherwise standard cash model (Riddick and Whited, 2009). In the model, time is discrete and infinite. Within the industry, a continuum of firms with mass one manufacture an identical product. Firms compete on the product market and face financial frictions. Each period, incumbent firms make their exit decisions. Firms that choose to continue to operate produce goods and make financial, R&D-investment, and dividend-distribution choices. Potential entrants make their entry decisions by weighing the expected benefits and costs, and firms that eventually choose to enter decide their R&D spending.

We first specify the demand function for the industry and the firm's production technology, knowledge accumulation process, and financing options, then state the firm's problem and the industry equilibrium.

3.1 Demand and Technology

A firm $i \in [0,1]$ at time t uses capital $k_{i,t} = 1$ to produce output, subject to the firm-specific technology level,

$$y_{i,t} = e^{\bar{z} + z_{i,t}}. \tag{1}$$

Here, $\bar{z}$ is the frontier technology level and $z_{i,t}$ is the firm's relative technological position within the industry. The relative position $z_{i,t}$ is measured as the distance between the firm's productivity and that of industry leaders, and is determined by the firm's investment in knowledge, its past technological position, and intra-industry knowledge spillover. Note that we assume capital stock to be constant across firms and time. This assumption has little effect on our model's key implications and is made to keep the model tractable, given

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the stylized fact that R&D intensity is independent of firm size (Klette and Kortum, 2004).

The industry in which the competing firms operate faces a downward-sloping demand function, which is given by

$$P_t = Q_t^{-\frac{1}{\alpha}} = \left(\int_0^1 y_{i,t} di \right)^{-\frac{1}{\alpha}}, \qquad (2)$$

where P_t and Q_t are industry price and quantity level, and α denotes the price elasticity of demand.

3.2   Knowledge Investment and Production

In every period t, firm i invests in R&D and learns via spillover from competing firms that have relatively more advanced technologies. The firm's total input of knowledge production, $D_{i,t}$, at period t is therefore given by

$$D_{i,t} = d_{i,t} + \theta S_{i,t-1}. \qquad (3)$$

Here, $d_{i,t}$ is firm i's own R&D spending, θ captures the magnitude of knowledge spillover, and $S_{i,t-1}$ is the average previous-period knowledge investment by firms that have stronger technological positions than firm i in the current period, that is, $S_{i,t-1} = \int_{\{j:z_{j,t}>z_{i,t}\}} d_{j,t-1} dj$. From this point on, we drop subscript i to simplify notation.

To capture the existence of R&D non-performers in the data, undertaking non-zero R&D investment is assumed to incur a fixed cost, $\gamma_0 \geq 0$. The firm must also pay costs for adjusting its knowledge investment level, defined as

$$A(d_{t-1}, d_t) = \gamma_0 \mathbf{1}_{d_t>0} + \gamma_1 |d_t - d_{t-1}| + \frac{\gamma_2}{2}(d_t - d_{t-1})^2, \qquad (4)$$

where $\gamma_1 \geq 0$ and $\gamma_2 \geq 0$. The flow adjustment costs can be justified by the fact that a large share of R&D expenses goes to scientists' salaries, and turnover in workers can

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trigger large costs and losses (Hall, 1993; Bond et al., 2005). This specification is close to the one assumed for physical capital adjustment costs (Abel and Eberly, 2002; Christiano et al., 2005; Schmitt-Grohe and Uribe, 2005; Cooper and Haltiwanger, 2006; and Del Negro and Schorfheide, 2008, among others). Note that the fixed cost of R&D is included in the A function and $\mathbf{1}_{d_t>0}$ is an indicator function that equals one if R&D investment is non-zero. The linear adjustment cost reflects the loss from disruption in restructuring knowledge production factors. The convex adjustment cost reflects an increasing marginal cost of flow adjustments, and is quadratic in changes in R&D investment. To allow for zero R&D expenditure and the adjustment cost function to be well defined, the second term is quadratic in changes in investment levels (i.e., $d_t - d_{t-1}$), rather than changes in rates (i.e., $\frac{d_t}{d_{t-1}} - 1$) as employed by Christiano et al. (2005) and Schmitt-Grohe and Uribe (2005).

The firm's future productivity level z_{t+1} is determined by its total knowledge input D_t, innovation uncertainty δ and ρ, and current status z_t, where the current productivity level z_t reflects the firm's knowledge stock and past R&D efforts. The transition in productivity from z_t to z_{t+1} is specified as follows:

$$
\Gamma(z_{t+1}|z_t) = \begin{cases} \bar{z} \geq z_{t+1} > z_t & \text{with probability } \Pr(z_{t+1} > z_t) \times \Pr(z_{t+1}|z_{t+1} > z_t), \\[2em] z_{t+1} = z_t & \text{with probability } \Pr(z_{t+1} = z_t), \\[2em] \underline{z} \leq z_{t+1} < z_t & \text{with probability } \Pr(z_{t+1} < z_t) \times \Pr(z_{t+1}|z_{t+1} < z_t), \end{cases}
\tag{5}
$$

where

$$
\Pr(z_{t+1}|z_{t+1} > z_t) = \frac{\frac{1}{(z_{t+1}-z_t)^\rho}}{\sum\limits_{z_{t+1}>z_t} \frac{1}{(z_{t+1}-z_t)^\rho}},
\tag{6}
$$

and

$$
\Pr(z_{t+1}|z_{t+1} < z_t) = \frac{\frac{1}{(z_t-z_{t+1})^\rho}}{\sum\limits_{z_{t+1}<z_t} \frac{1}{(z_t-z_{t+1})^\rho}}.
\tag{7}
$$

Specifically, the probability of transitioning from current level z_t to future level z_{t+1} is equal to the product of the probability of directional movement and the probability of reaching z_{t+1} conditional on the directional changes. We follow Xu (2008) to specify the probability of directional movement. We assume that the firm improves its relative technological position and reaches a higher level with probability $\Pr(z_{t+1} > z_t) = \frac{(1-\delta)D_t}{1+D_t}$, maintains its past technological position with probability $\Pr(z_{t+1} = z_t) = \frac{1-\delta+\delta D_t}{1+D_t}$, and loses its position and falls behind with probability $\Pr(z_{t+1} < z_t) = \frac{\delta}{1+D_t}$. The parameter δ captures three knowledge-related risks: knowledge obsolescence or depreciation, firms' inability to keep up with competitors, and the unconditional uncertainty associated with innovation output. This specification also implies that higher investment in R&D improves firms' relative competitive positions by raising the likelihood of technological advancement.

Previous studies restrict firms from moving beyond the technology level that is closest to their current one, which is equivalent to the assumption that firms are only allowed to conduct incremental innovation and improve their technology gradually (Ericson and Pakes, 1995; Xu, 2008; Hashmi and Van Biesebroeck, 2016). Unlike those studies, we relax the assumption by incorporating radical innovation in the model. Incremental and radical innovations differ in several respects. In this paper, we focus on their differential effects on technology and revenue—that is, radical innovation improves technology more rapidly than incremental innovation and helps generate higher revenue. Specifically, we assume that firms' future technology z_{t+1} can move to any level, with the probability changing with its distance from current level z_t. The parameter ρ controls the likelihood of realizing radical innovation. The greater the value of ρ, the less likely firms will realize radical innovation and high revenue. Moreover, the parameter ρ captures a wide range of possibilities. When $\rho \to \infty$, the firm will move to the value closest to z_t with near certainty, which is equivalent to the assumption made in previous studies. When $\rho = 0$, the firm will have an equal chance of reaching any level other than z_t, that is, an equal probability of realizing incremental innovation or radical innovation. When $\rho \to -\infty$, the firm will move to the farthest value

of z_{t+1} with near certainty. We denote the conditional probability distribution for z_{t+1} by $\Gamma(z_{t+1}|z_t)$.

3.3 Financing

Firms can finance R&D investment through three different sources: current-period revenue, internal cash balance, and external borrowing.

Cash balance, c_t, earns a risk-free rate r. The amount of interest earned is taxed at the corporate tax rate τ_c when taxable income is positive.

External borrowing takes the form of equity issuance. This assumption follows the observation by Brown et al. (2009) that equity finance is a more relevant substitute for internal cash flow because of the intangible nature and low collateral value of R&D. Equity-issuance cost is assumed to be proportional to the amount issued at a rate of λ (Hennessy and Whited, 2007; Nikolov and Whited, 2014). Following previous studies, we describe negative equity flow $e_t < 0$ as equity issuance and positive equity flow $e_t \geq 0$ as dividend payment.

3.4 The Firm's Problem

3.4.1 The Incumbent's Problem

Each period, after productivity z_t is realized, the firm decides whether to leave the market by weighing the expected benefits of continuing to operate and of exiting.

If the firm chooses to stay, it sells its output at the industry price P_t. Therefore, taxable income is

$$\pi_t(y_t, c_t, d_t; P_t, \mu_t) = P_t y_t - c_f + r c_t - d_t, \tag{8}$$

in which c_f is the fixed operational cost. Upon receiving its profit, the firm makes decisions about R&D investment and cash savings. If available internal resources are insufficient to cover those expenses, the firm borrows externally by issuing equity; otherwise, it distributes

dividends. Net cash flow is

$$g_I(e_t) = (1 - \mathbf{1}_{e_t \geq 0} \tau_d + \mathbf{1}_{e_t < 0} \lambda) e_t(\pi_t, c_t, c_{t+1}, d_{t-1}, d_t), \tag{9}$$

where

$$e_t(\pi_t, c_t, c_{t+1}, d_{t-1}, d_t) = (1 - \tau_c \mathbf{1}_{\pi_t \geq 0}) \pi_t + (c_t - c_{t+1}) + \tau_{rd} d_t - A(d_{t-1}, d_t). \tag{10}$$

The first term of e_t is the firm's net income, and the other terms are the net change in cash, R&D subsidy, and adjustment costs, respectively. Parameters τ_c and τ_{rd} are the corporate income tax rate and R&D tax-credit rate, respectively. The indicator function $\mathbf{1}_{e_t \geq 0}$ equals one if the firm distributes dividends and zero otherwise, while $\mathbf{1}_{e_t < 0}$ equals one if the firm issues equity and zero otherwise. On the other hand, the indicator function $\mathbf{1}_{\pi_t \geq 0}$ means that the firm is only taxed when taxable income is positive.

If the firm chooses to exit, the corresponding net cash flow is

$$g_X(e_t) = (1 - \mathbf{1}_{e_t \geq 0} \tau_d + \mathbf{1}_{e_t < 0} \lambda) e_t(\pi_t, c_t, c_{t+1} = 0, d_{t-1}, d_t = 0). \tag{11}$$

The risk-neutral incumbent maximizes its value. Moving on to the recursive formulation, let $V_I(z, c, d_{-1}; P, \mu)$ and $V_X(z, c, d_{-1}; P, \mu)$ denote the value functions of continuing to operate and exiting, respectively. The parameter μ is the current-period joint distribution of idiosyncratic productivity level, cash balances, and previous R&D spending, which will be specified in Subsection 3.5. Also, let x' denote the continue/exit decision where $x' = 0$ indicates that the firm continues and $x' = 1$ indicates that the firm exits. Then the incumbent's problem becomes

$$V(z, c, d_{-1}; P, \mu) = \max_{x' \in \{0,1\}} \{V_I(z, c, d_{-1}; P, \mu), V_X(z, c, d_{-1}; P, \mu)\}, \tag{12}$$

where

$$V_I(z, c, d_{-1}; P, \mu) = \max_{c', d}\{g_I(e) + \beta \mathbb{E} V(z', c', d; P', \mu')\}, \tag{13}$$

and

$$V_X(z, c, d_{-1}; P, \mu) = g_X(e). \tag{14}$$

Here, subscript -1 denotes a variable in the preceding period, and a prime denotes a variable in the subsequent period. The parameter β is the discount factor and equals $\frac{1}{1+r}$.

3.4.2 The Potential Entrant's Problem

A potential entrant pays a cost, c_E, at the beginning of a period to draw a z with probability

$$\Pr(z > \underline{z}) = \frac{\frac{1}{(z-\underline{z})^\rho}}{\sum\limits_{z > \underline{z}} \frac{1}{(z-\underline{z})^\rho}}. \tag{15}$$

Similar to before, we denote the corresponding probability distribution as $\Gamma_E(z)$.

Upon seeing z, the potential entrant can either choose to throw away the draw, or commit to enter the economy and produce y. If the potential entrant commits to enter, it carries $c = 0$ and $d_{-1} = 0$ from the previous period because it was not operational, and chooses c' and d to maximize the expected discounted value of the firm.

With this form of entry, the potential entrant throws away low-z draws because potential profits are low and it does not want to pay the adjustment costs. On the other hand, high-z draws induce entry in order to capture more substantial profits. If a firm enters, it also invests in cash and R&D to set itself up for the future.

The free-entry condition is

$$\int \max\{V_I(z, 0, 0; P, \mu), 0\} d\Gamma_E(z) \leq c_E, \tag{16}$$

and the condition holds with equality when there is a non-zero mass of entry.

3.5 Law of Motion for Distribution μ

Conditional on the current-period joint distribution $\mu(z, c, d_{-1})$ of idiosyncratic productivity level, cash balances, and previous R&D spending, the next-period distribution is determined by

$$\mu'(z', c', d) = \int I(z, c, d_{-1}; P, \mu) d\Gamma(z'|z) d\mu(z, c, d_{-1}) + M' \int I(z, 0, 0; P, \mu) d\Gamma(z'|z) d\Gamma_E(z),$$
$$(17)$$

where $I(z, c, d_{-1}; P, \mu) \equiv \mathbf{1}_{\mathcal{C}(z,c,d_{-1};P,\mu)=c'} \mathbf{1}_{\mathcal{D}(z,c,d_{-1};P,\mu)=d} \mathbf{1}_{\mathcal{X}(z,c,d_{-1};P,\mu)=0}$ is a combined indicator function for incumbents, $I(z, 0, 0; P, \mu) \equiv \mathbf{1}_{\mathcal{C}(z,0,0;P,\mu)=c'} \mathbf{1}_{\mathcal{D}(z,0,0;P,\mu)=d} \mathbf{1}_{\mathcal{X}(z,0,0;P,\mu)=0}$ is a combined indicator function for potential entrants, and M' is the mass of potential entrants. Note that $\mathcal{C}(z, c, d_{-1}; P, \mu)$, $\mathcal{D}(z, c, d_{-1}; P, \mu)$, and $\mathcal{X}(z, c, d_{-1}; P, \mu)$ are the cash, R&D, and exit decision rules, respectively, for incumbents, while $\mathcal{C}(z, 0, 0; P, \mu)$, $\mathcal{D}(z, 0, 0; P, \mu)$, and $\mathcal{X}(z, 0, 0; P, \mu)$ are the cash, R&D, and exit decision rules, respectively, for potential entrants. The "exit" decision $\mathcal{X}(z, 0, 0; P, \mu) = 1$ for potential entrants means that they throw away the z draws, while the "continue" decision $\mathcal{X}(z, 0, 0; P, \mu) = 0$ means that they enter and produce with their z draws.

The entry and exit dynamics in this type of model can be best described as "bottom churning." That is, the worst firms exit every period and are replaced by entrants with higher z draws.

3.6 Industry Equilibrium

In this paper, we focus on the stationary industry equilibrium.

Definition 1 *A **stationary industry equilibrium** is a stationary distribution μ, a price P, a quantity Q, and policy functions $\mathcal{C}(z, c, d_{-1}; P, \mu)$, $\mathcal{D}(z, c, d_{-1}; P, \mu)$, and $\mathcal{X}(z, c, d_{-1}; P, \mu)$ such that:*

(i) policy functions solve the firm's problem, given industry price P and distribution μ;

(ii) the distribution μ is invariant over time;

(iii) the free-entry condition is satisfied; and

(iv) the product market clears.

3.7 Optimal Policy Rules

In this subsection, we characterize firms' optimal R&D, cash, and exit decisions by plotting policy functions and develop the intuition behind them.

3.7.1 Optimal R&D Investment

Figure 2 plots the optimal response of R&D investment (d) to changes in the firm's relative technological position within the industry (z), previous R&D investment level (d_{-1}), and the beginning-of-period cash balance (c). Specifically, we discretize z into 10 categories and let z_1 denote the lowest level of technology in the industry and z_{10} the technological frontier. Figure 2 contains 10 panels that depict the optimal R&D investment as a function of (d_{-1}, c) for each z.

[Figure 2 about here.]

In each of the 10 panels, the optimal R&D investment increases in the previous R&D expenditures. This result is driven by the existence of flow adjustment costs. That is, to save substantial adjustment costs, firms have incentives to smooth their R&D expenses and avoid deviating too much from previous spending patterns. The only exception is for firms with the lowest productivity and low cash balances. These firms find it optimal to exit the market with zero investment.

The response of R&D investment to cash balances differs among firms and depends on their relative technological positions. Firms that decide to stay in the market with the lowest productivity $(z = z_1)$ and low cash balances choose to take risks and aggressively invest in R&D so as to survive in the market. This risk-taking motive disappears as internal cash and

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survival probability increase. Firms with low productivity ($z_2 \leq z \leq z_4$), on average, do not respond to changes in cash holdings and become R&D non-performers when previous R&D spending is low. This interesting result is possibly driven by the presence of knowledge spillovers. Firms with low productivity tend to free ride on the other firms' knowledge sharing, which leads the former to exert low R&D effort. Firms with high productivity ($z_9 \leq z \leq z_{10}$) also do not respond to cash balances, yet for a different reason. These firms' profits are sufficient to cover investment expenses, and thus internal cash balances become irrelevant to their R&D decisions. On the other hand, firms with medium-level productivity ($z_5 \leq z \leq z_8$) increase R&D investment slightly when their cash balances increase. This suggests that these firms are, in general, financially constrained and experience a small degree of R&D underinvestment. When they have more internal resources, they invest more to improve productivity.

Given previous R&D spending and internal cash balances, optimal R&D investment rises with relative technological position. This pattern is driven by both knowledge spillover and financial frictions. When z is small, firms take advantage of knowledge spillover and do not have strong incentives to invest in R&D. As z rises, the size of the spillover drops and the marginal benefit of knowledge investment goes up. In addition, higher cash inflow allows firms to devote more internal resources to R&D without heavily tapping into external finance.

3.7.2 Optimal Cash Holdings

Figure 3 presents the optimal cash policy (c') as a function of previous R&D investment (d_{-1}) and beginning-of-period cash balance (c) for each value of relative technological position (z). To facilitate the interpretation, we also plot firms' dividend-distribution/equity-issuance functions in Figure 4.

[Figure 3 about here.]

[Figure 4 about here.]

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Firms in different technological positions value internal cash differently. Those in relatively disadvantageous positions ($z_1 \leq z \leq z_6$) build up their internal cash balances and pay zero dividends when R&D expenditures are low. Their optimal cash holdings rise with their beginning-of-period cash balances. The positive effect of beginning-of-period cash c on cash policy c', however, gradually falls as previous R&D investment increases. This result is driven by R&D flow adjustment costs. To avoid suffering large adjustment costs, firms choose to maintain high R&D spending even if they have to issue expensive equity to cover the expenses.

Firms in relatively advantageous positions ($z_7 \leq z \leq z_8$) behave similarly, except that their cash policy barely moves with previous R&D spending d_{-1}. These firms make higher revenues and augment their cash balances to guarantee that sufficient internal funds will be available for future R&D investment.

Industry leaders ($z_9 \leq z \leq z_{10}$) face fierce market competition. Although enjoying strong competitive positions, earning high revenues, and seldom being financially constrained, they always choose to keep cash on hand as a precaution and pay out remaining funds as dividends to shareholders.

3.7.3 Entry and Exit

Lastly, we show the optimal exit decision together with the probability distribution of entrants' relative productivity levels.

Figure 5 suggests that firms with the weakest competitive positions and low internal cash balances find that they are unlikely to improve future cash flows and decide to exit, while all other firms choose to stay and continue to compete in the market.

[Figure 5 about here.]

Furthermore, only firms with the lowest productivity draws decide not to enter the market. The probability distribution of entrants' relative productivity is right skewed, with

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a slowly decaying right tail. In addition, more than 90% of the entrants have below-average productivity.

[Figure 6 about here.]

In the next section, we apply the model to the data and assess how key R&D features contribute to the positive correlation between R&D expenditures and cash holdings.

4   Quantitative Analysis

In the following subsections, we quantitatively evaluate the role of R&D features in explaining the well-documented positive R&D-cash correlation. To that end, we first select and construct a set of data moments, using a sample of firms that (i) operate in 3-digit SIC high-tech industries—SIC 283, SIC 357, SIC 366, SIC 367, SIC 382, SIC 384, and SIC 737— and (ii) have positive sales, positive assets, and non-missing R&D investment for the period 2000-2014 from Compustat.[4] We then perform simulated methods of moments estimation (SMM) to infer model parameters from selected data moments, and use the obtained parameter estimates to examine the model's quantitative implications for innovative firms' cash and R&D policies. Lastly, we study our findings' policy implications and assess the value of cash.

4.1   Parameterization

We set the length of a period in the model to be one year. The average real risk-free interest rate during the 2000s was 3.1%. We therefore set r to be 3%.

The frontier technology level $\bar{z}$ is set to be $\frac{3\sigma}{\sqrt{1-\rho^2}}$, where ρ and σ are the persistence and standard deviation of idiosyncratic productivity processes, respectively. To estimate

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[4]In approximately 17% of the firm-year observations, we have missing R&D expenditures. Although deleting those observations leads to a loss of data, the sample still contains enough information about firms' R&D behavior.

these two parameters, we perform the following two steps. Given our production function specification, we first run regression model (18):

$$\log Y_{i,t} = \alpha_0 + firm_i + year_t + \epsilon_{i,t}, \tag{18}$$

where $Y_{i,t}$ is the real sales of firm i in year t, and the error term $\epsilon_{i,t}$ represents the idiosyncratic productivity in the model. To control for firm-specific time-invariant characteristics and common macroeconomic shocks across firms, we also include firm and time fixed effects. We then collect the estimated residuals and run the regression model below to calibrate ρ and σ:

$$\hat{\epsilon}_{i,t} = \rho \hat{\epsilon}_{i,t-1} + \varepsilon_{i,t}.$$

The estimated coefficient gives the persistence ρ, and the average of the cross-sectional dispersion of the estimated residuals $\hat{\varepsilon}_{i,t}$ across time gives the standard deviation σ. Using the constructed sample, we get $\rho = 0.51$ and $\sigma = 0.63$, and therefore set the frontier technology level $\bar{z}$ to be 2.19. The distance to the technology frontier, z, can take values in the interval $[-2\bar{z}, 0]$.

We follow Gao (2015) to choose the value of price elasticity of demand; Gao uses Compustat data to estimate price elasticity and finds that its value has risen to 6.8 in the 2000s. We therefore set α to be 7.

We calibrate dividend tax, corporate income tax, and R&D tax credit as follows. Dividend tax is chosen to be 15%, a rate commonly used in the literature (Hennessy and Whited, 2005). Corporate income tax τ_c is set at 35%, which is the statutory corporate income tax in the 2000s. The Internal Revenue Code provides three methods to calculate R&D tax credits, the simplest of which is called the Alternative Simplified Credit method. Using this approach, firms can claim a tax credit equal to 14% of qualified R&D expenditures that exceed a calculated base amount, while the base amount cannot be less than 50% of their current-year qualified expenditures. Therefore, we set the R&D tax credit to be 6%,

slightly lower than half the 14% rate.

[Table 1 about here.]

The remaining parameters are estimated using an SMM approach. That is, we recover underlying parameters from a list of selected moments by minimizing the distance between the moments constructed from model-simulated data and the moments computed with actual data. We choose the following moments to match: the 25th and 75th percentiles of R&D-to-sales and cash-to-sales ratios, serial correlation of within-firm R&D-to-sales and cash-to-sales ratios, correlation between R&D-to-sales and cash-to-sales ratios, fraction of firms with zero R&D investment, and firm exit rates.

In particular, in the face of high fixed costs of undertaking R&D γ_0, firms may select into non-R&D performers. The fraction of firms with zero R&D investment therefore can be used to infer γ_0. The persistence of with-firm R&D and cash ratios provides information on the magnitude of linear and convex R&D adjustment costs γ_1 and γ_2. The 75th percentile of R&D ratio is informative about the size of knowledge spillover θ. Intuitively, an increase in θ tends to have a discouraging effect on leaders' R&D investments. Cash-poor firms tend to be more sensitive to changes in credit market conditions. The 25th percentile of cash ratio thus contains information about equity-issuance costs λ. An increase in innovation uncertainty δ and a drop in the probability of realizing radical innovation/breakthrough ρ have different implications for followers' R&D efforts. The former implies a higher chance of innovation failure and higher exit rates and induces followers to invest more in R&D in order to survive. We therefore use the 25th percentile of R&D ratio to identify δ. Changes in ρ affect the prospects for leaders' future cash flow, which has important implications for their cash policies. We thus use the 75th percentile of cash ratio to estimate ρ. Lastly, we infer fixed operating costs c_f from firm exit rates. As c_f increases, fewer firms can cover the costs and are more likely to choose to exit the market.

Parameters are shown in Table 1. Panel A summarizes the parameters that are either directly calibrated from data or borrowed from other relevant studies. Panel B reports the

remaining parameters, which are estimated jointly by SMM. The corresponding standard errors are presented next to the parameters in parentheses, and the standard errors indicate that the model moments are sufficiently sensitive to the parameters.

4.2   Estimation Results

In this subsection, we report estimation results of the model described in Section 3. The sample used for estimation consists of Compustat high-tech firms for the period 2000-2014. We drop observations with non-positive sales, non-positive assets, or missing R&D investment. To control for outliers, we compute firms' individual R&D-to-sales and cash-to-sales ratios and winsorize the variables at the bottom 1% and top 5% levels. We then use the processed sample to construct data moments, by first calculating the variables for each year and then taking the mean value across years.

4.2.1   Parameter Estimates

Parameter estimates are reported in Panel B of Table 1. The estimated γ_0 is close to zero—that is, the fixed cost of undertaking R&D each period is negligible. The estimated γ_1 and γ_2 are 0.195 and 1.96, respectively, implying high flow adjustment costs.

Very few structural estimates of R&D adjustment costs are available in the literature. Li and Liu (2012) find the convex R&D *stock* adjustment cost is larger than that of physical capital; their estimates range from 3.26 to 67.47, depending on model specifications. Our estimate of the convex *flow* adjustment costs γ_2 appears to be close to the lower bound of their estimates. Given the different adjustment-cost specifications, one should be cautious about making direct comparisons. However, our estimate delivers a message consistent with that of Li and Liu and other R&D studies—that is, the convex R&D adjustment cost is high.

We also compare our adjustment-cost estimates to those of physical capital adjustment to get a rough idea of the reliability of our estimates. Christiano et al. (2005) and Del

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Negro and Schorfheide (2008) consider capital *flow* adjustment costs, in contrast to capital *stock* adjustment costs. Christiano et al. find the convex cost parameter to be 2.48 using their baseline model, whereas that of Del Negro and Schorfheide ranges between 8 and 11.[5] Cooper and Haltiwanger (2006) and Bloom (2009) consider capital stock adjustment costs and adopt a specification with both linear and convex terms. Cooper and Haltiwanger use plant-level data and find the linear capital adjustment cost to be approximately 4% of capital stock and the convex capital adjustment cost parameter to be 0.049. Bloom, using Compustat, finds the linear adjustment cost to be 1.5% of sales and the convex adjustment parameter to not be statistically significantly different from zero. Previous studies that consider only convex capital stock adjustment costs usually find the adjustment parameter to be smaller than 5.5 (Whited, 1992; Gilchrist and Himmelberg, 1995; and Hall, 2002). Compared to these estimates, ours appears to fall within a reasonable range.

Two other parameters inferred from firms' R&D and cash behavior are unconditional innovation uncertainty δ and knowledge spillover θ. The estimate of δ is 0.431, which implies that substantial risks are associated with innovation in general. The estimate of θ is critical for measuring returns to R&D for policy considerations. Our estimate of θ is 1.23, which is smaller than the estimate provided by Xu (2008), yet still indicates sizeable intra-industry externalities.

The estimated linear equity-issuance cost λ is 0.19. This is higher than the value estimated by Hennessy and Whited (2007) who find the linear cost of equity issuance to be approximately 0.09 when allowing for fixed equity-issuance costs. We conjecture that our higher estimate of linear equity-issuance costs arises for two reasons. First, issuing equity incurs zero fixed costs in our model, which would be partially absorbed and reflected by higher linear issuance costs. Second, we examine high-tech firms, which tend to be collateral poor due to information asymmetries and thus face higher external borrowing costs.

The parameter ρ is newly introduced to the R&D literature and associated with the

[5]See also Schmitt-Grohe and Uribe (2005).

conditional probability of realizing radical innovation. It relaxes the restriction imposed by previous studies in which firms can only conduct incremental innovation and move to a productivity level that is equal or close to their current positions (Xu, 2008; Hashmi and Van Biesebroeck, 2016). When ρ equals zero, there is an equal chance of realizing incremental and radical innovation and reaching any level other than the current one. The larger the parameter, the greater the likelihood that firms will move to the closest value. The estimated ρ is 1.85, implying a moderate chance of having a breakthrough and moving beyond the value closest to the current level of technology.

Lastly, the fixed operating cost c_f is 1.43, which is chosen to match the observed firm-exit rates. This value amounts to roughly 27% of an average firm's sales.

4.2.2 Simulated Model Moments

Table 2 reports the data moments and their corresponding simulated model moments, including the first and second moments of R&D intensity and cash holdings, share of non-R&D performers, exit rates, and the turnover rate of industry leaders. To be consistent with our model, we follow Duffie et al. (2007) and treat it as an exit if firms are deleted from Compustat due to bankruptcy or liquidation (data item $dlrsn$ is 2 or 3). We define the turnover of leaders as the number of firms leaving the top decile market share of the industry during one year.

[Table 2 about here.]

Panel A presents the targeted model moments at the point estimates reported in Table 1. The cross-sectional heterogeneity in R&D intensity and cash holdings, the high correlation between these two margins, and the exit rates are all well matched. The serial correlations of within-firm R&D investment and cash holdings, however, are undershot by the model, 0.787 vs. 0.437 and 0.742 vs. 0.468, respectively. We would ideally like to achieve a close match for both cross-sectional and within-firm moments. However, this difficult moment

matching issue is common in models of firm dynamics since there is generally a tremendous amount of cross-sectional variability in firm level data. We choose to assign more weight on cross-sectional moments, because they are more important for achieving overall model validity.

To further evaluate model fitness, we compare the nontargeted moments in the model with those in the data and report results in Panel B of Table 2 and Figure 7. The model explains innovative firms' R&D investment and cash-holding behavior reasonably well. Model-generated moments are close to data moments in most cases, except for industry average R&D intensity and its cross-sectional dispersion.

[Figure 7 about here.]

Moreover, the model-implied probability distributions of firms' R&D-to-sales ratio and cash-to-sales ratio resemble their corresponding empirical distributions closely. To derive the probability distribution in the data, we compute the range of the variable, divide the range evenly into 10 intervals, and calculate the percentage of firms that fall in each. We repeat this process for each period and compute the average across periods. The distribution of firms' R&D intensity can be described as a Pareto distribution. The model successfully replicates a high fraction of firms that have relatively low R&D-intensity and a slowly decaying long tail. The probability distribution of cash-to-sales ratio closely tracks that of R&D intensity. The model slightly overshoots the first group, 90.6% vs. 97.7%, and undershoots the second, 4.5% vs. 1.3%.

Overall, the model is able to explain the key patterns of firms' R&D and cash-holding behavior observed in the data. This strengthens the reliability of parameter estimates reported in Table 1.

4.3 The Role of Key R&D Features

In this subsection, we rely on the structural estimates obtained above to quantify the importance of key R&D features in explaining innovative firms' cash and R&D choices. We consider the following features: R&D flow adjustment costs (γ_0,γ_1, and γ_2), innovation uncertainty (δ and ρ), knowledge spillover (θ), financial frictions caused by the non-collaterability of R&D and information asymmetry between firms and investors (λ), and market competition (α and c_f). We change one parameter at a time, holding all other parameters constant. Two effects are examined: (i) the effects at the local margin by increasing the value of each parameter by 10%, and (ii) the effects at the global margin by shutting down each feature.[6] Results of the effects at the local margin and global margin are reported in Panels A and B of Table 3, respectively.

[Table 3 about here.]

4.3.1 R&D Adjustment Costs

Brown and Petersen (2011) argue that adjusting R&D spending is costly, and therefore firms facing financial frictions tend to accumulate valuable internal funds to smooth their R&D investment and avoid potentially large adjustment costs. More specifically, a large share of R&D expenses goes to pay the salaries of highly educated scientists, engineers, and other specialists. Their effort creates a firm's knowledge base, which is embedded in its human capital. Turnover among these skilled workers can erode the firm's knowledge base and lead to dissemination of proprietary information. Firms, therefore, have strong incentives to retain skilled employees, as reflected by the highly persistent R&D spending—which, in turn, implies substantial adjustment costs.

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[6]To estimate the effect of each feature at the global margin, we reset the parameter values as follows. We set adjustment costs (γ_0, γ_1 and γ_2), knowledge spillover (θ), and fixed operating costs (c_f) to be zeros. We cut the value of unconditional innovation uncertainty δ by half, which is roughly equal to the uncertainty level that an average non-high-tech firm faces, and raise ρ by half, which implies that firms are unlikely to realize breakthroughs. We set the linear equity-issuance cost to be 3%, that is, firms can borrow funds at risk-free rates. Lastly, we cut α by half, which suggests that firms face a less competitive market and enjoy higher gross profit margins.

Our estimation results, however, suggest that R&D adjustment cost is not a first-order factor in explaining innovative firms' high cash balances and the observed high R&D-cash correlation.

The estimate of the fixed adjustment cost γ_0 is close to zero. Its changes have no impacts on R&D, cash or their correlation. A 10% increase in γ_1 raises the adjustment costs uniformly for R&D-performing firms and prompts them to smooth R&D spending across time. However, the effect is negligible. It leads to slight drops in industry average R&D-to-sales ratio and the R&D-cash correlation, and has no impacts on cash policies. The complete removal of linear adjustment cost, $\gamma_1 = 0$, also has a minor effect on cash and R&D and drives up R&D-cash correlation slightly.

A larger convex cost γ_2 of R&D adjustment generates a stronger precautionary motive for cash holdings and prompts cash-poor firms to save more. At the local margin, it does not affect cash-rich firms' decisions, but has a significant impact on cash-constrained firms' cash policies. On average, it barely changes the cash-to-sales ratio, which rises slightly from 1.25 to 1.27. At the global margin, the effect of γ_2 is sizeable. If we set zero convex adjustment costs, the average cash-to-sales ratio drops from 1.25 to 0.85. The decline in cash ratio arises from two channels. First, zero convex adjustment costs cut expenses and make cash less valuable, regardless of R&D spending. Second, zero convex adjustment costs give R&D-intensive firms lower incentives to maintain high R&D, which in turn weakens demand for cash. The R&D-cash correlation, accordingly, drops from 0.885 to 0.761.

When we shut down adjustment costs entirely by setting γ_0, γ_1, and γ_2 to zeros, we find that the interaction of different types of adjustment costs yields a stronger effect. Without the R&D smoothing motive generated by flow adjustment costs, the average cash ratio drops by more than half, while the correlation between cash and R&D spending remains high.

4.3.2 Innovation Uncertainty

4.3.2.1 Unconditional Innovation Uncertainty

The parameter δ captures the unconditional innovation uncertainty, which affects the marginal product of R&D investment and can be treated as the opposite of innovation efficiency studied by Lyandres and Palazzo (2014). Lyandres and Palazzo suggest a positive role of innovation efficiency in shaping high-tech firms' cash policies, that is, a negative effect of innovation uncertainty on cash holdings. They argue that an increase in innovative efficiency generates stronger precautionary considerations by raising the likelihood of innovation success and higher opportunity costs of being financially distressed.[7]

At the local margin, the responses of high R&D-intensive firms to an increase in δ are consistent with the conclusion derived by Lyandres and Palazzo (2014). As δ rises, high R&D-intensive firms are more concerned about the higher marginal cost of R&D spending and decide to cut their investments. Therefore, they demand less cash. In addition to the mechanism proposed by Lyandres and Palazzo, our results suggest a new channel to explain the negative effects of innovation uncertainty on cash holdings. An increase in innovation uncertainty δ significantly drives up firm exit rates. It encourages low R&D-intensive firms to invest more in R&D, so that they can survive, improve innovation success rates, and catch up with competitors. These firms make relatively low profits. Shifting more resources to R&D implies fewer left for cash savings. Their cash holdings, therefore, drop significantly.

The effect of δ at the global margin, however, is rather different from that at the local margin, implying a nonmonotonic impact of δ on R&D. When we reduce δ by half, the average cash ratio drops markedly. As unconditional innovation uncertainty falls and thus the success rate of R&D investment increases, firms choose to cut their R&D spending when they achieve a particular success rate and become more certain about future cash flows. This in turn lowers the precautionary motive for holding cash.

Moreover, unconditional innovation uncertainty is a key driver behind the high R&D-cash

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[7]See also Hsu et al. (2016).

correlation. A 50% reduction in δ weakens the correlation by 50%, from 0.885 to 0.451.

4.3.2.2   Conditional Probability of Breakthrough

Incremental and radical innovations have different impacts on firms' competitive positions and revenue. No attention so far has been paid to the role of this feature in cash policies.

As shown in Table 3, firms' R&D investments react differently to an increase in ρ—that is, a decrease in the probability of realizing radical innovation. In response to a 10% increase in ρ, high R&D-intensive firms choose to cut their R&D spending, because a lower probability of being caught up by followers and realizing radical breakthroughs reduces their incentive to innovate. Low R&D-intensive firms, however, remain concerned about permanent business closure and choose to invest in R&D at a rate similar to the benchmark case. When we further reduce the likelihood of realizing radical innovation by raising ρ by 50%, the mechanism stated above becomes stronger. High R&D-intensive firms cut their R&D by one-third.

An increase in ρ weakens incentives to invest in R&D, which lowers firms' need for internal cash to finance R&D expenditures. This leads to significant drops in average cash ratio and the comovement between R&D and cash holdings. A 50% increase in ρ causes a 60% decline in the correlation.

4.3.3   Knowledge Spillover

Qiu and Wan (2015) emphasize a positive effect of technology spillover on cash policies. They argue that the enhancement of the marginal product of R&D via spillover provides firms with stronger incentives to apply external knowledge and perform R&D, which in turn leads to a higher demand for cash.

At the global margin, the effect of spillover on cash holdings is in line with the findings by Qiu and Wan (2015), yet suggests a different mechanism. In the absence of knowledge spillover (i.e., $\theta = 0$), firms must invest in R&D on their own to improve their competitive

positions. They allocate more resources to R&D and leave fewer for cash savings. Their R&D spending therefore increases, while cash holdings drop significantly. Knowledge spillover is another key contributor to the high R&D-cash correlation. Without any spillover, the R&D-cash correlation drops to 0.35.

At the local margin, the impacts of an increase in spillover on cash and R&D are opposite to findings by Qiu and Wan (2015); the effect on cash holdings appears to be minor. The average cash ratio drops slightly, from 1.25 to 1.19, in response to a 10% rise in spillover rate. The effect on R&D is significant but negative. As spillover becomes greater and rises to 1.36, high-R&D-spending firms effectively have lower returns to knowledge investment. They are discouraged from innovating and choose to cut their R&D. In particular, firms at the 75th percentile of R&D intensity reduce their R&D-to-sales ratio from 0.42 to 0.32, which causes the average R&D ratio to drop by 6 percentage points.

4.3.4   Financial Frictions

One of the features frequently used to explain the observed high R&D-cash correlation is financial frictions (Falato et al., 2013, 2014; Hall and Lerner, 2010). Due to information asymmetries and low collateral value of R&D, high-tech firms face expensive equity-issuance costs. To avoid underinvestment in R&D caused by financial constraints, firms accumulate internal funds.

Our results suggest that in the presence of severe financing frictions, a further increase in financing cost λ has minor adverse effects on R&D investment. This finding implies that allowing firms to build up internal cash reserves largely resolves the problem of underinvestment in R&D caused by financial frictions. Furthermore, a continued rise in financing costs only influences cash-poor firms' cash decisions. They choose to raise their cash balances significantly, from 17% to 28%, so as to save more financing costs in case they are financially distressed in the future.

Allowing firms to borrow without limit at risk-free interest rates at the global margin

lowers the value of cash, and the average cash ratio correspondingly drops to 0.22. The non-zero cash holdings arise from the non-zero dividend tax τ_d. A positive dividend tax plays a role similar to equity-issuance costs λ. It imposes higher costs on dividend payment, and provides firms with stronger incentive to retain earnings for future investments (Zhao, 2016). The relaxation of financing constraints has little effect on R&D investment, which further confirms our finding that the existence of cash stock mitigates the underinvestment problem induced by financial frictions.

4.3.5 Market Competition

Market competition is another often-discussed determinant of innovating firms' cash policies (He and Wintoki, 2015; Lyandres and Palazzo, 2016; Ma et al., 2014). It can be captured by two parameters in our model: price elasticity of demand (α) and fixed operating costs (c_f). Different transmission channels of market competition have different policy implications.

Price elasticity of demand reflects the degree of responsiveness in demand quantity with respect to price changes. As the elasticity α increases, the demand function becomes flatter, and market competition intensifies. Our results suggest different effects on the local and global margins. A marginally higher elasticity has little effect on cash and R&D policies. However, when we assume away the market competition by setting α at the value commonly used for the manufacturing sector, demand elasticity matters significantly. A price elasticity of 3.5 implies a profit margin of 40%. Sufficient cash inflow reduces the chance of being financially constrained and lowers the value of cash holdings.

An increase in operating costs c_f affects cash decisions through two channels. First, c_f is a key determinant of entry and exit rates. A higher c_f requires a higher productivity for firms to enter and survive, which reduces competitive pressures for survivors. Firms therefore cut their R&D spending, which in turn causes cash holdings to fall. Second, higher operating costs imply a higher chance of being financially constrained in the future, which implies a higher value of cash holdings and drives up cash demand. The effect of c_f on cash

holdings is nonmonotonic. The first effect dominates on the local margin, while the second dominates on the global margin.

4.3.6 Discussion

In sum, Table 3 sheds light on the main channels through which R&D investment and cash policies are closely linked. The reported results suggest that on the local margin, the key contributor to the high R&D-cash correlation is innovation uncertainty (δ and ρ). The results on the global margin confirm its role, and further suggest that financial frictions, knowledge spillover, and market competition are the other three factors that are critical for understanding innovative firms' large cash reserves. The absence of any one of the four features will result in a low cash ratio and cause the model to fail to reproduce the high R&D-cash correlation observed in the data.

R&D adjustment costs play a less important role than the other four elements, because the absence of adjustment costs mainly affects the real costs of investment and, in turn, the level of R&D expenditures. The presence of financial frictions and cash-flow uncertainty guarantees the value of cash, regardless of the magnitude of R&D adjustment costs.

4.3.7 Policy Implications

In this subsection, we study the implications of our model. In particular, we revisit two important questions: the R&D tax credit's effectiveness in mitigating the R&D underinvestment problem, and the impacts of corporate income tax cuts on cash holdings and the economy.

4.3.7.1 R&D Tax Credit

A classic question in R&D literature concerns the impacts of knowledge spillover and financing frictions on R&D investment. Previous studies argue that both factors can cause market failure for R&D. An extensive body of empirical evidence supports the former, while

empirical support for the latter is more mixed.[8]

Our results are in line with previous empirical findings. We find severe market failures induced by knowledge spillover—a 24% drop in R&D effort for high-R&D-spending firms in response to a 10% increase in the externality. However, we find no support for the underinvestment problem caused by financial frictions. Worsened credit conditions are fully absorbed by changes in cash policies, which largely eliminate the induced market failure. As shown in Panel A of Table 3, a rise in external financing costs leads cash-poor firms to increase their internal liquidity by 65%, yet barely affects their R&D decisions.

One of the often-used solutions to the underinvestment problem that stems from knowledge spillover is the R&D tax credit. We use the model to examine its effect and report results in Panel C of Table 3. The R&D tax credit effectively stimulates the R&D spending in high R&D-intensive firms, yet has no effects on low R&D-intensive firms. Without the incentive scheme ($\tau_{rd} = 0$), the high R&D-intensive firms lower their spending by 22%.

4.3.7.2 Corporate Income Tax

The Trump administration has proposed a corporate tax cut, which aims to create jobs and restore booming economic growth. In addition, Foley et al. (2007) find that U.S. multinationals stockpile foreign earnings to avoid repatriation taxes. Corporate tax reduction, therefore, can lower the cost of repatriating foreign income and shift internal foreign cash back home to fund domestic investments, although empirical evidence suggests that the repatriation tax holiday in 2004 failed to produce these intended outcomes.[9] In this subsection, we use the model to investigate the effects of Trump's planned corporate income tax cut, from the current rate of 35% to 15%.

Results are reported in Panel C of Table 3. They suggest that a cut in income tax rates to 15% boosts high R&D-spending firms' investments by 9 percentage points and increases cash holdings substantially. The effect on cash can be explained by the slight response

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[8]See, for example, the literature review provided by Hall and Lerner (2010).

[9]According to the IRS, less than 10% of companies with overseas subsidiaries opted to repatriate cash in 2004. Moreover, most of the repatriated cash was used for shareholder payouts (Dharmapala et al., 2011).

of cash policies to increases in linear equity-issuance costs, which suggests that internally generated cash flow is a much more important source of cash balances than external equity issuance—that is, high-tech firms rely more heavily on the cash flow generated from sales than external funds when they build up their cash reserves. As income tax drops, after-tax cash flow increases and firms choose to save more for future use.

In addition, consistent with the findings of Dharmapala et al. (2011), our results suggest that firms tend to distribute more dividends when corporate income tax declines, because more internal resources are available. In particular, firms in the first quartile of the equity-flow distribution become dividend payers, and, on average, dividend payment increases by 50%.[10]

Overall, this experiment suggests that lowering corporate income tax rates will increase investment at a moderate rate and bring about a significant increase in dividend payouts, but is unlikely to lower cash reserves.

4.4   The Value of Cash

Lastly, we quantify the extent to which high-tech firms benefit from their cash holdings and speak to the question of whether underinvestment and/or cash hoarding occurs. The dynamic framework developed in Section 3 provides a reliable laboratory for estimating both the short-run and long-run value of cash. The short-run gain is measured by changes in optimal R&D investments and dividend payments in the current period, while the long-run benefit is captured by changes in firm value as a result of the future path of relative technological positions and dividend payments. We assess the value of cash by examining the effects of a temporary fall in cash holdings (a 10% reduction in the beginning-of-period cash balances) and a permanent cash elimination (restrictions on cash holdings, $c = c' = 0$), using the parameter estimates obtained above in Subsection 4.2.1. Results are reported in Table 4.

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[10]These results are not shown in the table, but are available on request.

4.4.1 Effects of a Temporary Drop in Cash

A 10% drop in firms' beginning-of-period cash balances reduces the internal resources available to finance R&D investment and dividend payment in the short run. On average, the temporary drop in cash balances is largely absorbed by dividend policy. Firms cut dividends by 22% and attempt to smooth and maintain their R&D spending.

Moreover, the 10% reduction in cash holdings has a minor long-run effect. It causes a 1% drop in the average firm value, mainly through a temporary cut in dividend payments from leaders and a temporary increase in equity issuance from firms that experience financial distress.

4.4.2 Effects of Permanent Cash Elimination

Complete elimination of the cash-holding option leads to a 10.5% average value loss, as a result of a combination of changes in R&D spending, dividend payout/equity issuance, and the stationary distribution of relative productivity. Disallowing internal cash accumulation has two impacts on R&D investment and dividend payment. On the one hand, the lack of beginning-of-period internal cash holdings tightens budget constraints and reduces the resources available for both. On the other hand, the elimination of the cash-saving option forces firms to allocate all after-tax revenues between the two margins.

On average, firms raise R&D investment by 0.8%. This result is driven by firms with relatively low productivity. In the case of the no cash-saving option, those firms increase their R&D spending significantly—by 17%—as a result of lower marginal costs of R&D investment. Specifically, those firms are financially distressed and expect to be financially constrained in the future. When they are allowed to save, their financial-distress status is captured by a significant increase in the shadow value of cash holdings, which is higher than the gross external borrowing costs $1 + \lambda$. The high shadow value of cash effectively drives up

the marginal cost of R&D, because firms allocate resources between competing uses—R&D and cash—until they generate the same marginal returns per dollar. Preventing firms from taking the saving option lowers the marginal cost of R&D investment, which becomes the gross external borrowing costs $1 + \lambda$, and in turn leads to higher R&D spending in low R&D-intensive firms. In addition, firms that enjoy high productivity and large market shares have sufficient cash flows, and their marginal cost of R&D investment remains the same before and after the elimination of the saving option. Therefore, they maintain their first-best investment levels and keep their R&D policies unchanged.

Average equity flow falls by 7.31%. Without the cash-saving option, financially flexible firms pay out resources that would otherwise be held as internal cash, and push up the median equity flow from 0.38 to 0.92. However, currently financially constrained firms must fund their R&D spending by aggressively issuing equity, as a result of zero beginning-of-period internal cash reserves. The increase in equity issuance outweighs the increase in dividend payments, leading to a net drop in average equity flow. Moreover, higher average R&D spending improves productivity. Compared to the benchmark case, the stationary distribution of productivity z becomes increasingly negatively skewed, with average productivity increasing from 1.2107 to 1.2492, or by 3%. Improved productivity intensifies market competition and drives down product price P. As such, industry leaders experience a modest drop in revenue and cut their dividend payments slightly, by 3.51%.

Overall, innovative firms' high cash reserves are induced by rational behavior and held for precautionary purposes. The existence of cash increases average firm value by 10.5% by saving the equity-issuance costs incurred by financially constrained firms. However, one interesting implication emerges from this counterfactual experiment. When external finance is available, cash is not absolutely necessary for innovation, but is more efficient in facilitating investments than external finance.

5 Conclusions

Innovative firms hold a large amount of cash, as demonstrated by the well-documented positive R&D-cash correlation. In this paper, we systematically analyze how unique features of R&D shape R&D and cash decisions and assess the value of innovative firms' cash reserves.

The model embeds five key features of R&D-intensive firms: R&D adjustment costs, financial frictions, knowledge spillover, innovation uncertainty, and market competition. We show that the estimated baseline model is able to replicate the empirical moments of industry-level and firm-level R&D and cash choices. We then use the validated model to determine the quantitative importance of the R&D features considered in resolving innovative firms' cash-holding puzzle. We find that innovation uncertainty matters the most for firms. Furthermore, this feature, along with financial frictions, knowledge spillover, and market competition, are essential for understanding innovative firms' high cash reserves. The absence of any of these four factors would cause our comprehensive model to fail to explain the patterns of cash behavior observed in the data. On the other hand, R&D adjustment costs has a weak relationship with cash policy contrary to the popular hypothesis.

We further explore the model's policy implications. We find that (i) the R&D tax credit can effectively stimulate R&D spending in high R&D-intensive firms and solve the market failure caused by knowledge spillover, yet has no effects on low R&D-intensive firms; and (ii) a corporate income tax cut will increase investments at a moderate rate and increase dividend payouts substantially, but is unlikely to lower cash reserves.

Finally, we estimate the value of innovative firms' cash balances. A temporary 10% drop in the beginning-of-period cash holdings causes a 1% decline in the average firm value, through dividend cuts by financially flexible firms and increased equity issuance by financially distressed firms. Permanent removal of the cash-saving option reduces average firm value by 10.5%. The value drop arises from a dramatic increase in equity financing by

financially constrained firms.

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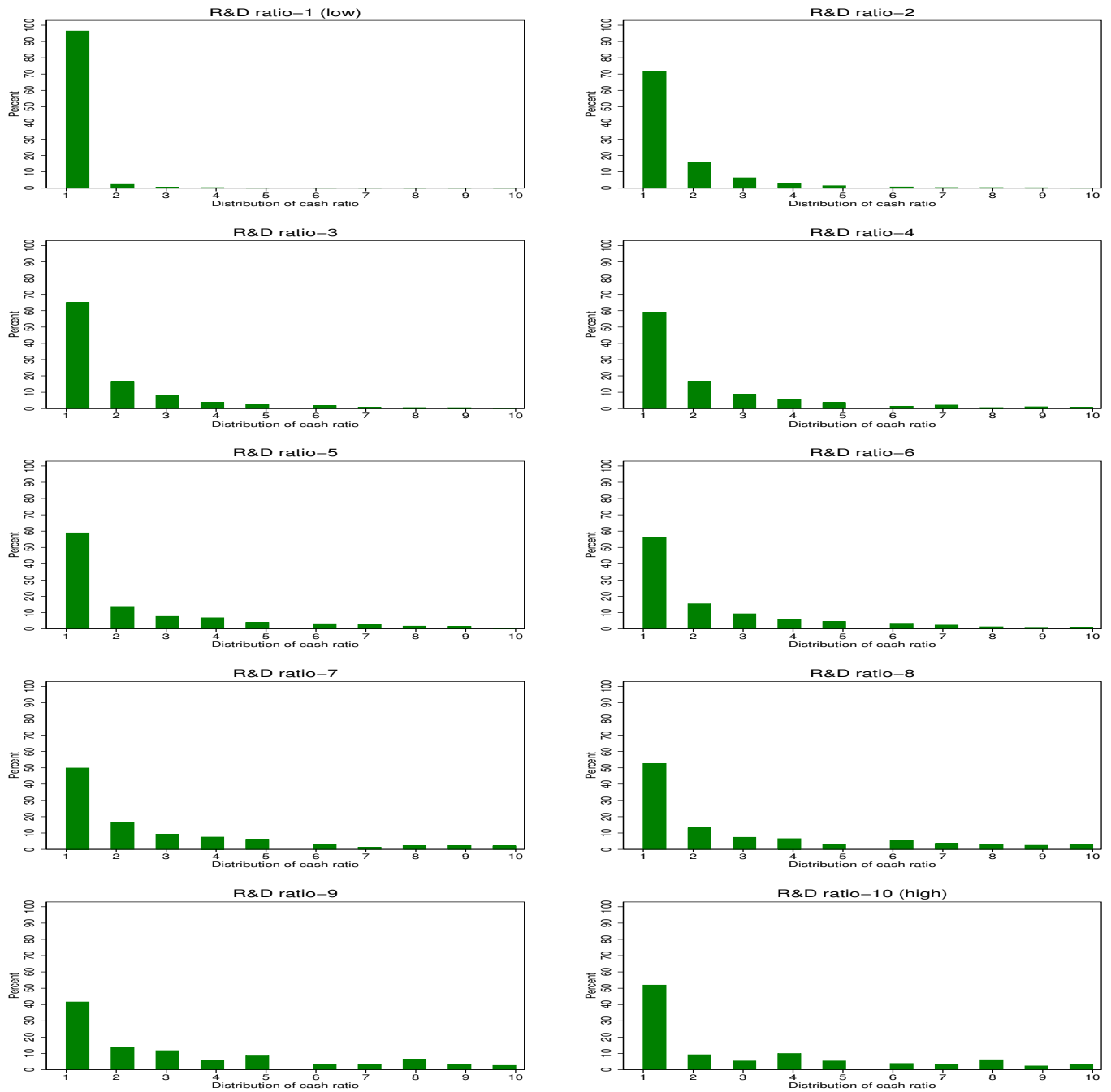
Figure 1: **Distribution of Cash Holdings in 10 Portfolios Formed on the Basis of R&D Expenses.** This figure plots the distribution of cash-to-sales ratio in 10 R&D-to-sales groups that are equally spaced. The sample includes all Compustat firm-year observations in the 2000s with positive total assets and sales and non-missing R&D expenditures. Both cash and R&D ratios are winsorized at the top 5% and bottom 1% for each year.
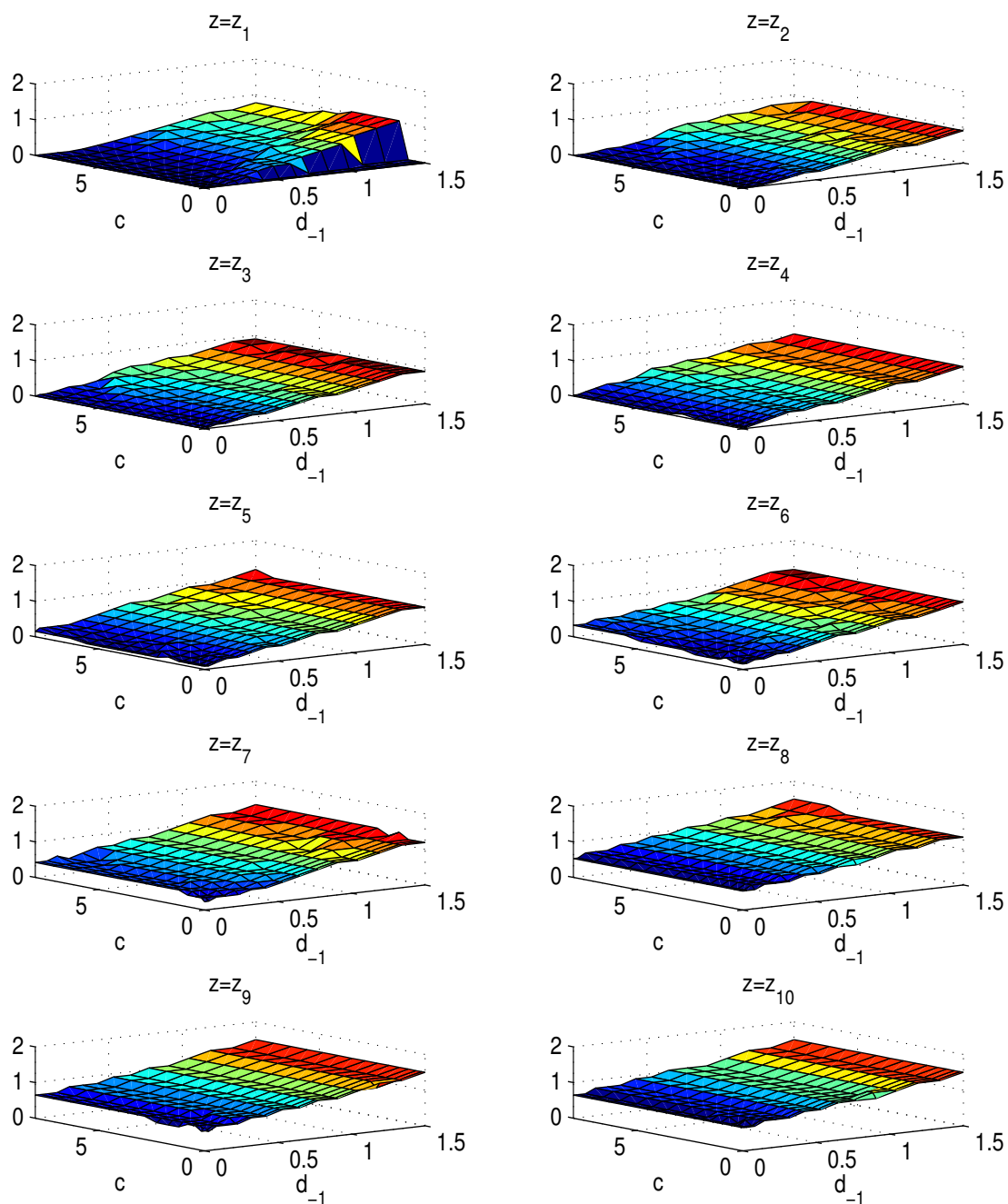
Figure 2: **R&D Policy Functions.** This figure plots optimal R&D responses with respect to firms' relative technological positions within the industry (z), previous R&D investment levels (d_{-1}), and beginning-of-period cash balances (c).
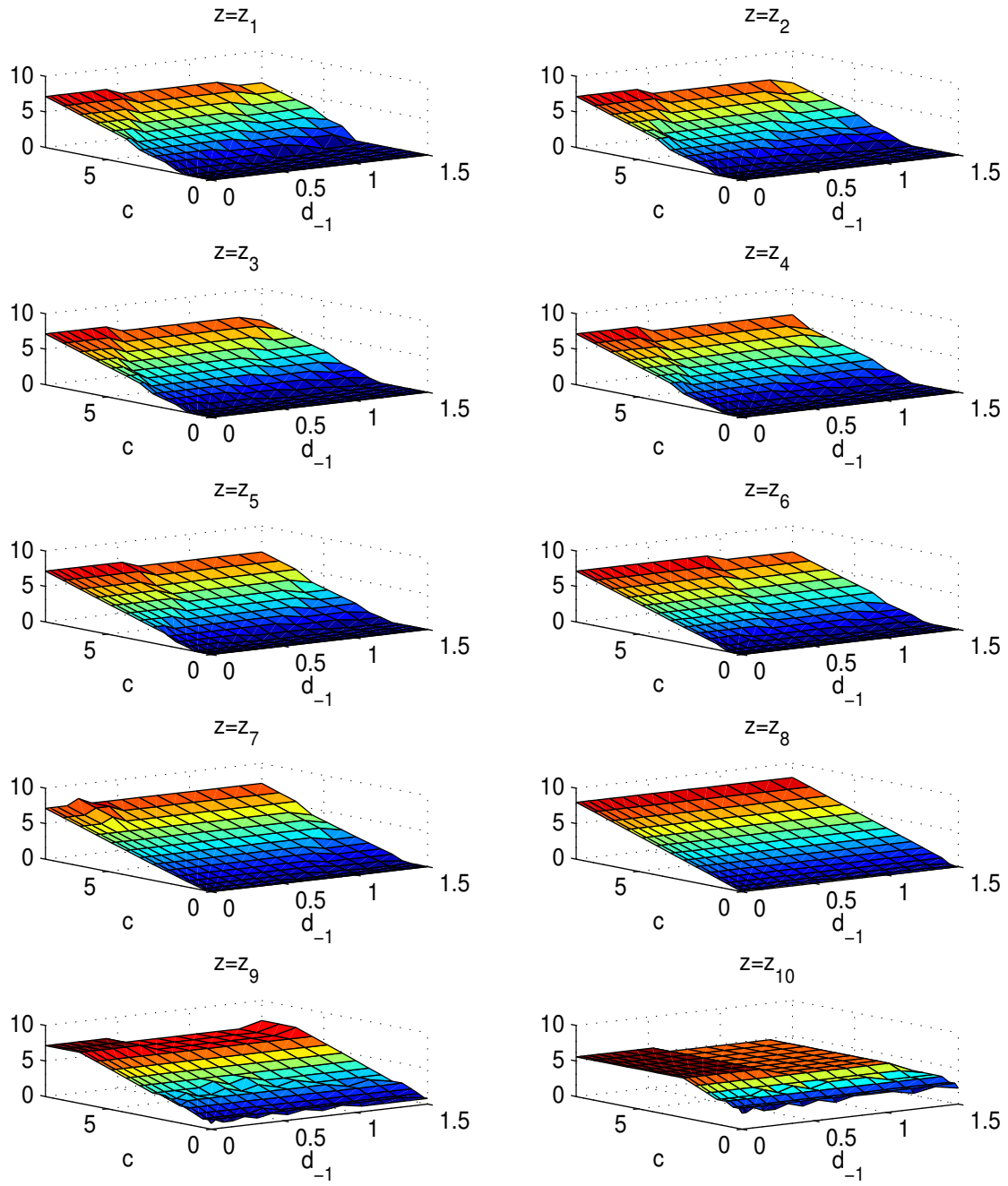
Figure 3: **Cash Policy Functions.** This figure plots optimal cash holdings with respect to firms' relative technological positions within the industry (z), previous R&D investment levels (d_{-1}), and beginning-of-period cash balances (c).
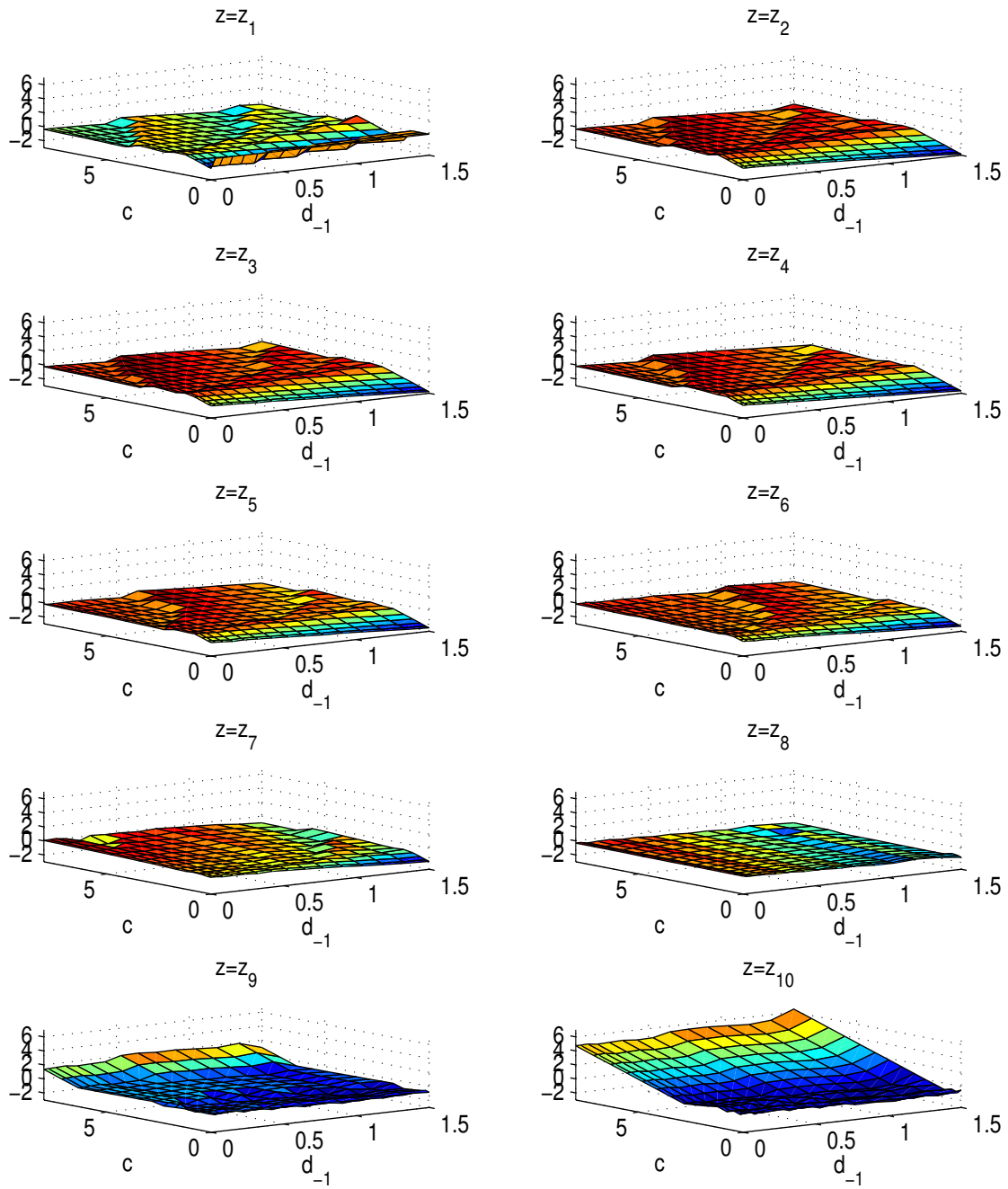
Figure 4: **Dividend-Distribution/Equity-Issuance Functions.** This figure plots optimal dividend-distribution /equity-issuance decisions with respect to firms' relative technological positions within the industry (z), previous R&D investment levels (d_{-1}), and beginning-of-period cash balances (c).

Figure 5: **Exit Policy Functions.** This figure plots optimal exit decisions with respect to firms' relative technological positions within the industry (z), previous R&D investment levels (d_{-1}), and beginning-of-period cash balances (c). The decision takes value 0 when the firm exits, and value 1 when the firm continues to operate.
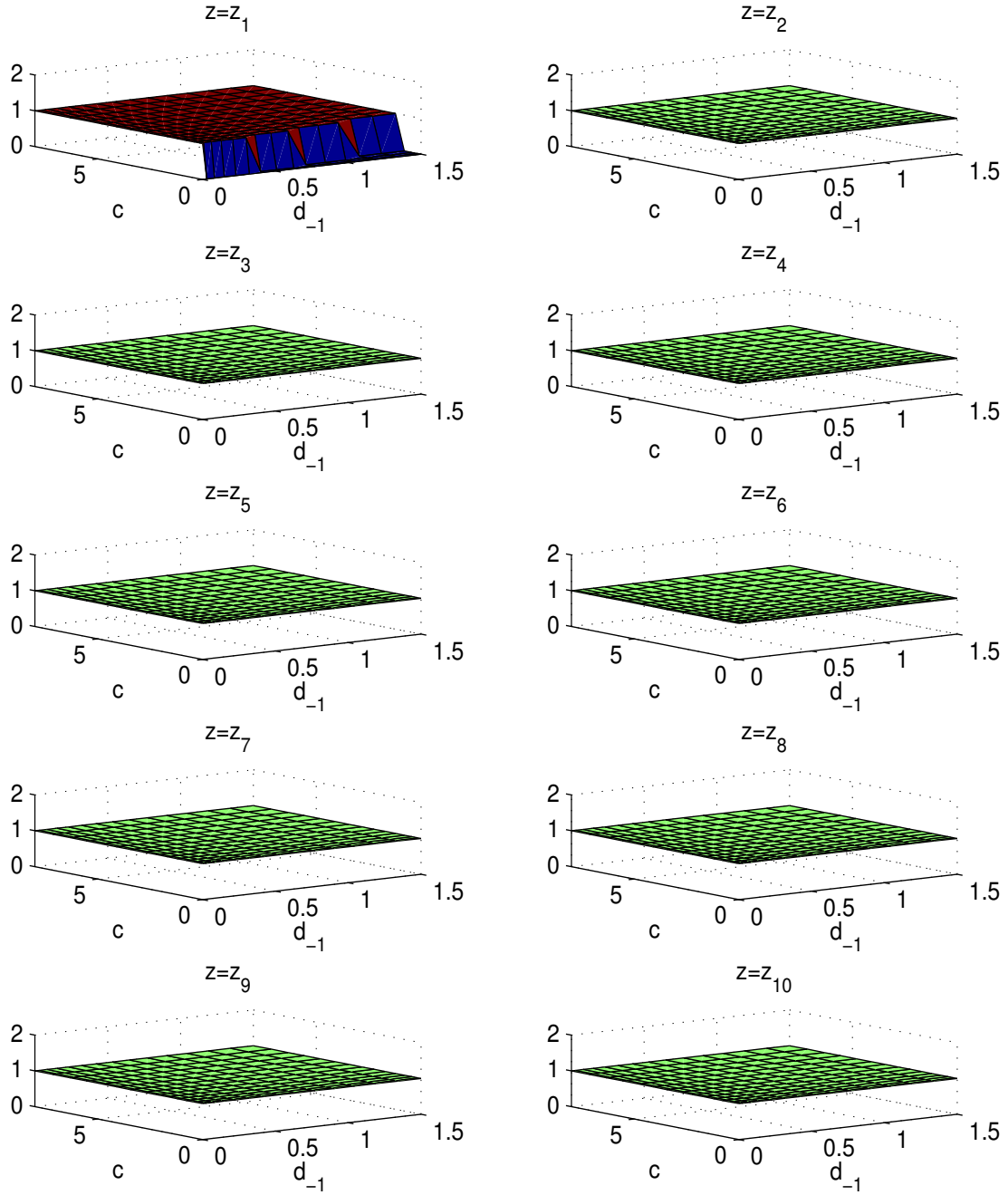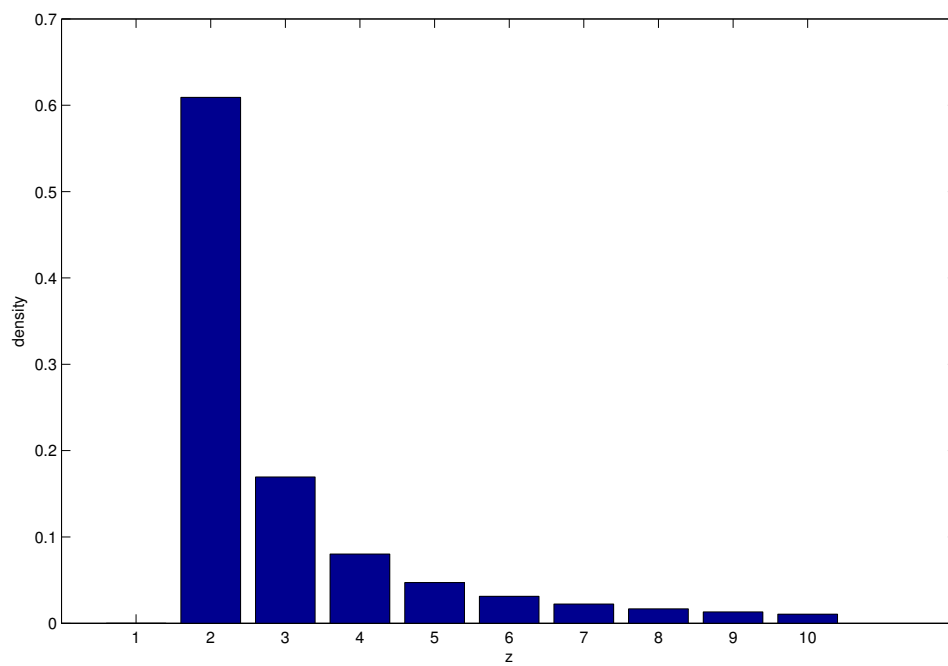
Figure 6: **Distribution of Entrants' Productivity.** This figure plots the model-implied distribution of entrants' relative productivity in the stationary industry equilibrium.
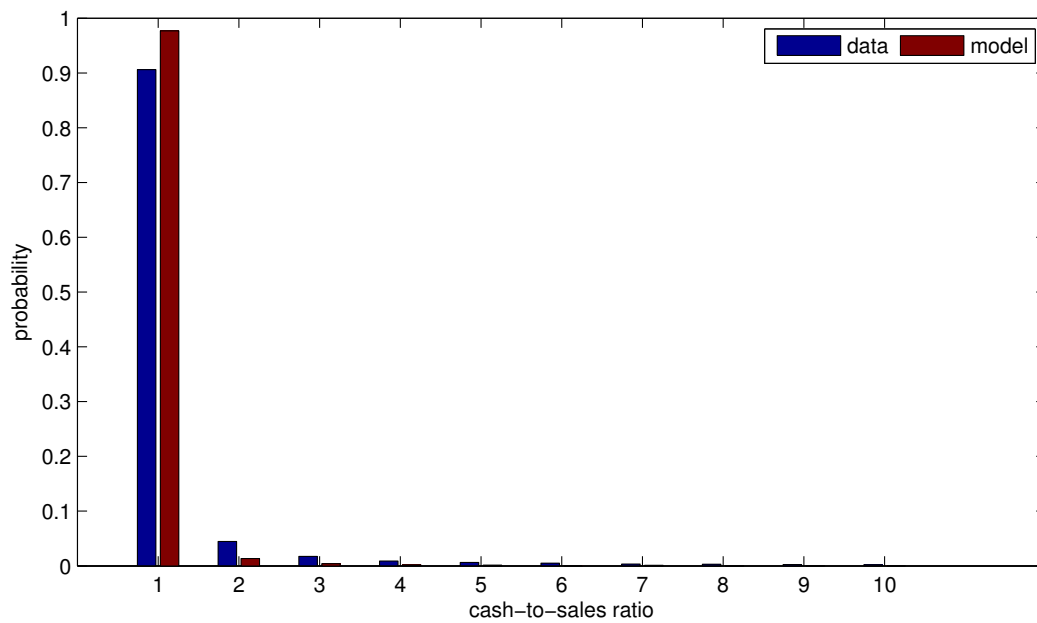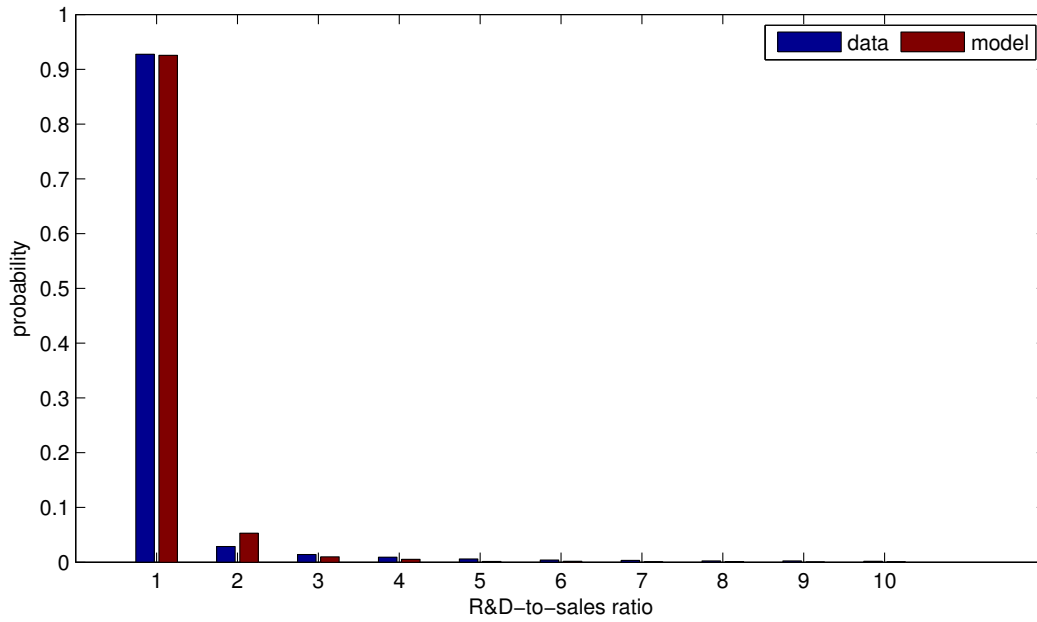
Figure 7: **Probability Distribution of R&D-to-Sales and Cash-to-Sales Ratios.** This figure plots both the probability distribution of firms' R&D-to-sales and cash-to-sales ratios in the data (the blue bar on the left) and that implied by the model (the red bar on the right).

Table 1: **Model Parameterizations**

Table 1 summarizes the parameters used to solve the model at annual frequency. Panel A reports the parameters calibrated separately by one-to-one matching. Panel B presents estimation results by taking parameters in Panel A as given and matching nine selected data moments jointly. Standard errors are presented in parentheses.

Panel A: **Parameters Calibrated Separately**		
real risk-free rate (r)	0.03	
frontier technology level $(\bar{z})$	2.19	
price elasticity of demand (α)	7.00	
dividend tax (τ_d)	0.15	
statutory corporate income tax (τ_c)	0.35	
R&D tax credit (τ_{rd})	0.06	
Panel B: **Parameters Estimated by SMM**		
linear costs of external finance (λ)	0.1886	(0.0049)
fixed adjustment cost (γ_0)	0.0002	(0.00004)
linear adjustment cost (γ_1)	0.1951	(0.0526)
convex adjustment cost (γ_2)	1.9632	(0.0419)
unconditional innovation uncertainty (δ)	0.4310	(0.0018)
knowledge spillover (θ)	1.2344	(0.0092)
probability of breakthrough (ρ)	1.8453	(0.0127)
fixed operating cost (c_f)	1.4292	(0.0102)

Table 2: **Simulated Model Moments**

Table 2 reports both data moments and simulated model moments to evaluate model fit. Panel A shows the moments selected to match, and Panel B presents nontargeted moments. Data moments are calculated based on a sample of Compustat high-tech firms over the period 2000-2014.

Moments	data	model
Panel A: **Targeted Moments**		
(i) R&D:		
25th percentile of R&D-to-sales ratio	0.070	0.191
75th percentile of R&D-to-sales ratio	0.375	0.419
serial correlation of within-firm R&D-to-sales ratio	0.787	0.437
fraction of firms with zero R&D investment	0.020	0.047
(ii) cash:		
25th percentile of cash-to-sales ratio	0.162	0.174
75th percentile of cash-to-sales ratio	1.112	1.116
serial correlation of within-firm cash-to-sales ratio	0.742	0.468
correlation with R&D-to-sales ratios	0.834	0.886
(iii) market competition:		
exit rate	0.004	0.004
Panel B: **Nontargeted Moments**		
(i) R&D:		
industry average R&D-to-sales ratio	0.914	0.465
industry median R&D-to-sales ratio	0.158	0.216
cross-sectional dispersion of R&D-to-sales ratio	2.121	0.951
(ii) cash:		
industry average cash-to-sales ratio	1.830	1.252
industry median cash-to-sales ratio	0.429	0.686
cross-sectional dispersion of cash-to-sales ratio	3.867	3.437
(iii) market competition:		
turnover rate of leaders	0.064	0.076

Table 3: **The Role of R&D Features**

Table 3 summarizes the results for three sets of counterfactual experiments. Panel A reports the effects of each key R&D feature on firms' R&D and cash choices at the local margin, by increasing the value of each parameter by 10%. Panel B reports the effects of those features at the global margin, by shutting down each feature alternately. Panel C concerns the effects of the R&D tax credit and corporate income tax.

	cash			R&D			
	mean	1st quartile	3rd quartile	mean	1st quartile	3rd quartile	corr(c, d)
Benchmark Model	1.25	0.17	1.12	0.47	0.19	0.42	0.885
A: **Local Margin**							
R&D Adjustment Costs							
fixed adjustment cost ($\gamma_0 = 0.0002$)	1.25	0.18	1.12	0.46	0.19	0.42	0.885
linear adjustment cost ($\gamma_1 = 0.215$)	1.25	0.17	1.12	0.46	0.19	0.42	0.884
convex adjustment cost ($\gamma_2 = 2.160$)	1.27	0.28	1.12	0.47	0.19	0.42	0.886
Uncertainty							
unconditional uncertainty ($\delta = 0.474$)	0.67	0.00	0.65	0.45	0.21	0.37	0.768
probability of breakthrough ($\rho = 2.03$)	0.53	0.06	0.52	0.43	0.19	0.40	0.729
Externality							
knowledge spillover ($\theta = 1.358$)	1.19	0.17	1.12	0.41	0.19	0.32	0.932
Financial Frictions							
equity-issuance cost ($\lambda = 0.208$)	1.27	0.28	1.12	0.46	0.19	0.42	0.892
Market Competition							
demand elasticity ($\alpha = 7.7$)	1.23	0.17	1.10	0.45	0.19	0.44	0.890
fixed operating costs ($c_f = 1.5721$)	0.83	0.11	0.80	0.45	0.19	0.40	0.773
B: **Global Margin**							
R&D Adjustment Costs							
fixed adjustment cost ($\gamma_0 = 0$)	1.25	0.17	1.12	0.46	0.19	0.42	0.885
linear adjustment cost ($\gamma_1 = 0$)	1.21	0.15	1.11	0.44	0.19	0.39	0.912
convex adjustment cost ($\gamma_2 = 0$)	0.85	0.00	0.80	0.33	0.19	0.31	0.761
adjustment cost ($\gamma_0 = \gamma_1 = \gamma_2 = 0$)	0.56	0.00	0.52	0.34	0.21	0.35	0.801
Uncertainty							
unconditional uncertainty ($\delta = 0.216$)	0.13	0.06	0.10	0.31	0.11	0.19	0.451
probability of breakthrough ($\rho = 3.69$)	0.10	0.00	0.18	0.29	0.17	0.28	0.352
Externality							
knowledge spillover ($\theta = 0$)	0.12	0.00	0.00	0.59	0.22	0.57	0.350
Financial Frictions							
linear equity-issuance cost ($\lambda = 0.03$)	0.22	0.00	0.18	0.48	0.19	0.45	0.636
Market Competition							
demand elasticity ($\alpha = 3.5$)	0.08	0.00	0.00	0.36	0.19	0.31	0.411
fixed operating costs ($c_f = 0$)	0.06	0.00	0.00	0.53	0.17	0.56	0.427
C: **Policy Implications**							
R&D tax credit ($\tau_{rd} = 0$)	0.97	0.06	0.95	0.42	0.19	0.35	0.868
income tax ($\tau_c = 0.15$)	2.38	1.02	1.85	0.51	0.19	0.51	0.869

Table 4: **The Value of Cash**

Table 4 summarizes the estimated value of cash by examining the effects of a temporary fall in cash holdings (10% reduction in beginning-of-period cash balances) and permanent cash elimination (restrictions on cash holdings, $c = c' = 0$). Panel A reports the changes in firm value. Panels B and C present the changes in R&D investment and equity flow, respectively.

	10% reduction in cash			elimination of cash		
	before	after	change	before	after	change
A: Firm Value $(V(z, c, d_{-1}; P, \mu))$						
mean firm value	29.318	29.011	-1.0%	29.318	26.249	-10.5%
median firm value	35.601	35.182	-1.2%	35.601	30.909	-13.2%
1st quartile of firm value	21.406	21.406	0%	21.406	21.005	-1.87%
3rd quartile of firm value	38.881	38.463	-1.1%	38.881	34.214	-12.0%
B: R&D Investment (d)						
mean R&D investment	1.0443	1.0436	-0.7%	1.0443	1.0531	0.8%
median R&D investment	1.3422	1.3422	0%	1.3422	1.3422	0%
1st quartile of R&D investment	0.7731	0.7731	0%	0.7731	0.9055	17.1%
3rd quartile of R&D investment	1.3422	1.3422	0%	1.3422	1.3422	0%
C: Equity Flow (e)						
mean equity flow	0.8728	0.6792	-22%	0.8728	0.8090	-7.31%
median equity flow	0.3781	0.3911	3.4%	0.3781	0.9239	144%
1st quartile of equity flow	-0.0951	-0.1252	-31.7%	-0.0951	-0.7706	-710%
3rd quartile of equity flow	2.5083	2.0898	-16.7%	2.5083	2.4202	-3.51%