Corporate Governance, Managerial Compensation, and Disruptive Innovations*

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Abstract

Whether a CEO manages the innovation efforts of the firm in line with shareholder preferences has a substantial impact on market value and firm growth, which in turn influence aggregate productivity growth and welfare. Using data on U.S. public firms, we find that (i) firms with better corporate governance tend to adopt highly incentivized contracts rich in stock options; and (ii) such contracts are more likely to lead to disruptive innovations – patented inventions that are in the upper tail of the distribution in terms of quality and originality. We develop and estimate a new dynamic general equilibrium model of firm-level innovation with agency frictions and endogenous determination of executive contracts. The model is used to study the joint dynamics of corporate governance, managerial compensation, and disruptive innovations. Better corporate governance can reduce the influence of the CEO in the determination of the compensation structure. This leads to more incentivized contracts and boosts innovation, with substantial benefits for the shareholders, as well as the broader economy through knowledge spillovers. Shutting down the agency frictions leads to an increase in long-run output growth, which translates into a significant welfare gain in consumption equivalent terms.

Keywords: Agency frictions, corporate governance, innovation, managerial compensation.
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1 Introduction

Innovation is the primary engine of economic growth in economies at the technological frontier; and a path to higher profits and firm growth at the micro-level. Companies like Apple, Alphabet, Microsoft, and Amazon.com which dominate the list of top U.S. public firms by market capitalization can dispel any doubts to the contrary. The CEO of a firm plays a crucial role in directing and overseeing its innovation efforts. This, however, creates a tension: the interests of the shareholders and those of the CEO might not perfectly align with each other, opening the door to agency frictions. In turn, these frictions can result in suboptimal investment in innovation, leading to losses in firm value for the shareholders, and low economic growth and welfare for the broader economy.

Better corporate governance can help align the interests of the managers and the shareholders, and thus alleviate the negative impact of agency frictions. Recent empirical studies confirm the significance of corporate governance in the growth process (see Nicolo, Laeven, and Ueda (2006), Claessens (2012), and Bloom and Reenen (2007) among others). A recent report by OECD (2012) summarizes this body of evidence by arguing that "corporate governance exerts a strong influence upon innovative activity and entrepreneurship. Better corporate governance, therefore, should manifest itself in enhanced corporate performance and can lead to higher economic growth." Although there is a broad consensus that corporate governance can be relevant for innovation and economic growth, little agreement has been reached on the channels through which it operates. Despite the substantial, and largely separate, literatures on corporate governance, agency frictions, and firm innovation, little work has been done to quantify the effects of agency frictions between the shareholders and the managers on firm innovation, managerial compensation structure, and economic growth. This paper aims to fill this gap.

To achieve this purpose, we start by documenting new stylized facts that shed light on the mechanisms through which corporate governance influences firm innovation. One increasingly popular method employed by U.S. public companies is increasing the share of stock options in manager compensation. We find that firms with better governance (as proxied by institutional ownership) tend to adopt executive compensation contracts with a higher fraction of stock options. The convex payoff structure of state-contingent stock options provides incentives to the managers to engage in risky innovative activities, contributing to firm value and economic growth. In order to undertake the analysis, we combine micro-data on patented inventions from United States Patent and Trademark Office (USPTO) with data on U.S. public firms from Compustat and executive compensation information from Execucomp and Capital IQ People Intelligence databases for the time period 1992-2004. Unlike the majority of the papers using similar data, our focus is on the quality, not the quantity, of innovations. To this purpose, we employ three scale-independent measures of disruptive innovation: (i) average citations received by patents of the firm, (ii) the fraction of a firm's patents that make it to the top 10% in terms of patent quality, and (iii) the average originality of the patents; a measure which captures the variety of distinct technology classes the new innovation is combining together and building upon. The new stylized facts we document can be summarized as follows:

1. Higher institutional owner fraction among shareholders is positively associated with disruptive innovations at the firm level.
2. Higher institutional owner fraction leads to more incentivized CEO contracts, which contain more stock options and restricted stock grants relative to the total compensation.
3. In turn, more incentivized CEO contracts are associated with more disruptive innovations at the firm level.
4. The positive association between institutional owner fraction and disruptive innovations is realized largely through the mechanism of more incentivized CEO contracts.

How much do agency frictions between managers and shareholders matter for innovation, firm growth, firm value, and economic growth? To what extent could the inefficiencies caused by agency frictions be alleviated through better corporate governance and more incentivized executive compensation contracts? Are there systematic differences in the degree of this inefficiency across industries? To answer these questions, we develop and estimate a new dynamic general equilibrium model with firm-level innovation, and endogenously-determined managerial compensation contracts. In the model, the board of the firm designs the CEO's compensation contract. Taking the contract as given, the CEO makes the innovation decisions. The board, however, does not fully represent the preferences of the shareholders. The CEO's compensation structure is the product of a tug-of-war between the CEO and the shareholders. The CEO has some influence over the final decision of the board, and his preferences enter the board's objective function along with those of the shareholders. Consequently, the agreed-upon compensation contract deviates from the shareholder-optimal contract that would maximize firm value. Better corporate governance acts to reduce the CEO influence, enabling the board to choose contracts with a higher fraction of stock options. This in turn motivates the manager to carry out more disruptive innovations.[1] Better corporate governance thus leads to a higher rate of innovation and more knowledge spillovers, increasing long-run productivity growth and social welfare.

On the quantitative front, the model is successful in replicating the abovementioned stylized facts, and the measured correlations play a significant role in disciplining the quantitative implications of the estimated model. Using simulated method of moments (SMM), the model parameters are estimated to best fit a wide-ranging set of facts about the U.S. firms, such as the aggregate output growth rate, share of R&D expenditures, CEO compensation to market capitalization ratio, and the correlation structure between firm innovation, corporate governance, and the share of stock options in the CEO's total compensation. Using the estimated parameter values, we document the

[1] The CEO can under- or over-invest in innovation depending on parameter values. Under the estimated parameter values, it turns out to be the case that the shareholders prefer more innovation than the CEOs on average, which is guided by the direction of the correlation patterns between firm innovation, corporate governance, and the share of stock options in executive compensation.

model's implications for the U.S. economy by conducting a series of counterfactual experiments. Through these experiments, we quantify the importance of the agency frictions between the CEO and the shareholders on quantities of interest such as firm innovation, economic growth, and social welfare. Comparative statics exercises reveal how the importance of the agency friction changes in response to changes in CEO influence (which is inversely related to corporate governance), R&D efficiency of the firms, and innovativeness of the CEOs. An experiment in which we shut down agency frictions through removing CEO influence over the board results in an increase in firm innovation by 62.5 percent of its value. Equilibrium output growth rate increases by 1.17% on top of its targeted value of 2.00%.[2] Eliminating agency frictions would also result in a significant increase in consumption-equivalent terms. This increase in welfare is the direct consequence of the increased long-run growth rate of the economy, which dominates the negative effects of a decrease in initial consumption as a result of increased R&D expenditures used to finance the increase in the rate of innovation.

This paper is related to a growing strand of literature studying the impact of corporate governance on firm innovation. Chemmanur and Tian (2017) find that anti-takeover provisions and institutional ownership spur corporate innovation. Francis and Smith (1995), Eng and Shackell (2001), and Aghion, Reenen, and Zingales (2013) find that greater institutional ownership is associated with more innovation. Balsmeier, Fleming, and Manso (2016) investigate the impact of board independence on innovation. We find that their metric is positively correlated with our measures of disruptive innovation. Although there is a large strand of previous literature documenting the positive impact of corporate governance on firm innovation, relatively less is known about the channel through which it operates. This paper aims to provide a micro-foundation to shed light on the mechanisms that underlie these empirical facts. Moreover, existing literature mostly focuses on the the quantity rather than the quality of innovation, as we discussed earlier. We use scale-independent measures, and focus on highly-cited disruptive innovations instead, as these are more likely to represent new ideas that result in significant knowledge spillovers and fuel economic growth.

This paper is complementary to a large strand of literature studying how institutional investors affect executive compensation structures. Smith (1996) and Gillan and Starks (2000) report public fund managers often voice the opinion that managerial compensation should be linked to corporate performance. Chidambaran and John (2008) and Hartzell and Starks (2003) document that institutional ownership is positively related to the pay-for-performance sensitivity of executive compensation. Consistent with the existing literature, we also find that firms with higher institutional ownership tend to adopt compensation contracts with high per-for-performance sensitivity owing to a high fraction of stock options. We move one step further to study the impact of executive compensation for firm innovation.

This paper is also related to the literature exploring the effects of executive compensation on managerial risk-taking and firm capital structure. Coles, Daniel, and Naveen (2006) argue that CEO compensation that features high sensitivity of CEO wealth to stock price volatility implements riskier

[2] This number is an upper bound, since we attribute all economic growth to firm innovation.

policy choices – higher R&D expenditures, leverage, etc. Panousi and Papanikolaou (2012) maintain that compensation with stock options could mitigate the negative impact of managerial risk aversion on investment. Nikolov and Whited (2014) develop and estimate a dynamic model to study the impact of agency frictions on cash holdings of a firm. Morellec, Nikolov, and Schurhoff (2012) develop a dynamic tradeoff model to examine the importance of manager-shareholder conflicts in capital structure choice. They find that adding agency cost would help resolve the low leverage puzzle and the time series patterns of leverage ratios. They also find that the variations of agency costs is sizable, and the level of agency conflicts is correlated with commonly used proxies for corporate governance. Edmans, Gabaix, Sadzik, and Sannikov (2012) study optimal CEO compensation in a dynamic framework and find that the optimal contract could be implemented by escrowing the CEO's pay into a "Dynamic Incentive Accounting" that comprises cash and the firm's equity featuring stat-dependent rebalancing and time-dependent vesting. Ederer and Manso (2013) find that compensation based on pay-for-performance principle is effective in inducing managerial effort and productivity, and the combination of tolerance for early failure and reward for long-term success is effective in motivating innovation. Glover and Levine (2017) find the average CEO compensation contract incentivizes overinvestment by 1.3 percentage per year. Page (2017) estimates a dynamic model of CEO compensation and effort provision. He finds that variation in CEO attributes explains the majority of variation in compensation and removing CEO influence increases shareholder value. Dittmann and Maug (2007) calibrate a static structural model to find the best mix of straight equity, stock options, and cash compensation that keeps CEO effort at the same level while decreasing the costs to the firm. Despite the substantial literature on corporate governance and agency frictions, what is less well-understood is the joint dynamics of CEO compensation and firm innovation, which our paper aims to clarify by providing new empirical evidence and a quantitative model. Different from this strand of literature which often treats the executive compensation as exogenously given, we study the joint determination of managerial compensation, firm innovation, and economic growth in a united dynamic framework.

The dynamic general equilibrium model featuring endogenous productivity and output growth links this paper to the literature on endogenous growth, pioneered by Aghion and Howitt (1992), Lucas (1988), and Romer (1990).[3] In terms of the particular model used in this paper, the closest two papers are Akcigit, Celik, and Greenwood (2016) and Celik (2017). The firm-level innovation decision determines the probability of a successful innovation, which results in a permanent increase in firm's productivity. The increase in productivity benefits from Romer-type productivity spillovers, resulting in under-investment in innovation from a social planner's point of view. The firms have an incentive to invest in costly R&D to improve the innovation probability, since their profits are linearly increasing in their relative productivity compared to the average productivity in the broader economy. This model differs from the two papers in that the CEO of a firm chooses the innovation probability. Due to the misalignment of incentives between the CEO and the shareholders of a firm, the CEO might under- or over-invest in innovation depending upon how his contract is structured.

[3]See Aghion and Howitt (2009) and Acemoglu (2009) for literature surveys.

Therefore, the agency frictions between the CEO and the shareholders generates an additional mechanism through which the innovation in a competitive equilibrium might be further below the value in the Pareto efficient allocation. Another closely related paper is ongoing work by Greenwood, Han, and Sanchez (2017), which focuses on how the monitoring frictions between venture capitalists and the start-ups they support can influence economic growth and welfare. In their setting, the venture capitalists play a similar role to that of the institutional owners in our current model.

The paper is organized as follows. In Section 2, we document several novel empirical facts on the relationship among institutional ownership, executive compensation contracts, and disruptive innovation. In Section 3, we develop a general equilibrium quantitative framework with endogenous growth and managerial compensation contract to study the joint dynamics of corporate governance, managerial compensation, and firm innovation. In Section 4, we document the model's implications for US firms by carrying out a series of counterfactual experiments. Concluding remarks are in Section 5.

2 Empirical Analysis

2.1 Data Sources

USPTO Utility Patents Grant Data (PDP): The patent grant data are obtained from the NBER Patent Database Project (PDP) and contain data for all 3,279,509 utility patents granted between the years 1976-2006 by the USPTO. This dataset includes extensive information on each granted patent, including the unique patent number, a unique identifier for the assignee, the nationality of the assignee, the technology class, and backward and forward citations in the sample up to 2006. Following a dynamic assignment procedure, we link this dataset to the Compustat dataset.

Compustat North American Fundamentals: We draw our main sample from the Compustat for publicly traded firms in North America. This dataset contains balance sheets reported by the companies annually between 1974 and 2006. It comprises 29,378 different companies, and 390,467 company year observations. The main variables of interest are net sales, employment, firm age (defined as time since entry into the Compustat sample), SIC code, R&D expenditures, total liabilities, net income, and plant property and equipment as a proxy for physical capital.

Executive Compensation Data (Execucomp and Capital IQ databases) : Standard and Poor's Execucomp provides detailed information for all components of CEO compensation from 1992. We supplement the missing information in Execucomp with the information from Capital IQ database where applicable.

Thomson-Reuters Institutional Holdings (13F) database: We obtain institutional ownership information from the Thomson-Reuters Institutional Holdings (13F) database. This data compiles SEC Form 13-F filings of institutional holdings. It provides Institutional Common Stock Holdings and Transactions, as reported on Form 13F filed with the SEC. Under rule 13(f), all institutional investors managing more than \$100 million in equity are required to file all equity holdings greater than 10,000 shares or \$200,000 in market value with the SEC on a quarterly basis.

2.2 Variable Construction

Average Patent Citations: Our first measure of disruptive innovations is the number of citations a patent received as of 2006. We use the truncation correction weights devised by Hall, Jaffe, and Trajtenberg (2001) to correct for systematic citation differences across different technology classes and for the fact that earlier patents will have more years during which they can receive citations (truncation bias). The average patent citations of a firm in a year is computed as the average number of citations received by the patents the firm applied for in that year. This is a scale-free variable.

Tail Innovations: The tail innovation index is defined as the fraction of a firm's patents that are in the top p% of all the patents according to number of citations received among all patents applied for in that year. Namely, let $s_{ft}(p)$ denote the fraction of a firm's patents that are above the p^{th} percentile of the year t distribution according to citations. Our baseline tail innovation index, $\text{Tail}_{ft}(p)$, is simply $s_{ft}(0.90)/s_{ft}(0)$, and thus measures the fraction of patents by firm f at time t with citations above the $90th$ percentile.

Generality and Originality: We also use the generality and originality indices devised by Hall, Jaffe, and Trajtenberg (2001). Let $i \in I$ denote a technology class and $s_{ij} \in [0, 1]$ denote the share of citations that patent j receives from patents in technology class i (with $\sum_{i \in I} s_{ij} = 1$). Then for a patent j with positive citations, we define: $\text{Generality}_j = 1 - \sum_{i \in I} s_{ij}^2$. This index thus measures the dispersion of the citations received by a patent in terms of the technology classes of citing patents. Greater dispersion of citations is interpreted as a sign of greater generality. The originality index is defined similarly except that we use the citations that a patent makes to other patents. The patent classes used in the baseline analysis are the two-digit International Patent Classification (IPC) classes. For robustness, the same measures are recalculated using the technological subcategories defined in Hall, Jaffe, and Trajtenberg (2001), and the US Patent Class categories assigned internally by the USPTO. The average originality (generality) of a firm's innovation in a given year is the average originality (generality) of all the patents the firm applied for in that year.

CEO Compensation Measures: We define the empirical measures of the compensation components to be consistent with the model as follows. Equity compensation is defined as the fraction of equity held by the manager, i.e. the shares owned by the CEO, excluding options, divided by the common shares outstanding, as reported in ExecuComp. For option compensation, we use the CEO's granted options value calculated using Black-Scholes formula. Finally, salary compensation is defined following Dittmann and Maug (2007) as the sum of salary and bonus. Given these, option/income ratio is the income from options divided by total compensation; share/income ratio is the income from shares owned divided by total compensation; and deferred ratio is the sum of the two.

2.3 Empirical Results

2.3.1 Baseline Results

Our main estimating equations are as follows:

$$\text{innovation}_{it} = \boldsymbol{\alpha}\ \text{inst ownership}_{it} + \boldsymbol{X}'_{it}\,\boldsymbol{\beta} + \delta_s + v_t + \varepsilon_{it} \tag{1}$$

$$\text{pay structure}_{it} = \boldsymbol{\gamma}\ \text{inst ownership}_{it} + \boldsymbol{X}'_{it}\,\boldsymbol{\beta} + \delta_s + v_t + \varepsilon_{it} \tag{2}$$

$$\text{innovation}_{it} = \boldsymbol{\theta}\ \text{pay structure}_{it} + \boldsymbol{X}'_{it}\,\boldsymbol{\beta} + \delta_s + v_t + \varepsilon_{it} \tag{3}$$

where innovation_{it}, $\text{inst ownership}_{it}$, $\text{pay structure}_{it}$ are the measures of disruptive innovation, institutional ownership fraction, and CEO compensation structure for firm i at year t respectively; $\boldsymbol{X}_{it}$ is a vector of control variables including firm size, firm age,[4] R&D stock,[5] stock price volatility,[6] leverage, and market-to-book ratio; δ_s denotes a full set of four-digit main SIC fixed effects, so that the comparisons are always across firms within a narrowly defined industry; v_t denotes a full set of year fixed effects. Finally, ϵ_{it} denotes the error term.

Our empirical results are presented in Tables 1 to 9. Table 1 reports the results of the first estimating equation. Three columns of Table 1 correspond to three different measures of disruptive innovation: tail innovation, average patent quality, and average originality. In all three cases, firms with higher institutional ownership tend to carry out more disruptive innovations. All else equal, when institutional ownership increases by one percentage point, tail innovation increases by 0.0317 percentage points; average citations of patents increase by 2.956; and average patent originality index increases by 0.0419 pp. These results are consistent with earlier findings in Aghion, Reenen, and Zingales (2013) which use total patent citations as their measure of innovation; a scale-dependent measure.

Table 2 reports the results of the second estimating equation. We find that firms with high institutional ownership tend to adopt more incentivized managerial compensation contracts, featuring higher fraction of deferred income, which is defined as the fraction of stock and options in the CEO's total compensation. Ceteris paribus, one percentage point increase in the institutional ownership fraction is associated with a 0.265 percentage point increase in deferred ratio, a 0.231 percentage point increase in the option to income ratio, and a 0.026 percentage point increase in the share to income ratio. The decomposition of deferred income into option and stock income reveals that the positive association is largely driven by the positive impact of institutional ownership on the option-to-income ratio. This will be a recurring pattern in the remainder of the empirical analysis, and this is the primary reason underlying our choice in picking stock options (as opposed to stocks) as the state-contingent component of manager compensation in our quantitative model.

We report the impact of managerial compensation on disruptive innovation in Tables 3 to 5.

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[4] The firm age is calculated as the difference between the current year and the year in which the firm first entered the Compustat sample. The results are unchanged if one uses the IPO year instead.

[5] This is a discounted sum of past R&D expenditures as in Aghion, Reenen, and Zingales (2013).

[6] Stock price volatility is the coefficient of variation of the daily stock price, obtained from the CRSP database.

We find that higher deferred ratio is positively associated with disruptive innovation as measured by tail innovation, average patent quality, and average originality. Column 1 of Tables 3 to 5 presents fixed effect panel regressions of disruptive innovation on deferred ratio. When deferred ratio increases by one percentage point, tail innovation increases by 0.0147 percentage points, average patent citations increases by 1.112, and average patent originality increase by 0.01472 pp. Column 2 of each table repeats the specification in column 1, further controlling for institutional ownership. We find that the impact of deferred ratio on disruptive innovation is still positive and statistically significant after controlling for institutional ownership, which is also significant itself. This implies that, besides affecting the manager's innovation decision through the compensation structure, institutional ownership also affects the firm innovation directly to an extent (potentially through mechanisms such as monitoring the manager and several others proposed in the literature). However, note that the coefficients for deferred ratio are more significant compared to those for institutional ownership, suggesting that the managerial compensation channel is the dominant one. We further decompose deferred ratio into option to income ratio and share to income ratio in column 3. We find that the positive correlation between deferred ratio and disruptive innovation is mainly driven by the impact of option to income ratio. These findings are consistent with previous studies in the literature such as Coles, Daniel, and Naveen (2006), Panousi and Papanikolaou (2012) who find that CEO compensation contracts with higher pay-for-performance components, and especially stock options, tend to encourage the CEO take more risk.

Lending credence to our claims in the introduction regarding the effects of corporate governance and innovation on firm value and profitability, we find that institutional ownership is positively associated with firm value, and firms with more disruptive innovations tend to have higher a market-to-book ratio. The results are shown in Table 6.

2.3.2 Robustness and Instrumental Variable Regressions

The coefficient of institutional ownership fraction may be biased if large institutional shareholders select firms to invest in on the basis of characteristics that are observable to them, but not to us. For example, large institutions might invest in firms when they anticipate an increase in their innovation. One could also theorize that firms might adopt more incentivized CEO contracts in order to attract institutional investors. To mitigate such concerns, following Hartzell and Starks (2003), we use share turnover[7] as an instrument for institutional ownership and re-estimate the impact of institutional ownership on managerial compensation. Share turnover serves as a reasonable instrument since it is correlated with institutional ownership, but is unlikely to affect CEO compensation structure directly. To mitigate similar concerns, we repeat the regression of innovation on institutional ownership, where we use an indicator variable which equals one after the firm's inclusion in the S&P 500 index as an instrument for institutional ownership, following Aghion, Reenen, and Zingales (2013). As discussed in Aghion, Reenen, and Zingales (2013), S&P 500 inclusion can serve as a reasonable

[7]Share turnover is defined as the average daily volume of traded shares, normalized by the number of common shares outstanding. This information is obtained from the CRSP database.

instrument for institutional ownership. An S&P firm is more likely to attract institutional investors. One major reason is that fund managers are typically benchmarked against the S&P 500, which creates an incentive for them to weight their portfolio towards S&P 500 firms. S&P inclusion, however, is less likely to be correlated with disruptive innovations. Standard and Poor's explicitly states that the decision of whether including the firm in the S&P 500 or not is not an opinion on that company's investment potential. It mainly depends on whether the firm can represent a certain sector well. Hence the exclusion restriction is likely to be satisfied. The IV estimation results are shown in Table 7. The relationship between key variables of interests still hold.

We further test the direction of causality between institutional ownership and managerial compensation structure in Table 8 and Table 9. In column 1 of Table 8, we regress deferred ratio on lagged institutional ownership. In column 2, we regress institutional ownership on lagged deferred ratio. In both regressions, we control for the lagged dependent variable and other covariates, time and industry dummies as in the baseline regressions. All estimated coefficients are standardized ("betas") so their magnitudes are comparable. We find that lagged institutional ownership has a much stronger impact on the deferred ratio than vice versa. If the correlation between institutional ownership and deferred ratio is due to the *Endogenous Selection Hypothesis* (firms adopt more incentivized compensation contract to attract more institutional owners) rather than the *Investor Monitoring Hypothesis* (firms with higher institutional ownership can reduce the influence of the CEO in the determination of CEO compensation and adopt contract with higher deferred ratio), we should observe the coefficient on lagged deferred ratio to be greater; but the opposite is revealed to be the case. We perform similar tests for the correlation between option income ratio and institutional ownership in Table 9 and obtain similar results.

Overall the evidence from the instrumental variable regressions that use share turnover or inclusion in the S&P 500 index as instruments, and the reverse causality tests, suggest that the relationship between institutional ownership and managerial compensation structure, and the relationship between institutional ownership and disruptive innovations do not simply arise from endogenous selection.

To mitigate the concern that the correlation between institutional ownership is driven by certain special industries, such as high-tech industries or pharmaceuticals, we test the baseline results by dividing the whole sample into subsamples of high-tech and low-tech firms only.[8] The same exercise is repeated for pharmaceutical and non-pharmaceutical firms. The result are shown in the Online Appendix A.5. The results are very similar for the high-tech and low-tech subsamples, and the same is true for the non-pharmaceutical subsample.

We further probe the robustness of our baseline results by replacing the four-digit SIC dummies in our baseline specification with two-digit, or three-digit SIC dummies, and Blundell, Griffith, and Reenen (1999) firm fixed effects. The result are shown in the Online Appendix A.5. The

[8] High-tech firms are those in SIC 35 and 36, which include industrial and commercial machinery and equipment and computer equipment; and electronic and other electrical equipment and components, and low-tech firms are the rest

estimates are once again very close to those in our baseline regressions, although significance is somewhat reduced in the case of firm fixed effects regressions for specifications where the number of observations is low. The signs, however, are maintained. This result is not unexpected, as most of the variation in explanatory variables is driven by cross-sectional differences.

We are also interested in whether the decision to include certain firms or firm-year observations is influencing the results. One can think of three different specifications: (i) including all observations, (ii) focusing on only firms that have patents, (iii) focusing on only firm-year observations which have a non-zero number of patents. Our results go through with all three different specifications, where our baseline results correspond to the first case. The results for the latter two specifications are included in the Online Appendix A.5. The results are very similar, suggesting that the relationships we find hold regardless of whether one considers the intensive or the extensive margin in generating disruptive innovations.

Finally, we further check the robustness of the baseline results by adding additional control variables: log employment, log sales, log physical capital, asset maturity, S&P rating, investment grade, total compensation, profitability, g-index, and self-citation fraction. We also test the impact of institutional ownership on alternative dependent variables: Citations within 5 years, originality based on USPC and HJT technological subcategories, different cut-offs for tail innovations, citations weighted by total patent count in a year, and citations excluding self-citations. The baseline results still hold with additional control variables and with alternative dependent variables.

3 Model

Time is discrete and denoted by $t \in \{0, 1, 2, ...\}$. There are three types of agents: the representative household, the firms, and their CEOs. The representative household supplies labor in exchange of wages, and owns all the assets in the economy. There is a continuum of firms with measure one, and each firm has a CEO. At time $t = 0$, the contract between the firm and the CEO is determined endogenously. Given the contract, the CEO chooses the production inputs and the innovation probability of the firm he is managing. If corporate governance is not perfect, the CEO can influence the structure of his own compensation and distort the contract he is offered away from the contract that would be optimal for the shareholders. Consequently, the firm can end up under- or over-investing in innovation as a result of the agency frictions.

3.1 Representative Household's Problem

The representative household is infinitely lived. It supplies labor $L = 1$ inelastically and receives the wage rate w_t. It can freely borrow and save at the real interest rate r_t. There are no aggregate fluctuations in the model, so the representative household's problem is deterministic. The decision problem is stated as:

$$\max_{\vec{C},\vec{A}} \left\{ \sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\omega}}{1-\omega} \right\}, \text{such that} \tag{4}$$

$$C_t + A_{t+1} \leq (1+r_t)A_t + w_t, \forall t \in \mathbb{Z}^{++} \tag{5}$$

with $\vec{C} = \{C_t\}_{t=0}^{\infty}$ and $\vec{A} = \{A_t\}_{t=1}^{\infty}$, given A_0. The Euler equation of this standard problem is

$$C_t^{-\omega} = \beta(1+r_{t+1})C_{t+1}^{-\omega} \tag{6}$$

3.2 Static Profit Maximization of the Firm

There is a continuum of firms with measure one. A firm can produce the final good in the economy under perfect competition according to the production function

$$y_t = z_t^{\zeta} k_t^{\kappa} l_t^{\lambda} \tag{7}$$

where z_t is the firm-specific productivity, l_t is the labor input, and k_t is the capital input. We impose $\zeta \in (0,1)$, $\kappa \in (0,1)$, $\lambda \in (0,1)$, and $\zeta + \kappa + \lambda = 1$. Since $\kappa + \lambda < 1$, there is decreasing returns to scale, and therefore the firm has positive profits that are increasing in productivity z_t which is shown below. The static profit maximization of the firm can be written as:

$$\max_{k_t, l_t \geq 0} \left\{ z_t^{\zeta} k_t^{\kappa} l_t^{\lambda} - (r_t + \delta)k_t - w_t l_t \right\} \tag{8}$$

Define average productivity of all the firms at time t as $\bar{z}_t$. Later on, it will be shown that the static profits of a firm along a balanced growth path are given by

$$\Pi(z_t, \bar{z}_t) = \pi \frac{z}{\bar{z}^{\lambda/(\lambda+\zeta)}} \tag{9}$$

where π is a time-invariant constant. For now, denote the static profits as $\Pi(z, \Theta)$ where Θ denotes all the relevant state variables for the aggregate economy.

3.3 Dynamic Profit Maximization of the Firm Without Agency Frictions

First, we state a firm's dynamic profit maximization problem where it can choose its own innovation rate. In the next subsection which introduces agency frictions, the CEO of the firm will overtake this decision, and maximize his own utility subject to his contract.

The firm can increase its productivity z_t over time through innovation. Innovation is stochastic. If the firm is successful in innovation, its new productivity becomes $z_{t+1} = z_t + \gamma \bar{z}_t$, where $\gamma > 0$ is a scale parameter. If the firm fails to innovate, its productivity remains as is ($z_{t+1} = z_t$), but its relative productivity falls due to growth of average productivity $\bar{z}_t$ along the balanced growth path. Let $i \in [0,1]$ denote the probability of succeeding in innovation. In order to generate a probability i

of successful innovation, the firm has to incur R&D costs given by

$$C(i,\bar{z}) = \hat{C}(i)\frac{\bar{z}}{\bar{z}^{\lambda/(\lambda+\zeta)}}, \text{ where} \tag{10}$$

$$\hat{C}(i) = -\chi(\ln(1-i)+i). \tag{11}$$

The parameter $\chi > 0$ is the scale parameter that governs how efficient the firm is in coming up with new innovations, with a lower value of χ indicating a more innovative firm. Given these components, the dynamic profit maximization of the firm (without any agency frictions) can be written as follows:

$$V_{\text{nf}}(z,\Theta) = \max_{i\in[0,1]} \left\{ \Pi(z,\Theta) - C(i,\bar{z}) + \frac{i}{1+r}V_{\text{nf}}(z+\gamma\bar{z},\Theta') + \frac{1-i}{1+r}V_{\text{nf}}(z,\Theta') \right\} \tag{12}$$

The subscript "nf" stands for "no (agency) frictions." The first expression denotes the static profit of the firm that depends on the firm's own productivity z, and the aggregate state of the economy Θ. The second term denotes the R&D costs incurred by the firm so that it can successfully innovate to improve its productivity next period by $\gamma\bar{z}$. The third term denotes the continuation value of the firm conditional on a successful innovation, discounted by the real interest rate. The final term is the continuation value of the firm conditional on a failed innovation attempt. The first order condition with respect to i is as follows:

$$\frac{\partial C(i,\bar{z})}{\partial i} = \frac{1}{1+r}\left[V_{\text{nf}}(z+\gamma\bar{z},\Theta') - V_{\text{nf}}(z,\Theta')\right] \tag{13}$$

Theorem 1. *Along a balanced growth path equilibrium, the value function of the firm without agency frictions takes the form:*

$$V_{nf}(z,\bar{z}) = v_1^{nf}\hat{z} + v_2^{nf}\tilde{z} \tag{14}$$

where $\hat{z} = \frac{z}{\bar{z}^{\lambda/(\lambda+\zeta)}}$*, and* $\tilde{z} = \frac{\bar{z}}{\bar{z}^{\lambda/(\lambda+\zeta)}}$*, whereas* v_1^{nf} *and* v_2^{nf} *are time-invariant constants.*

Proof of Theorem 1. See the proof of Theorem 2 in Appendix A. □

Corollary 1. *The first order condition with respect to successful innovation probability* i *in the dynamic profit maximization problem of the firm without agency frictions is given by*

$$\frac{\partial C(i,\bar{z})}{\partial i} = \frac{1}{1+r}\left[v_1^{nf}\gamma\tilde{z}\right]. \tag{15}$$

This equation pins down the optimal innovation rate i, which does not depend on the firm's productivity z, the aggregate productivity $\bar{z}$, or time.

3.4 Preferences and Compensation Structure of the CEO

Next, we introduce agency frictions to the setting. Each firm in the model has a CEO who chooses the levels of production inputs k and l, as well as the probability of successful innovation

i. A CEO has standard time-separable constant relative risk aversion (CRRA) preferences over consumption, and receives disutility from exerting effort to oversee the firm's innovation efforts.[9] The preferences are represented by:

$$U(\vec{c},\vec{i}) = \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\bar{z}_t^{\frac{(1-\omega)\zeta}{\lambda+\zeta}}\right)\right] \tag{16}$$

with $\vec{c} = \{c_t\}_{t=0}^{\infty}$, $\vec{i} = \{i_t\}_{t=0}^{\infty}$, $\beta \in (0,1)$, $\omega \neq 1$ is the CRRA parameter. The term $v(i)$ captures the disutility from overseeing innovation[10] and is given by:

$$v(i) = -\nu(\ln(1-i) + i) \tag{17}$$

where $\nu > 0$ is the scale parameter which determines the efficiency of the CEO in overseeing innovations, with a lower value of ν indicating a more innovative CEO.

CEO compensation consists of two components: Salary which is not state-contingent, and stock options which has a state-contingent payoff. Suppose the firm pays out its period profits $\Pi(z,\Theta) - C(i,\bar{z})$ as dividends to its shareholders every period. Define the strike price of the firm as the ex-dividend equity value at time t, i.e.:

$$S(z_t,\Theta_t) = (V(z_t,\Theta_t) - [\Pi(z_t,\Theta_t) - C(i_t,\bar{z}_t)]) \tag{18}$$

where $V(z,\Theta)$ denotes the value function of the firm with agency frictions. The compensation of the CEO of a firm in period t is written as:

$$c_t = s_t\tilde{z}_t + o_t \max\{0, V(z_t,\Theta_t) - (1+r_{t-1})S(z_{t-1},\Theta_{t-1})\} \tag{19}$$

In this equation, s_t denotes the (normalized) salary received by the CEO, whereas o_t denotes the share options granted to the CEO as a fraction of the total shares of the firm. The second term has a positive value if the value of the firm next period exceeds the strike price this period, and is zero otherwise. Therefore, the option part of the compensation of the CEO is convex in the future value of the firm.

3.5 CEO's Decision Problem

Given a compensation structure, the CEO of the firm chooses the levels of production inputs k and l, as well as the probability of successful innovation i. For simplicity, we will assume that the

[9] Note that we do not require the CEO to desire less innovation than the owners. This will be determined through the estimation of the R&D cost parameter of the firm χ and the innovation disutility parameter of the CEO ν.

[10] The multiplicative term $\bar{z}_t^{\frac{(1-\omega)\zeta}{\lambda+\zeta}}$ is included to make sure that the disutility from the innovation effort does not shrink over time along the balanced growth path. It can be thought of as the value of time spent on leisure increasing in tandem with aggregate productivity.

CEO's contract is time-invariant, i.e. $s_t = s$, $\forall t$ and $o_t = o$, $\forall t$.[11] Notice that choosing the optimal levels of capital k and labor l is costless for the CEO. Therefore he will choose the optimal levels in the static profit maximization problem. That only leaves the decision for the innovation rate i. Given s and o, the CEO's decision problem can be written as follows:

$$\begin{aligned} W(z, z_{-1}, \Theta, \Theta_{-1}) = \quad & \max_{i\in[0,1]} \quad \Bigg\{ \frac{\left(s\tilde{z} + o \max\left\{0, V(z,\Theta) - (1+r_{-1})S(z_{-1},\Theta_{-1})\right\}\right)^{1-\omega}}{1-\omega} - v(i)\tilde{z}^{(1-\omega)} \\ & + \beta i W(z+\gamma\bar{z}, z, \Theta', \Theta) + \beta(1-i) W(z, z, \Theta', \Theta) \Bigg\} \end{aligned} \tag{20}$$

The first term is the CEO's utility from consumption in the current period, which is increasing in the deterministic salary and state-contingent stock option components. The stock option component requires keeping track of the previous period's productivity z_{-1} and aggregate state variable Θ_{-1}. The second term is the disutility from innovation. With probability i, the innovation attempt in the current period will succeed, and next period's productivity will be $z' = z + \gamma\bar{z}$. With the complementary probability $(1-i)$, the innovation attempt fails, and the firm continues with its old productivity $z' = z$.

Before we move on to the determination of the CEO's compensation structure, it is useful to show that the economic environment much simpler along a balanced growth path equilibrium. Given a particular contract (s, o), Theorem 2 establishes some intuitive closed-form results.

Theorem 2. *Given a contract (s, o) for the CEOs, the following are true for a balanced growth path equilibrium where the average productivity level $\bar{z}$ grows at the constant rate g_z:*

1. *Static profits of a firm with productivity z is given by*

$$\Pi(z, \bar{z}) = \pi\hat{z}$$

   where π is a time-invariant constant.

2. *The CEO's optimal innovation decision $\hat{i}$ is a time-invariant constant. In particular, it does not depend on firm's productivity z or average productivity level $\bar{z}$.*

3. *For a given time-invariant innovation decision i, the value function of the firm takes the form*

$$V(i, z, \bar{z}) = v_1\hat{z} + v_2(i)\tilde{z} \tag{21}$$

   where v_1 is a time-invariant constant, and $v_2(i)$ is a function of i.

4. *The growth rate of the average productivity level is $g_z = \hat{i}\gamma$.*

[11] This is without loss of generality. In an alternate setting with no long-term commitment on either side, the optimal contract would be time-invariant along the balanced growth path equilibrium.

5. *The aggregate variables $Y_t, C_t, K_t, X_t, C_{m,t}$ and the real wage rate w_t grow at the constant gross rate $G_\zeta = (1+g_z)^{\lambda/(\lambda+\zeta)}$. The real interest rate r is time-invariant.*

3.6 Determination of the Compensation of the CEO

Ideally, the compensation of the CEO would be directly chosen by the shareholders. In reality, the CEOs have some influence over the determination of their compensation; hence, they can distort the compensation structure to suit their own preferences as opposed to that of the shareholders. In order to model this in a simple way, the objective function used in the determination of CEO compensation will put some weight on both the utility of the CEO and the utility of the shareholders. This is similar to Page (2016). Let $\eta \in (0,1)$ denote the weight of CEO's preferences, and $1-\eta$ denote that of the shareholders. The compensation determination problem is written as:

$$\max_{s\geq 0, o\in[0,1]} \left\{ \eta \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\tilde{z}_t^{1-\omega}\right)\right] + (1-\eta)\mathbb{E}\left[V(z_0,\Theta_0) - \sum_{t=0}^{\infty} \frac{c_t}{\prod_{T=1}^{t}(1+r_T)}\right]\right\} \tag{22}$$

$$c_t = s\tilde{z}_t + o\max\left\{0, V(z_t,\Theta_t) - (1+r_{t-1})S(z_{t-1},\Theta_{t-1})\right\}, \forall t \tag{23}$$

$$i_t = \hat{i}(s,o) \tag{24}$$

$$\underline{\mathrm{U}} = \mathbb{E}\left[\sum_{t=0}^{\infty} \frac{c_t}{\prod_{T=1}^{t}(1+r_T)}\right] \tag{25}$$

The first term in the objective function represents the CEO's influence in the determination of his compensation structure between salary s and stock options o, which is increasing in η. The second term in the objective function represents the shareholders' influence, where their preferences are simply the expected value of the firm at time $t=0$ minus the present discounted value of the expected payments to the CEO. The first set of constraints is the compensation of the CEO at different periods. The second set of constraints is to recognize that the CEO will choose the level of innovation i_t given his compensation structure. Therefore the level of innovation is equal to the policy function associated with the CEO's decision problem, $\hat{i}(s,o)$. The last constraint requires the present discounted value of the expected payments to the CEO to be equal to $\underline{\mathrm{U}}$, which represents the outside option of the CEO.

First, notice that given $i_t = \hat{i}(s,o)$, the expected utility of the CEO can be written as

$$\mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\tilde{z}_t^{1-\omega}\right)\right] \tag{26}$$

$$= \sum_{t=0}^{\infty} (\beta G_\zeta^{1-\omega})^t \left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right]\tilde{z}_0^{1-\omega} \tag{27}$$

$$= \frac{1}{1-\beta G_\zeta^{1-\omega}} \left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right]\tilde{z}_0^{1-\omega} \tag{28}$$

Next, the expected utility of the shareholders becomes

$$\mathbb{E}\left[V(z_0, \Theta_0) - \sum_{t=0}^{\infty} \frac{c_t}{\prod_{T=1}^{t}(1+r_T)}\right] \tag{29}$$

$$= \quad v_1 \hat{z}_0 + v_2(\hat{i}(s,o))\tilde{z}_0 - \underline{\mathrm{U}} \tag{30}$$

The first and third terms are independent of the choice of s or o; so they can be moved out of the maximization. Notice that the real interest rate is constant in the balanced growth path equilibrium. Then:

$$\underline{\mathrm{U}} \quad = \quad \mathbb{E}\left[\sum_{t=0}^{\infty} \frac{c_t}{(1+r)^t}\right] = \frac{1+r}{1+r-G_\zeta}\left[s + \frac{o\gamma v_1}{G_\zeta}\hat{i}(s,o)(1-\hat{i}(s,o))\right]\tilde{z}_0 \tag{31}$$

Hence, choosing either s or o completely determines the other. Thus the maximization problem has a single relevant dimension. Since the domain of o is compact, it makes sense to search over the values of $o \in [0,1]$ which maximizes the objective function. Putting all components together, the problem can be rewritten as follows:

$$\max_{o\in[0,1]} \quad \left\{\frac{\eta\tilde{z}_0^{1-\omega}}{1-\beta G_\zeta^{1-\omega}}\left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right]\right. \tag{32}$$

$$\left. +(1-\eta)v_2(\hat{i}(s,o))\tilde{z}_0\right\}, \text{such that} \tag{33}$$

$$\underline{\mathrm{U}} \quad = \quad \frac{1+r}{1+r-G_\zeta}\left[s + \frac{o\gamma v_1}{G_\zeta}\hat{i}(s,o)(1-\hat{i}(s,o))\right]\tilde{z}_0 \tag{34}$$

3.7 Introducing Firm and CEO Type Heterogeneity

In the baseline model, the only difference between firms is firm-specific productivity z, and it is shown that the value of z only influences static profit maximization (the choice of k and l), whereas it has no influence on the dynamic decisions (the choice of i by the CEO, or the choice of s and o by the board at time $t = 0$). The CEOs are completely homogeneous. We will now generalize the model to allow for firm and CEO type heterogeneity.

Let there be a finite number of firm types indexed by $m \in \{1, 2, ..., M\}$ and a finite number of CEO types indexed by $n \in \{1, 2, ..., N\}$. For simplicity, we can define firm-CEO pair types indexed by $j = \{1, 2, ..., J\}$ where $J = M \times N$. From this point onwards, we will refer to a firm-CEO pair type as a firm type for brevity. The firms are allowed to differ from each other in cost of R&D χ_j and CEO influence parameter η_j. The CEOs are allowed to differ from each other in disutility from innovation ν_j, constant relative risk aversion parameter ω_j, and expected present discounted value of future compensation $\underline{\mathrm{U}}_j$.[12] Hence, each firm type j can be summarized by a five dimensional

[12]Consequently, the parameter ω now refers only to the CRRA parameter of the representative household.

vector $(\chi_j, \eta_j, \nu_j, \omega_j, \underline{\mathrm{U}}_j)$.[13]

Despite the richer environment, solving for the balanced growth path equilibrium of the economy remains the same except a few changes which will be discussed below. The determination of the compensation of the CEO for firm type j is given by:

$$\max_{o_j \in [0,1]} \quad \left\{ \frac{\eta_j \tilde{z}_0^{1-\omega_j}}{1-\beta G_\zeta^{1-\omega}} \left[\frac{i_j}{1-\omega_j} \left(s_j + \frac{o_j \gamma v_1 (1-i_j)}{G_\zeta} \right)^{1-\omega_j} + \frac{(1-i_j) s_j^{1-\omega_j}}{1-\omega_j} - v_j(i_j) \right] \right.$$
$$\left. + (1-\eta_j) v_{2,j}(i_j) \tilde{z}_0 \right\}, \text{such that} \tag{35}$$

$$\underline{\mathrm{U}}_j = \frac{1+r}{1+r-G_\zeta} \left[s_j + \frac{o_j \gamma v_1}{G_\zeta} i_j (1-i_j) \right] \tilde{z}_0 \tag{36}$$

$$v_j'(i_j) = \beta G_\zeta^{1-\omega_j} \left[\frac{\left(s_j + \frac{o_j \gamma v_1}{G_\zeta}(1-i_j) \right)^{1-\omega_j}}{1-\omega_j} - \frac{s_j^{1-\omega_j}}{1-\omega_j} - \frac{i_j o_j \gamma v_1}{G_\zeta} \left(s_j + \frac{o_j \gamma v_1}{G_\zeta}(1-i_j) \right)^{-\omega_j} \right] \tag{37}$$

where

$$v_j(i_j) = -\nu_j(\ln(1-i_j) + i_j), \tag{38}$$

$$\hat{C}_j(i_j) = -\chi_j(\ln(1-i_j) + i_j), \text{ and} \tag{39}$$

$$v_{2,j}(i_j) = \left(1 - \frac{G_\zeta}{1+r}\right)^{-1} \left(\frac{i_j \gamma v_1}{(1+r) G_\lambda} - \hat{C}_j(i_j) \right). \tag{40}$$

In essence, this is nothing but solving J similar problems side by side. The interaction between the firm types comes through the general equilibrium effects on the real wage rate w, the productivity distribution $Z(z)$, and the growth rate of its mean, g_z. Let $\mu_j \in [0,1]$ denote the fraction of firms of type j in the economy, such that $\sum_{j=1}^{J} \mu_j = 1$. Consider the law of motion for productivity of a type j firm:

$$z_{t+1}^j = z_t^j + \gamma \bar{z}_t \mathbb{I}_j \tag{41}$$

where $\mathbb{I}_j$ is the innovation indicator function which equals 1 with probability i_j, and is 0 otherwise. Taking the unconditional expectation of both sides delivers the law of motion for the average productivity of all firms with type j:

$$\bar{z}_{t+1}^j = \bar{z}_t^j + \gamma \bar{z}_t i_j \tag{42}$$

The average productivity level for all the firms in the economy is trivially the weighted sum of

[13] Note that we could also introduce heterogeneity in CEO time discount factor β or productivity increase scale parameter γ if needed following the same idea.

average productivity levels for particular firm types j, i.e. $\bar{z}_t = \sum_{j=1}^{J} \mu_j \bar{z}_t^j$. Consequently,

$$\begin{aligned} \bar{z}_{t+1} &= \sum_{j=1}^{J} \mu_j \bar{z}_{t+1}^j && (43) \\ &= \sum_{j=1}^{J} \mu_j \left(\bar{z}_t^j + \gamma \bar{z}_t i_j \right) && (44) \\ &= \sum_{j=1}^{J} \mu_j \bar{z}_t^j + \gamma \bar{z}_t \sum_{j=1}^{J} \mu_j i_j && (45) \\ &= \bar{z}_t \left(1 + \gamma \sum_{j=1}^{J} \mu_j i_j \right) && (46) \end{aligned}$$

Therefore, the growth rate of the average productivity level $\bar{z}$ along a balanced growth path equilibrium is now given by:

$$g_z = \gamma \sum_{j=1}^{J} \mu_j i_j \tag{47}$$

3.8 Competitive Equilibrium and the Social Planner's Solution Without Agency Frictions

In order to assess the impact of the agency frictions that arise as a result of CEO influence over the board's decision problem, one can compute the competitive equilibrium allocation where the firms can choose the quantities that are optimal for the shareholders. However, even the economy with no agency frictions does not attain the first-best, since the firms do not internalize the positive spillovers of their own innovation to the rest of the economy, which happens through their positive effect on the average productivity level $\bar{z}$. In order to compute the first-best allocation, one needs to solve the social planner's problem where the effects of innovation are internalized.[14] The balanced growth path equilibria for the competitive equilibrium with no agency frictions, and the social planner's problem and solution are presented and calculated in Section A.2 of the Theory Appendix.

3.9 Alternate Specifications for the Determination of the CEO's Contract

Section 3.6 introduced the compensation determination problem where the board assigned the weight η to the CEO's utility, and $(1 - \eta)$ to that of the shareholders of the firm. Beyond the standard incentive compatibility constraint, the board was required to provide a certain present discounted value of future compensation to the CEO. It is important to consider whether alternate specifications of this particular section of the model can influence the qualitative and quantitative implications one can derive.

[14] We assume the social planner only values the utility of the representative household.

We consider three alternative specifications for the compensation determination problem, which can be found in the Theory Appendix. Section A.3 relaxes the present discounted value of future compensation constraint. In this flexible compensation specification, the board can choose both the composition and the level of the CEO's compensation (as opposed to only the composition in the baseline model). Section A.4 replaces the same constraint by another one which promises the CEO a certain level of utility instead. Consequently, the CEO's influence parameter η loses its meaning, and the board's problem is reduced into a standard principal-agent problem where the principal's utility is equal to that of the shareholders. Section A.5 takes another approach, and considers the problem where the CEO and the shareholders are both risk-neutral agents. In this setting, it is possible to get simpler closed-form solutions, and the present discounted value of future compensation becomes equivalent to the individual rationality constraint of a principal-agent problem. The qualitative and quantitative implications of these alternate specifications will be touched upon later in the quantitative analysis.

4 Quantitative Analysis

4.1 Estimation

The computation of the balanced growth path equilibrium requires assigning values to the parameters, and choosing the number of distinct firm types. In our baseline calibration, we introduce firm heterogeneity in terms of the CEO influence parameter η only – i.e. the firms in the model differ from each other only in terms of firm-specific productivity z, and the quality of corporate governance which is inversely related to CEO influence. This is done by assuming a discrete uniform distribution over η, with the upper bound η_{ub} and the lower bound η_{lb}. For computational simplicity, we choose the number of distinct firm types to be five. Under this specification, there are twelve parameter values to be determined: $\omega, \beta, \zeta, \kappa, \lambda, \delta, \gamma, \nu, \chi, \eta_{lb}, \eta_{ub}$, and $\underline{\text{U}}$. Some common parameters are chosen from existing studies, whereas the rest are estimated following a simulated method of moments (SMM) approach. We discuss the sources of the externally calibrated parameters below:

1. *CRRA parameter:* The constant relative risk aversion parameter is taken to be $\omega = 2.00$, consistent with the estimates listed in Kaplow (2005).

2. *Discount factor:* We pick the discount factor to be $\beta = 0.9815$; a standard value for annual real business cycle models.

3. *Factor shares in production:* Corrado, Hulten, and Sichel (2009) calculate the shares of tangible capital, labor, and intangible capital to be $\kappa = 0.25$, $\lambda = 0.60$ and $\zeta = 0.15$ respectively. The share of intangible capital they calculate is mapped to the share of productivity of a firm in generating output in the model. An alternative interpretation of ζ would be the average mark-up in the economy, which is consistent with the value of 15% used in Midrigan and Xu (2014), and well within the range of other values commonly used in the literature.

4. *Depreciation rate for capital:* The annual depreciation rate of physical capital is chosen as 6.9% which is consistent with the U.S. National Income and Product Accounts.

4.2 Targeted Moments and Identification

Six parameters remain to be determined: the productivity increase parameter conditional on successful innovation γ, the CEO disutility parameter ν, the R&D cost parameter χ, the upper and lower bounds for the distribution of CEO influence across firm types η_{ub} and η_{lb}, and the present discounted value of the compensation of the CEO, $\underline{\mathrm{U}}$. All of these parameters are jointly estimated to match the following the targeted data moments:

1. *Long-run output growth:* Since 1945, the the aggregate output in the U.S. grew at circa 2% per year. The parameter γ determines the increase in productivity a successful innovation generates, and hence it plays the foremost role in determining the output growth rate in the model.

2. *Firm R&D intensity:* In order to discipline the R&D spending in the model, we target the ratio of R&D expenditures to GDP in the U.S. Akcigit, Hanley, and Serrano-Velarde (2016) report this number to be 2.91%. This target plays the largest role in determining the R&D cost parameter χ in the model.

3. *Ratio of CEO compensation to market capitalization:* In the model, the parameter $\underline{\mathrm{U}}$ determines the expected total compensation of the CEO under the optimal contract. We discipline this parameter by targeting the average ratio of total CEO compensation to the market capitalization of the firm they work for. In our data, this ratio is calculated to be 0.33%.

4. *Correlation of innovation with option ratio:* The disutility parameter of the CEO ν largely determines the response of a CEO's innovation decision to the option to income ratio implied by his contract. To discipline this elasticity, we require the correlation between innovation and option to income ratio in the model to match the correlation between tail innovations and option to income ratio in the data, which has the value 0.9511.

5. *Correlation of institutional ownership with innovation and option ratio:* In the model, CEO influence η, which is inversely related to corporate governance quality, directly affects the option to income ratio in the optimal contract, and indirectly influences the innovation rate chosen by the CEO. In our empirical analysis, we focus on institutional ownership as our prime measure of corporate governance. In order to estimate the lower and upper bounds of CEO influence parameter η, we target the correlation of institutional ownership with innovation and option to income ratio, where we impose the model counterpart of institutional ownership to simply be $1 - \eta$.[15] The values of the two correlations in the data are 0.6407 for innovation,

[15] Recall that the value of η has no cardinal meaning in the model, since the preferences of the CEO and the shareholders are ordinal. Therefore any inverse relationship would be acceptable. We only care about η's influence on the observables, which the estimation correctly captures.

and 0.8697 for option to income ratio.

The detailed estimation procedure is illustrated in the Appendix. Panel A of Table 10 reports the values of the parameters, whereas Panel B of the same table provides an overview of the values of the targeted moments in the data and the estimated model. The model tightly matches the six data moments.

4.3 Welfare Analysis

In order to calculate welfare, we need to compute the consumption stream of the representative household. There are two components required for this: The growth rate of consumption $G_\zeta - 1$, the initial consumption level C_0. From goods market clearing, we have:

$$Y_t = C_t + C_{m,t} + X_t + I_t \tag{48}$$

where the terms on the right hand side are aggregates for consumption of the representative household C_t, consumption of the managers $C_{m,t}$, R&D spending X_t and investment in physical capital I_t respectively. In order to calculate C_t, we need expressions for $C_{m,t}$, X_t, and I_t.

In a balanced growth path equilibrium, aggregate physical capital stock grows according to $K_{t+1} = G_\zeta K_t$. By definition, aggregate investment at time t is $I_t = K_{t+1} - K_t(1-\delta)$. Hence we have $I_t = K_t(G_\zeta - 1 + \delta)$. To calculate I_t, we need K_t. Recall that the first order condition with respect to capital of the firm's static profit maximization yields $y(z_t, \bar{z}_t) = \frac{\kappa}{r_t+\delta} k(z_t, \bar{z}_t)$. Hence, we have:

$$\begin{aligned} \frac{K_t}{Y_t} &= \int \frac{k(z_t, \bar{z}_t)}{y(z_t, \bar{z}_t)} dZ(z) = \frac{\kappa}{r+\delta} && (49) \\ \Rightarrow I_t &= \frac{K_t}{Y_t} Y_t (G_\zeta - 1 + \delta) = \frac{\kappa\pi(G_\zeta - 1 + \delta)}{\zeta(r+\delta)} \tilde{z}_t && (50) \end{aligned}$$

For aggregate R&D spending, we have

$$X_t = \hat{C}(i)\tilde{z}_t \tag{51}$$

For aggregate consumption of the managers, we have:

$$C_{m,t} = \mathbb{E}[c_t] = \left(s + \frac{o\gamma v_1}{G_\zeta} i(1-i) \right) \tilde{z}_t \tag{52}$$

Hence, the initial consumption level C_0 is given by:

$$C_0 = \left[\frac{\pi}{\zeta} - \frac{\kappa\pi(G_\zeta - 1 + \delta)}{\zeta(r+\delta)} - \hat{C}(i) - \left(s + \frac{o\gamma v_1}{G_\zeta} i(1-i) \right) \right] \tilde{z}_0 \tag{53}$$

Social welfare is defined as the utility of the representative consumer. In a balanced growth path equilibrium, this is given by

$$W = \sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\omega}}{1-\omega} = \frac{C_0^{1-\omega}}{(1-\omega)(1-\beta G_\zeta^{1-\omega})} \tag{54}$$

Welfare comparisons between different economies will be conducted by comparing the balanced growth path equilibria.[16] In order to make two different economies A and B comparable, both economies will be started at the same average productivity level $\bar{z}_0^A = \bar{z}_0^B = 1$. Let $x > 0$ be the scalar such that multiplying the representative consumer's consumption in economy A with x results in a welfare number equivalent to the one in economy B. Simple algebra reveals that x is given by

$$x = (W^B/W^A)^{1/(1-\omega)} \tag{55}$$

where W^A and W^B denote the welfare in economies A and B respectively. The welfare gain or loss a move from economy A to economy B provides in consumption equivalent terms is given by $x - 1$. This welfare measure is used in all quantitative exercises.

4.4 Marginal Benefit and Marginal Cost of the CEO's Innovation Decision

To better visualize the the tradeoffs the CEO faces in choosing the innovation probability under different contracts (s, o), we plot the marginal benefit and marginal cost of innovation for the CEO in Figure 1. The marginal cost of the CEO is the disutility from innovation, and depends solely on the disutility parameter ν of the CEO. The left panel depicts the marginal benefit curve under three different levels of stock options: low, medium, and high. Holding salary constant, an increase in stock options in the contract shifts the marginal benefit curve up, inducing the CEO to choose a higher rate of innovation in equilibrium. Similar to the previous exercise, the right panel depicts the marginal benefit curve under three different levels of state-incontingent salary: low, medium, and high. Holding the stock options constant, increasing the level of the salary component results in an income effect. Since the CEO is now wealthier, an increase in the salary reduces the incentives of the CEO to engage in disruptive innovation.

4.5 Board Objective Function and Innovation Decision Rule

We plot board objective function and the CEO's innovation policy function in Figure 2. The left panel depicts the board objective as a function of the stock options offered to the CEO. The right panel plots the CEO's innovation decision as a function of the stock options as well. The board objective function is maximized at the amount of stock options marked by the dashed line. Given the stock options (and the implied salary) chosen by the board, the manager chooses the innovation level that maximizes his own utility under the contract. This innovation level is lower

[16] Hence this analysis ignores the welfare effects of the transition to the new steady state.

than the shareholder-optimal innovation level, which is the one the firm would have chosen under the no agency frictions case. Δi captures the efficiency loss. The green line on the right panel depicts the optimal innovation that would be chosen by the social planner. Since the social planner also internalizes the positive externalities resulting from knowledge spillovers, the social planner's optimal innovation rate is much higher than that of the decentralized economy, which implies that there is room for policy intervention such as R&D subsidies. For the details on the calculation of the social planner's allocation, see Section A.2 of the Theory Appendix.

4.6 Comparative Statics

We now examine the innovation decisions of the firms, the compensation structure, output growth rate, and social welfare provided that the firms and managers had different fundamental characteristics other than those implied by the parameter estimates from Table 10. This is summarized in Figures 3 to 5. For each panel in each figure, we solve and simulate the model 20 times, each time corresponding to different value of the parameter in question. For each of these 20 simulations, we calculate the relevant moments. Figure 3 shows the comparative statics of the impact of changing the parameter that governs CEO influence, η. We find that an increase in CEO influence would reduce the fraction of stock options in the CEO compensation and increase the fraction state-incontingent pay, salary, in the CEO compensation. CEO influence has a negative impact on firm's innovation, which leads to lower aggregate output growth rate and consumption equivalent welfare. We also plot the optimal innovation level of the shareholder by the dashed red line in the innovation panel. The red line captures the optimal innovation choice of the firm without agency friction conditional on other firms in the economy are still subject to agency frictions. When other firms suffer from the more severe distortion caused by increased agency frictions, it becomes more attractive for the firm to carry out more innovation since the firm could capture a larger market share and profit by increasing its productivity.

Figure 4 show the comparative statics of the impact of changing the parameter that governs firm's R&D cost, χ. We find that with higher R&D cost, the firm chooses a contract that results in a lower innovation level. We plot the optimal innovation level of the shareholders by the dashed red line in the innovation panel as well. The distance between the dashed red line and solid blue line represents the deviation of innovation from the shareholder-optimal level. We find that the distortion caused by agency frictions is more severe for more innovative firms (firms with lower R&D cost). If a firm is less efficient in innovation, it need less innovation effort from the CEO, and therefore it would adopt a less incentivized compensation contract, featuring a lower fraction of stock options and a high fraction of salary. The equilibrium output growth rate and social welfare decrease since the firm carries out less innovation.

Figure 5 shows the comparative statics of the impact of changing the parameter that governs CEO innovation disutility, ν. When it becomes more costly for the CEO to oversee innovation, the firm needs to adopt a more incentivized compensation contract to motivate the manager to exert the same effort. Hence the option ratio increases and the salary ratio decreases in the CEO compensation. We also plot the CEO's optimal innovation decision in the innovation panel. The red dashed line captures the innovation the firm would choose if it were not subject to the agency frictions while all other firms in the economy were subject to the agency frictions. When it becomes more costly for all other firms' managers to oversee innovation, the benefit for innovation increases since the firm could capture a larger market share by increasing its relative productivity. Hence the optimal innovation decision is upward sloping. Also, the gap between the optimal innovation rate and innovation rate chosen by the CEO is smaller if it is less costly for the CEO to oversee the innovation. In other words, the agency friction is less severe if the CEO is more innovative. The equilibrium output growth rate and social welfare are decreasing in ν since the firms carry out less innovation.

4.7 Key Relationships: Model vs. Data

Figure 6 depicts the relationship between innovation and corporate governance both in the model and the data. To measure corporate governance in the data, we first divide firms into 100 quantiles based on their institutional ownership fraction. Then for firms on each governance quantile, we calculate their average tail innovation. We centralize the measure of innovation by demeaning it and then dividing it by its standard deviation. Each red dot in the figure represents the value of the mean option ratio for a corporate governance index quantile. The linear fitted value is plotted in the red dashed line. The slope of the fitted line captures the elasticity between corporate governance and disruptive innovation. Similarly, the mean innovation ratio is calculated for each of the 100 different values of CEO influence parameters in the model and is plotted by the blue curve. In both the model and the data, we observe a positive correlation between firms' corporate governance and disruptive innovation. The model tightly matches the elasticity between corporate governance and firm innovation. In both the model and the data, firms with better corporate governance tend to come up with more disruptive innovation.

Figure 7 depicts the relationship between option ratio and corporate governance in the model and data. For each governance quantile, we calculate the average option ratio in the CEO compensation contract. Then we centralize the measure by demeaning it and then dividing it by its standard deviation. Each red dot in the figure represents the value of the mean option ratio for a corporate governance index quantile. The linear fitted value is plotted by the the red dashed line. The slope of the fitted line captures the elasticity between corporate governance and option ratio. Similarly, the mean option ratio is calculated for each of the 100 different values of CEO influence parameters in the model and is plotted in the blue curve. In both the model and the data, we observe a positive correlation between firms' corporate governance and disruptive innovation. The model also matches the elasticity between corporate governance and option ratio very tightly. In both the model and the data, contracts adopted by firms with better corporate governance tend to have a higher fraction of stock options.

4.8 Firm Size Distribution and Corporate Governance

The model can generate interesting implications on the interactions between the firm size distribution and corporate governance. We plot the model-generated firm size distribution in Figure 8. This figure depicts the distribution of firm size for different levels of corporate governance based on the simulated firm panel. Different from the majority of existing dynamic corporate finance models which largely face difficulty in matching the firm size distribution, the model is able to generate a firm size distribution with fat tails. In the model, firms with better corporate governance tend to grow faster and end up with larger sizes. This is consistent with the empirical findings in previous literature. (See Bloom and Reenen (2007) among others.)

4.9 Reducing Agency Frictions

Table 11 compares the impact of agency frictions on welfare, option ratio, output growth rate, R&D intensity, disruptive innovation, consumption and social welfare. The first column reports the baseline model results. The second column reports the results of a counterfactual economy with CEO influence η set to 50% of its value, keeping the value of other parameters the same as in the baseline model. The third column reports the results of the model without any agency frictions. The managers are motivated to engage more in disruptive innovation due to higher stock options. Both the average innovation and R&D intensity increase, which in turn leads to an increase in equilibrium output growth rate and social welfare. Disruptive innovation increases by 13.4% of its value; R&D intensity increases by 3.6% of its value; and output growth rate increases by 0.25 percentage points. Consumption equivalent welfare improves by 5.2%. When we completely shut down all agency frictions through removing CEO influence altogether, disruptive innovation increases by 62.5% of its value; R&D intensity increases by 72.6% of its value; and output growth rate increases by 1.17 pp. Consumption equivalent welfare improves by around 20%. Keep in mind that these figures are an upper bound for the actual effects since our model attributes all economic growth to this particular mechanism.

5 Conclusion

We examine the impact of agency frictions between managers and shareholders on executive compensation structure and firm innovation. We first document several new stylized facts about the correlation patterns of corporate governance, managerial compensation and disruptive innovations. Firms with better corporate governance tend to adopt executive compensation contracts with a high fraction of stock options, which incentivizes the managers to engage in innovative activities and thereby improve firm value and boost economic growth. Then we develop a quantitative framework to shed light on the key mechanisms that underlie these facts, and assess their quantitative significance. We contribute to the literature by being the first to build a quantitative model with endogenous CEO compensation and economic growth to study the joint dynamics of agency frictions, CEO compensation, and firm innovation. The CEO can influence the board's decision such that the final compensation contract deviates from the shareholder-optimal contract which would maximize firm value. Better corporate governance reduces the CEO's influence, thereby enabling the board to choose contracts that have a higher fraction of stock options, which motivates the manager to carry out more disruptive innovations. We estimate the model using comprehensive micro-data to discipline the the sensitivity of the innovation decision to CEO compensation structure and corporate governance. We find that the impact of agency frictions on disruptive innovation and output growth is quite sizable. Shutting down agency frictions through removing CEO influence could increase the average innovation rate by 62.5 percent of its value, output growth by 1.17 percentage points, and improve consumption equivalent welfare by around 20 percent.

The quantitative findings suggest that there is significant room for policy intervention which can bring the economy closer to the efficient allocation through the alleviation of the agency frictions. While no magic recipe exists for improving corporate governance, understanding how and why institutional investors pick the firms they do might be quite valuable a future research avenue. Another option would be changing how various components of CEO compensation is taxed by the government, which can provide more incentives for firms to increase the state-contingent parts of CEO compensation such as stock options. Furthermore, the social planner's optimal rate of innovation is much higher than that of the decentralized economy, which implies that there is room for subsidizing innovation. Reducing R&D costs, through R&D tax credit or other government subsidies, could improve the innovation level and output growth. In particular, our paper highlights that there might be industry-specific variations in the optimal subsidy rates depending on the severity of the agency frictions within particular industries.

To keep the analysis tractable, we focus on a stylized model that abstracts from some features that might have significant influence on a firm's innovation decision. For example, when analyzing the impact of agency frictions, we abstract from the firm's financing decisions in the model, since we assume perfect credit markets; and assume that the firm can adjust its physical capital without incurring any adjustment costs. Adding these components could make the model more empirically relevant for studying the tradeoff between physical capital investment vs. intangible capital investment in the form of R&D spending. We intentionally keep the model as parsimonious as possible for tractability and clarity of the theoretical results. However, the key mechanism of the model is likely to carry over to an alternate model with these additional features. Another important direction for future research is to study optimal managerial compensation contract while also considering the synergy between the manager and the inventors – the economic agents who operate under the CEO to come up with the disruptive innovations. We expect future studies along these lines to be both promising and fruitful.

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Appendix A

A Theoretical Proofs and Computational Algorithm

A.1 Proofs

Proof of Theorem 2. We will use the guess-and-verify method. Start with the derivation of the value function of the firm given a time-invariant innovation decision i. The value function of the firm can be written recursively as:

$$V(i,z,\bar{z}) = \Pi(z,\bar{z}) - C(i,\bar{z}) + \frac{i}{1+r}V(i,z+\gamma\bar{z},\bar{z}') + \frac{1-i}{1+r}V(i,z,\bar{z}') \tag{56}$$

For clarity, define $G_\lambda = (1+g_z)^{\lambda/(\lambda+\zeta)}$ and $G_\zeta = (1+g_z)^{\zeta/(\lambda+\zeta)}$. Plugging in the guesses for the value function and static profits, we get:

$$\begin{aligned} v_1\hat{z} + v_2(i)\tilde{z} &= \pi\hat{z} - \hat{C}(i)\tilde{z} + \frac{i}{1+r}\left[\frac{v_1}{G_\lambda}\hat{z} + \frac{v_1\gamma}{G_\lambda}\tilde{z} + v_2(i)G_\zeta\tilde{z}\right] \\ &\quad + \frac{1-i}{1+r}\left[\frac{v_1}{G_\lambda}\hat{z} + v_2(i)G_\zeta\tilde{z}\right] \qquad (57) \\ v_1\hat{z} + v_2(i)\tilde{z} &= \left[\pi + \frac{v_1}{(1+r)G_\lambda}\right]\hat{z} + \left[-\hat{C}(i) + \frac{iv_1\gamma}{(1+r)G_\lambda} + \frac{v_2(i)G_\zeta}{1+r}\right]\tilde{z} \qquad (58) \end{aligned}$$

Hence:

$$\begin{aligned} v_1 &= \left(1 - \frac{1}{(1+r)G_\lambda}\right)^{-1}\pi \qquad (59) \\ v_2(i) &= \left(1 - \frac{G_\zeta}{1+r}\right)^{-1}\left(\frac{i\gamma v_1}{(1+r)G_\lambda} - \hat{C}(i)\right) \qquad (60) \end{aligned}$$

Now, we will turn to the CEO's decision problem. Before writing the problem explicitly, we will show that the value of an option can be greatly simplified. Consider the non-zero term $V(z,\Theta) - S(z_{-1},\Theta_{-1})$. Let $\mathbb{I}_{-1}$ be the indicator function for whether the previous period's innovation succeeded or failed. Consequently, we have $z = z_{-1} + \mathbb{I}_{-1}\gamma\bar{z}_{-1}$. Plugging in the definitions and the guess for the firm's value function, we get:

$$\begin{aligned} & V(z,\Theta) - (1+r)S(z_{-1},\Theta_{-1}) \qquad (61) \\ =\; & V(z,\Theta) - (1+r)\left(V(z_{-1},\Theta_{-1}) - [\Pi(z_{-1},\Theta_{-1}) - C(i_{-1},\bar{z}_{-1})]\right) \qquad (62) \\ =\; & V(z,\Theta) - (1+r)\left(\frac{i_{-1}}{1+r}V(z_{-1}+\gamma\bar{z}_{-1},\Theta) + \frac{1-i_{-1}}{1+r}V(z_{-1},\Theta)\right) \qquad (63) \\ =\; & \frac{v_1}{G_\lambda}\hat{z}_{-1} + \mathbb{I}_{-1}v_1\gamma\tilde{z}_{-1} + v_2(i)\tilde{z} - \left(\frac{v_1}{G_\lambda}\hat{z}_{-1} + i_{-1}v_1\gamma\tilde{z}_{-1} + v_2(i)\tilde{z}\right) \qquad (64) \\ =\; & [\mathbb{I}_{-1} - i_{-1}]\frac{v_1\gamma}{G_\zeta}\tilde{z} \qquad (65) \end{aligned}$$

Notice that this term is greater than zero if and only if $\mathbb{I}_{-1} = 1$, i.e. if the innovation effort in the previous period succeeded. Hence, an option will deliver a non-zero return if and only if last period's innovation was successful. Define $x = \max\{0, \mathbb{I}_{-1} - i_{-1}\}$. Then we can write the normalized decision problem of the CEO as:

$$\hat{W}(x) = \max_{i\in[0,1]}\left\{\frac{\left(s + \frac{o\gamma v_1}{G_\zeta}x\right)^{1-\omega}}{1-\omega} - v(i) + i\beta G_\zeta^{1-\omega}\hat{W}(1-i) + (1-i)\beta G_\zeta^{1-\omega}\hat{W}(0)\right\} \tag{66}$$

It is straightforward to notice that the choice of i will not depend on current consumption $s + \frac{o\gamma v_1}{G_\zeta} x$, firm productivity z, or average productivity level $\bar{z}$. Hence the policy function $\hat{i}$ will be a time-invariant constant. In fact, it is possible to calculate the value of $\hat{i}$ by solving a single non-linear equation in this setting. The sequential problem of the CEO can be rewritten as:

$$U(\vec{c}, \vec{i}) = \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \tilde{z}_t^{1-\omega} \left(\frac{(s + \frac{o\gamma v_1}{G_\zeta} \max\{0, \mathbb{I}_{t-1} - i_{t-1}\})^{1-\omega}}{1-\omega} - v(i_t) \right)\right] \tag{67}$$

Determination of $\vec{i}$ completely pins down the values of $\vec{c}$. In turn, the first order condition with respect to i_t is given by:

$$v'(i_t) = \beta G_\zeta^{1-\omega} \left[\frac{\left(s + \frac{o\gamma v_1}{G_\zeta}(1-i_t)\right)^{1-\omega}}{1-\omega} - \frac{s^{1-\omega}}{1-\omega} - \frac{i_t o\gamma v_1}{G_\zeta}\left(s + \frac{o\gamma v_1}{G_\zeta}(1-i_t)\right)^{-\omega} \right] \tag{68}$$

Notice that all the terms except i_t are time-independent. The unique solution to this equation pins down $\hat{i}$. The first term is the utility from consumption at time $t+1$ conditional on successful innovation. The second term is the same for the case where innovation fails. The last term captures the fact that increasing i_t actually reduces the payout of the option conditional on success, since the payout is linear in $(1 - i_t)$.

Next, we show that $\Pi(z, \bar{z}) = \pi \hat{z}$. The static profit maximization of a firm is stated as follows:

$$\Pi(z, \Theta) = \max_{k,l \geq 0} \{z^\zeta k^\kappa l^\lambda - (r+\delta)k - wl\} \tag{69}$$

First order conditions imply $l^* = \frac{\lambda y^*}{w}$ and $k^* = \frac{\kappa y^*}{r+\delta}$, hence we have

$$\begin{aligned} y^* &= z^\zeta \left(\frac{\kappa y^*}{r+\delta}\right)^\kappa \left(\frac{\lambda y^*}{w}\right)^\lambda \\ y^* &= \left[\left(\frac{\kappa}{r+\delta}\right)^\kappa \left(\frac{\lambda}{w}\right)^\lambda\right]^{1/\zeta} z \end{aligned} \tag{70}$$

and the profits are simply equal to $\Pi(z, \Theta) = \zeta y^*$. Let $Z(z)$ denote the distribution of firm productivities. From the labor market clearing condition, we get

$$L = \int l^*(z) dZ(z)$$

$$L = \frac{\lambda}{w}\left[\left(\frac{\kappa}{r+\delta}\right)^\kappa \left(\frac{\lambda}{w}\right)^\lambda\right]^{1/\zeta} \int z dZ(z) \tag{71}$$

$$\left(\frac{w}{\lambda}\right)^{\frac{\lambda+\zeta}{\zeta}} = \left(\frac{\kappa}{r+\delta}\right)^{\kappa/\zeta} \frac{\bar{z}}{L} \tag{72}$$

$$w = \lambda\left(\frac{\kappa}{r+\delta}\right)^{\frac{\kappa}{\lambda+\zeta}} L^{-\frac{\zeta}{\lambda+\zeta}} \bar{z}^{\frac{\zeta}{\lambda+\zeta}} \tag{73}$$

$$w = \lambda\left(\frac{\kappa}{r+\delta}\right)^{\frac{\kappa}{\lambda+\zeta}} \tilde{z} \tag{74}$$

where the last line is due to the normalization of the inelastic labor supply to $L = 1$. The identity shows that the wage rate grows with the gross rate G_ζ along the balanced growth path. The Euler equation of the representative consumer pins down the time-invariant real interest rate r along the balanced growth path. Since the consumption of the representative household grows at the gross rate G_ζ, we have

$$r = G_\zeta^\omega \beta^{-1} - 1 \tag{75}$$

Plugging the expressions for the wage and interest rates into the profits yields

$$\begin{aligned}
\Pi(z, \Theta) &= \zeta \left[\left(\frac{\kappa}{r+\delta} \right)^\kappa \left(\frac{\lambda}{w} \right)^\lambda \right]^{1/\zeta} z & (76)\\
&= \zeta \left(\frac{\kappa}{r+\delta} \right)^{\frac{\kappa}{1-\kappa}} \hat{z} & (77)\\
&= \zeta \left(\frac{\kappa}{G_\zeta^\omega \beta^{-1} - 1 + \delta} \right)^{\frac{\kappa}{1-\kappa}} \hat{z} & (78)\\
&= \pi \hat{z} & (79)
\end{aligned}$$

where $\pi \equiv \zeta \left(\frac{\kappa}{G_\zeta^\omega \beta^{-1} - 1 + \delta} \right)^{\frac{\kappa}{1-\kappa}}$ is a time-invariant constant. Since $y^* = \frac{\pi \hat{z}}{\zeta}$, the aggregate output Y is calculated as

$$Y = \int \frac{\pi}{\zeta} \hat{z} dZ(z) = \frac{\pi}{\zeta} \tilde{z}. \tag{80}$$

This verifies that the aggregate output grows at the gross rate G_ζ. Finally, since all firms choose the same innovation probability $\hat{i}$, the average productivity level $\bar{z}$ grows according to the law of motion

$$\bar{z}' = \bar{z} + \hat{i}\gamma\bar{z} \tag{81}$$

which implies that the growth rate is $g_z = \hat{i}\gamma$. □

A.2 Competitive Equilibrium vs. the Social Planner's Solution with No Agency Frictions

A.2.1 Competitive Equilibrium with No Agency Frictions

First, we calculate the optimal innovation decision i for a firm with no agency frictions:

$$\begin{aligned}
\frac{\partial C(i, \bar{z})}{\partial i} &= \frac{1}{1+r} \left[V_{\mathrm{nf}}(z + \gamma\bar{z}, \Theta') - V_{\mathrm{nf}}(z, \Theta') \right] & (82)\\
\chi \frac{i}{1-i} &= \frac{v_1^{\mathrm{nf}} \gamma}{(1+r) G_\lambda} & (83)\\
i \left(\chi + \frac{v_1^{\mathrm{nf}} \gamma}{(1+r) G_\lambda} \right) &= \frac{v_1^{\mathrm{nf}} \gamma}{(1+r) G_\lambda} & (84)\\
i &= \frac{v_1^{\mathrm{nf}} \gamma}{\chi (1+r) G_\lambda + v_1^{\mathrm{nf}} \gamma} & (85)
\end{aligned}$$

where we have

$$v_1^{\text{nf}} = \left(1 - \frac{1}{(1+r)G_\lambda}\right)^{-1} \pi, \tag{86}$$

$$\pi = \zeta \left(\frac{\kappa}{G_\zeta^\omega \beta^{-1} - 1 + \delta}\right)^{\frac{\kappa}{1-\kappa}}, \text{ and} \tag{87}$$

$$g_z = \gamma i \tag{88}$$

Initial consumption level C_0 is calculated as:

$$C_0 = \left[\frac{\pi}{\zeta} - \frac{\kappa\pi(G_\zeta - 1 + \delta)}{\zeta(r+\delta)} - \hat{C}(i)\right] \tilde{z}_0 \tag{89}$$

A.2.2 Social Planner's Solution with No Agency Frictions

The social planner seeks to maximize the lifetime utility of the representative consumer subject to the production and innovation technologies. We will assume the initial value of the physical capital to output ratio is equal to its steady-state level, and focus on balanced growth path allocations. Let $\mathbb{I}(n,t)$ denote the indicator function which equals one if innovation effort at time t in firm n succeeds, and equals zero otherwise. The history of innovation realizations up until time t is given by $h_t \equiv \{[\mathbb{I}(n,T)]_{n\in[0,1]}\}_{T=0}^{t-1}$. The problem can be stated as follows:

$$\max_{\{[l(n,t),k(n,t),i(n,t)]_{n\in[0,1]},C_t,K_{t+1},X_t\}_{t=0}^{\infty}} \left\{\mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \frac{C_t^{1-\omega}}{1-\omega}\right]\right\}, \text{such that} \tag{90}$$

$$Y_t = \int z(n,t)^\zeta k(n,t)^\kappa l(n,t)^\lambda dn, \forall t, \forall h_t \tag{91}$$

$$K_t = \int k(n,t) dn, \forall t, \forall h_t \tag{92}$$

$$L_t = \int l(n,t) dn, \forall t, \forall h_t \tag{93}$$

$$X_t = \int \hat{C}(i(n,t)) \tilde{z}_t dn, \forall t, \forall h_t \tag{94}$$

$$C_t + K_{t+1} + X_t = Y_t + K_t(1-\delta), \forall t, \forall h_t \tag{95}$$

$$z(n,t+1) = z(n,t) + \gamma \bar{z}_t \mathbb{I}(n,t), \forall n, \forall t, \forall h_t \tag{96}$$

Similar to the competitive equilibrium case, all aggregate variables will turn out to be non-stochastic, and the expectation operator will only be relevant for the choice of $i(n,t)$, the innovation probability chosen at time t for firm n, as the realization of a successful innovation is stochastic at this level. The Lagrangian is written as follows:

$$\begin{aligned}\mathcal{L} = \mathbb{E}\Bigg[\sum_{t=0}^{\infty}\Bigg[&\beta^t \frac{C_t^{1-\omega}}{1-\omega} + \mu_{Y,t}\left(\int z(n,t)^\zeta k(n,t)^\kappa l(n,t)^\lambda dn + K_t - \delta \int k(n,t) dn - C_t - K_{t+1} - X_t\right) \\ &+\mu_{K,t}\left(K_t - \int k(n,t)dn\right) + \mu_{L,t}\left(L_t - \int l(n,t)dn, \forall t, \forall h_t\right) + \mu_{X,t}\left(X_t - \int \hat{C}(i(n,t))\tilde{z}_t dn\right)\Bigg]\Bigg]\end{aligned}$$

We will start with solving the static problem of choosing physical capital and labour to be used by each firm n. The first order conditions with respect to $k(n,t)$ and $l(n,t)$ are:

$$\frac{\partial \mathcal{L}}{\partial k(n,t)} = \frac{\mu_{Y,t}\kappa}{k(n,t)} z(n,t)^{\zeta} k(n,t)^{\kappa} l(n,t)^{\lambda} - \mu_{K,t} - \mu_{Y,t}\delta = 0, \forall n, \forall t \tag{97}$$

$$\frac{\partial \mathcal{L}}{\partial l(n,t)} = \frac{\mu_{Y,t}\lambda}{l(n,t)} z(n,t)^{\zeta} k(n,t)^{\kappa} l(n,t)^{\lambda} - \mu_{L,t} = 0, \forall n, \forall t \tag{98}$$

Therefore we have:

$$y(n,t) = z^{\zeta} \left(\frac{\kappa y(n,t)}{\frac{\mu_{K,t}}{\mu_{Y,t}} + \delta} \right)^{\kappa} \left(\frac{\lambda y(n,t)}{\frac{\mu_{L,t}}{\mu_{Y,t}}} \right)^{\lambda} \tag{99}$$

$$y(n,t) = \left[\left(\frac{\kappa}{\frac{\mu_{K,t}}{\mu_{Y,t}} + \delta} \right)^{\kappa} \left(\frac{\lambda}{\frac{\mu_{L,t}}{\mu_{Y,t}}} \right)^{\lambda} \right]^{1/\zeta} z(n,t) \tag{100}$$

Define $r_t \equiv \frac{\mu_{K,t}}{\mu_{Y,t}}$ and $w_t \equiv \frac{\mu_{L,t}}{\mu_{Y,t}}$ for convenience. Labor feasibility constraint implies:

$$L_t = \int \frac{\lambda}{w_t} y(n,t) dn \tag{101}$$

$$L_t = \frac{\lambda}{w_t} \left[\left(\frac{\kappa}{r_t + \delta} \right)^{\kappa} \left(\frac{\lambda}{w_t} \right)^{\lambda} \right]^{1/\zeta} \int z_t dZ_t(z_t) \tag{102}$$

$$w_t = \lambda \left(\frac{\kappa}{r_t + \delta} \right)^{\frac{\kappa}{\lambda+\zeta}} L_t^{-\frac{\zeta}{\lambda+\zeta}} \tilde{z}_t \tag{103}$$

$$w_t = \lambda \left(\frac{\kappa}{r_t + \delta} \right)^{\frac{\kappa}{\lambda+\zeta}} \tilde{z}_t \tag{104}$$

where the last line comes from the normalization $L_t = 1, \forall t$. Next, consider the dynamic problem of choosing how much physical capital to save for the next period. The first order conditions for C_t and K_{t+1} are given by:

$$\frac{\partial \mathcal{L}}{\partial C_t} = \beta^t C_t^{-\omega} - \mu_{Y,t} = 0, \forall t \tag{105}$$

$$\frac{\partial \mathcal{L}}{\partial K_{t+1}} = -\mu_{Y,t} + \mu_{Y,t+1} + \mu_{K,t+1} = 0, \forall t \tag{106}$$

Combining the two, we obtain the standard Euler equation:

$$\beta^t C_t^{-\omega} = \beta^{t+1} C_{t+1}^{-\omega} + r_{t+1} \beta^{t+1} C_{t+1}^{-\omega}, \forall t \tag{107}$$

$$\frac{1}{1 + r_{t+1}} = \beta \left(\frac{C_{t+1}}{C_t} \right)^{-\omega}, \forall t \tag{108}$$

As mentioned, we are interested in a balanced growth path allocation. Assume that aggregate variables grow at the gross rate $G_{\zeta} = (1 + g_z)^{\zeta/(\lambda+\zeta)}$ as in the competitive equilibrium case. Then we have:

$$r \equiv r_{t+1} = \beta^{-1} G_{\zeta}^{\omega} - 1, \forall t \tag{109}$$

Hence, the output of firm n at time t becomes:

$$\begin{aligned} y(n,t) &= \left[\left(\frac{\kappa}{r+\delta}\right)^{\kappa}\left(\frac{\lambda}{w_t}\right)^{\lambda}\right]^{1/\zeta} z(n,t) && (110)\\ &= \left(\frac{\kappa}{r+\delta}\right)^{\frac{\kappa}{1-\kappa}} \frac{z(n,t)}{\bar{z}_t^{\lambda/(\zeta+\lambda)}} && (111)\\ &= \left(\frac{\kappa}{G_\zeta^\omega \beta^{-1} - 1 + \delta}\right)^{\frac{\kappa}{1-\kappa}} \hat{z}(n,t) && (112)\\ &= \frac{\pi}{\zeta}\hat{z}(n,t) && (113)\end{aligned}$$

where $\pi \equiv \zeta \left(\frac{\kappa}{G_\zeta^\omega \beta^{-1}-1+\delta}\right)^{\frac{\kappa}{1-\kappa}}$ is a time-invariant constant. Then aggregate output Y_t is simply:

$$Y_t = \int \frac{\pi}{\zeta}\hat{z}(n,t)dn = \frac{\pi}{\zeta}\tilde{z}_t \qquad (114)$$

We are left with the dynamic innovation decision. This is more delicate, as the choice of innovation probability $i(n,t)$ influences the allocation through its effects on $z(n,t+T), \forall T \in \mathbb{Z}^{++}$. This, in turn has two effects: (1) the direct effect on the future production of firm n, $y(n,t+T), \forall T \in \mathbb{Z}^{++}$, and (2) the indirect effect of positive technological spillovers due to increasing average firm productivity $\bar{z}_{t+T}, \forall T \in \mathbb{Z}^{++}$. We will first show that $i(n,t) \equiv i_t, \forall n, \forall t$. From the law of motion of firm productivity, we have:

$$\begin{aligned} \mathbb{E}_t[z(n,t+T)] &= z(n,t) + \gamma\bar{z}_t\mathbb{E}_t[\mathbb{I}(n,t)] + \gamma\mathbb{E}_t\left[\sum_{\hat{t}=t+1}^{T} \bar{z}_{\hat{t}}\mathbb{I}(n,\hat{t})\right], \forall t, \forall T \in \mathbb{Z}^{++} && (115)\\ \mathbb{E}_t[z(n,t+T)] &= z(n,t) + \gamma\bar{z}_t i(n,t) + \gamma\mathbb{E}_t\left[\sum_{\hat{t}=t+1}^{T} \bar{z}_{\hat{t}}\mathbb{I}(n,\hat{t})\right], \forall t, \forall T \in \mathbb{Z}^{++} && (116)\\ \frac{\partial \mathbb{E}_t[z(n,t+T)]}{\partial i(n,t)} &= \gamma\bar{z}_t, \forall t, \forall T \in \mathbb{Z}^{++} && (117)\end{aligned}$$

Notice that the term does not depend on the value of $z(n,t+T)$, but only $\bar{z}_t$. This is due to the additive structure of the law of motion. Now, focus on the direct effect on the future production of firm n at time $t+T$:

$$\begin{aligned} \frac{\partial \mathbb{E}_t[y(n,t+T)]}{\partial i(n,t)} &= \frac{\partial \mathbb{E}_t\left[\frac{\pi}{\zeta}\frac{z(n,t+T)}{\bar{z}_{t+T}^{\lambda/(\zeta+\lambda)}}\right]}{\partial i(n,t)} && (118)\\ &= \frac{\pi}{\zeta\bar{z}_{t+T}^{\lambda/(\zeta+\lambda)}}\frac{\partial \mathbb{E}_t[z(n,t+T)]}{\partial i(n,t)} && (119)\\ &= \frac{\pi}{\zeta\bar{z}_{t+T}^{\lambda/(\zeta+\lambda)}}\gamma\bar{z}_t && (120)\end{aligned}$$

Then:

$$
\begin{aligned}
\frac{\partial}{\partial i(n,t)}\mathbb{E}_t\left[\sum_{T=1}^{\infty}\mu_{Y,T}y(n,t+T)\right] &= \sum_{T=1}^{\infty}\mu_{Y,t+T}\frac{\pi}{\zeta\bar{z}_{t+T}^{\lambda/(\zeta+\lambda)}}\gamma\bar{z}_t &(121)\\
&= \frac{\pi\gamma\bar{z}_t}{\zeta}\sum_{T=1}^{\infty}\frac{\beta^{t+T}C_{t+T}^{-\omega}}{\bar{z}_{t+T}^{\lambda/(\zeta+\lambda)}} &(122)\\
&= \frac{\pi\gamma\bar{z}_t}{\zeta}\frac{\beta^t C_t^{-\omega}}{\bar{z}_t^{\lambda/(\zeta+\lambda)}}\sum_{T=1}^{\infty}\left(\frac{\beta G_\zeta^{-\omega}}{G_\lambda}\right)^T &(123)\\
&= \frac{\pi\gamma\mu_{Y,t}\tilde{z}_t}{\zeta}\sum_{T=1}\left(\frac{1}{(1+r)G_\lambda}\right)^T &(124)\\
&= \frac{\pi\gamma\mu_{Y,t}\tilde{z}_t}{\zeta}\left(1-\frac{1}{(1+r)G_\lambda}\right)^{-1} &(125)\\
&= \frac{\gamma v_1^{\text{nf}}}{\zeta}\mu_{Y,t}\tilde{z}_t &(126)
\end{aligned}
$$

First, notice that the term does not depend on n. Second, the expression is very similar to the marginal benefit from innovation to a private firm in the competitive equilibrium. We have an additional factor $1/\zeta$, since we are looking at total output of the firm as opposed to its profits. Next, we consider the costs of increasing the innovation probability $i(n,t)$. The first order condition with respect to X_t delivers $\frac{\partial\mathcal{L}}{\partial X_t} = -\mu_{Y,t}+\mu_{X,t} = 0$, so $\mu_{X,t} = \mu_{Y,t}, \forall t$. Then we have:

$$
\frac{\partial}{\partial i(n,t)}\left[-\mu_{X,t}\hat{C}(i(n,t))\tilde{z}_t\right] = -\chi\frac{i(n,t)}{1-i(n,t)}\mu_{Y,t}\tilde{z}_t \tag{127}
$$

So the cost does not depend on n either; and it is multiplied by the same factor $\mu_{Y,t}\tilde{z}_t$ as the marginal benefit from innovation from the direct effect on production. Since the direct benefit, the indirect benefit, and the cost are all independent of n, we conclude $i(n,t) = i_t, \forall n, \forall t$. Then we can write the aggregate law of motion for average productivity level as:

$$
\begin{aligned}
\bar{z}_{t+1} &= \bar{z}_t + \gamma\bar{z}_t i_t &(128)\\
\Rightarrow g_{z,t} &= \gamma i_t &(129)
\end{aligned}
$$

Along a balanced growth path, the growth rate is constant, so we have $g_z = \gamma i$. With all these results, we can restate the social planner's problem as follows:

$$
\begin{aligned}
\max_{i\in[0,1]} & \quad \left\{\frac{C_0^{1-\omega}}{(1-\omega)(1-\beta G_\zeta^{1-\omega})}\right\}\text{, such that} &(130)\\
C_0 &= \left[\frac{\pi}{\zeta}-\frac{\pi}{\zeta}\frac{\kappa}{r+\delta}(G_\zeta-1+\delta)-\hat{C}(i)\right]\tilde{z}_0 &(131)\\
G_\zeta &= (1+\gamma i)^{\zeta/(\lambda+\zeta)} &(132)\\
\pi &= \zeta\left(\frac{\kappa}{G_\zeta^\omega\beta^{-1}-1+\delta}\right)^{\frac{\kappa}{1-\kappa}} &(133)\\
r &= \beta^{-1}G_\zeta^\omega - 1 &(134)
\end{aligned}
$$

All the constraints can be plugged into the objective function, so we have one equation to maximize by choosing $i\in[0,1]$ with no other constraints. As expected, the only difference of the social planner's allocation from the competitive equilibrium allocation is due to the social planner's internalization of the positive spillover effects of innovation. The physical capital and labor allocations between the firms with different productivities are essentially the same.

A.3 Determination of the Compensation of the CEO with Flexible Total Compensation

In this section, we drop the last constraint that requires the present discounted value of the expected payments to the CEO to be equal to $\underline{\mathrm{U}}$. Therefore both the composition and the level of the payment are endogenously determined.

$$\max_{s\geq 0, o\in[0,1]} \left\{ \eta \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\tilde{z}_t^{1-\omega}\right)\right] + (1-\eta)\mathbb{E}\left[V(z_0,\Theta_0) - \sum_{t=0}^{\infty}\frac{c_t}{\prod_{T=1}^{t}(1+r_T)}\right]\right\}, \text{such that} \tag{135}$$

$$c_t = s\tilde{z}_t + o\max\{0, V(z_t,\Theta_t) - (1+r_{t-1})S(z_{t-1},\Theta_{t-1})\}, \forall t \tag{136}$$

$$i_t = \hat{i}(s,o) \tag{137}$$

First, notice that given $i_t = \hat{i}(s,o)$, the expected utility of the CEO can be written as

$$\mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\tilde{z}_t^{1-\omega}\right)\right] \tag{138}$$

$$= \sum_{t=0}^{\infty}(\beta G_\zeta^{1-\omega})^t\left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right]\tilde{z}_0^{1-\omega} \tag{139}$$

$$= \frac{1}{1-\beta G_\zeta^{1-\omega}}\left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right]\tilde{z}_0^{1-\omega} \tag{140}$$

Next, the expected utility of the shareholders becomes

$$\mathbb{E}\left[V(z_0,\Theta_0) - \sum_{t=0}^{\infty}\frac{c_t}{\prod_{T=1}^{t}(1+r_T)}\right] \tag{141}$$

$$= v_1\hat{z}_0 + v_2(\hat{i}(s,o))\tilde{z}_0 - \mathbb{E}\left[\sum_{t=0}^{\infty}\frac{c_t}{(1+r)^t}\right] \tag{142}$$

$$= v_1\hat{z}_0 + v_2(\hat{i}(s,o))\tilde{z}_0 - \frac{1+r}{1+r-G_\zeta}\left[s + \frac{o\gamma v_1}{G_\zeta}\hat{i}(s,o)(1-\hat{i}(s,o))\right]\tilde{z}_0 \tag{143}$$

The first term is independent of the choice of s or o; so it can be moved out of the maximization. Notice that the real interest rate is constant in the balanced growth path equilibrium. The maximization problem has two choice variables: s and o. Since the domain of o is compact, it makes sense to search over the values of $o \in [0,1]$ which maximizes the objective function. Putting all components together, we have:

$$\max_{s\geq 0, o\in[0,1]} \left\{ \frac{\eta\tilde{z}_0^{1-\omega}}{1-\beta G_\zeta^{1-\omega}}\left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right] \right.$$
$$\left. +(1-\eta)\left(v_2(\hat{i}(s,o)) - \frac{1+r}{1+r-G_\zeta}\left[s + \frac{o\gamma v_1}{G_\zeta}\hat{i}(s,o)(1-\hat{i}(s,o))\right]\right)\tilde{z}_0\right\} \tag{144}$$

Without loss of generality, set $\bar{z}_0 = 1$, which implies $\tilde{z}_0 = \tilde{z}_0^{1-\omega} = 1$.

Algorithm: Maximize equation (144) by choosing $s \geq 0$ and $o \in [0,1]$ subject to equation (68).

A.4 Determination of the Compensation of the CEO using Standard Principal-Agent Framework

In this section, we change the last constraint that requires the present discounted value of the expected payments to the CEO to be equal to $\underline{\mathrm{U}}$ with a CEO utility constraint. This turns the problem into a standard principal-agent problem.

$$\max_{s\geq 0, o\in[0,1]} \left\{\eta\mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\tilde{z}_t^{1-\omega}\right)\right] + (1-\eta)\mathbb{E}\left[V(z_0,\Theta_0) - \sum_{t=0}^{\infty}\frac{c_t}{\prod_{T=1}^{t}(1+r_T)}\right]\right\}, \text{such that} \tag{145}$$

$$c_t = s\tilde{z}_t + o\max\{0, V(z_t,\Theta_t) - (1+r_{t-1})S(z_{t-1},\Theta_{t-1})\}, \forall t \tag{146}$$

$$i_t = \hat{i}(s,o) \tag{147}$$

$$\underline{\mathrm{U}} = \mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\tilde{z}_t^{1-\omega}\right)\right] \tag{148}$$

This turns the first term in the objective function into a constant $\eta\underline{\mathrm{U}}$; so it can be moved out of the maximization. Likewise, the factor $(1-\eta) > 0$ in front of the expression for shareholder utility also becomes inconsequential, and can be moved out of the maximization.

First, notice that given $i_t = \hat{i}(s,o)$, the expected utility of the CEO can be written as

$$\mathbb{E}\left[\sum_{t=0}^{\infty}\beta^t\left(\frac{c_t^{1-\omega}}{1-\omega} - v(i_t)\tilde{z}_t^{1-\omega}\right)\right] \tag{149}$$

$$= \sum_{t=0}^{\infty}(\beta G_\zeta^{1-\omega})^t\left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right]\tilde{z}_0^{1-\omega} \tag{150}$$

$$= \frac{1}{1-\beta G_\zeta^{1-\omega}}\left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta}\right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o))\right]\tilde{z}_0^{1-\omega} \tag{151}$$

Since the expected utility of the CEO must equal $\underline{\mathrm{U}}$, choosing either s or o completely determines the other. Next, the expected utility of the shareholders becomes

$$\mathbb{E}\left[V(z_0,\Theta_0) - \sum_{t=0}^{\infty}\frac{c_t}{\prod_{T=1}^{t}(1+r_T)}\right] \tag{152}$$

$$= v_1\hat{z}_0 + v_2(\hat{i}(s,o))\tilde{z}_0 - \mathbb{E}\left[\sum_{t=0}^{\infty}\frac{c_t}{(1+r)^t}\right] \tag{153}$$

$$= v_1\hat{z}_0 + v_2(\hat{i}(s,o))\tilde{z}_0 - \frac{1+r}{1+r-G_\zeta}\left[s + \frac{o\gamma v_1}{G_\zeta}\hat{i}(s,o)(1-\hat{i}(s,o))\right]\tilde{z}_0 \tag{154}$$

The first term is independent of the choice of s or o; so it can be moved out of the maximization. Notice that the real interest rate is constant in the balanced growth path equilibrium. The maximization problem has two choice variables: s and o, but since choosing one completely determines the other, we can restict the attention to choosing o only. Since the domain of o is compact, it makes sense to search over the values of $o \in [0,1]$ which maximizes the objective function. Putting all components together, we have:

$$\max_{o\in[0,1]} \quad \left\{ v_2(\hat{i}(s,o)) - \frac{1+r}{1+r-G_\zeta}\left[s + \frac{o\gamma v_1}{G_\zeta}\hat{i}(s,o)(1-\hat{i}(s,o)) \right] \right\}, \text{such that} \tag{155}$$

$$\underline{\mathrm{U}} \;=\; \frac{1}{1-\beta G_\zeta^{1-\omega}}\left[\frac{\hat{i}(s,o)}{1-\omega}\left(s + \frac{o\gamma v_1(1-\hat{i}(s,o))}{G_\zeta} \right)^{1-\omega} + \frac{(1-\hat{i}(s,o))s^{1-\omega}}{1-\omega} - v(\hat{i}(s,o)) \right] \tilde{z}_0^{1-\omega} \tag{156}$$

Without loss of generality, set $\bar{z}_0 = 1$, which implies $\tilde{z}_0 = \bar{z}_0^{1-\omega} = 1$.

Algorithm: Maximize equation (155) by choosing $o \in [0,1]$ subject to equations (68) and (156).

A.5 CEO's Decision Problem with Stocks (Risk Neutral)

Each firm in the model has a CEO who chooses the levels of production inputs k and l, as well as the probability of successful innovation i. The CEO is risk-neutral in terms of consumption, discounts the future at rate β, and receives disutility from exerting effort to oversee the firm's innovation efforts. The preferences are represented by:

$$U(\vec{c},\vec{i}) = \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \left(c_t - v(i_t)\tilde{z}_t \right) \right] \tag{157}$$

with $\vec{c} = \{c_t\}_{t=0}^{\infty}$, $\vec{i} = \{i_t\}_{t=0}^{\infty}$, $\beta \in (0,1)$, and $v(i)$ captures the disutility from exerting effort $(v'(i) \geq 0, v''(i) > 0)$.[17]

CEO compensation consists of three components: Salary s_t which is not state-contingent, dividend payments from stocks d_t which depend on the productivity of the firm z_t and the aggregate state of the economy Θ_t, and stock options o_t which has a state-contingent payoff. The compensation of the CEO of a firm in period t is written as:

$$c_t = s_t\tilde{z}_t + d_t(\Pi(z,\Theta) - \hat{C}(i)\tilde{z}) + o_t \max\left\{0, V(z_t,\Theta_t) - (1+r_{t-1})S(z_{t-1},\Theta_{t-1})\right\} \tag{158}$$

In this equation, s_t denotes the (normalized) salary received by the CEO, whereas d_t denotes the fraction of the firm's dividends that are paid to the CEO as a result of his stock ownership. Finally, o_t denotes the share options granted to the CEO as a fraction of the total shares of the firm. The third term has a positive value if the value of the firm next period exceeds the strike price this period, and is zero otherwise. Therefore, the option part of the compensation of the CEO is convex in the future value of the firm.

Assuming the value function of the firm given a time-invariant innovation decision i is given by $V(i,z,\hat{z}) = v_1\hat{z} + v_2(i)\tilde{z}$, the sequential problem of the CEO along a balanced growth path equilibrium is given by:

$$U(\vec{c},\vec{i}) = \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \left(s\tilde{z}_t + d(\pi\hat{z}_t - \hat{C}(i)\tilde{z}_t) + \frac{o\gamma v_1}{G_\zeta}\max\{0, \mathbb{I}_{t-1} - i_{t-1}\}\tilde{z}_t - v(i_t)\tilde{z}_t \right) \right] \tag{159}$$

[17] The multiplicative term $\tilde{z}_t$ is to make sure that the disutility from the innovation effort does not shrink over time along the balanced growth path. It can be thought of as the value of time spent on leisure increasing in tandem with aggregate productivity.

The first order condition with respect to i_t is given by:

$$d\hat{C}'(i_t) + v'(i_t) = \left[d\pi\gamma \sum_{T=1}^{\infty} \left(\frac{\beta}{G_\lambda}\right)^T + \beta o \gamma v_1 (1 - 2i_t)\right] \tag{160}$$

$$d\hat{C}'(i_t) + v'(i_t) = \left[d\pi\gamma \frac{\beta}{G_\lambda - \beta} + \beta o \gamma v_1 (1 - 2i_t)\right] \tag{161}$$

Notice that all the terms except i_t are time-independent. The unique solution to this equation pins down $\hat{i}$. On the left-hand-side, the first term originates from the cost of increasing innovation that the CEO internalizes due to his stock holdings, and the second term comes from the disutility of innovation effort. On the right-hand-side, the first term is the effect of increasing firm's productivity: Since the productivity increase is permanent, the CEO enjoys increased future dividends, but this positive impact tapers off as the average productivity in the economy grows over time and the contribution of the one-time jump to the relative productivity of the firm diminishes. The second term originates from the stock options granted to the CEO, delivering a positive payoff only when the innovation succeeds.

B Tables and Figures

Table 1: The Impact of Institutional Ownership on Firm Innovation

	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	3.170	2.956	4.192
	(0.387)***	(0.360)***	(0.495)***
size	0.257	0.375	0.460
	(0.060)***	(0.056)***	(0.084)***
log(R&D stock)	0.903	0.950	2.215
	(0.066)***	(0.066)***	(0.096)***
leverage	-1.548	-1.769	-2.029
	(0.349)***	(0.337)***	(0.423)***
age	-0.048	-0.030	0.026
	(0.007)***	(0.007)***	(0.013)**
CV price	-0.521	-0.318	-0.350
	(0.452)	(0.388)	(0.484)
R^2	0.11	0.16	0.28
N	55,013	55,013	55,013

Notes: The baseline tail innovation index measures the fraction of patents by each firm at each year with citations above the $90th$ percentile. The average patent citations of a company in a year is computed as the average number of citations received by the patents the company applied for in that year. We also use the originality indices devised by Hall, Jaffe, and Trajtenberg (2001), which is calculated as the dispersion of the citations a patent makes to other patents across different technology classes. The patent classes used in the baseline analysis are the two-digit International Patent Classification (IPC) classes. The average originality of a firm's innovation in a given year is the average originality of all the patents the firm applied for in that year. See Section 2.2 for more detailed variable definitions. Other control variables are firm size, firm age, the coefficient of variation of firm stock price, the firm's R&D stock, and leverage. Firm size is measured by the firm's total assets. Firm R&D stock is computed using permanent inventory method following the literature. Leverage is defined as total debt to asset ratio. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 2: The Impact of Institutional Ownership on Managerial Compensation Structure

	deferred ratio	option/income ratio	share/income ratio
institutional ownership	0.265	0.231	0.026
	(0.014)***	(0.018)***	(0.008)***
size	0.034	0.019	0.010
	(0.003)***	(0.004)***	(0.002)***
log(R&D stock)	0.015	0.017	-0.001
	(0.002)***	(0.002)***	(0.001)
leverage	-0.065	-0.043	0.012
	(0.014)***	(0.019)**	(0.008)
age	-0.001	-0.002	0.000
	(0.000)***	(0.000)***	(0.000)***
CV price	0.041	0.116	-0.014
	(0.018)**	(0.026)***	(0.010)
R^2	0.22	0.22	0.13
N	21,741	16,425	16,425

Notes: We define the empirical measures of the compensation components to be consistent with the model as follows. Equity compensation is defined as the fraction of equity held by the manager, i.e. the shares owned by the CEO, excluding options, divided by the common shares outstanding, as reported in ExecuComp. For option compensation, we use the CEO's granted options value calculated using Black-Scholes formula. Finally, salary compensation is defined following Dittmann and Maug (2007) as the sum of salary and bonus. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 3: The Impact of Managerial Compensation Structure on Firm Innovation

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	1.473	1.308	
	(0.417)***	(0.423)***	
size	0.459	0.352	0.392
	(0.095)***	(0.110)***	(0.160)**
log(R&D stock)	0.852	0.861	0.806
	(0.096)***	(0.097)***	(0.122)***
leverage	-1.658	-1.613	-2.559
	(0.601)***	(0.632)**	(0.935)***
age	-0.054	-0.052	-0.047
	(0.010)***	(0.010)***	(0.013)***
CV price	-1.415	-1.139	0.773
	(0.774)*	(0.821)	(1.293)
institutional ownership		1.307	0.401
		(0.606)**	(0.935)
option/income ratio			1.322
			(0.565)**
share/income ratio			0.768
			(0.767)
R^2	0.15	0.15	0.18
N	21,787	21,506	16,371

Notes: Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 4: The Impact of Managerial Compensation Structure on Firm Innovation: Average Patent Quality

	Average citations of patents	Average citations of patents	Average citations of patents
deferred ratio	1.112	1.000	
	(0.423)***	(0.427)**	
size	0.319	0.252	0.440
	(0.087)***	(0.101)**	(0.151)***
log(R&D stock)	0.899	0.907	0.856
	(0.092)***	(0.093)***	(0.119)***
leverage	-1.865	-1.921	-3.644
	(0.674)***	(0.721)***	(1.129)***
age	-0.033	-0.032	-0.031
	(0.009)***	(0.009)***	(0.012)***
CV price	-0.663	-0.565	1.736
	(0.660)	(0.688)	(1.175)
institutional ownership		0.883	1.376
		(0.559)	(0.903)
option/income ratio			1.026
			(0.619)*
share/income ratio			1.157
			(0.759)
R^2	0.23	0.23	0.24
N	21,787	21,506	16,371

Notes: Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 5: The Impact of Managerial Compensation Structure on Firm Innovation: Average Originality

	Average patent originality	Average patent originality	Average patent originality
deferred ratio	1.472	1.086	
	(0.396)***	(0.406)***	
size	0.849	0.663	0.537
	(0.129)***	(0.145)***	(0.203)***
log(R&D stock)	1.985	1.997	1.821
	(0.137)***	(0.140)***	(0.175)***
leverage	-2.842	-2.738	-2.466
	(0.741)***	(0.789)***	(1.109)**
age	0.028	0.031	0.049
	(0.017)*	(0.017)*	(0.021)**
CV price	0.411	0.957	1.093
	(0.857)	(0.900)	(1.238)
institutional ownership		2.511	1.185
		(0.729)***	(1.040)
option/income ratio			1.207
			(0.494)**
share/income ratio			1.580
			(1.237)
R^2	0.36	0.36	0.39
N	21,787	21,506	16,371

Notes: Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 6: The Impact of Managerial Compensation and Innovation on Firm Value

	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio
institutional ownership	0.669				
	(0.067)***				
size	-0.253	-0.195	-0.197	-0.193	-0.206
	(0.018)***	(0.012)***	(0.012)***	(0.012)***	(0.013)***
log(R&D stock)	0.162	0.117	0.111	0.112	0.076
	(0.013)***	(0.010)***	(0.010)***	(0.010)***	(0.011)***
leverage	-0.057	-0.281	-0.273	-0.292	-0.286
	(0.105)	(0.070)***	(0.070)***	(0.071)***	(0.071)***
age	-0.009	-0.007	-0.007	-0.008	-0.008
	(0.001)***	(0.001)***	(0.001)***	(0.001)***	(0.001)***
CV price	0.050	0.315	0.311	0.325	0.319
	(0.086)	(0.069)***	(0.068)***	(0.069)***	(0.069)***
tail(10/90) innovation		0.008			
		(0.001)***			
avg patent quality			0.012		
			(0.001)***		
avg originality				0.006	
				(0.001)***	
total patent number					0.149
					(0.015)***
R^2	0.17	0.18	0.18	0.18	0.18
N	54,698	97,531	97,531	97,531	97,531

Notes: Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 7: Instrumenting Institutional Ownership with S&P 500 Inclusion and Share Turnover

	Deferred ratio	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	0.748	35.044	30.507	29.060
	(0.061)***	(11.010)***	(10.148)***	(12.559)**
size	-0.006	-1.999	-1.575	-1.300
	(0.006)	(0.782)**	(0.718)**	(0.890)
log(R&D stock)	0.020	1.213	1.217	2.457
	(0.002)***	(0.137)***	(0.123)***	(0.156)***
leverage	-0.029	1.843	1.162	0.617
	(0.017)*	(1.253)	(1.153)	(1.396)
age	-0.001	-0.125	-0.097	-0.034
	(0.000)***	(0.029)***	(0.027)***	(0.033)
CV price	0.135	2.814	2.565	2.253
	(0.023)***	(1.264)**	(1.145)**	(1.441)
instrument	share turnover	S&P 500	S&P 500	S&P 500
N	21,741	55,013	55,013	55,013

Notes: Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 8: Institutional Ownership and Deferred Ratio – Direction of Causality

	Deferred ratio	Institutional ownership
lagged inst. ownership	0.148	0.837
	(0.009)***	(0.004)***
lagged deferred ratio	0.281	0.018
	(0.008)***	(0.003)***
R^2	0.27	0.81
N	21,169	23,288

Notes: Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. Both regressions control for year dummies and a full set of four-digit SIC industry dummies and other covariates in the baseline regressions. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 9: Institutional Ownership and Option/Income Ratio – Direction of Causality

	Option/income ratio	Inst. ownership
lagged inst. ownership	0.163	0.781
	(0.012)***	(0.006)***
lagged option/income ratio	0.252	0.001
	(0.009)***	(0.003)
R^2	0.27	0.77
N	16,047	17,362

Notes: Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. Both regressions control for year dummies and a full set of four-digit SIC industry dummies and other covariates in the baseline regressions. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table 10: Model Parameters and Target Moments

A. Parameter estimates

Parameter	*Value*	*Description*	*Identification*
		External Estimation	
δ	0.069	capital depreciation rate	US NIPA
ς	0.15	productivity share in production	Corrado, Hulten, and Sichel (2009)
κ	0.25	capital share in production	Corrado, Hulten, and Sichel (2009)
λ	0.6	labor share in production	Corrado, Hulten, and Sichel (2009)
ω	2.0	CRRA parameter	Kaplow (2005)
β	0.9815	discount factor	risk free rate
		Internal Estimation	
γ	0.7914	technology spillover	Output growth rate
ν	5.4899	CEO disutility	$corr(innovation, option\, ratio)$.
χ	2.1448	R&D cost	R&D intensity
η_{lb}, η_{ub}	0.0002, 0.2059	lower and upper bound of CEO influence	$corr(innovation, inst\, own), corr(option\, ratio, inst\, own)$
$\underline{U}$	0.3237	CEO outside option	total CEO compensation/market capitalization

B. Moments

Target Moments	Data	Model
$corr(innovation, inst\, own)$	0.6407	0.8697
$corr(innovation, option\, ratio)$	0.9511	0.9802
$corr(option\, ratio, inst\, own)$	0.9440	0.7631
R&D intensity	2.9%	2.81%
Total CEO compensation/market capitalization	0.0033	0.0033
Output growth rate	2%	2%

Notes: Calculations are based an annual sample of firms is from 1990 to 2004 at annual frequency. The estimation is done with SMM, which chooses model parameters by matching the moments from a simulated panel of firms to the corresponding moments from the data. Panel A reports the estimated parameters, Panel B reports the simulated and actual moments. See Section 4.1 for details.

Table 11: Welfare Analysis

	Baseline	Agency friction(50%)	No Agency Friction
Welfare	-26.6103	-25.2979	-22.1764
Ouput growth rate	2.00%	2.25%	3.17%
R&D intensity	2.81%	2.91%	4.85%
Disruptive innovation	0.1313	0.1489	0.2134
Consumption	0.9968	0.9848	0.9265
Welfare change	-	0.0519	0.1999

Notes: This table compares the impact of agency frictions on welfare, output growth rate, R&D intensity, disruptive innovation, consumption and social welfare. The first column reports the baseline model results. The second column reports the results of a counterfactual economy with CEO influence η set to 50% of its value, keeping the value of other parameters the same as in the baseline model. The third column reports the results of the model without any agency frictions.

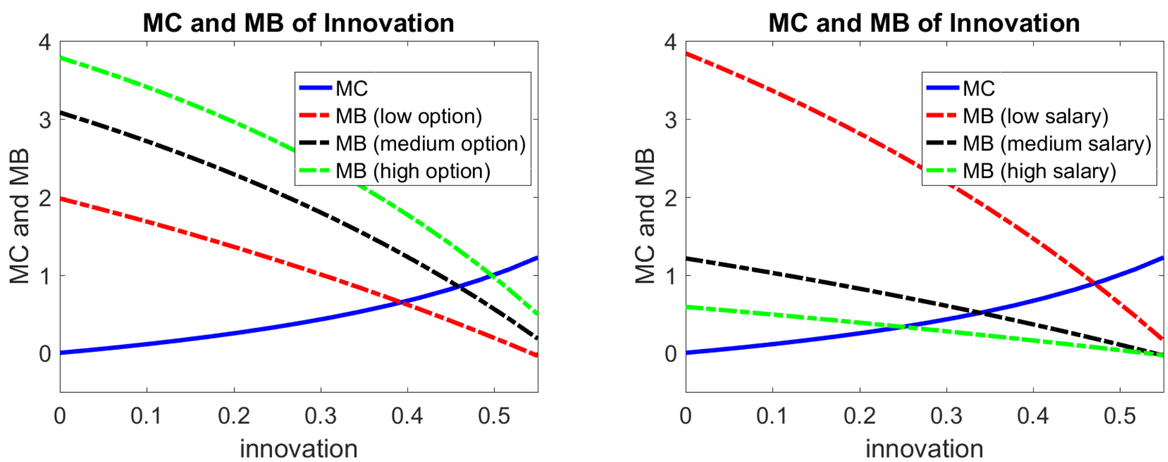

Figure 1: CEO's Innovation Decision

Notes: To better visualize the the tradeoffs the CEO faces in choosing the innovation probability under different contracts (s, o), we plot the marginal benefit and marginal cost of innovation for the CEO in this figure. The marginal cost of the CEO is the disutility from innovation, and depends solely on the disutility parameter ν of the CEO. The left panel depicts the marginal benefit curve under three different levels of stock options: low, medium, and high. Holding salary constant, an increase in stock options in the contract shifts the marginal benefit curve up, inducing the CEO to choose a higher rate of innovation in equilibrium. Similar to the previous exercise, the right panel depicts the marginal benefit curve under three different levels of state-incontingent salary: low, medium, and high. Holding the stock options constant, increasing the level of the salary component results in an income effect. Since the CEO is now wealthier, an increase in the salary reduces the incentives of the CEO to engage in disruptive innovation.

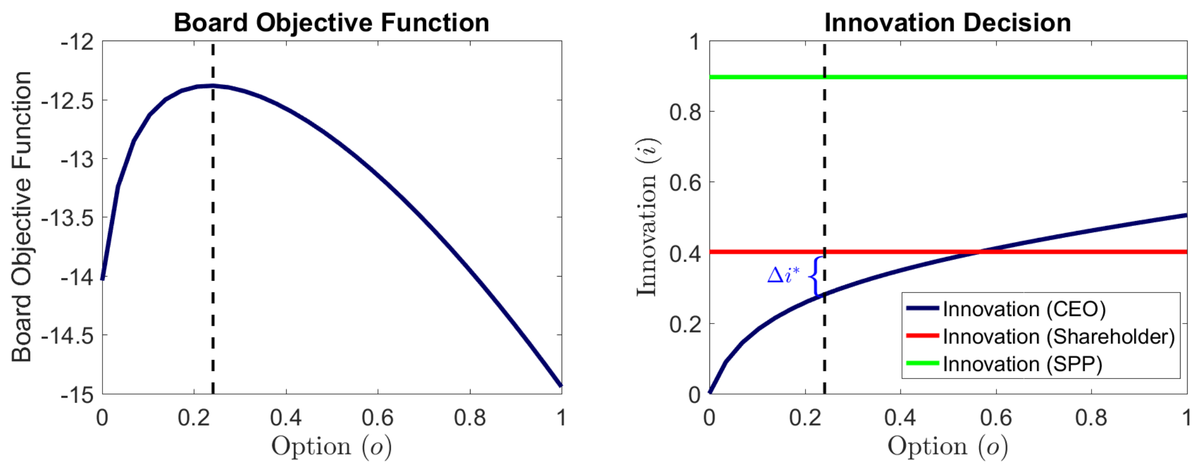

FIGURE 2: EQUILIBRIUM CEO COMPENSATION AND INNOVATION DECISION

Notes: This figure depicts board objective function and the CEO's innovation policy function. The left panel depicts the board objective as a function of the stock options offered to the CEO. The right panel plots the CEO's innovation decision as a function of the stock options as well. The board objective function is maximized at the amount of stock options marked by the dashed line. Given the stock options (and the implied salary) chosen by the board, the manager chooses the innovation level that maximizes his own utility under the contract. This innovation level is lower than the shareholder-optimal innovation level, which is the one the firm would have chosen under the no agency frictions case. Δi captures the efficiency loss. The green line on the right panel depicts the optimal innovation that would be chosen by the social planner. Since the social planner also internalizes the positive externalities resulting from knowledge spillovers, the social planner's optimal innovation rate is much higher than that of the decentralized economy, which implies that there is room for policy intervention such as R&D subsidies. For the details on the calculation of the social planner's allocation, see Section A.2 of the Theory Appendix.

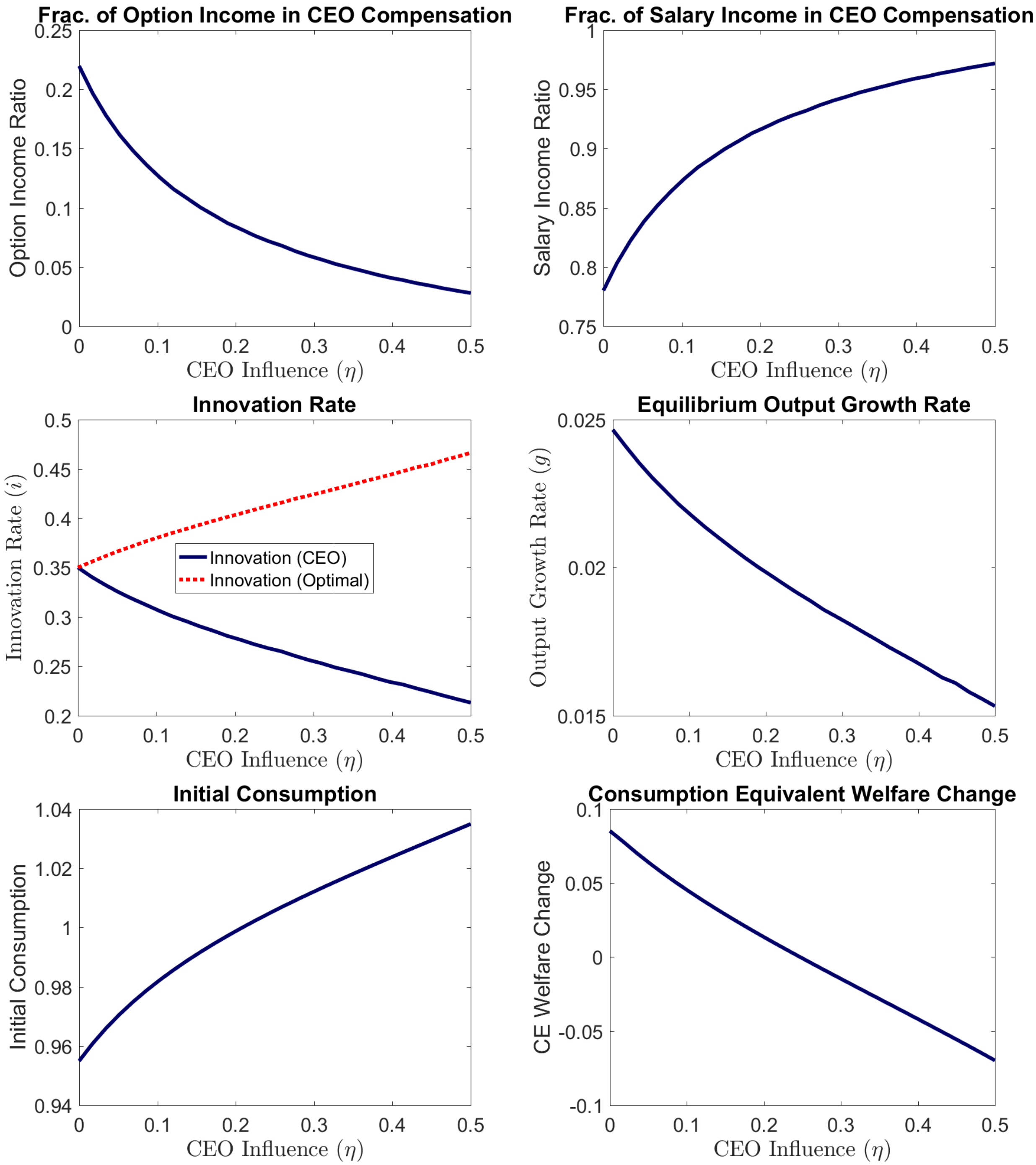

FIGURE 3: COMPARATIVE STATICS: CEO INFLUENCE (η)

Notes: This figure depicts comparative statics under different values of the CEO influence parameter (η). For each panel, we solve and simulate the model 30 times, each time corresponding to a different value of CEO influence while keeping other parameters unchanged. For each of these 30 simulations, we calculate the relevant moments.

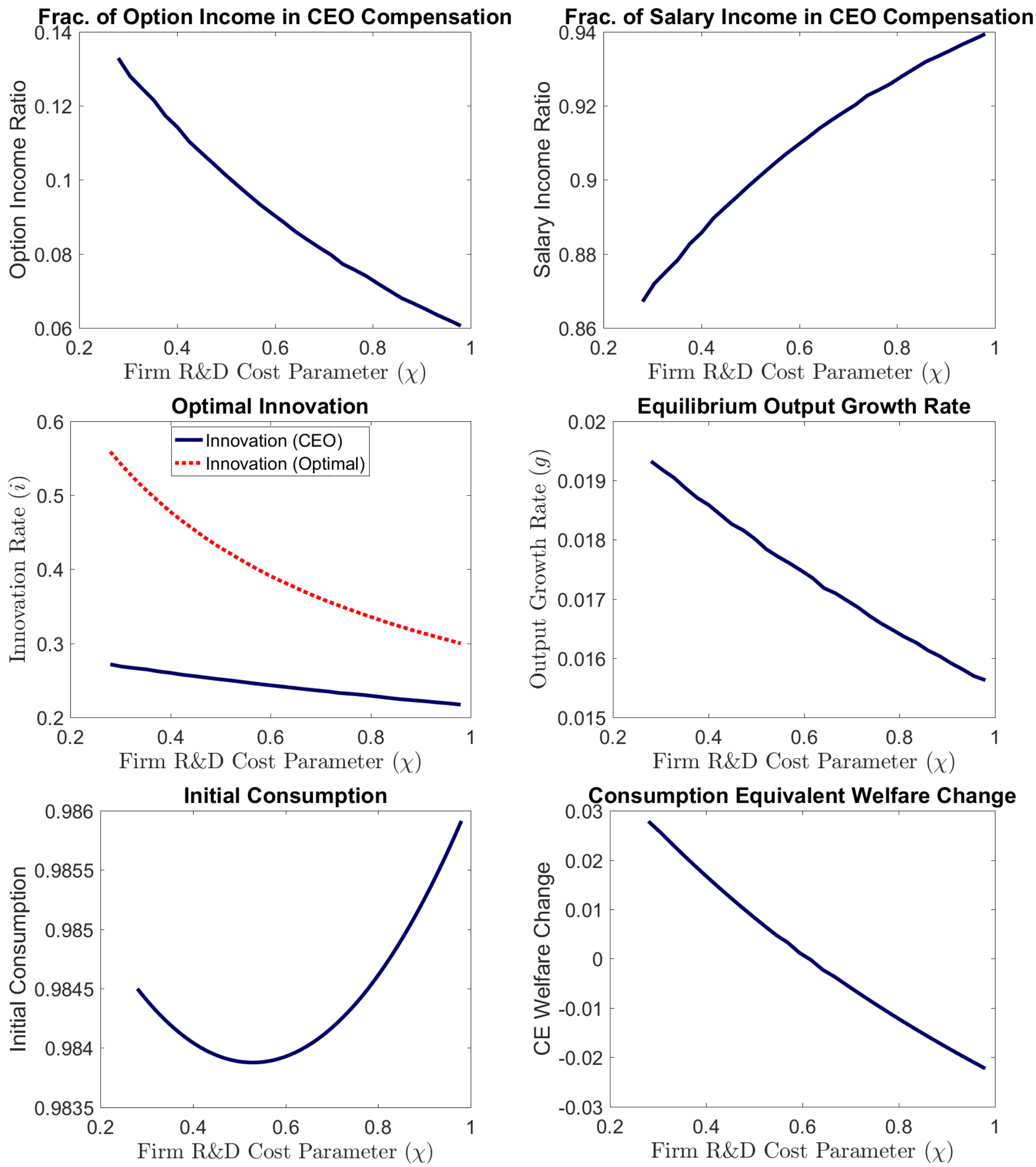

Figure 4: Comparative Statics: Firm's R&D Cost (χ)

Notes: This figure depicts comparative statics under different values of the firm's R&D cost parameter, χ. For each panel, we solve and simulate the model 30 times, each time corresponding to a different value of R&D cost while keeping other parameters unchanged. For each of these 30 simulations, we calculate the relevant moments.

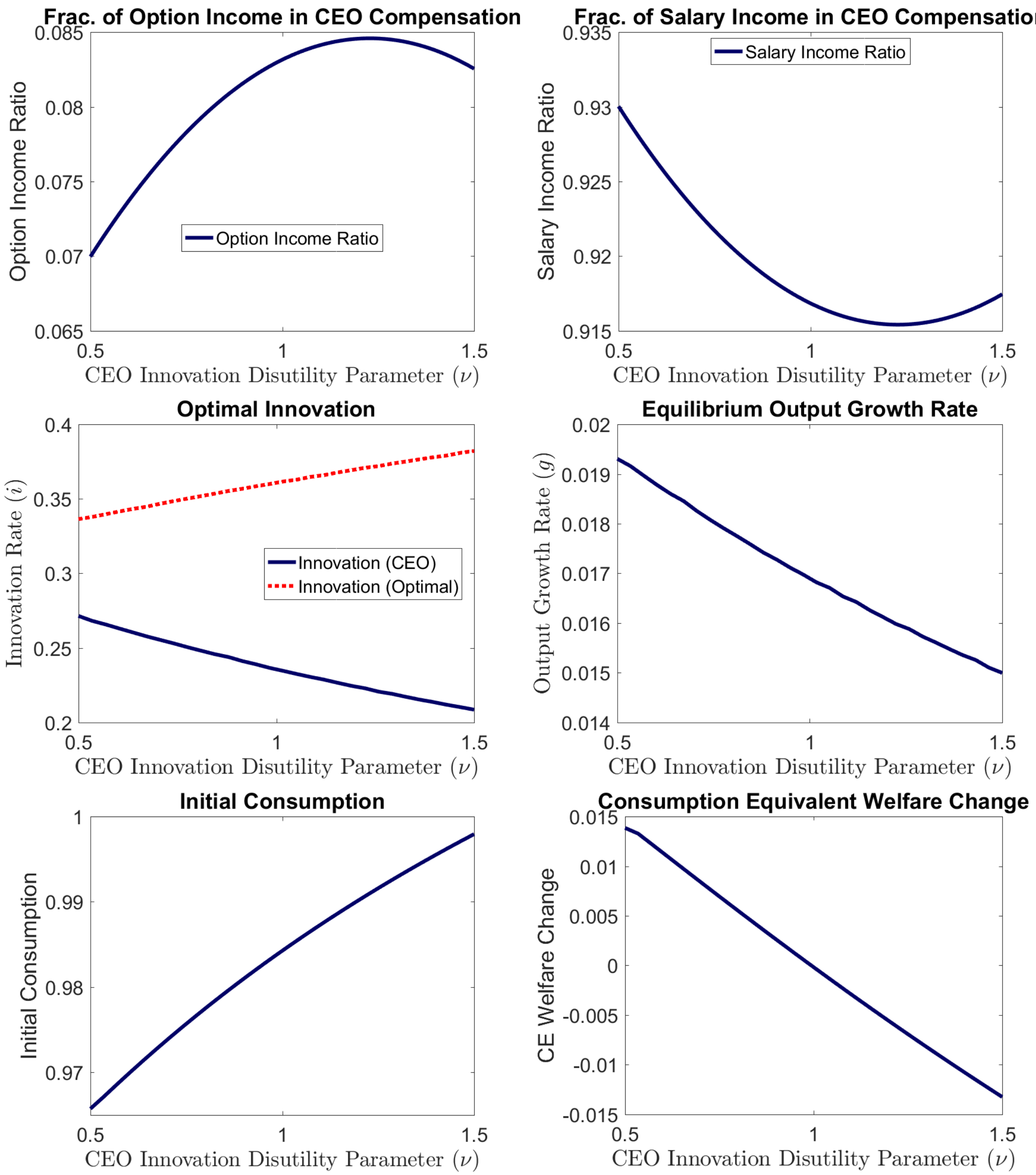

Figure 5: Comparative Statics: CEO's Innovation Disutility (ν)

Notes: This figure depicts comparative statics under different values of the CEO's innovation disutility parameter, ν. For each panel, we solve and simulate the model 30 times, each time corresponding to a different value of CEO's innovation disutility while keeping other parameters unchanged. For each of these 30 simulations, we calculate the relevant moments.

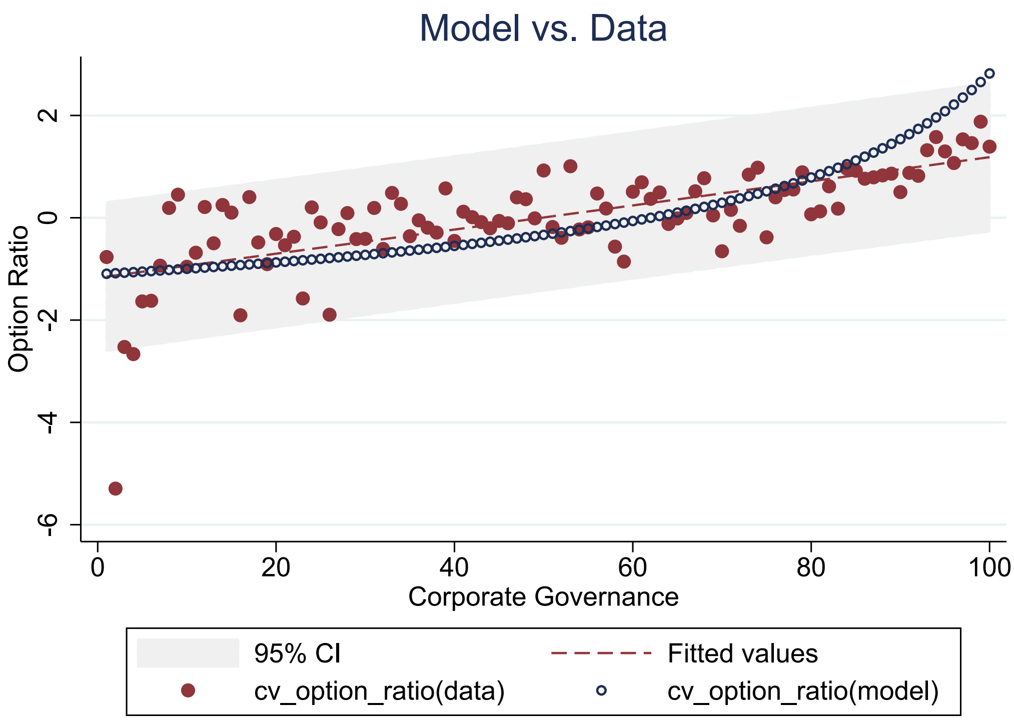

Figure 6: Corporate Governance and CEO Compensation Structure

Notes: This figure depicts the relationship between option ratio and corporate governance index in the data and model. We first divide firms into 100 quantiles based on their institutional ownership. Then for each quantile, we calculate the average option ratio in the CEO compensation contract. Each red dot in the figure represents the value of the mean option ratio for a corporate governance index quantile. The linear fitted value is plotted by the red dashed line. Similarly, the mean option ratio is calculated for each of the 100 different values of CEO influence parameters in the model and is plotted by the blue curve.

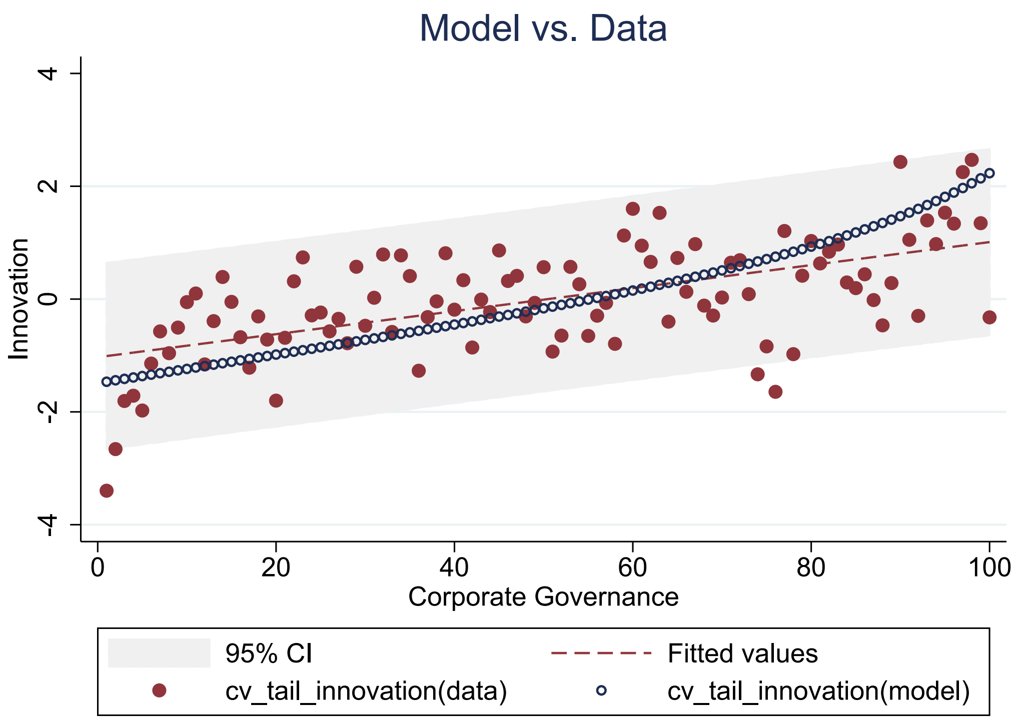

Figure 7: Corporate Governance and Disruptive Innovation

Notes: This figure depicts the relationship between disruptive innovation and corporate governance index in the data and model. We first divide firms into 100 quantiles based on their institutional ownership. Then for each quantile, we calculate the average tail innovation. Each red dot in the figure represents the value of the mean tail innovation for a corporate governance index quantile. The linear fitted value is plotted by the red dashed line. Similarly, the mean tail innovation is calculated for each of the 100 different values of CEO influence parameters in the model and is plotted by the blue curve.

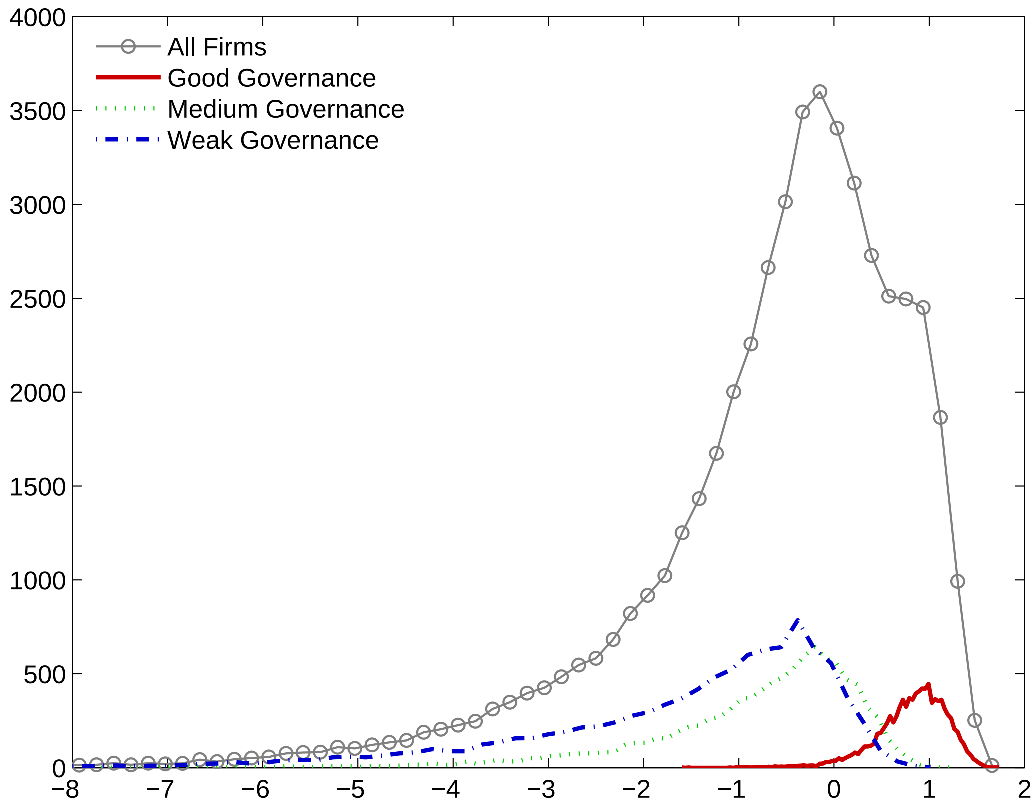

Figure 8: Firm Size Distribution

Notes: This figure depicts the distribution of firm size for different levels of corporate governance based on the simulated firm panel. The model is able to produce a firm size distribution with fat left tail similar to the data. Firms with better corporate governance tend to have a larger size.

Appendix B: Online Materials for "Corporate Governance, Managerial Compensation, and Disruptive Innovation" (Not for Publication)

November 1st, 2017

- *Additional Graphs and Tables* -

Table B1: The Impact of Institutional Ownership on Firm Innovation

	Tail innovations	Average Patent Quality	Average Patent Originality
institutional ownership	4.982	4.742	5.107
	(0.704)***	(0.642)***	(0.796)***
size	0.242	0.369	0.811
	(0.124)*	(0.113)***	(0.156)***
log(R&D stock)	0.699	0.767	1.680
	(0.104)***	(0.099)***	(0.140)***
leverage	-2.466	-2.582	-3.237
	(0.762)***	(0.685)***	(0.843)***
age	-0.098	-0.078	-0.057
	(0.012)***	(0.011)***	(0.018)***
CV price	-1.036	-0.650	-0.280
	(0.926)	(0.774)	(0.910)
R^2	0.09	0.15	0.19
N	28,945	28,945	28,945

Notes: This regression results are based a different subsample of firm-year observations where the firm had at least one patent within the period 1976-2004. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B2: The Impact of Institutional Ownership on Managerial Compensation Structure

	deferred ratio	option/income ratio	share/income ratio
institutional ownership	0.273	0.231	0.022
	(0.019)***	(0.024)***	(0.010)**
size	0.035	0.021	0.008
	(0.004)***	(0.005)***	(0.002)***
log(R&D stock)	0.013	0.014	-0.001
	(0.003)***	(0.003)***	(0.001)
leverage	-0.062	-0.071	0.017
	(0.020)***	(0.026)***	(0.012)
age	-0.001	-0.002	0.000
	(0.000)***	(0.000)***	(0.000)**
CV price	0.080	0.133	-0.024
	(0.025)***	(0.032)***	(0.010)**
R^2	0.23	0.25	0.14
N	13,595	11,004	11,004

Notes: This regression results are based a different subsample of firm-year observations where the firm had at least one patent within the period 1976-2004. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B3: The Impact of Managerial Compensation Structure on Firm Innovation

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	2.320	2.019	
	(0.666)***	(0.675)***	
size	0.466	0.285	0.134
	(0.162)***	(0.174)	(0.237)
log(R&D stock)	0.625	0.651	0.646
	(0.131)***	(0.133)***	(0.156)***
leverage	-1.473	-1.327	-2.078
	(1.045)	(1.054)	(1.393)
age	-0.091	-0.087	-0.077
	(0.015)***	(0.015)***	(0.018)***
CV price	-1.885	-1.346	-0.001
	(1.292)	(1.329)	(1.835)
institutional ownership		2.539	0.932
		(1.010)**	(1.447)
option/income ratio			2.197
			(0.858)**
share/income ratio			1.084
			(1.153)
R^2	0.14	0.15	0.16
N	13,606	13,501	10,980

Notes: This regression results are based a different subsample of firm-year observations where the firm had at least one patent within the period 1976-2004. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B4: The Impact of Managerial Compensation Structure on Firm Innovation: Average Patent Quality

	Average citations of patents	Average citations of patents	Average citations of patents
deferred ratio	1.917	1.672	
	(0.679)***	(0.689)**	
size	0.271	0.135	0.154
	(0.148)*	(0.157)	(0.222)
log(R&D stock)	0.670	0.692	0.708
	(0.119)***	(0.120)***	(0.143)***
leverage	-1.770	-1.723	-2.649
	(1.068)*	(1.103)	(1.568)*
age	-0.061	-0.059	-0.058
	(0.012)***	(0.013)***	(0.015)***
CV price	-0.812	-0.468	1.417
	(1.046)	(1.060)	(1.632)
institutional ownership		1.952	1.682
		(0.907)**	(1.389)
option/income ratio			1.950
			(0.950)**
share/income ratio			1.680
			(1.118)
R^2	0.25	0.25	0.24
N	13,606	13,501	10,980

Notes: This regression results are based a different subsample of firm-year observations where the firm had at least one patent within the period 1976-2004. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B5: The Impact of Managerial Compensation Structure on Firm Innovation: Average Originality

	Average patent originality	Average patent originality	Average patent originality
deferred ratio	1.871	1.277	
	(0.610)***	(0.618)**	
size	1.035	0.805	0.536
	(0.213)***	(0.229)***	(0.295)*
log(R&D stock)	1.571	1.586	1.480
	(0.188)***	(0.190)***	(0.223)***
leverage	-2.930	-2.679	-1.592
	(1.259)**	(1.290)**	(1.640)
age	-0.039	-0.036	-0.000
	(0.023)*	(0.023)	(0.026)
CV price	0.598	1.460	0.729
	(1.367)	(1.399)	(1.697)
institutional ownership		3.825	1.819
		(1.134)***	(1.470)
option/income ratio			1.264
			(0.708)*
share/income ratio			2.757
			(1.741)
R^2	0.25	0.25	0.28
N	13,606	13,501	10,980

Notes: This regression results are based a different subsample of firm-year observations where the firm had at least one patent within the period 1976-2004. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B6: The Impact of Managerial Compensation and Innovation on Firm Value

	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio
institutional ownership	0.476				
	(0.102)***				
size	-0.318	-0.274	-0.276	-0.272	-0.307
	(0.029)***	(0.022)***	(0.022)***	(0.022)***	(0.023)***
log(R&D stock)	0.187	0.148	0.144	0.148	0.096
	(0.018)***	(0.014)***	(0.014)***	(0.014)***	(0.014)***
leverage	-0.196	-0.468	-0.460	-0.490	-0.458
	(0.178)	(0.118)***	(0.118)***	(0.118)***	(0.118)***
age	-0.010	-0.009	-0.008	-0.009	-0.010
	(0.002)***	(0.002)***	(0.002)***	(0.002)***	(0.002)***
CV price	0.062	0.372	0.364	0.386	0.370
	(0.136)	(0.107)***	(0.107)***	(0.108)***	(0.107)***
tail(10/90) innovation		0.006			
		(0.001)***			
avg patent quality			0.009		
			(0.001)***		
avg originality				0.004	
				(0.001)***	
total patent number					0.179
					(0.018)***
R^2	0.20	0.23	0.23	0.23	0.23
N	28,821	51,480	51,480	51,480	51,480

Notes: This regression results are based a different subsample of firm-year observations where the firm had at least one patent within the period 1976-2004. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B7: Instrumenting Institutional Ownership with S&P 500 Inclusion and Share Turnover

	deferred ratio	Tail innovations	Average patent quality	Average patent originality
institutional ownership	0.846	40.395	35.165	29.328
	(0.089)***	(12.000)***	(10.836)***	(12.214)**
size	-0.007	-2.082	-1.628	-0.779
	(0.008)	(0.816)**	(0.733)**	(0.823)
log(R&D stock)	0.018	1.087	1.100	1.946
	(0.003)***	(0.180)***	(0.158)***	(0.199)***
leverage	-0.036	1.577	0.891	-0.472
	(0.023)	(1.642)	(1.457)	(1.604)
age	-0.001	-0.193	-0.160	-0.123
	(0.000)**	(0.036)***	(0.032)***	(0.038)***
CV price	0.185	2.572	2.449	2.188
	(0.033)***	(1.581)	(1.377)*	(1.582)
R^2	0.13	.	0.02	0.12
N	13,595	28,945	28,945	28,945
Instrument	turnover	S&P	S&P	S&P

Notes: This regression results are based a different subsample of firm-year observations where the firm had at least one patent within the period 1976-2004. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B8: The Impact of Institutional Ownership on Firm Innovation

	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	4.019	3.142	0.674
	(1.077)***	(0.926)***	(0.877)
size	-0.643	-0.426	-0.307
	(0.225)***	(0.177)**	(0.191)
log(R&D stock)	0.143	0.039	-0.270
	(0.185)	(0.153)	(0.157)*
leverage	-1.503	-1.037	-2.259
	(1.329)	(1.021)	(1.104)**
age	-0.095	-0.073	0.004
	(0.020)***	(0.016)***	(0.019)
CV price	-1.286	-0.601	0.039
	(1.730)	(1.313)	(1.211)
R^2	0.14	0.26	0.16
N	15,769	15,769	15,769

Notes: This regression results are based a different subsample of firm-year observations where the firm applied for at least one patent. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B9: The Impact of Institutional Ownership on Managerial Compensation Structure

	deferred ratio	option/income ratio	share/income ratio
institutional ownership	0.273	0.232	0.013
	(0.026)***	(0.031)***	(0.012)
size	0.029	0.014	0.009
	(0.005)***	(0.006)***	(0.003)***
log(R&D stock)	0.012	0.014	-0.002
	(0.003)***	(0.003)***	(0.002)
leverage	-0.083	-0.110	0.017
	(0.027)***	(0.030)***	(0.013)
age	-0.001	-0.001	0.001
	(0.000)	(0.000)***	(0.000)**
CV price	0.091	0.121	-0.013
	(0.035)***	(0.040)***	(0.013)
R^2	0.23	0.27	0.16
N	8,205	7,108	7,108

Notes: This regression results are based a different subsample of firm-year observations where the firm applied for at least one patent. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B10: The Impact of Managerial Compensation Structure on Firm Innovation

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	2.913	2.696	
	(0.960)***	(0.970)***	
size	-0.220	-0.363	-0.578
	(0.284)	(0.287)	(0.346)*
log(R&D stock)	0.085	0.101	0.100
	(0.222)	(0.224)	(0.244)
leverage	-0.896	-0.754	-1.635
	(1.596)	(1.591)	(1.900)
age	-0.091	-0.088	-0.080
	(0.024)***	(0.024)***	(0.026)***
CV price	-2.884	-2.379	-2.140
	(2.091)	(2.114)	(2.482)
institutional ownership		2.728	1.448
		(1.602)*	(2.051)
option/income ratio			2.902
			(1.170)**
share/income ratio			2.852
			(1.601)*
R^2	0.19	0.19	0.21
N	8,208	8,180	7,096

Notes: This regression results are based a different subsample of firm-year observations where the firm applied for at least one patent. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B11: The Impact of Managerial Compensation Structure on Firm Innovation: Average Patent Quality

	Average citations of patents	Average citations of patents	Average citations of patents
deferred ratio	2.496	2.367	
	(0.984)**	(1.008)**	
size	-0.240	-0.325	-0.379
	(0.212)	(0.221)	(0.281)
log(R&D stock)	0.022	0.027	-0.000
	(0.187)	(0.190)	(0.214)
leverage	-0.454	-0.283	-0.839
	(1.349)	(1.368)	(1.732)
age	-0.074	-0.072	-0.068
	(0.018)***	(0.018)***	(0.021)***
CV price	-1.850	-1.640	-0.596
	(1.500)	(1.497)	(1.969)
institutional ownership		1.545	0.957
		(1.379)	(1.867)
option/income ratio			2.703
			(1.313)**
share/income ratio			3.142
			(1.464)**
R^2	0.34	0.34	0.33
N	8,208	8,180	7,096

Notes: This regression results are based a different subsample of firm-year observations where the firm applied for at least one patent. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B12: The Impact of Managerial Compensation Structure on Firm Innovation: Average Originality

	Average patent originality	Average patent originality	Average patent originality
deferred ratio	-0.028	-0.037	
	(0.681)	(0.687)	
size	-0.315	-0.321	-0.051
	(0.249)	(0.257)	(0.292)
log(R&D stock)	-0.229	-0.239	-0.359
	(0.189)	(0.192)	(0.208)*
leverage	-3.054	-2.979	-1.359
	(1.515)**	(1.552)*	(1.686)
age	0.015	0.015	0.010
	(0.023)	(0.023)	(0.025)
CV price	0.481	0.385	-2.257
	(1.666)	(1.676)	(1.833)
institutional ownership		0.349	1.483
		(1.253)	(1.443)
option/income ratio			-0.152
			(0.760)
share/income ratio			2.741
			(1.615)*
R^2	0.23	0.23	0.25
N	8,208	8,180	7,096

Notes: This regression results are based a different subsample of firm-year observations where the firm applied for at least one patent. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B13: The Impact of Managerial Compensation and Innovation on Firm Value

	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio
institutional ownership	0.350				
	(0.136)**				
size	-0.369	-0.297	-0.298	-0.296	-0.354
	(0.040)***	(0.030)***	(0.030)***	(0.030)***	(0.032)***
log(R&D stock)	0.206	0.145	0.143	0.147	0.082
	(0.024)***	(0.018)***	(0.018)***	(0.018)***	(0.017)***
leverage	-0.082	-0.462	-0.455	-0.492	-0.439
	(0.258)	(0.181)**	(0.180)**	(0.181)***	(0.179)**
age	-0.005	-0.004	-0.004	-0.004	-0.005
	(0.003)*	(0.002)*	(0.002)*	(0.002)**	(0.002)**
CV price	0.198	0.475	0.463	0.500	0.460
	(0.182)	(0.144)***	(0.144)***	(0.145)***	(0.144)***
tail(10/90) innovation		0.006			
		(0.001)***			
avg patent quality			0.009		
			(0.001)***		
avg originality				0.002	
				(0.001)**	
total patent number					0.205
					(0.022)***
R^2	0.22	0.26	0.26	0.26	0.26
N	15,719	27,218	27,218	27,218	27,218

Notes: This regression results are based a different subsample of firm-year observations where the firm applied for at least one patent. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B14: Instrumenting Institutional Ownership with S&P 500 Inclusion and Share Turnover

	deferred ratio	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	0.876	32.234	28.053	-3.235
	(0.121)***	(9.464)***	(8.174)***	(6.535)
size	-0.007	-2.190	-1.793	-0.093
	(0.009)	(0.601)***	(0.513)***	(0.407)
log(R&D stock)	0.018	0.592	0.435	-0.333
	(0.004)***	(0.243)**	(0.193)**	(0.190)*
leverage	-0.074	1.323	1.459	-2.651
	(0.030)**	(1.768)	(1.416)	(1.259)**
age	-0.001	-0.207	-0.172	0.019
	(0.000)	(0.044)***	(0.037)***	(0.034)
CV price	0.197	1.113	1.517	-0.293
	(0.046)***	(1.963)	(1.516)	(1.318)
R^2	0.12	0.08	0.19	0.16
N	8,205	15,769	15,769	15,769
instrument	share turnover	S&P 500	S&P 500	S&P 500

Notes: This regression results are based a different subsample of firm-year observations where the firm applied for at least one patent. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B15: The Impact of Institutional Ownership on Firm Innovation

A. High Tech Firms

	Tail innovations	Average Patent Quality	Average patent originality
institutional ownership	9.058	7.949	7.298
	(1.319)***	(1.254)***	(1.441)***
R^2	0.11	0.18	0.21
N	8,714	8,714	8,714

B. Low Tech Firms

	Tail innovations)	Average Patent Quality	Average patent originality
institutional ownership	1.933	1.879	3.566
	(0.378)***	(0.346)***	(0.520)***
R^2	0.09	0.13	0.28
N	46,299	46,299	46,299

Notes: We divide the baseline sample into to two subsamples: high-tech firms and low-tech firms. High-tech firms are those in SIC 35 and 36, which include industrial and commercial machinery and equipment and computer equipment; and electronic and other electrical equipment and components, and low-tech firms are the rest. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B16: The Impact of Institutional Ownership on Managerial Compensation Structure

A. High Tech Firms

	deferred ratio	option/income ratio	share/income ratio
institutional ownership	0.264	0.210	0.013
	(0.033)***	(0.045)***	(0.016)
R^2	0.25	0.25	0.15
N	3,529	2,686	2,686

B. Low Tech Firms

	deferred ratio	option/income ratio	share/income ratio
institutional ownership	0.266	0.237	0.028
	(0.016)***	(0.020)***	(0.009)***
R^2	0.21	0.21	0.12
N	18,212	13,739	13,739

Notes: We divide the baseline sample into to two subsamples: high-tech firms and low-tech firms. High-tech firms are those in SIC 35 and 36, which include industrial and commercial machinery and equipment and computer equipment; and electronic and other electrical equipment and components, and low-tech firms are the rest. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B17: The Impact of Managerial Compensation Structure on Firm Innovation

A.High Tech Firms

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	3.259	2.262	
	(1.164)***	(1.166)*	
institutional ownership		7.699	9.608
		(1.910)***	(2.923)***
option/income ratio			2.477
			(1.528)
share/income ratio			0.491
			(2.325)
R^2	0.18	0.18	0.18
N	3,535	3,498	2,682

B.Low Tech Firms

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	1.088	1.135	
	(0.441)**	(0.449)**	
institutional ownership		-0.124	-1.716
		(0.610)	(0.924)*
option/income ratio			1.231
			(0.603)**
share/income ratio			0.802
			(0.812)
R^2	0.12	0.12	0.14
N	18,252	18,008	13,689

Notes: We divide the baseline sample into to two subsamples: high-tech firms and low-tech firms. High-tech firms are those in SIC 35 and 36, which include industrial and commercial machinery and equipment and computer equipment; and electronic and other electrical equipment and components, and low-tech firms are the rest. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B19: The Impact of Managerial Compensation Structure on Firm Innovation: Average Originality

A. High Tech Firms

	Average patent originality	Average patent originality	Average patent originality
deferred ratio	3.591	2.764	
	(1.009)***	(0.983)***	
institutional ownership		6.988	2.954
		(2.105)***	(2.697)
option/income ratio			2.222
			(1.074)**
share/income ratio			4.363
			(4.185)
R^2	0.22	0.23	0.22
N	3,535	3,498	2,682

B. Low Tech Firms

	Average patent originality	Average patent originality	Average patent originality
deferred ratio	1.005	0.720	
	(0.431)**	(0.446)	
institutional ownership		1.635	0.873
		(0.771)**	(1.123)
option/income ratio			0.962
			(0.556)*
share/income ratio			1.075
			(1.279)
R^2	0.35	0.36	0.39
N	18,252	18,008	13,689

Notes: We divide the baseline sample into to two subsamples: high-tech firms and low-tech firms. High-tech firms are those in SIC 35 and 36, which include industrial and commercial machinery and equipment and computer equipment; and electronic and other electrical equipment and components, and low-tech firms are the rest. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B20: The Impact of Managerial Compensation and Innovation on Firm Value

A. Low Tech Firms

	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio
institutional ownership	1.081				
	(0.176)***				
tail(10/90) innovation		0.007			
		(0.001)***			
avg patent quality			0.010		
			(0.002)***		
avg originality				0.007	
				(0.002)***	
total patent number					0.250
					(0.032)***
R^2	0.12	0.14	0.14	0.13	0.14
N	8,669	15,678	15,678	15,678	15,678

B. Low Tech Firms

	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio
institutional ownership	0.593				
	(0.072)***				
tail(10/90) innovation		0.008			
		(0.001)***			
avg patent quality			0.012		
			(0.001)***		
avg originality				0.006	
				(0.001)***	
total patent number					0.126
					(0.018)***
R^2	0.18	0.19	0.19	0.19	0.19
N	46,029	81,853	81,853	81,853	81,853

Notes: We divide the baseline sample into to two subsamples: high-tech firms and low-tech firms. High-tech firms are those in SIC 35 and 36, which include industrial and commercial machinery and equipment and computer equipment; and electronic and other electrical equipment and components, and low-tech firms are the rest. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B21: Instrumenting Institutional Ownership with S&P 500 Inclusion and Share Turnover

A. High Tech Firms

	deferred ratio	Tail innovations	Average Patent Quality	Average patent originality
institutional ownership	1.037	30.490	15.318	-50.473
	(0.177)***	(31.202)	(25.452)	(60.951)
instrument	share turnover	S&P 500	S&P 500	S&P 500
N	3,529	8,714	8,714	8,714

B. Low Tech Firms

	deferred ratio	Tail innovations	Average Patent Quality	Average patent originality
institutional ownership	0.676	35.980	34.059	42.194
	(0.064)***	(11.624)***	(11.147)***	(15.301)***
N	18,212	46,299	46,299	46,299

Notes: We divide the baseline sample into to two subsamples: high-tech firms and low-tech firms. High-tech firms are those in SIC 35 and 36, which include industrial and commercial machinery and equipment and computer equipment; and electronic and other electrical equipment and components, and low-tech firms are the rest. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B22: The Impact of Institutional Ownership on Firm Innovation (excluding Pharmaceutical Firms)

	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	3.188	2.951	3.778
	(0.400)***	(0.374)***	(0.494)***
R^2	0.11	0.16	0.29
N	51,317	51,317	51,317

Notes: The estimation results are based on the baseline sample excluding all the pharmaceutical firms. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B23: The Impact of Institutional Ownership on Managerial Compensation Structure (excluding Pharmaceutical Firms)

	deferred ratio	option/income ratio	share/income ratio
institutional ownership	0.266	0.234	0.025
	(0.015)***	(0.019)***	(0.008)***
R^2	0.21	0.22	0.13
N	20,346	15,633	15,633

Notes: The estimation results are based on the baseline sample excluding all the pharmaceutical firms. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B24: The Impact of Managerial Compensation Structure on Firm Innovation (excluding Pharmaceutical Firms)

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	1.511	1.348	
	(0.434)***	(0.442)***	
institutional ownership		1.379	0.573
		(0.640)**	(0.985)
option/income ratio			1.323
			(0.581)**
share/income ratio			0.687
			(0.782)
R^2	0.16	0.16	0.18
N	20,387	20,129	15,583

Notes: The estimation results are based on the baseline sample excluding all the pharmaceutical firms. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B25: The Impact of Managerial Compensation Structure on Firm Innovation: Average Patent Quality (excluding Pharmaceutical Firms)

	Average citations of patents	Average citations of patents	Average citations of patents
deferred ratio	1.123	1.007	
	(0.447)**	(0.452)**	
institutional ownership		0.940	1.598
		(0.593)	(0.950)*
option/income ratio			1.032
			(0.641)
share/income ratio			1.119
			(0.773)
R^2	0.23	0.23	0.24
N	20,387	20,129	15,583

Notes: The estimation results are based on the baseline sample excluding all the pharmaceutical firms. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B26: The Impact of Managerial Compensation Structure on Firm Innovation: Average Originality (excluding Pharmaceutical Firms)

	Average patent originality	Average patent originality	Average patent originality
deferred ratio	1.263	0.904	
	(0.382)***	(0.392)**	
institutional ownership		2.600	1.521
		(0.719)***	(1.008)
option/income ratio			0.892
			(0.476)*
share/income ratio			0.976
			(1.216)
R^2	0.37	0.37	0.40
N	20,387	20,129	15,583

Notes: The estimation results are based on the baseline sample excluding all the pharmaceutical firms. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B27: The Impact of Managerial Compensation and Innovation on Firm Value (excluding Pharmaceutical Firms)

	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio
institutional ownership	0.638				
	(0.065)***				
tail(10/90) innovation		0.008			
		(0.001)***			
avg patent quality			0.012		
			(0.001)***		
avg originality				0.006	
				(0.001)***	
total patent number					0.143
					(0.015)***
R^2	0.13	0.15	0.15	0.15	0.15
N	51,009	92,552	92,552	92,552	92,552

Notes: The estimation results are based on the baseline sample excluding all the pharmaceutical firms. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. The sample period is from 1990 to 2004 at annual frequency. All specifications control for the same set of explanatory variables, year dummies and a full set of four-digit SIC industry dummies unless mentioned otherwise. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B29: The Impact of Institutional Ownership on Firm Innovation (SIC-2)

	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	3.551	3.337	4.474
	(0.391)***	(0.367)***	(0.526)***
R^2	0.08	0.13	0.24
N	55,013	55,013	55,013

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and a full set of two-digit SIC industry dummies. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B30: The Impact of Institutional Ownership on Managerial Compensation Structure (SIC-2)

	deferred ratio	option/income ratio	share/income ratio
institutional ownership	0.269	0.253	0.017
	(0.014)***	(0.018)***	(0.008)**
R^2	0.18	0.16	0.08
N	21,741	16,425	16,425

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and a full set of two-digit SIC industry dummies. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B31: The Impact of Managerial Compensation Structure on Firm Innovation (SIC-2)

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	1.966	1.841	
	(0.423)***	(0.426)***	
institutional ownership		1.018	0.337
		(0.607)*	(0.913)
option/income ratio			2.204
			(0.567)***
share/income ratio			0.045
			(0.818)
R^2	0.11	0.11	0.12
N	21,787	21,506	16,371

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and a full set of two-digit SIC industry dummies. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B32: The Impact of Managerial Compensation Structure on Firm Innovation: Average Patent Quality (SIC-2)

	Average citations of patents	Average citations of patents	Average citations of patents
deferred ratio	1.465	1.386	
	(0.412)***	(0.413)***	
institutional ownership		0.635	1.292
		(0.554)	(0.879)
option/income ratio			1.713
			(0.581)***
share/income ratio			0.542
			(0.810)
R^2	0.19	0.19	0.19
N	21,787	21,506	16,371

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and a full set of two-digit SIC industry dummies. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B33: The Impact of Managerial Compensation Structure on Firm Innovation: Average Originality (SIC-2)

	Average patent originality	Average patent originality	Average patent originality
deferred ratio	1.208	0.807	
	(0.420)***	(0.437)*	
institutional ownership		2.387	1.032
		(0.788)***	(1.113)
option/income ratio			0.790
			(0.539)
share/income ratio			1.015
			(1.274)
R^2	0.29	0.29	0.31
N	21,787	21,506	16,371

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and a full set of two-digit SIC industry dummies. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B34: The Impact of Managerial Compensation and Innovation on Firm Value (SIC-2)

	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio	Market/Book Ratio
institutional ownership	0.719				
	(0.067)***				
tail(10/90) innovation		0.009			
		(0.001)***			
avg patent quality			0.013		
			(0.001)***		
avg originality				0.007	
				(0.001)***	
total patent number					0.140
					(0.015)***
R^2	0.13	0.15	0.15	0.15	0.15
N	54,698	97,531	97,531	97,531	97,531

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and a full set of two-digit SIC industry dummies. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B35: Instrumenting Institutional Ownership with S&P 500 Inclusion and Share Turnover (SIC-2)

	deferred ratio	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	0.804	33.187	28.592	21.096
	(0.057)***	(8.814)***	(8.041)***	(10.056)**
instrument	share turnover	S&P 500	S&P 500	S&P 500
N	21,741	55,013	55,013	55,013

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and a full set of two-digit SIC industry dummies. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B36: The Impact of Institutional Ownership on Firm Innovation (Firm Fixed Effects)

	Tail innovations	Average citations of patents	Average patent originality
institutional ownership	4.217	4.368	5.299
	(0.581)***	(0.574)***	(0.783)***
R^2	0.12	0.20	0.29
N	31,317	31,317	31,317

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and Blundell, Griffith, and Reenen (1999) firm fixed effects. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B37: The Impact of Managerial Compensation Structure on Firm Innovation (Firm Fixed Effects)

	Tail innovations	Tail innovations	Tail innovations
deferred ratio	1.500	1.212	
	(0.594)**	(0.599)**	
institutional ownership		2.402	2.596
		(0.919)***	(1.123)**
option/income ratio			1.222
			(0.696)*
share/income ratio			-0.319
			(0.906)
R^2	0.13	0.13	0.14
N	13,201	13,098	11,776

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and Blundell, Griffith, and Reenen (1999) firm fixed effects. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.

Table B38: The Impact of Managerial Compensation Structure on Firm Innovation: Average Patent Quality (Firm Fixed Effects)

	Average citations of patents	Average citations of patents	Average citations of patents
deferred ratio	1.144	0.911	
	(0.546)**	(0.534)*	
institutional ownership		1.864	3.115
		(0.875)**	(1.105)***
option/income ratio			0.918
			(0.640)
share/income ratio			0.731
			(0.916)
R^2	0.23	0.23	0.22
N	13,201	13,098	11,776

Notes: This table reports the regression results using the baseline sample controlling for the same set of explanatory variables, year dummies and Blundell, Griffith, and Reenen (1999) firm fixed effects. Robust asymptotic standard errors reported in parentheses are clustered at the firm level. See text and notes to Table 1 and Section 2.2 for detailed variable definitions. $***p < 0.01, **p < 0.05, *p < 0.1$.