Financial Heterogeneity and the Investment Channel of Monetary Policy *

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Abstract

We study the role of financial frictions and firm heterogeneity in determining the investment channel of monetary policy. Empirically, we show that firms with low default risk – those with low debt burdens and high credit ratings – are the most responsive to monetary shocks. We interpret these findings using a heterogeneous firm New Keynesian model with default risk. In our model, low-risk firms are more responsive to monetary shocks because their marginal cost of finance is relatively flat. The aggregate effect of monetary policy therefore depends on the distribution of default risk, which varies over time.

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1 Introduction

Aggregate investment is one of the most responsive components of GDP to changes in monetary shocks. Our goal in this paper is to understand the role of financial frictions in determining this investment channel of monetary policy. Given the rich heterogeneity in financial positions across firms, a key question is: which firms are the most responsive to changes in monetary policy and why? The answer to this question is theoretically ambiguous. On the one hand, financial frictions generate an upward-sloping marginal cost curve for investment, which dampens the response of investment to monetary policy for firms more severely affected by financial frictions. On the other hand, monetary policy may flatten out this marginal cost curve – for example, by increasing cash flows or improving collateral values – which amplifies the response of investment for affected firms. This latter view is the conventional wisdom of the literature, often informed by applying the financial accelerator logic across firms.

We address the question of which firms respond the most to monetary policy and why using new cross-sectional evidence and a heterogeneous firm New Keynesian model. Our empirical work combines monetary shocks, measured using the high-frequency event-study approach, with quarterly Compustat data. We find that firms with low default risk – those with low debt burdens and high credit ratings – are significantly and robustly more responsive to monetary policy than other firms in our sample. Motivated by this evidence, our model embeds a heterogeneous firm investment model with default risk into the benchmark New Keynesian environment and studies the effect of a monetary shock. Monetary policy stimulates investment by directly increasing the expected return on capital – which drives the response of low-risk firms – and indirectly increasing cash flows and improving collateral values – which drives the response of high-risk firms. In our calibrated model, as in the data, low-risk firms are more responsive to monetary policy, indicating that the direct effects dominate the indirect ones. These heterogeneous responses imply that the aggregate effect of a given monetary shock is smaller when default risk in the economy is high.

Our first key empirical result is that firms with low leverage ratios are significantly more responsive to monetary policy. Our baseline empirical specification estimates how the semi-elasticity of a firm's investment with respect to a monetary policy shock varies with the firm's leverage, conditioning on both firm fixed effects – to capture permanent differences across firms – and sector-by-quarter fixed effects – to capture differences in how sectors respond to aggregate shocks. A firm with one cross-sectional standard deviation more leverage than the average firm is about half as responsive to monetary policy as the average firm in our specification. Furthermore, the 50% least-leveraged firms in our sample drive nearly all the aggregate response to monetary policy in our sample.

Although we do not exploit exogenous variation in leverage, we provide two additional results which suggest that these heterogeneous responses by leverage is driven by heterogeneity in default risk. First, low-leverage firms have high credit ratings, implying that they are financially healthy. Second, firms with high credit ratings are also more responsive to monetary policy, even conditional on leverage. All together, we interpret our empirical findings as showing that firms with two key proxies for low default risk – low leverage and high credit ratings – are more responsive to monetary policy. We emphasize the heterogeneity by leverage as our baseline empirical result because it easily maps into our model.

We also provide three pieces of evidence that these heterogeneous responses are not driven by other firm-level characteristics. First, the results are not driven by permanent heterogeneity in financial positions because they are robust to using within-firm variation in leverage. Second, our results are not driven by differences in past sales growth, realized future sales growth, or size. Third, other unobservable factors are unlikely to drive our results because we find similar results if we instrument leverage with past leverage (which is likely more weakly correlated with unobservables).[1]

In order to interpret these empirical results, we embed a model of heterogeneous firms facing default risk into the benchmark New Keynesian framework. There is a group of heterogeneous firms who invest in capital using either internal funds or external borrowing; these firms can default on their debt, leading to an external finance premium. There is also a group of retailer firms with sticky prices, generating a New Keynesian Phillips curve linking

[1] Another concern is that our monetary policy shocks are correlated with other economic conditions that are in fact driving the differences across firms. Although our shock identification was designed to address this concern, we also show that there are not significant differences in how firms respond to changes in other cyclical variables like GDP growth, the unemployment rate, the inflation rate, or the VIX index.

nominal variables to real outcomes. We calibrate the model to match key features of firms' investment, borrowing, and lifecycle dynamics in the micro data. Our model generates realistic behavior along non-targeted dimensions of the data, such as measured investment-cash flow sensitivities. The peak responses of aggregate investment, output, and consumption to a monetary policy shock are in line the peak responses estimated in the data by Christiano, Eichenbaum and Evans (2005).

In our calibrated model, firms with low default risk are more responsive to monetary policy shocks than firms with high default risk, consistent with the data. These heterogeneous responses depend crucially on how monetary policy shifts the marginal cost of capital. On the one hand, firms with high default risk face a steeper marginal cost curve than other firms, which dampens their response to the shock. On the other hand, the marginal cost curve shifts more strongly for high-risk firms due to changes in cash flows and collateral values, which amplifies their response. This latter force is dominated by the former force in our calibrated model. We estimate our empirical specification on panel data simulated from our model and find that the coefficient capturing heterogeneous responses in our model is within one standard error of its estimate in the data.

Finally, we show that the aggregate effect of a given monetary shock depends on the distribution of default risk across firms. We perform a simple calculation which exogenously varies the initial distribution of firms in the period of the shock. A monetary shock will generate an approximately 25% smaller change in the aggregate capital stock starting from a distribution with 50% less net worth than the steady state distribution. Under the distribution with low average net worth, more firms have a high risk of default and are therefore less responsive to monetary policy. More generally, this calculation suggests a potentially important source of time-variation in monetary transmission: monetary policy is less powerful when more firms have risk of default.

Related Literature Our paper contributes to four key strands of literature. The first studies the transmission of monetary policy to the aggregate economy. Bernanke, Gertler and Gilchrist (1999) embed the financial accelerator in a representative firm New Keynesian model and find that it amplifies the aggregate response to monetary policy. We build on

Bernanke, Gertler and Gilchrist (1999)'s framework to include firm heterogeneity. Consistent with their results, we find that the response of aggregate investment to monetary policy is larger in our model than in a model without financial frictions at all. However, among the 96% of firms affected by financial frictions in our model, those with low risk of default are more responsive to monetary policy than those with high risk of default, generating an additional source of state dependence.

Second, we contribute to the literature that studies how the effect of monetary policy varies across firms. A number of papers, including Kashyap, Lamont and Stein (1994), Gertler and Gilchrist (1994), and Kashyap and Stein (1995) argue that smaller and presumably more credit constrained firms are more responsive to monetary policy along a number of dimensions. We contribute to this literature by showing that low leverage and highly rated firms are also more responsive to monetary policy. These characteristics are essentially uncorrelated with firm size in our sample. In addition, we use a different empirical specification, identification of monetary policy shocks, sample of firms, and time period.[2,3]

Third, we contribute to the literature which studies how incorporating micro-level heterogeneity into the New Keynesian model affects our understanding of monetary transmission. To date, this literature has focused on how household-level heterogeneity affects the consumption channel of monetary policy; see, for example, Auclert (2017); McKay, Nakamura and Steinsson (2015); Wong (2016); or Kaplan, Moll and Violante (2017). We instead explore the role of firm-level heterogeneity in determining the investment channel of monetary policy. In contrast to the heterogeneous-household literature, we find that both direct and indirect effects of monetary policy play a quantitatively important role in driving the investment channel. The direct effect of changes in the real interest rates are smaller for consumption than for investment because households attempt to smooth consumption while firms do not

[2]In a recent paper, Crouzet and Mehrotra (2017) find some evidence of differences in cyclical sensitivity by firm size during extreme business cycle events. Our work is complementary to their's by focusing on the conditional response to a monetary policy shock and using our economic model to draw aggregate implications.

[3]Ippolito, Ozdagli and Perez-Orive (2017) study how the effect of high-frequency shocks on firm-level outcomes depends on firms' bank debt. In order to merge in data on bank debt, Ippolito, Ozdagli and Perez-Orive (2017) must focus on the 2004-2008 time period. Given this small sample, Ippolito, Ozdagli and Perez-Orive (2017) do not consistently find significant differences in investment responses across firms. In addition, Ippolito, Ozdagli and Perez-Orive (2017) use a different empirical specification and focus on stock prices as the main outcome of interest.

smooth investment over time.

Finally, we contribute to the literature studying the role of financial heterogeneity in determining the business cycle dynamics of aggregate investment. Our model of firm-level investment builds heavily on Khan, Senga and Thomas (2016), who study the effect of financial shocks in a flexible price model. We contribute to this literature by introducing sticky prices and studying the effect of monetary policy shocks. In addition, we extend Khan, Senga and Thomas (2016)'s model to include capital quality shocks and a time-varying price of capital in order to generate variation in the implicit collateral value of capital, as in the financial accelerator literature. Khan and Thomas (2013) and Gilchrist, Sim and Zakrajsek (2014) study related flexible-price models of investment with financial frictions. Our model is also related to Arellano, Bai and Kehoe (2016), who study the role of financial heterogeneity in determining employment decisions.

Road Map Our paper is organized as follows. Section 2 provides the empirical evidence that the firm-level response to monetary policy varies with leverage and credit rating. Section 3 develops our heterogeneous firm New Keynesian model to interpret this evidence. Section 4 provides a theoretical characterization of the channels through which monetary policy drives investment in our model. Section 5 then calibrates the model and verifies that it is consistent with key features of the joint distribution of investment and leverage in the micro data. Section 6 uses the model to study the monetary transmission mechanism. Section 7 concludes.

2 Empirical Results

We document two sets of empirical results. First, we find that firms with low debt burdens, as measured by their leverage ratios, are significantly more responsive to monetary policy shocks than are high debt burdens. Second, we argue that these heterogeneous responses are driven by heterogeneity in default risk. In particular, we find that low-leverage firms have high credit ratings, and that highly related or highly solvent firms are also more responsive to monetary policy.

2.1 Data Description

Our sample combines monetary policy shocks with firm-level outcomes from quarterly Compustat data.

Monetary Policy Shocks We measure monetary shocks using the high-frequency, event-study approach pioneered by Cook and Hahn (1989). Following Gurkaynak, Sack and Swanson (2005) and Gorodnichenko and Weber (2016), we construct our shock $\varepsilon_t^{\mathrm{m}}$ as

$$\varepsilon_t^{\mathrm{m}} = \tau(t) \times (\mathtt{ffr}_{t+\Delta_+} - \mathtt{ffr}_{t-\Delta_-}), \tag{1}$$

where t is the time of the monetary announcement, $\mathtt{ffr}_t$ is the implied Fed Funds Rate from a current-month Federal Funds future contract at time t, Δ_+ and Δ_- control the size of the time window around the announcement, and $\tau(t)$ is an adjustment for the timing of the announcement within the month.[4] We focus on a window of Δ_- = fifteen minutes before the announcement and Δ_+ = forty five minutes after the announcement. Our shock series begins in January 1990, when the Fed Funds futures market opened, and ends in December 2007, before the financial crisis.[5] During this time there were 183 shocks with a mean of approximately zero and a standard deviation of 9 basis points.[6]

We time aggregate the high-frequency shocks to the quarterly frequency in order to merge them with our firm-level data. We construct a moving average of the raw shocks weighted by the number of days in the quarter after the shock occurs.[7] Our time aggregation strategy

[4]This adjustment accounts for the fact that Fed Funds Futures pay out based on the average effective rate over the month. It is defined as $\tau(t) \equiv \frac{\tau_m^n(t)}{\tau_m^n(t) - \tau_m^d(t)}$, where $\tau_m^d(t)$ denotes the day of the meeting in the month and $\tau_m^n(t)$ the number of days in the month.

[5]We stop in December 2007 to study a period of conventional monetary policy, which is the focus of our economic model.

[6]In our economic model, we interpret our measured monetary policy shock as an innovation to a Taylor Rule. An alternative interpretation of the shock, however, is that it is driven by the Fed providing information to the private sector. In Section 2.3 we argue that the information component of Fed announcements does not drive our results.

[7]Formally, the monetary-policy shock in quarter q is defined as

$$\varepsilon_q^{\mathrm{m}} = \sum_{t \in J(q)} \omega^a(t) \varepsilon_t^{\mathrm{m}} + \sum_{t \in J(q-1)} \omega^b(t) \varepsilon_t^{\mathrm{m}} \tag{2}$$

where $\omega^a(t) \equiv \frac{\tau_q^n(t) - \tau_q^d(t)}{\tau_q^n(t)}$, $\omega^b(t) \equiv \frac{\tau_q^d(t)}{\tau_q^n(t)}$, $\tau_q^d(t)$ denotes the day of the monetary-policy announcement in the

Table 1
Summary Statistics of Monetary Policy Shocks

	high frequency	smoothed	sum
mean	-0.0185	-0.0429	-0.0421
median	0	-0.0127	-0.00509
std	0.0855	0.108	0.124
min	-0.463	-0.480	-0.479
max	0.152	0.233	0.261
num	164	71	72

Notes: Summary statistics of monetary policy shocks. "High frequency" shocks are estimated using event study strategy in (1). "Smoothed" shocks are time aggregated to the quarterly frequency using the weighted average (2). "Sum" refers to time aggregating by simply summing all shocks within a quarter.

ensures that we weight shocks by the amount of time firms have had to react to them. Table 1 indicates that these "smoothed" shocks have similar features to the original high-frequency shocks. For robustness, we will also use the alternative time aggregation of simply summing all the shocks that occur within the quarter, as in Wong (2016). Table 1 shows that the moments of these alternative shocks do not significantly differ from the moments of the smoothed shocks.

Firm-Level Variables We draw firm-level variables from quarterly Compustat, a panel of publicly listed U.S. firms. Compustat satisfies three key requirements for our study: it is quarterly, a high enough frequency to study monetary policy; it is a long panel, allowing us to use within-firm variation; and it contains rich balance-sheet information, allowing us to construct our key variables of interest. To our knowledge, Compustat is the only U.S. dataset that satisfies these three requirements. The main disadvantage of Compustat is that it excludes privately held firms which are likely subject to more severe financial frictions.[8] In Section 5, we calibrate our economic model to match a broad sample of firms, not just those in Compustat.

quarter, $\tau_q^n(t)$ denotes the number of days in the monetary-policy announcement's quarter, and $J(q)$ denote the set periods t contained in quarter q.

[8] Crouzet and Mehrotra (2017) construct a non-public, high-quality quarterly panel using micro data from the Quarterly Financial Reports. A key advantage of this dataset is that covers a much broader set of firm sizes than Compustat. However, it only covers the manufacturing sector and only follows small firms for eight quarters, which limits the ability to use within-firm variation.

Our main measure of investment is $\Delta \log k_{jt+1}$, where k_{jt+1} is the book value of the firm's tangible capital stock of firm j at the end of period t. We use this log-difference specification because investment is highly skewed, implying that suggesting a log-linear rather than level-linear regression specification. We use the net change in log capital rather than the log of gross investment because gross investment often takes negative values. In Appendix A, we show that our results hold for other measures of investment as well.

We use two different measures of a firm's financial position. First, we measure leverage as the firm's debt-to-asset ratio ℓ_{jt}, where debt is the sum of short term and long term debt and assets is the book value of assets.[9] Second, we measure the firm's credit rating using S&P's rating of the firm's long-term debt.

Appendix A.1 provides details of our data construction, which follows standard practice in the investment literature. Table 2 presents simple summary statistics of the final sample used in our analysis. The mean capital growth rate is roughly 0.4% quarterly with a standard deviation of 9.3%. The mean leverage ratio is approximately 27% with a cross-sectional standard deviation of 36%.

TABLE 2
SUMMARY STATISTICS OF FIRM-LEVEL VARIABLES

Statistic	$\Delta \log k_{jt}$	$\frac{i_{jt}}{k_{jt}}$	$\mathbb{1}\{\frac{i_{jt}}{k_{jt}} > 1\%\}$	ℓ_{jt}
Average	0.005	0.041	0.734	0.267
Median	-0.004	0.028	1.000	0.204
Std	0.094	0.105	0.442	0.361
Top 5%	0.133	0.173	1.000	0.725

Notes: Summary statistics of firm-level outcome variables. $\Delta \log k_{jt+1}$ is the net change in the capital stock. $\frac{i_{jt}}{k_{jt}}$ is the firm's investment rate. $\mathbb{1}\left\{\frac{i_{jt}}{k_{jt}} > 1\%\right\}$ is an indicator variable for whether a firm's investment rate is greater than 1%. ℓ_{jt} is the ratio of total debt to total assets.

[9] We focus much of our empirical analysis on leverage because it has two key advantages over other measures of financial position. First, leverage is tightly linked, both empirically and theoretically, to the costs of external finance (see, for example, Kaplan and Zingales, 1997; Whited and Wu, 2006; Tirole, 2010). Second, leverage exhibits considerable within-firm variation, which we use to control for permanent heterogeneity in financial position.

2.2 Heterogeneous Responses By Leverage

We begin our empirical analysis by studying heterogeneity by leverage. Our baseline empirical specification is

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}, \tag{3}$$

where α_j is a firm j fixed effect, α_{st} is a sector s by quarter t fixed effect, $\varepsilon_t^{\mathrm{m}}$ is the monetary policy shock, ℓ_{jt} is the firm's leverage ratio, Z_{jt} is a vector of firm-level controls, and e_{jt} is a residual.[10] Our main coefficient of interest is β, which measures how the semi-elasticity of investment $\Delta \log k_{jt+1}$ with respect to monetary shocks $\varepsilon_t^{\mathrm{m}}$ depends on the firm's leverage ℓ_{jt-1}.[11] This coefficient estimate is conditional on a number of controls that may simultaneously affect investment and leverage, but which are outside the scope of our economic model in Section 3. First, firm fixed effects α_j capture permanent differences in investment behavior across firms. Second, sector-by-quarter fixed effects α_{st} capture differences in how broad sectors are exposed to aggregate shocks. Finally, the firm-level controls Z_{jt} include the level of leverage ℓ_{jt}, total assets, sales growth, current assets as a share of total assets, and a fiscal quarter dummy.

Table 3 reports the results from estimating the baseline specification (3). We perform two normalizations to make the estimated coefficient β easily interpretable. First, we standardize leverage ℓ_{jt} over the entire sample, so that the units of leverage are standard deviations relative to its mean value in our sample. Second, we normalize the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive value corresponds to a cut in interest rates. Column (1) reports the coefficient without the firm-level controls Z_{jt-1} and implies that a firm with one standard deviation more leverage than the average firm has a nearly one unit lower semi-elasticity of investment. Adding firm-level controls Z_{jt-1} in column (2) does not substantially change this point estimate. Hence, low-leverage firms are more responsive to the monetary shocks $\varepsilon_t^{\mathrm{m}}$.

[10] The sectors s we consider are: agriculture, forestry, and fishing; mining; construction; manufacturing; transportation communications, electric, gas, and sanitary services; wholesale trade; retail trade; and services. We do not include finance, insurance, and real estate or public administration.

[11] We lag both leverage ℓ_{jt-1} and the controls Z_{jt-1} to ensure they are predetermined at the time of the monetary shock. Note that both k_{jt+1} and ℓ_{jt} measure end-of-period stocks. We denote the end-of-period capital stock with k_{jt+1} rather than k_{jt} to be consistent with the standard notation in our economic model in Section 3.

Table 3
Heterogeneous Responses by Leverage

	(1)	(2)	(3)
leverage × ffr shock	-0.94***	-0.74**	-0.75**
	(0.33)	(0.28)	(0.30)
ffr shock			1.39
			(1.00)
Observations	239523	239523	239523
R^2	0.106	0.118	0.103
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Notes: Results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

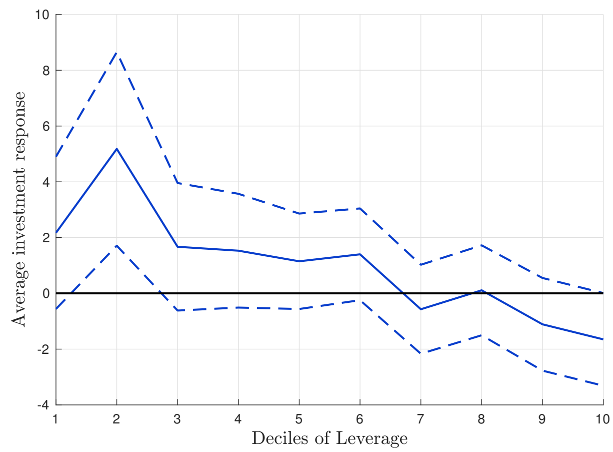
where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

A natural way to assess the economic significance of our estimated interaction coefficient β is to compare it to the average effect of a monetary policy shock. However, in our baseline specification (3), the average effect is absorbed by the sector-by-quarter fixed effect α_{st}. Column (3) relaxes this restriction by estimating

$$\Delta \log k_{jt+1} = \alpha_j + \gamma \varepsilon_t^{\mathrm{m}} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}_1' Z_{jt-1} + \mathbf{\Gamma}_2' Y_t + \varepsilon_{jt}, \tag{4}$$

where Y_t is a vector of aggregate controls for GDP growth, the inflation rate, the unemployment rate, and the VIX index. The average investment semi-elasticity is roughly 1.4. Hence, our point estimate in column (2) indicates that a firm with leverage one standard deviation higher than the average firm is roughly half as responsive to monetary policy as the average firm. However, the estimated average effect γ is not statistically significant because the time-series variation in the monetary shocks $\varepsilon_t^{\mathrm{m}}$ is small and we cluster our standard errors at the quarterly level.

Figure 1: Aggregated Semi-Elasticity With Respect To Monetary Policy Shocks



Notes: Semi-elasticity of aggregated investment with respect to monetary policy shocks for deciles of leverage distribution. Reports estimated semi-elasticities β_j from specification

$$\Delta \log K_{jt+1} = \mathbf{\Gamma}' Y_t + \beta_j \varepsilon_t^{\mathrm{m}} + e_{jt}$$

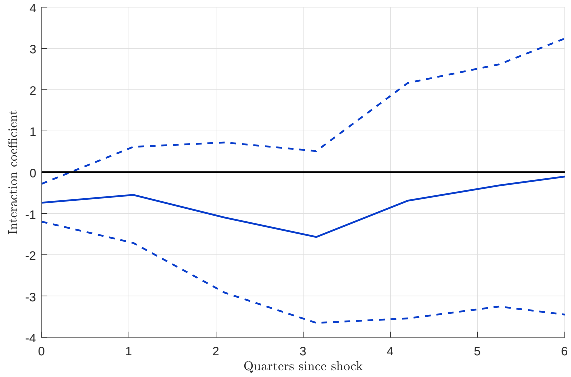
where $\Delta \log K_{jt+1}$ is the aggregated investment of firms with leverage in the jth decile of the leverage distribution in quarter t and Y_t is a vector containing GDP growth, the inflation rate, the unemployment rate, and the VIX index. Dotted lines provide 90% standard error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates).

Aggregate Implications In order to further assess the economic significance of these heterogeneous responses and whether the heterogeneity survives aggregation, we estimate the regression

$$\Delta \log K_{jt+1} = \mathbf{\Gamma}' Y_t + \beta_j \varepsilon_t^{\mathrm{m}} + \varepsilon_{jt}, \tag{5}$$

where the outcome $\Delta \log K_{jt+1}$ is the total investment done by firms in the j^{th} decile of the leverage distribution in quarter t, and again Y_t contains controls for aggregate GDP growth, the inflation rate, the unemployment rate, and the VIX index. Figure 1 plots the aggregated semi-elasticities β_j against decile j. The aggregated semi-elasticity declines fairly steadily with leverage, even though this specification is far less structured and more aggregated than our benchmark (3). Furthermore, the aggregated semi-elasticity is essentially zero past the 6^{th} decile of the leverage distribution, indicating that the total effect of monetary policy is driven almost entirely by low-leverage firms.

Figure 2: Dynamics of Differential Response to Monetary Shocks



Notes: dynamics of the interaction coefficient between leverage and monetary shocks over time. Reports the coefficient β_h over quarters h from

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}'_h Z_{jt-1} + e_{jt},$$

where α_{jh} is a firm fixed effect, α_{sth} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. Dashed lines report 90% error bands. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Dynamics To study the dynamics of these differential responses across firms, we estimate the Jorda (2005)-style local projection:

$$\log k_{jt+h} - \log k_{jt} = \alpha_{jh} + \alpha_{sth} + \beta_h \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}'_h Z_{jt-1} + \varepsilon_{jth}, \tag{6}$$

where $h \geq 1$ indexes quarters in the future. The coefficient β_h measures how the cumulative response of investment in quarter $t+h$ to a monetary policy shock in quarter t depends on the firm's leverage in quarter $t-1$. Figure 2 shows that the heterogeneous responses across firms are fairly short-lived. The heterogeneous responses disappear approximately six quarters after the initial shock, and the only statistically significant heterogeneity is upon impact of the shock. We therefore focus on the impact effect for the rest of the paper.[12]

[12]It is important to note that the short-lived dynamics of the cross-sectional differences that we find here are not necessarily in conflict with the long-lived and hump-shaped dynamics of aggregate variables typically estimated in VARs. The cross-sectional differences are simply a different object than aggregate investment. Gertler and Karadi (2015) show that the high-frequency monetary shocks generate aggregate impulse responses that are similar to the VAR literature using an instrumental variable VAR strategy. One explanation for the hump-shaped response of aggregate investment is that hump-shaped responses of other

Table 4
Stock Prices

	(1)	(2)	(3)
leverage × ffr shock	-8.22***	-8.22**	-6.12*
	(3.82)	(3.82)	(3.33)
ffr shock			6.22**
			(1.88)
Observations	32274	32274	32274
R^2	0.128	0.128	0.073
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Notes: Results from estimating the regression $r^{\mathrm{e}}_{jt+1} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1}\varepsilon^{\mathrm{m}}_t + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$ where $r^{\mathrm{e}}_{jt+1} = \frac{p_{jt+1}-p_{jt}}{p_{jt}}$ is the change in the firm's stock price on the announcement day, α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon^{\mathrm{m}}_t$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarter. We have normalized the sign of the monetary shock $\varepsilon^{\mathrm{m}}_t$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Supporting Evidence From Stock Prices Stock prices provide a natural reality check on our findings because they encode the extent to which monetary policy shocks are good news for firms. Additionally, stock prices are available at a high frequency, so they are not subject to time-aggregation bias. We therefore estimate the equation

$$r^{\mathrm{e}}_{jt+1} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1}\varepsilon^{\mathrm{m}}_t + \mathbf{\Gamma}' Z_{jt-1} + \varepsilon_{jt}, \tag{7}$$

where $r^{\mathrm{e}}_{jt+1} = \frac{p_{jt+1}-p_{jt}}{p_{jt}}$ is the percentage change in the firm's stock price between the beginning and end of the trading *day* in which a monetary policy announcement occurs. Accordingly, the time period in t is a day and the monetary policy shock $\varepsilon^{\mathrm{m}}_t$ is the original high-frequency shock. The firm-level covariates are the quarterly observations on day t.

Table 4 shows that stock prices of low-leverage firms are significantly more responsive to monetary policy shocks. Quantitatively, increasing leverage by one standard deviation

variables, such as consumption demand, spill over to investment through general equilibrium linkages. In this case, it is unclear that these spillovers would apply differentially across firms by leverage. Another explanation is that the hump-shaped aggregate dynamics reflect frictions to capital demand itself; again, it is unclear that such frictions should affect firms differentially by leverage.

decreases the exposure of stock returns to the monetary policy shock by more than eight percentage points. Hence, these results suggest that the stock market understands monetary policy expansions are better news for low-leverage firms.

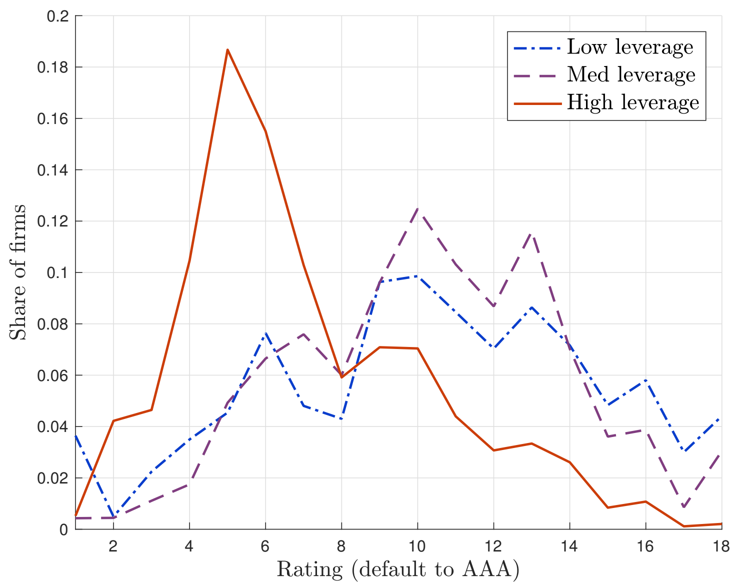
Additional Results Appendix A.2.1 contains six sets of additional results related to the analysis so far. First, it shows that the results are robust to including lagged investment to the set of firm-level controls. Second, it shows that the heterogeneous responses are driven by expansionary rather than contractionary shocks, although the two are not statistically distinguishable from each other. Third, it argues that our results are not driven by differences in cyclical sensitivities across firms. Fourth, it argues that our results are driven by the effect of monetary announcements on the realized short rate – as in our model – and not on expectations of the path of future rates. Fifth, it shows that these heterogeneous responses are also true for an extensive margin measure of investment. Sixth, it shows that the results hold for other measures of leverage.

2.3 Role of Default Risk in Heterogeneous Responses

In this subsection, we provide suggestive evidence that the heterogeneous responses by leverage documented above are driven, at least in part, by heterogeneity in default risk. Before doing so, we note that Appendix A.2.2 provides evidence against three competing hypotheses. First, it shows that our results hold using purely within-firm variation in leverage, ruling out the possibility that permanent heterogeneity in responsiveness (driven by, for example, differences in asset collateralizability across firms) drives our results. Second, it shows that our results continue to hold when we control for the interaction of the monetary policy shock with the firms' sales growth, future sales growth, or size, ruling out the possibility that our results are driven by some other observable that is simply mechanically correlated with leverage. Finally, it shows that our results are stronger when we instrument current leverage with past leverage, providing evidence against the possibility that unobservables which are contemporaneously correlated with leverage drive our results.

Our argument that the heterogeneous responses by leverage are driven, at least in part, by heterogeneity in default risk has two main components. First, firms with low leverage on

Figure 3: Distribution of Credit Ratings, Conditional on Leverage



Notes: Conditional distribution of credit ratings by leverage. "Low leverage" refers to observations in the bottom tercile of leverage. "Medium leverage" refers to observations in the middle tercile of leverage. "High leverage" refers to observations in the top tercile of leverage.

average have high credit ratings. Figure 3 plots the distribution of firm-level credit ratings for conditional on having low, medium, and high leverage. Most of the mass of the high-leverage distributions in concentrated in the left tail, below credit rating category 8 (BB). In contrast, most of the mass of medium- and particularly high-leverage distributions are in the right tail of the credit rating categories. Table 22 in Appendix A shows that this negative relationship between leverage and credit rating is also true conditional on the set of controls that enter our baseline regression (3).

The second component of our argument is that highly rated firms are more responsive to monetary policy. Table 5 estimates our baseline specification (3) with an additional interaction for credit rating; the coefficient estimate in column (2) implies that firms with a rating above AA have a 2.5 unit higher semi-elasticity with respect to monetary policy. This increase nearly triples the response relative to the average firm. Column (3) shows that this relationship continues to hold even conditional on leverage, consistent with the idea that both leverage and credit rating are imperfect proxies for firms' default risk.

TABLE 5
HETEROGENEOUS RESPONSES BY CREDIT RATING

	(1)	(2)	(3)
leverage $\times$ ffr shock	-0.73**		-0.71**
	(0.29)		(0.29)
$\mathbb{1}\{\texttt{rating}_{it} \geq AA\}\times$ ffr shock		2.50**	2.37**
		(1.14)	(1.16)
Observations	233232	233182	233182
R^2	0.119	0.119	0.119
Firm controls	yes	yes	yes
Time sector FE	yes	yes	yes
Time clustering	yes	yes	yes

Notes: Results from estimating variants of the baseline specification $\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta y_{jt-1}\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, y_{jt-1} is the firm's leverage or an indicator for having a credit rating above AA, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and time. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Appendix A Table 23 explores heterogeneity by size, cash flows, and dividend payments. Overall, the interaction between these variables is weaker than the interactions with leverage and credit ratings. Nonetheless, larger firms, firms with higher cash flows, and dividend-paying firms – characteristics typically associated with less severe financial frictions – are more responsive to monetary policy shocks.

3 Model

We now develop a heterogeneous firm New Keynesian model in order to interpret the cross-sectional evidence in Section 2 and draw out aggregate implications. We describe the model in three blocks: an investment block, which captures heterogenous responses to monetary policy; a New Keynesian block, which generates a Phillips curve; and a representative household, which closes the model.

3.1 Investment Block

The investment block contains a fixed mass of heterogeneous production firms that invest in capital subject to financial frictions. It builds heavily on the flexible-price model developed in Khan, Senga and Thomas (2016). Besides incorporating sticky prices, we extend Khan, Senga and Thomas (2016)'s framework in three additional ways. First, we add idiosyncratic capital quality shocks, which help us match observed default rates. Second, we incorporate aggregate adjustment costs in order to generate time-variation in the relative price of capital. Third, we assume that new entrants have lower initial productivity than average firms, which helps us match lifecycle dynamics.

Production firms Time is discrete and infinite. There is no aggregate uncertainty; in Sections 4 and 6 below, we study the transition path in response to an unexpected monetary shock. Each period, there is a fixed mass 1 of production firms.[13] Each firm $j \in [0,1]$ produces an undifferentiated good y_{jt} using the production function

$$y_{jt} = z_{jt}(\omega_{jt}k_{jt})^{\theta} n_{jt}^{\nu}, \tag{8}$$

where z_{jt} is an idiosyncratic total factor productivity shock, ω_{jt} is an idiosyncratic capital quality shock, k_{jt} is the firm's capital stock, n_{jt} is the firm's labor input, and $\theta + \nu < 1$. The idiosyncratic TFP shock follows an log-AR(1) process

$$\log z_{jt+1} = \rho z_{jt} + \varepsilon_{jt+1}, \text{ where } \varepsilon_{jt+1} \sim N(0, \sigma^2). \tag{9}$$

The capital quality shock is i.i.d. across firms and time and follows the log-normal process[14]

$$\log \omega_{jt} \sim N(-\frac{\sigma_{\omega}^2}{2}, \sigma_{\omega}^2).$$

[13] We describe the entry and exit process below, which keeps the total mass of firms fixed.

[14] We additionally assume that the idiosyncratic shock processes are bounded, which is important in our definition of unconstrained firms below. The idiosyncratic TFP shock is constrained to be in the interval $\left[-\frac{2.5\sigma}{\sqrt{1-\rho^2}}, \frac{2.5\sigma}{\sqrt{1-\rho^2}}\right]$ and the capital quality shock is in the interval $[-2.5\sigma_{\omega}, 2.5\sigma_{\omega}]$.

The capital quality shock also affects the value of the firm's undepreciated capital at the end of the period, $(1-\delta)\omega_{jt}k_{jt}$.

The timing of events within period is as follows.

(i) With probability π_d the firm receives an i.i.d. exit shock and must exit the economy after producing. Firms that do not receive the exit shock will be allowed to continue into the next period.

(ii) The firm decides whether or not to default. If the firm defaults it immediately and permanently exits the economy. In the event of default, lenders recover a fraction of the firm's capital stock (described in more detail below) and the remaining capital is transferred lump-sum to the household. In order to continue, the firm must pay back the face value of its outstanding debt, b_{jt}, and pay a fixed operating cost ξ in units of the final good.

(iii) Continuing firms produce using the production function (8). In order to produce, firms hire labor n_{jt} from a competitive labor market with real wage w_t. Firms sell their output to retailers (described below) in a competitive market at relative price p_t. At this point, firms that received the i.i.d. exit shock sell their undepreciated capital and exit the economy.

(iv) Continuing firms purchase new capital k_{jt+1} at relative price q_t. Firms have two sources of investment finance, each of which is subject to a friction. First, firms can issue new nominal debt with real face value $b_{jt+1} = \frac{B_{jt+1}}{\Pi_{t+1}}$, where B_{jt+1} is the nominal face value and Π_{t+1} is realized inflation on the final good (which is our numeraire, described below). Lenders offer a price schedule $\mathcal{Q}_t(z_{jt}, k_{jt+1}, b_{jt+1})$. The price schedule is decreasing in the amount of borrowing b_{jt+1} because firms may default on this borrowing (we derive this price schedule below). Second, firms can use internal finance by lowering dividend payments d_{jt} but cannot issue new equity, which bounds dividend payments $d_{jt} \geq 0$.[15]

[15] The non-negative dividend constraint captures two key facts about external equity documented in the corporate finance literature. First, firms face significant costs of issue new equity, both direct flotation costs (see, for example, Smith (1977)) and indirect costs (for example, Asquith and Mullins (1986)). Second, firms

We write the firm's optimization problem recursively. The individual state variable of a firm is its total factor productivity z and "cash on hand"

$$x = \max_n p_t z(\omega k)^\theta n^\nu - w_t n + q_t(1-\delta)\omega k - b - \xi.$$

Cash on hand x is the total amount of resources available to the firm other than additional borrowing. Conditional on continuing, the real equity value $v_t(z,x)$ solves the Bellman equation[16]

$$\begin{aligned} v_t(z,x) = \max_{k',b'} x - q_t k' + \mathcal{Q}_t(z,k',b')b' + \mathbb{E}_t\left[\Lambda_{t,t+1}\left(\pi_d \chi^1(x')x' + (1-\pi_d)\chi^2_{t+1}(z',x')v_{t+1}(z',x')\}\right)\right] \\ \text{such that } x - q_t k' + \mathcal{Q}_t(z,k',b')b' \geq 0 \qquad (10) \\ x' = \max_{n'} p_{t+1} z'(\omega' k')^\theta (n')^\nu - w_{t+1}n' + q_{t+1}(1-\delta)\omega' k' - \frac{b'}{\Pi_{t+1}} - \xi, \end{aligned}$$

where $\chi^1(x)$ and $\chi^2_t(z,x)$ are indicator variables for default conditional on the realization of the exit shock.

***Proposition* 1.** *Consider a firm at time t that is eligible to continue into the next period, has idiosyncratic productivity z, and has cash on hand x. The firm's optimal decision is characterized by one of the following three cases.*

(i) ***Default****: there exists a threshold $\underline{x}_t(z)$ such that the firm defaults if $x < \underline{x}_t(z)$.*

(ii) ***Unconstrained****: there exists a threshold $\overline{x}_t(z)$ such that the firm is* ***financially unconstrained*** *if $x > \overline{x}_t(z)$. Unconstrained firms follow the "frictionless" capital accumulation policy $k'_t(z,x) = k^*_t(z)$. Unconstrained firms are indifferent over any combination of b' and d such that they remain unconstrained for every period with probability one.*

issue external equity very infrequently (DeAngelo, DeAngelo and Stulz (2010)). The specific form of the non-negativity constraint is widely used in the macro literature because it allows for efficient computation of the model in general equilibrium. Other potential assumptions include proportional costs of equity issues (e.g., Gomes, 2001; Cooley and Quadrini, 2001; Hennessy and Whited, 2005; Gilchrist, Sim and Zakrajsek, 2014) and quadratic costs (e.g., Hennessy and Whited, 2007).

[16]Firms which receive the exogenous exit shock have simple decision rules. Those that do not default simply sell their undepreciated capital after production. Since these firms cannot borrow, they default whenever cash on hand $x < 0$.

(iii) ***Constrained***: *firms with* $x \in [\underline{x}_t(z), \overline{x}_t(z)]$ *are* ***financially constrained***. *Constrained firms' optimal investment* $k'_t(z,x)$ *and borrowing* $b'_t(z,x)$ *decisions solve the Bellman equation (10). Constrained firms also pay zero dividends, which implies*

$$q_t k' = x + \mathcal{Q}_t(z, k', b').$$

Proof. See Appendix B.1. ∎

Proposition 1 characterizes the decision rules which solve this Bellman equation. Firms with low cash on hand $x < \underline{x}_t(z)$ default because they cannot satisfy the non-negativity constraint on dividends $d \geq 0$. Firms with high cash on hand $x > \overline{x}_t(z)$ are *financially unconstrained* in the sense that they have no probability of default, which implies that any combination of external financing b' and internal financing d which leaves them unconstrained is optimal. Finally, firms with cash on hand $x \in [\underline{x}_t(z), \overline{x}_t(z)]$ are *financially constrained* in the sense that they affected by default risk. These firms set $d = 0$ because the value of resources inside the firm, used to lower borrowing costs, is higher than the value of resources outside the firm. Over 96% of firms in our calibration are affected by default risk in this way. Below, we focus our analysis on how these firms respond to monetary policy, since the analysis of the unconstrained firms is fairly standard. It is important to note that these constrained firms can be either *risky constrained* – have a positive probability of default in the next period – or *risk-free constrained* – have no probability of default in the next period yet not be financially unconstrained.

Lenders There is a representative financial intermediary that lends resources from the representative household to firms at the firm-specific price schedule $\mathcal{Q}_t(z, k', b')$. If the firm defaults on the loan in the following period, the lender recovers a fraction α of the market value of the firm's capital stock $q_{t+1}\omega' k'$. The price schedule prices this default risk competitively:

$$\mathcal{Q}_t(z,k',b') = \mathbb{E}_t\left[\Lambda_{t+1}\left(\frac{1}{\Pi_{t+1}} - \left(\pi_d \chi^1(x') + (1-\pi_d)\chi^2_{t+1}(z',x')\right)\left(\frac{1}{\Pi_{t+1}} - \min\{\frac{\alpha q_{t+1}(1-\delta)\omega' k'}{b'/\Pi_{t+1}}, 1\}\right)\right)\right], \tag{11}$$

where $x' = \max_{n'} p_{t+1} z(\omega' k')^\theta (n')^\nu - w_t n' + q_{t+1}(1-\delta)\omega' k' - b' - \xi$ is the cash on hand implied by k', b', and the realization of z'.

Entry Each period, a mass $\overline{\mu}_t$ of new firms enter the economy. We assume that the mass of new entrants is equal to the mass of firms that exit the economy so that the total mass of production firms is fixed in each period t. Each of these new entrants $j \in [0, \overline{\mu}_t]$ draws an idiosyncratic productivity shock z_{jt} from the time-invariant distribution

$$\mu^{\text{ent}}(z) \sim \log N\left(-m\frac{\sigma}{\sqrt{(1-\rho^2)}}, s\frac{\sigma}{\sqrt{(1-\rho^2)}}\right),$$

where $m \geq 0$ and $s \geq 0$ are parameters. We calibrate these parameters to match the average size and growth rates of new entrants, motivated by the evidence in Foster, Haltiwanger and Syverson (2016) that young firms have persistently low levels of measured productivity.[17] New entrants also draw capital quality from its ergodic distribution, are endowed with k_0 units of capital from the household, and have zero units of debt. They then proceed as incumbent firms.

3.2 New Keynesian Block

The New Keynesian block of the model is designed to parsimoniously generate a New Keynesian Phillips curve relating nominal variables to the real economy. Following Bernanke, Gertler and Gilchrist (1999), we keep the nominal rigidities separate from the investment block of the model.

Retailers and Final Good Producer There is a fixed mass of retailers $i \in [0, 1]$. Each retailer producers a differentiated variety $\widetilde{y}_{it}$ using the heterogeneous production firms' good as its only input:

$$\widetilde{y}_{it} = y_{it},$$

[17] Foster, Haltiwanger and Syverson (2016) argue that these low levels of measured productivity among young firms demand across firms rather than physical productivity. We remain agnostic about the interpretation of TFP in our model. Without the assumption that entrants have lower average productivity than existing firms, default risk would be disproportionately concentrated in a small group of young firms.

where y_{it} is the amount of the undifferentiated good demanded by retailer i. Retailers set a relative price for their variety $\widetilde{p}_{it}$ but must pay a quadratic price adjustment cost $\frac{\varphi}{2}\left(\frac{\widetilde{p}_{it}}{\widetilde{p}_{it-1}}-1\right)^2 Y_t$, where Y_t is the final good. The retailers' demand curve is generated by the representative final good producer, who has production function

$$Y_t = \left(\int \widetilde{y}_{it}^{\frac{\gamma-1}{\gamma}} \mathrm{d}i\right)^{\frac{\gamma}{\gamma-1}},$$

where γ is the elasticity of substitution over intermediate goods. The final good is the numeraire.

The retailers and final good producers aggregate into the familiar New Keynesian Phillips Curve:

$$\log \Pi_t = \frac{\gamma-1}{\varphi}\log\frac{p_t}{p^*} + \beta\mathbb{E}_t \log \Pi_{t+1}, \tag{12}$$

where Π_t is gross inflation of the final good and $p^* = \frac{\gamma-1}{\gamma}$ is the steady state relative price of the heterogeneous production firm output.[18] The Phillips Curve links the New Keynesian block to the investment block through the relative price p_t. When aggregate demand for the final good Y_t increases, retailers must increase production of their differentiated goods because of the nominal rigidities; this force increases demand for the production firms good y_{it}, which increases its relative price p_t and generates inflation through the Phillips Curve (12).

Capital Good Producer There is a representative capital good producer who produces aggregate capital K_{t+1} using the technology

$$K_{t+1} = \Phi\left(\frac{I_t}{K_t}\right)K_t + (1-\delta)K_t, \tag{13}$$

[18] We focus directly on the linearized formulation for computational simplicity.

where $\Phi(\frac{I_t}{K_t}) = \frac{\delta^{1/\phi}}{1-1/\phi}\left(\frac{I_t}{K_t}\right)^{1-1/\phi} - \frac{\delta}{\phi-1}$ and I_t are units of the final good used to produce capital.[19] Profit maximization pins down the relative price of capital as

$$q_t = \frac{1}{\Phi'(\frac{I_t}{K_t})} = \left(\frac{I_t/K_t}{\delta}\right)^{1/\phi}. \tag{14}$$

Monetary Authority The monetary authority sets the nominal risk-free interest rate R_t^{nom} according to the Taylor rule

$$\log R_t^{\text{nom}} = \log\frac{1}{\beta} + \varphi_\pi \log \Pi_t + \varepsilon_t^{\text{m}}, \text{ where } \varepsilon_t^m \sim N(0, \sigma_m^2),$$

where φ_π is the weight on inflation in the reaction function, and ε_t^{m} is the monetary policy shock.

3.3 Representative Household and Equilibrium

There is a representative household with preferences over consumption C_t and labor supply N_t represented by the expected utility function

$$\mathbb{E}_0 \sum_t^\infty \beta^t \left(\log C_t - \Psi N_t\right),$$

where β is the discount factor and Ψ controls the disutility of labor supply. The household owns all firms in the economy. The stochastic discount factor and nominal interest rate are linked through the Euler equation for bonds, $\Lambda_{t+1} = \frac{1}{R_t^{\text{nom}}/\Pi_{t+1}}$.

An equilibrium involves a set of value functions $v_t(z,x)$; decision rules $k_t'(z,x)$, $b_t'(z,x)$, $n_t(z,x)$; measure of firms $\mu_t(z,\omega,k,b)$; debt price schedule $\mathcal{Q}_t(z,k',b')$; and prices w_t, q_t, p_t, Π_t, $\Lambda_{t,t+1}$ such that (i) all firms optimize, (ii) lenders price default risk competitively, (iii) the household optimizes, (iii) the distribution of firms is consistent with decision rules, and (iv) all markets clear. Appendix B.2 precisely defines an equilibrium of our model.

[19] We use external adjustment costs rather than internal adjustment costs for two reasons. First, external adjustment costs generate time-variation in the price of capital, which allows us to study changes in the collateral value of capital. Second, because capital is liquid at the firm level, we can reduce the number of individual state variables, which is useful in the computation of the model.

4 Channels of Monetary Transmission

Before performing the quantitative analysis, we theoretically characterize the channels through which monetary policy affects investment in our model. This exercise identifies the key sources of heterogeneous responses across firms, which motivates our calibration in Section 5.

Monetary policy experiment We study the effect an unexpected innovation to the Taylor rule $\varepsilon_t^{\mathrm{m}}$ followed by a perfect foresight transition back to steady state. This approach allows for clean analytical results because there is no distinction between ex-ante expected real interest rates and ex-post realized real interest rates. We focus on financially constrained firms as defined in Proposition 1, which make up more than 96% of the firms in our calibration.

Impact on decision rules The optimal choice of investment k' and borrowing b' satisfy the following two conditions:

$$q_t k' = x + \frac{1}{R_t(z,k',b')} b' \tag{15}$$

$$\begin{aligned} \left(q_t - \varepsilon_{R,k'}(z,k',b')\frac{b'}{k'}\right)\frac{R_t^{\mathrm{sp}}(z,k',b')}{1-\varepsilon_{R,b'}(z,k',b')} =& \frac{1}{R_t}\mathbb{E}_t\left[\mathrm{MRPK}_{t+1}(z',k')\right] \\ &+ \frac{1}{R_t}\frac{\mathbb{C}ov_t(\mathrm{MRPK}_{t+1}(z',k'), 1+\lambda_{t+1}(z',k',b'))}{\mathbb{E}_t[1+\lambda_{t+1}(z',k',b'))]} \\ &+ \frac{1}{R_t} v_t^0(\underline{z}_{t+1}(k',b'))g(\underline{z}(k',b'))\left(\frac{\partial \underline{z}_{t+1}(k',b')}{\partial k'} - \frac{\partial \underline{z}_{t+1}(k',b')}{\partial b'}\right), \end{aligned} \tag{16}$$

where R_t is the risk-free rate between t and $t+1$, $R_t(z,k',b') = \frac{1}{\mathcal{Q}_t(z,k',b')}$ is the firm's implied interest rate schedule, $\varepsilon_{Rk'}(z,k',b')$ is the elasticity of the interest rate schedule with respect to investment k', $R_t^{\mathrm{sp}}(z,k',b') = R_t(z,k',b')/R_t$ is a measure of the borrowing spread, $\varepsilon_{Rb'}(z,k',b')$ is the elasticity of the debt price schedule with respect to borrowing, $\mathrm{MRPK}_{t+1}(z,k',b') = \frac{\partial}{\partial k'}(\max_{n'} p_{t+1} z'(\omega' k')^{\theta}(n')^{\nu} - w_{t+1}n' + q_{t+1}(1-\delta)\omega' k')$ is the return on capital to the firm, $\lambda_t(z,k,b)$ is the Lagrange multiplier on the non-negativity constraint on dividends, and $\underline{z}_t(k,b)$ is the default threshold in terms of productivity (which inverts the cash-on-hand threshold defined in Proposition 1). Condition (15) is the non-negativity constraint on dividends, which implies that capital expenditures $q_t k'$ must be financed either by internal resources x or new borrowing $\frac{1}{R_t(z,k',b')}b'$. Condition (16) is the intertemporal Euler equation, which equates the marginal cost of new capital k' on the left-hand side with the marginal benefit on on the right-hand side. The expectation and covariances in this expression are only taken over the states in which the firm does not default.

The marginal cost of capital is the product of two terms. The first term, $q_t - \varepsilon_{R,k'}(z,k',b')\frac{b'}{k'}$, is the relative price of new investment q_t net of the interest savings due to higher capital, $\varepsilon_{R,k'}(z,k',b')\frac{b'}{k'}$. The interest savings result from the fact that, all else equal, higher capital decreases expected losses due to default to the lenders. The second term in the marginal cost of capital is related to borrowing costs, $\frac{R_t^{\text{sp}}(z,k',b')}{1-\varepsilon_{R,b'}(z,k',b')}$. Borrowing costs enter the marginal cost of capital because borrowing is the marginal source of investment finance for these constrained firms. A higher interest rate spread or slope of that spread result in higher borrowing costs.

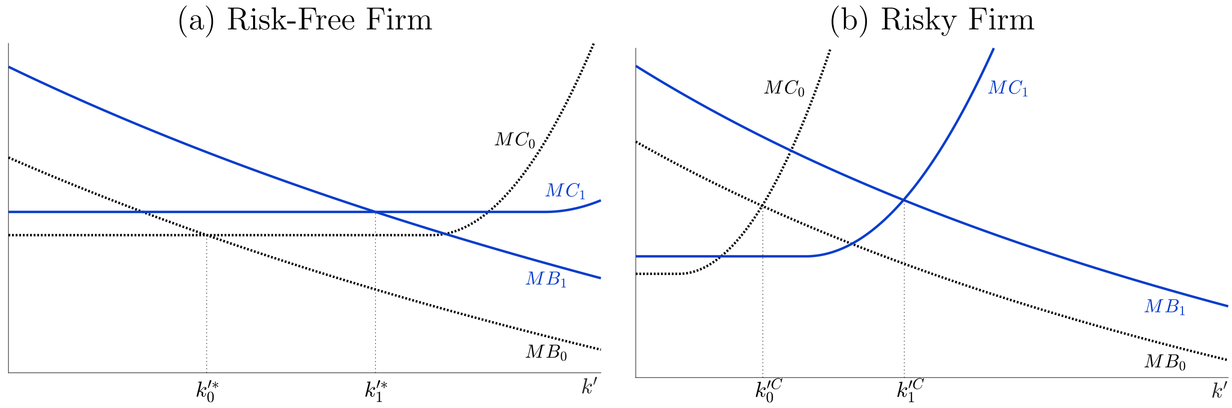
The marginal benefit of capital is the sum of three terms. The first term, $\frac{1}{R_t}\mathbb{E}_t\left[\text{MRPK}_{t+1}(z',k')\right]$, is the expected return on capital discounted by the real interest rate.[20] The second term, $\frac{1}{R_t}\frac{\mathbb{C}ov_t(\text{MRPK}_{t+1}(z',k'),1+\lambda_{t+1}(z',k',b'))}{\mathbb{E}_t[1+\lambda_{t+1}(z',k',b'))]}$, captures the covariance of the return on capital with the firm's shadow value of resources; capital is more valuable to the firm if it pays a high return when the firm values additional resources. The third term, $\frac{1}{R_t}v_t^0(\underline{z}_{t+1}(k',b'))g(\underline{z}_{t+1}(k',b'))(\frac{\partial \underline{z}_{t+1}(k',b')}{\partial k'} - \frac{\partial \underline{z}_{t+1}(k',b')}{\partial b'})$, captures how the additional investment affects the firm's default probabilities and, therefore, the value of the firm. In our calibration, this term is negligible because the value of the firm close to the default threshold, $v_t^0(\underline{z}_{t+1}(k',b'))$, is essentially zero.

Figure 4 plots the marginal benefit and marginal cost schedules as a function of capital accumulation k'. In order to illustrate the key economic mechanisms, we compare how these curves shift following an expansionary monetary policy shock for two polar examples of firms. These firms share the same level of productivity but differ in their initial cash on hand; the first firm has high cash on hand and is currently risk-free (though it is still constrained in the sense of Proposition 1), while the second has low cash on hand and is risky constrained.

Risk-Free Firm The left panel of Figure 4 plots the two schedules for the risk-free firm. The marginal cost curve is flat when capital accumulation k' can be financed without incur-

[20] Firms discount using the risk-free rate because there is no aggregate risk.

FIGURE 4: Response to Monetary Policy for Risk-Free and Risky Firms



Notes: Marginal benefit and cost curves as a function of capital investment k' for firms with same productivity. Left panel is for a firm with high initial cash on hand and right panel is for a firm with low initial cash on hand. Marginal cost curve is the left-hand side of (16) and marginal benefit left-hand side of (16). Dashed black lines plot the curves before the expansionary monetary policy shock, and solid blue lines plot the curves after the shock.

ring default risk and becomes upward sloping when investment is so large that the borrowing required creates default risk and therefore a credit spread. The marginal benefit curve is downward sloping due to diminishing returns of capital. In the initial equilibrium, the firm is risk-free because the two curves intersect in the flat region of the marginal cost curve.

The expansionary monetary shock shifts both the marginal benefit and marginal cost curves. The marginal benefit curves shifts out for two reasons. First, the shock decreases the real interest rate, which decreases the firm's discount rate R_t and therefore increases the discounted return on capital. Second, the shock also changes the relative price of output p_{t+1}, the real wage w_t, and the relative price of undepreciated capital q_{t+1} due to general equilibrium. In our calibration, these changes increase the return on capital $\text{MRPK}_{t+1}(z, k', b')$ and therefore further shift out the marginal benefit curve.[21]

The expansionary shock also shifts up the marginal cost curve because the increase in investment demand increases the relative price of capital q_t. In the new equilibrium, the firm has increased its investment and remains risk-free because the marginal benefit and marginal cost curves still intersect along the flat region of marginal cost.

[21] The shock also affects the covariance term and the change in default threshold, which are difficult to analytically characterize.

Risky Firm The right panel of Figure 4 plot how the marginal benefit and marginal cost schedules shift for the risky firm. Because this firm has low initial cash on hand x, it needs to borrow more than the risk-free firm to achieve the same level of investment. Hence, its marginal cost curve is upward-sloping over a larger region of the state space

The key difference between the risky and the risk-free firm is how monetary policy shifts the marginal cost curve. As for the risk-free firm, the curve shifts up because the relative price of capital q_t increases, but there are two additional effects for the risky firm. First, monetary policy increases cash on hand x, which decreases the amount the firm needs to borrow to finance any level of investment and therefore extends the flat region of the marginal cost curve. Monetary policy increases cash on hand according to:

$$\frac{\partial \log x}{\partial \varepsilon_t^{\mathrm{m}}} = \frac{1}{1-\nu-\theta}\left(\frac{\partial \log p_t}{\partial \varepsilon_t^{\mathrm{m}}} - \nu \frac{\partial \log w_t}{\partial \varepsilon_t^{\mathrm{m}}}\right)\frac{\iota_t(z,k)}{x} + \frac{\partial \log q_t}{\partial \varepsilon_t^{\mathrm{m}}}\frac{q_t(1-\delta)\omega k}{x} + \frac{\partial \log \Pi_t}{\partial \varepsilon_t^{\mathrm{m}}}\frac{b/\Pi_t}{x}, \tag{17}$$

where $\iota_t(z,k) = \max_n p_t z k^{\theta} n^{\nu} - w_t n$. This expression (17) contains three ways that monetary policy affects cash flows. First, monetary policy affects current revenues by changing the relative price of output p_t net of real labor costs νw_t. Second, monetary policy affects the value of firms' undepreciated capital stock by changing the relative price of capital q_t. Finally, monetary policy changes the real value of outstanding nominal debt through inflation Π_t.

The second key difference in how monetary policy affects the risky firm's marginal cost curve is that it flattens the upward-sloping region, reflecting reduced credit spreads. Credit spreads fall because the expansionary shock decreases the expected losses from default to the lender. Recall that, in the event of default, lenders recover $\alpha q_{t+1}\omega_{jt+1}k_{jt+1}$ per unit of debt; since the shock increases the relative price of capital q_{t+1}, it also increases the recovery rate. In addition, monetary policy also decreases the probability of default, although this effect is quantitatively small in our calibration.

Whether the risky firm is more or less responsive than the risk-free firm depends crucially on the size of these two shifts in the marginal cost curve. Theoretically, they may or may not be large enough to induce the risky firm to be more responsive to monetary policy than the risk-free firm. The goal of our calibration is to quantitatively discipline these shifts using our model of investment under default risk.

Table 6
Fixed Parameters

Parameter	Description	Value
Household		
β	Discount factor	0.99
Firms		
ν	Labor coefficient	0.64
θ	Capital coefficient	0.21
δ	Depreciation	0.026
New Keynesian Block		
ϕ	Aggregate capital AC	4
γ	Demand elasticity	10
φ_π	Taylor rule coefficient	1.25
φ	Price adjustment cost	90

Notes: Parameters exogenously fixed in the calibration.

5 Parameterization

We now calibrate the model and verify that its steady state behavior is consistent with key features of the micro data. In Section 6, we use the calibrated model to quantitatively study the effect of a monetary policy shock $\varepsilon_t^{\mathrm{m}}$.

5.1 Calibration

We calibrate the model in two steps. First, we exogenously fix a subset of parameters. Second, we choose the remaining parameters in order to match moments in the data.

Fixed Parameters Table 6 lists the parameters that we fix. The model period is one quarter, so we set the discount factor $\beta = 0.99$. We set the coefficient on labor $\nu = 0.64$. We choose the coefficient on capital $\theta = 0.21$ to imply a total returns to scale of 85%. Capital depreciates at rate $\delta = 0.026$ quarterly to match the average aggregate investment rate of nonresidential fixed investment reported in Bachmann, Caballero and Engel (2013).

We choose the elasticity of substitution in final goods production $\gamma = 10$, implying a steady state markup of 11%. This choice implies that the steady state labor share is $\frac{\gamma-1}{\gamma}\nu \approx 58\%$, close to the current U.S. labor share reported in Karabarbounis and Neiman

TABLE 7
FITTED PARAMETERS

Parameter	Description	Value
Idiosyncratic shock processes		
ρ	Persistence of TFP	0.86
σ	SD of innovations to TFP	0.03
σ_ω	SD of capital quality	0.04
Financial frictions		
ξ	Operating cost	0.02
α	Loan recovery rate	0.91
Firm lifecycle		
m	Mean shift of entrants' prod.	2.92
s	SD of entrants' prod	1.11
k_0	Initial capital	0.46
π_d	Exogeneous exit rate	0.02

Notes: Parameters chosen to match the moments in Table 8.

(2013). We choose the coefficient on inflation in the Taylor rule $\varphi_\pi = 1.25$, in the middle of the range commonly considered in the literature. Finally, we set the price adjustment cost parameter $\varphi = 90$ to generate the slope of the Phillips Curve equal to 0.1, as in Kaplan, Moll and Violante (2017).

Fitted Parameters We choose the parameters listed in Table 7 to match the empirical moments reported in Table 8. The first set of parameters govern the idiosyncratic shocks: ρ and σ control the AR(1) process for TFP and σ_ω controls the i.i.d. process for capital quality. The second set of parameters govern the frictions to external finance: the fixed operating cost ξ controls how often firms default and the recovery rate α controls the credit spread conditional on default. The final set of parameters govern the firm lifecycle: the parameters m and s control the productivity distribution of new entrants, k_0 controls the initial capital stock of new entrants, and π_d is the probability of receiving an exogenous exit shock.

We target four key sets of statistics in our calibration.[22] First, we target the dispersion of plant-level investment rates in Census microdata reported by Cooper and Haltiwanger

[22] At each step of this moment-matching process, we choose the disutility of labor supply Ψ to generate a steady state employment rate of 60%.

(2006).[23] The dispersion of investment rates places discipline on the degree of idiosyncratic risk faced by firms. Cooper and Haltiwanger (2006)'s sample is a balanced panel of plants that have survived at least sixteen years; to mirror this sample selection in the model, we condition on firms that have survived for twenty years, and our calibration results are robust to different choices of this cutoff.

The second set of moments we target are related to firms' use of external finance. Following Bernanke, Gertler and Gilchrist (1999), we target a mean default rate of 3% as estimated in a survey of businesses by Dun and Bradstreet. We target an average annual credit spread implied by BAA rated corporate bond yields to the ten-year Treasury yield.[24] Finally, we target the average firm-level gross leverage ratio of 34.4% from the microdata underlying the Quarterly Financial Reports, as reported in Crouzet and Mehrotra (2017).

The final two sets of moments are informative about firm lifecycle dynamics. We target the average size of firms one year old and two years old relative to the average size of all firms in the economy. The relative size of one year old firms is informative about the size of new entrants, and the difference between the sizes of one and two year old firms is informative about how quickly young firms grow. We also target the average exit rate and the share of firms in the economy at age one and two. The difference in shares of age one and two firms is informative about the exit rate of young firms. All of these statistics are computed from the Business Dynamics Statistics (BDS), the public-release sample of statistics aggregated from the Census' Longitudinal Business Database (LBD).

Table 8 shows that our model matches the targeted moments reasonably well.[25] The model closely matches the dispersion of investment rates, which captures the degree of idiosyncratic risk faced by firms. The model also closely matches the average gross leverage ratio and the

[23]An issue with this empirical target is that production units in our model correspond more closely to firms than to plants. We prefer to use the plant-level data from Cooper and Haltiwanger (2006) because it carefully constructs measures of retirement and sales of capital to measure negative investment, which is important in our model because capital is liquid.

[24]We target credit spreads because the debt price schedule is central to the economic mechanisms in our model. To the extent that observed credit spreads are driven by risk premia rather than risk-neutral pricing of default risk, we may overstate the importance of default risk in our calibration. We do not believe this is a major concern because our calibrated debt recovery rate is broadly in line with estimated loss in default from the corporate finance literature. For robustness, we also directly targeted estimates of the cost of default from this literature, rather than the level of spreads, and found similar steady state behavior.

[25]We do not match the moments exactly because our model is nonlinear. We use simulated annealing to minimize the weighted sum of squared errors implied by these moments.

TABLE 8
CALIBRATION TARGETS AND MODEL FIT

Moment	Description	Data	Model
Investment behavior (annual)			
$\sigma\left(\frac{i}{k}\right)$	SD investment rate	33.7%	31.8%
Financial behavior (annual)			
$\mathbb{E}\left[\text{default rate}\right]$	Mean default rate	3.00%	2.01%
$\mathbb{E}\left[\text{credit spread}\right]$	Mean credit spread	2.35%	2.54%
$\mathbb{E}\left[\frac{b}{k}\right]$	Mean gross leverage ratio	34.4%	33.6%
Firm Growth (annual)			
$\mathbb{E}[n_1]/\mathbb{E}[n]$	Size of age 1 firms (relative to mean)	28%	42%
$\mathbb{E}[n_2]/\mathbb{E}[n]$	Size of age 2 firms (relative to mean)	36%	66%
Firm Exit (annual)			
$\mathbb{E}\left[\text{exit rate}\right]$	Mean exit rate	8.7%	7.88%
$\mathbb{E}\left[M_1\right]/\mathbb{E}\left[M\right]$	Share of firms at age 1	10.5%	7.4%
$\mathbb{E}\left[M_2\right]/\mathbb{E}\left[M\right]$	Share of firms at age 2	8.1%	6.1%

Notes: Empirical moments targeted in the calibration. Investment behavior drawn from the distribution of plant-level investment rates in Census microdata, 1972-1988, reported in Cooper and Haltiwanger (2006). These investment moments are drawn from a balanced panel; we mirror this sample selection in the model by computing investment moments for firms who have survived at least twenty years. The mean default rate is from Dun and Bradstreet survey, as reported by Bernanke, Gertler and Gilchrist (1999). The average firm-level gross leverage ratio is taken from the micro data underlying the Quarterly Financial Reports, and is reported in Crouzet and Mehrotra (2017). The average credit spread is measured as the yield on BAA rated corporate bonds relative to a ten-year Treasury bond. The mean exit rate is computed from the Business Dynamics Statistics (BDS). The average size of firms age one and two is relative to the average size of firms the economy, and also drawn from the BDS. The shares of firms at age one and two are also drawn from the BDS.

average credit spreads, but it underpredicts the mean default rate. Firms in our model grow too quickly relative to the data, which is not surprising because we do not include other frictions to firm growth such as capital adjustment costs or customer accumulation. Finally, the model underpredicts the total amount of firm exit (due to the fact that it underpredicts the average default rate), but it does provide a good match of the ratio of exit rates of age 1 to age 2 firms.

The calibrated parameters in Table 7 are broadly comparable to existing estimates in the literature. Idiosyncratic TFP shocks are less persistent and more volatile than aggregate productivity shocks, consistent with direct measurements of plant- or firm-level productivity. The calibrated loan recovery rate is 91%, in line with the low estimated costs of default in the literature. New entrants start with significantly lower productivity and capital than the average firm.

5.2 Financial Heterogeneity in the Model and the Data

Appendix B.3 analyzes firms' decision rules in the stationary distribution and identifies two key sources of financial heterogeneity across firms. The first source is lifecycle dynamics; firms are born below their optimal scale, i.e. $k_0 < k^*(z)$, and need to growth their capital stock. These young firms initially borrow in order to accumulate capital, increasing their risk of default and therefore borrowing costs. The second source of financial heterogeneity is TFP shocks z; a positive shock increases the firm's optimal scale $k^*(z)$, which again induces debt-financed capital accumulation.

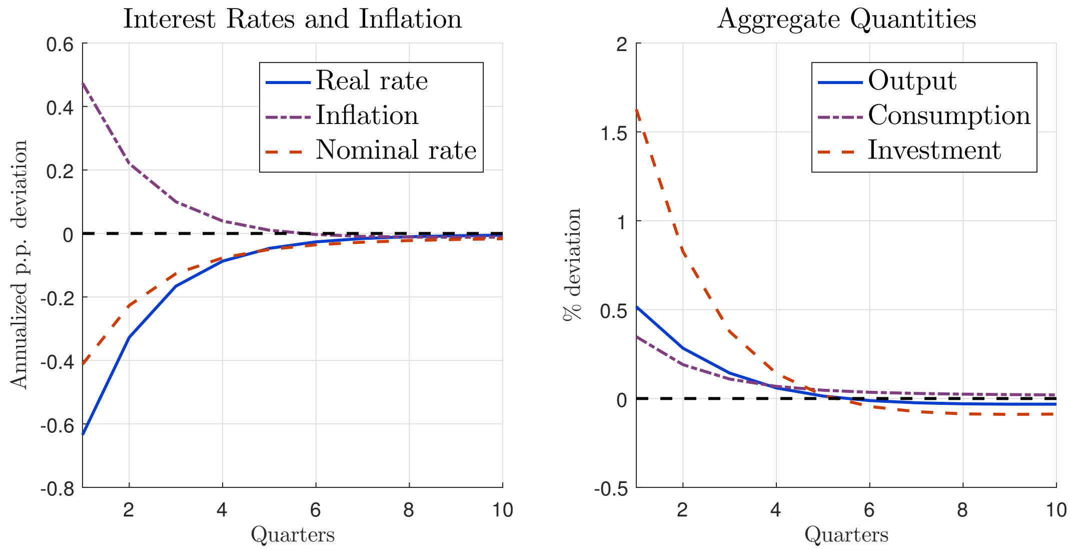
Appendix B.3 also compares the behavior of the model to three key non-targeted dimensions of the data that are informative about these sources of financial heterogeneity. First, we find that firms in our model reach their average size after five years, which is faster than in the data. This rapid speed of convergence is not surprising because our model abstracts from other sources of lifecycle dynamics, such as firm-level adjustment costs or customer base concerns. Second, we show that the joint distribution of investment and leverage rates in our model is comparable to Census and Compustat data. Finally, we show that measured investment-cash flow sensitivities in our model are roughly in line with the data.

6 Monetary Policy Analysis

We now quantitatively analyze the effect of a monetary policy shock $\varepsilon_t^{\mathrm{m}}$. Section 6.1 begins the analysis by computing the aggregate impulse responses to an expansionary shock in our calibrated model. Section 6.2 studies the heterogeneous effects of monetary policy across firms and shows that, consistent with the empirical results from Section 2, risky firms are less responsive to monetary policy. Finally, Section 6.3 shows that the aggregate effect of monetary policy depends on the distribution of net worth.

The economy is initially in steady state and unexpectedly receives a $\varepsilon_0^{\mathrm{m}} = -0.0025$ innovation to the Taylor rule which reverts to 0 according to $\varepsilon_{t+1}^{\mathrm{m}} = \rho_m \varepsilon_t^{\mathrm{m}}$ with $\rho_m = 0.5$. We compute the perfect foresight transition path of the economy as it converges back to steady

FIGURE 5: Aggregate Responses to Expansionary Monetary Shock



Notes: Aggregate impulse responses to a $\varepsilon_0^{\mathrm{m}} = -0.0025$ innovation to the Taylor rule which decays at rate $\rho_m = 0.5$. Computed as the perfect foresight transition in response to a series of unexpected innovations starting from steady state.

state.[26]

6.1 Aggregate Response to Monetary Policy

Figure 5 plots the responses of key aggregate variables to this expansionary shock. The shock lowers the nominal interest rate; because prices are sticky, this also lowers the real interest rate. The lower real interest rate stimulates investment demand for the reasons discussed in Section 4. It also stimulates consumption demand from the household through the Euler equation. Higher aggregate demand for goods raises inflation. This process increases investment by 1.6%, output by 0.5%, and consumption by 0.35% for a 0.4% change in the annualized nominal interest rate, broadly in line with the peak effect of monetary policy estimated in Christiano, Eichenbaum and Evans (2005).[27]

[26] Allowing for persistence in the monetary policy shocks themselves is a simple way to create inertia in response to a monetary shock. In the representative firm version of the model, the response is very similar to a version of the model in which the innovations are transitory but the Taylor rule includes interest rate smoothing.

[27] Our model does not generate the hump-shaped aggregate responses emphasized by Christiano, Eichenbaum and Evans (2005). We could do so by incorporating adjustment costs to investment rather than capital.

Table 9
Regression Results

	Model		Data	
	(1)	(2)	(1)	(2)
leverage × ffr shock	-1.193	-0.955	-0.93^{***}	-0.73^{***}
			(0.34)	(0.29)
R^2	0.151	0.216	0.107	0.119
Firm controls	no	yes	no	yes

Notes: Results from running the baseline specification $\Delta \log k_{jt} = \alpha_j + \alpha_t + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$ on model-simulated data, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is the firm's leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage and size. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean. The sample period is four quarters before the monetary shock through ten quarters after the shock. To mirror the sample selection into Compustat, we condition on firms that have survived at least ten years. "Data" refers to results in Table 3.

6.2 Heterogeneous Responses to Monetary Policy

We now study the heterogeneous responses to monetary policy across firms in our model and show that they are consistent with the data.

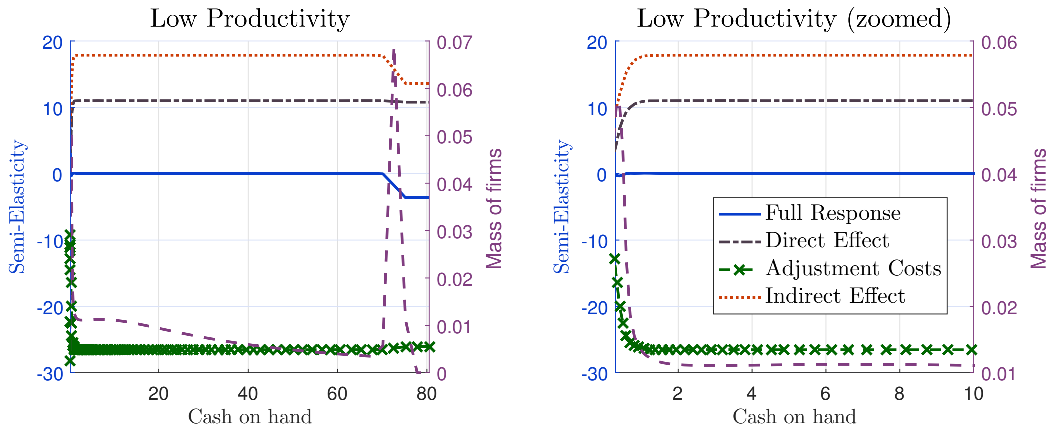
Model-Implied Regression Coefficients In order to directly compare out model to the data, we simulate a panel of firms in response to the monetary shock and estimate the regression specification (3) on the simulated panel. We mirror the sample selection into Compustat by conditioning on firms that have survived at least ten years. We identify the innovation to the Taylor rule $\varepsilon_t^{\mathrm{m}}$ with the high-frequency shocks that we measure in the data.[28] We estimate the regression using data from one year before the shock to ten quarters after the shock.

Table 9 shows that the estimated interaction coefficient in the model is within one stan-

However, we prefer to focus on capital adjustment costs because they are a parsimonious way to capture movements in the relative price of capital.

[28] In our model, the change in the nominal interest rate is smaller than the innovation to the Taylor rule because the monetary authority responds to the increased inflation. This fact may lead to an inconsistency between the monetary shocks in the model and the measured shocks in the data, which are based on changes in expected rates. Our implicit assumption is that the feedback effect through the Taylor rule takes sufficient time that it is not incorporated into the measure of the high-frequency shocks. Because we use the one-month futures, our assumption requires that the monetary authority respond to inflation with at most a one month lag.

FIGURE 6: Decomposition of Semi-Elasticity of Capital to Monetary Policy Shock



Notes: Semi-elasticity of capital and stationary distribution of firms conditional on idiosyncratic productivity one standard deviation below the mean. Left column plots over the entire state space while right column focuses on low levels of cash on hand x. “Direct effect” refers to only the real interest rate changes, holding all other prices fixed at steady state. “Adjustment cost” refers to changing the price of capital for new investment only. “Indirect effect” refers to changing all other prices.

dard error of the empirical estimate. Hence, the shifts in the marginal cost curve for risky firms discussed in Section 4 are not large enough to compensate for its upward slope. Column (1) estimates the regression (3) without any firm-level controls Z_{jt}. In both the model and the data, a firm with one standard deviation more leverage than the average firm has an investment semi-elasticity approximately one percentage point lower than the average firm. Columns (2) includes firm-level controls Z_{jt} and shows that this conclusion does not substantially change. The R^2 of the regressions are higher in our model, indicating that the data contain more unexplained sources of variation in investment.[29]

Channels Driving Heterogeneous Responses Figure 6 plots the semi-elasticity of investment k' with respect to the monetary shock as a function of cash on hand x, and decomposes this elasticity into the three different categories: the direct effect, which works through changes in the real interest rate, the adjustment cost effect, which works through changes in

[29] Our results are somewhat sensitive to the number of periods we include in the regression. To investigate this sensitivity, we ran our baseline specification (3) using only the period of the shock. Because this specification only includes one quarter of data, we cannot estimate the fixed effects and the coefficient on leverage simply captures cross-sectional heterogeneity in how firms respond to the shock. Even in this much simpler setting, the estimated coefficient is strongly negative without controls. However, the coefficient significantly falls with controls because we exploiting different sources of variation than in our baseline specification.

the relative price of new capital, and the indirect effect, which works through all other prices. We compute the contribution of each of these channels by feeding in the relevant series of prices to the firms in our model, holding all other prices fixed at their steady state values.

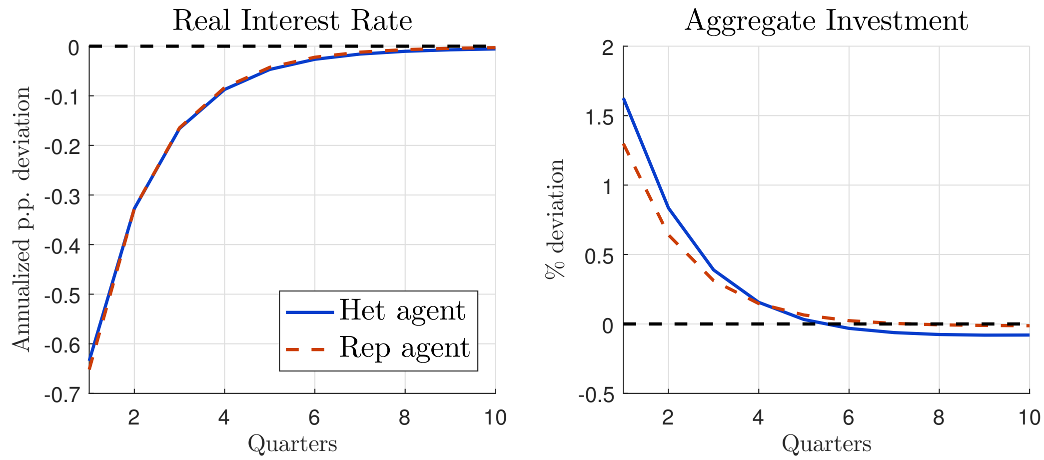
Both the direct and indirect effects have a strong stimulative effect on investment while the adjustment cost has a strong negative impact on investment. However, all these effects are dampened for risky firms relative to risk-free firms due to the upward-sloping marginal cost curve plotted in Figure 4. Completely financially unconstrained firms with $x > \overline{x}_t(z)$ have a lower semi-elasticity than all these firms because they are less exposed to the indirect effects of monetary policy. In terms of the Euler equation (16), unconstrained firms have zero covariance between the shadow value of funds and the return on capital.

The fact that both the direct and indirect effects play a quantitatively important role in driving the investment channel of monetary policy contrasts with Auclert (2017)'s and Kaplan, Moll and Violante (2017)'s decomposition of the consumption channel. In the context of a household's consumption-savings problem, they find that the contribution of the direct effect of lower real interest rates is small relative to the indirect general equilibrium effects of higher labor income. In our model, direct interest rate effects are stronger because firms are more price-sensitive than households. In fact, without any financial frictions at all, the partial equilibrium elasticity of investment with respect to interest rates would be nearly infinite (see House (2014)). Households are less price sensitive because of consumption-smoothing motives.

6.3 Aggregate Implications of Financial Heterogeneity

In this subsection, we study two ways in which financial heterogeneity matters for understanding the aggregate monetary transmission mechanism. First, we show that the aggregate effect of monetary policy is larger in our model than in a comparable version of the model without financial frictions (which collapses to a representative firm). Second, we show that the aggregate effect of a given monetary policy shock in our model significantly depends on the initial distribution of net worth.

Figure 7: Aggregate Impulse Responses in Full Model vs. Rep Firm Model

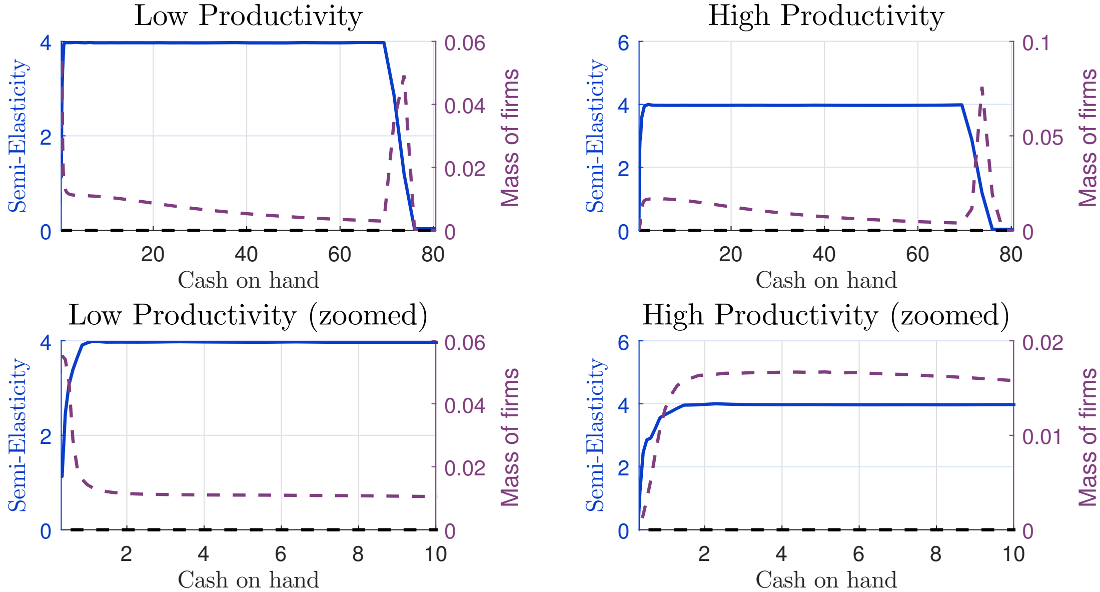


Notes: Aggregate impulse responses to a $\varepsilon_0^{\mathrm{m}} = -0.0025$ innovation to the Taylor rule which decays at rate $\rho_m = 0.5$. Computed as the perfect foresight transition in response to a series of unexpected innovations starting from steady state. "Het agent" refers to calibrated heterogeneous firm model from the main text. "Rep agent" refers to a version of the model in which the heterogeneous production sector is replaced by a representative firm with the same production function and no financial frictions.

Comparison to Frictionless Model We eliminate financial frictions by removing the non-negativity constraint on dividends; in this case, the investment block of the model collapses to a financially unconstrained representative firm (see Khan and Thomas (2008) Appendix B). Figure 7 shows that the impact effect of monetary policy on investment is 25% larger in our full model than in the representative firm benchmark. Hence, despite the fact that risky constrained firms are less responsive than risk-free constrained firms, both types of constrained firms are more responsive than completely unconstrained firms.

To understand this result, Figure 8 plots the semi-elasticity of capital with respect to the monetary policy shock for firms in our model, assuming that they face the equilibrium path of prices from the representative firm model. By construction, the response of unconstrained firms with $x \geq \overline{x}(z)$ is the same as the representative firm in the frictionless benchmark. In contrast, both the risky and risk-free constrained firms are significantly more responsive than the unconstrained firms. Both types of constrained firms are more responsive because their marginal value of additional cash-on-hand is strictly larger than for completely unconstrained firms. Within constrained firms with low cash-on-hand, risky constrained firms are less responsive than risk-free constrained firms, consistent with the results in Section 6.2.

Figure 8: Semi-Elasticity of Capital w.r.t. Monetary Shock, Rep Firm Model Prices



Notes: Left column plots the semi-elasticity of capital and stationary distribution of firms conditional on idiosyncratic productivity one standard deviation below the mean. Right column plots the same objects conditional on idiosyncratic productivity one standard deviation above the mean. The left y-axis measures the semi-elasticity of capital with respect to the monetary policy shock (measured in annual percentage points and absolute value). The right y-axis measures the stationary distribution of firms. Top row plots these functions over the entire space of cash on hand. Bottom row plots these functions for low levels of cash on hand only. Decision rules are computed given the equilibrium path of prices from the representative firm model.

Higher investment demand from constrained firms puts additional upward pressure on the relative price of capital q_t in the general equilibrium of our full model. Unconstrained firms, who have a small positive response facing the representative firm model's prices, now have a large negative response.

State Dependence of Aggregate Transmission We now show that the aggregate effect of monetary policy is smaller when the initial distribution of firms contains more risky firms. In order to illustrate the quantitative magnitude of this mechanism, we perform a simple calculation: we take the semi-elasticity of capital with respect to monetary policy as fixed and vary the initial distribution of firms.[30]

[30] This exercise does not allow for prices to vary with the initial distribution. However, the exercise is a nevertheless an important necessary condition for the general equilibrium model to generate state dependence. We perform the simple exercise of fixing the elasticities and varying the distribution for two reasons.

We vary the initial distribution of firms in production $\hat{\mu}(z,x)$ by taking the weighted average of two reference distributions. The first reference distribution is the steady-state distribution $\hat{\mu}^*(z,x)$. The second reference distribution $\widetilde{\mu}(z,x)$ assumes that the conditional distribution of cash-on-hand for every level of productivity is equal to the distribution of cash-on-hand conditional on the lowest realization of productivity in steady state. We normalize the second reference distribution so that the marginal distribution of productivity is the same as in the steady state distribution. Hence, $\widetilde{\mu}(z,x)$ is an example of a distribution in which firms of all productivity levels have a poor distribution of cash on hand. We then compute the initial distribution as a weighted average of these two reference distributions, $\hat{\mu}(z,x) = \hat{\omega}\widetilde{\mu}(z,x)+(1-\hat{\omega})\hat{\mu}^*(z,x)$. We vary $\hat{\omega} \in [0,1]$ to trace out linear combinations of distributions between the steady state ($\hat{\omega}=0$) and the low cash on hand ($\hat{\omega}=1$) distributions. We then compute the change in the aggregate capital stock in response to the monetary policy shock for each of these initial distributions.

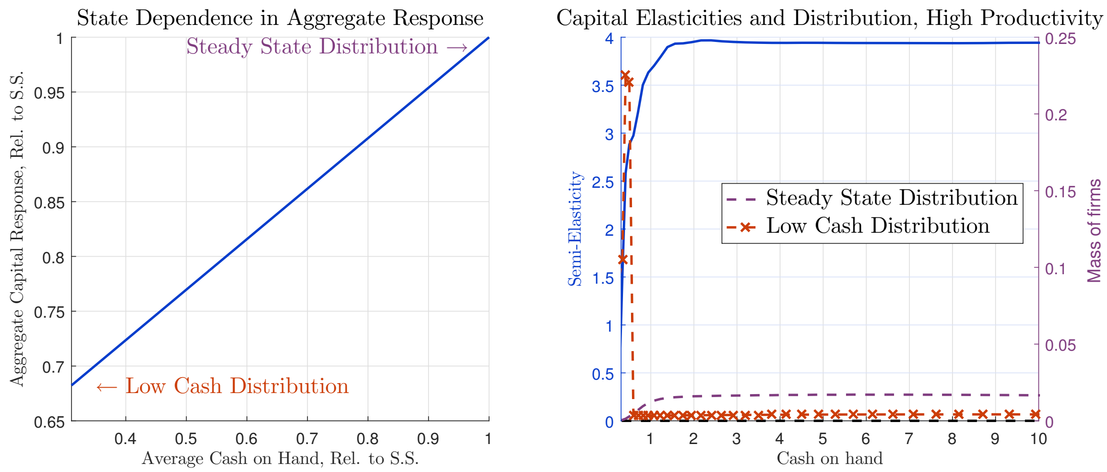
The left panel of Figure 9 shows that the change in the aggregate capital stock is 30% smaller starting from the low-cash distribution $\widetilde{\mu}(z,x)$ than starting from the steady state distribution $\hat{\mu}^*(z,x)$, and the response varies linearly in between these two extremes. Average cash-on-hand is 70% lower and there are twice as many risky constrained firms in the low-cash distribution than in the steady state distribution. The right panel of Figure 9 shows that this effect is due to the fact that the low-cash distribution $\widetilde{\mu}(z,x)$ places more mass in the region of the state space where the elasticity of capital with respect to the monetary policy shock is low.

These results suggests a potentially powerful source of time-variation in the aggregate transmission mechanism: monetary policy is less powerful when net worth is low and default risk is high. A limitation of this analysis is that we have varied the initial distribution exogeneously. The natural next step in this analysis is to incorporate with various business cycle

First, since we do not have to re-compute the equilibrium transition path for each initial distribution, we can investigate state dependence with respect to a large number of initial distributions. Second, this exercise clearly isolates the impact of varying the initial distribution from the additional changes to firms' policy rules arising from changes in prices.

In this exercise, markets do not clear for a given initial distribution of cash-on-hand. We use the elasticities from the representative firm prices plotted in Figure 8 so that markets do not clear for any initial distribution. If we had used the equilibrium elasticities, markets would clear for some initial distributions and not others, potentially biasing our interpretation of the results.

Figure 9: Aggregate Response Depends on Initial Distribution



Notes: Dependence of aggregate response on initial distribution. We compute the change in aggregate capital for different initial distributions using the response to monetary policy computed under the price path from the representative firm model. We vary the initial distribution of firms in production $\hat{\mu}(z,x)$ by taking the weighted average of two reference distributions. The first reference distribution is the steady-state distribution $\hat{\mu}^*(z,x)$. The second reference distribution $\widetilde{\mu}(z,x)$ assumes that the conditional distribution of cash-on-hand for every level of productivity is equal to the distribution of cash-on-hand conditional on the lowest realization of productivity in steady state. We normalize the second reference distribution so that the marginal distribution of productivity is the same as in the steady state distribution. We then compute the initial distribution as a weighted average of these two distributions, $\hat{\mu}(z,x) = \hat{\omega}\widetilde{\mu}(z,x) + (1-\hat{\omega})\hat{\mu}^*(z,x)$. Left panel varies $\hat{\omega} \in [0,1]$ and plots the change in the aggregate capital stock upon impact against the average cash-on-hand of the initial distribution. Right panel plots the semi-elasticity of capital with respect to the shock over cash on hand for high productivity firms. The steady state distribution corresponds to $\hat{\omega} = 0$ and the low-cash distribution corresponds to $\hat{\omega} = 1$.

shocks into our model and study the types of distributions that actually arise in equilibrium.

7 Conclusion

In this paper, we have argued that financial frictions dampen the response of investment for firms with high default risk. Our argument had two main components. First, we showed in the micro data that firms with high leverage or low credit ratings invest significantly less than other firms following a monetary policy shock. Second, we built a heterogeneous firm New Keynesian model with default risk that is quantitatively consistent with these empirical results. In the model, monetary policy stimulates investment through a combination of direct and indirect effects. High-risk firms are less responsive to these changes because their marginal cost of investment finance is higher than for low-risk firms. The aggregate effect of monetary policy is primarily driven by these low-risk firms, which suggests a novel form of state dependence: monetary policy is less powerful when default risk in the economy is greater.

Our results may be of independent interest to policymakers who are concerned about the distributional implications of monetary policy across firms. An often-discussed goal of monetary policy is to provide resources to viable but credit constrained firms. Many policymakers' conventional wisdom, built on the financial accelerator mechanism, suggests that constrained firms will significantly increase their capital investment in response to expansionary monetary policy. Our results imply that, instead, expansionary policy will stimulate the less risky firms in the economy.

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Appendix (For Online Publication Only)

A Empirical Appendix

This appendix describes the firm-level variables used in the empirical analysis of the paper, based on quarterly Compustat data. The definition of the variables and sample selection follow standard practices in the literature (see, for example, Whited, 1992; Gomes, 2001; Eisfeldt and Rampini, 2006; Clementi and Palazzo, 2015).

A.1 Data Construction

Variables

1. *Investment, intensive margin* (baseline measure): defined as $\Delta \log(k_{jt+1})$, where k_{jt+1} denotes the capital stock of firm j at the end of period t. For each firm, we set the first value of k_{jt+1} to the level of gross plant, property, and equipment (`ppegtq`, item 118) in the first period in which this variable is reported in Compustat. From this period onwards, we compute the evolution of k_{jt+1} using the changes of net plant, property, and equipment (`ppentq`, item 42), which is a measure net investment with significantly more observations than `ppegtq` (net of depreciation). If a firm has a missing observation of `ppentq` located between two periods with nonmissing observations we estimate its value using a linear interpolation with the values of `ppentq` right before and after the missing observation; if two or more consecutive observations are missing we do not do any imputation. We only consider investment spells with 40 quarters or more in order to precisely estimate fixed effects.

2. *Investment, extensive margin*: defined as $\mathbb{1}\left\{\frac{i_{jt}}{k_{jt}} > 1\%\right\}$, where $i_{jt} = k_{jt+1} - (1-\delta_j)k_{jt}$ denotes gross investment. We measure δ_j using depreciation rates of Fixed Asset Tables from NIPA at the sector level.

3. *Leverage*: defined as the ratio of total debt (sum of `dlcq` and `dlttq`, items 45 and 71) to total assets (`atq`, item 44).

4. *Net leverage*: defined as the ratio of total debt minus net current assets (`actq`, item 40, minus `lctq`, item 49) to total assets.

5. *Real Sales Growth*: measured as log-differences in sales (`saleq`, item 2) deflated using CPI.

6. *Size*: measured as the log of total assets.

7. *Cash flow*: measured as EBITDA divided by capital stock.

8. *Dividend payer*: defined as a dummy variable taking a value of one in firm-quarter observations in which the firm paid dividends to preferred stock of the company (constructed using `dvpq`, item 24).

9. *Tobin's q*: defined as the ratio market to book value of assets. The market value of assets is measured as the book value, plus the market value of common stock, minus the book value of common stock `ceq`, plus deferred taxes and investment tax credit (item `txditcq`, item 52). The market value of common stock is computed as the product of price at quarter close (`prccq`) and common shares outstanding (`cshoq` item 61). We winsorize 1% of observations in each tail of the distribution.

10. *Sectoral dummies*. We consider the following sectors: (i) agriculture, forestry, and fishing: `sic` < 10; (ii) mining: `sic`$\in [10, 14]$; (iii) construction: `sic`$\in [15, 17]$; (iv) manufacturing: `sic`$\in [20, 39]$; (v) transportation, communications, electric, gas, and sanitary services: `sic`$\in [40, 49]$; (vi) wholesale trade: `sic`$\in [50, 51]$; (vii) retail trade `sic`$\in [52, 59]$; (viii) services: `sic`$\in [70, 89]$.

Sample Selection Our empirical analysis excludes:

1. Firms in finance, insurance, and real estate sectors (`sic`$\in [60, 67]$) and public administration (`sic`$\in [91, 97]$).

2. Firms not incorporated in the United States.

3. Firm-quarter observations with acquisitions (constructed based on `aqcy`, item 94) larger than 5% percent of assets.

4. Firm-quarter observations that satisfy one of the following conditions, aimed at excluding extreme observations:

    i. Investment rate is in the top and bottom 0.5 percent of the distribution.

    ii. Leverage higher than 10.

    iii. Net current assets as a share of total assets higher than 10 or below -10.

    iv. Quarterly real sales growth above 1 or below -1.

A.2 Additional Results

This appendix contains various additional results referenced in Section 2 of the main text.

A.2.1 Heterogeneity by Leverage

We begin by presenting additional analysis of the heterogeneous responses by leverage documented in Section 2.2.

Lagged Investment Table 10 shows that the main results in Table 3 continue to hold when controlling for lagged investment. This exercise is motivated by results in Eberly, Rebelo and Vincent (2012), who show that the R^2 of a similar investment regression significantly increases when one includes lagged investment. We find only a modest increase of R^2 in our sample. We conjecture the differences are due to three differences in sample selection: Eberly, Rebelo and Vincent (2012) use annual data while we use quarterly; they use a balanced panel 1981-2003 while we use an unbalanced panel 1990-2007; and they only use firms in top quartile of the capital distribution in 1981 while we do not select our sample on size.

Expansionary vs. Contractionary Shocks Table 11 separately estimates heterogeneous responses for expansionary and contractionary shocks. Although the differences by leverage are only significant for expansionary shocks, the difference between the is not statistically significant. This result is largely due to the fact that there are relatively few observations of contractionary shocks in our sample, creating a large standard error.

Table 10
Lagged Investment

	(1)	(2)	(3)
leverage × ffr shock	-0.81**	-0.59**	-0.59**
	(0.32)	(0.27)	(0.28)
investment $(t-1)$	0.07	0.07**	0.08***
	(0.28)	(0.03)	(0.01)
ffr shock			1.14
			(0.90)
Observations	238069	238069	238069
R^2	0.121	0.133	0.121
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Notes: Results from estimating variants of the model

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \rho \Delta \log k_{jt} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \boldsymbol{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Cyclical Sensitivities One possible concern that our monetary policy shocks may be correlated with other business cycle conditions which themselves drive differences across firms. Although our high-frequency shock identification is designed to address this concern, as a further check we interact leverage with various business cycle indicators in

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_1 \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \beta_2 \ell_{jt-1} Y_t + \boldsymbol{\Gamma}' Z_{jt-1} + e_{jt},$$

where Y_t is GDP growth, the inflation rate, the unemployment rate, or the VIX index. Table 12 shows that the estimated coefficients β in this regression are not economically meaningful or statistically different from zero for any of the business cycle indicators.

Monetary Policy Shocks We also report a number of robustness checks concerning the variation in our monetary policy shocks. First, following Gurkaynak, Sack and Swanson (2005) we decompose monetary policy announcements into a "target" component that affects

Table 11
Expansionary vs. Contractionary Shocks

	(1)	(2)
leverage × ffr shock	-0.74***	
	(0.28)	
leverage × pos ffr shock		-0.93**
		(0.36)
leverage × neg ffr shock		0.10
		(0.77)
Observations	239579	239579
R^2	0.118	0.118
Firm controls	yes	yes

Notes: Results from estimating variants of the baseline specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_1 \ell_{jt-1} \varepsilon_t^{\mathrm{m}} \mathbb{1}\{\varepsilon_t^{\mathrm{m}} \geq 0\} + \beta_2 \ell_{jt-1} \varepsilon_t^{\mathrm{m}} \mathbb{1}\{\varepsilon_t^{\mathrm{m}} < 0\} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

the level of the yield curve and a "path" component that affects the slope of the yield curve. Table 13 shows that the differential responses across firms we find in the main text are driven by the target component of the announcement, capturing the effect of the announcement on the level of the yield curve, rather than the path component of the announcement, capturing the effect on the slope of the yield curve. This result indicates that our results are primarily driven by the effect of Fed policy announcements on short-term interest rates rather than on expectations of growth in the future, which would affect long-term rates more than short-term.

Second, because the Fed began making formal policy announcements only after 1994, Table 14 estimates our baseline specification (3) using post-1994 data. Low-leverage firms continue to be more responsive in this specification. Third, Table 15 shows that our baseline results hold when we time-aggregate the high-frequency shocks by taking the simple sum within the quarter, rather than the weighted sum in the main text.

Table 12
Heterogeneous Responses to Business Cycle Conditions

	(1)	(2)	(3)	(4)	(5)
leverage × ffr shock	-0.85***	-0.73***	-0.74***	-0.83***	-0.96***
	(0.29)	(0.27)	(0.28)	(0.28)	(0.31)
leverage × dlog gdp	-0.08				-0.08
	(0.08)				(0.07)
leverage × dlog cpi		-0.05			-0.06
		(0.09)			(0.09)
leverage × ur			0.00		0.00
			(0.00)		(0.00)
leverage × vix				0.00	0.00
				(0.00)	(0.00)
Observations	239579	239579	239579	239579	239579
R^2	0.118	0.118	0.118	0.118	0.118
Firm controls	yes	yes	yes	yes	yes

Notes: Results from estimating variants of the baseline specification
$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} Y_t + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter, and Y_t is GDP growth (dlog gdp), the inflation rate (dlog cp), the unemployment rate (ur), or the VIX index (vix). Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Extensive Margin Measure of Investment Table 16 shows that our baseline results hold for an indicator for the firm's investment rate being greater than 1%, $\mathbb{1}\{\frac{i_{jt}}{k_{jt}} \geq 1\%\}$. This measure is motivated by the fact that many changes in micro-level investment occur along the extensive margin. Additionally, by focusing on large investment episodes, this measure is less prone to small measurement error in the capital stock. Quantitatively, firms with one cross-sectional standard deviation higher leverage are nearly 5% less likely to invest following an expansionary monetary policy shock.

Alternative Measures of Leverage The next set of robustness checks investigates heterogeneity by other measures of leverage. Table 17 runs our baseline specification (3) using leverage net of current assets and shows that our results continue to hold. Table 18 decomposes leverage into various types of debt and shows that our results hold for each of these

Table 13
Target vs. Path Decomposition

	(1)	(2)
leverage × ffr shock	-0.74**	
	(0.28)	
leverage × target shock		-1.23***
		(0.42)
leverage × path shock		1.50
		(4.35)
Observations	239523	233661
R^2	0.118	0.119

Notes: Results from estimating variants of the baseline specification

$$\Delta \log k_{jt} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Column (2) of both panels runs separate interactions of leverage with the target and path component of interest rates, as defined in Campbell et al. (2016). Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

types of debt.[31]

A.2.2 Heterogeneity in Default Risk

This appendix contains various results referenced in Section 2.3 of the main text.

Permanent Heterogeneity in Financial Positions In the economic model we develop in Section 3, low-leverage firms are less affected by financial frictions because they have low risk of default. The existence of permanent heterogeneity in firms' financial positions may break this tight positive relationship between leverage and default risk. For example, if low-leverage firms have poor collateral which limits their ability to borrow, then low-leverage firms may actually be the most affected by financial frictions. Another example is that low-

[31] This decomposition sheds light on the role of the "debt overhang" hypothesis in driving our results. Under this hypothesis, equity holders of highly leveraged firms capture less of the return on investment; since equity holders make the investment decision, they will choose to invest less following the monetary policy shock. However, because investment is long lived, this hypothesis would predict much stronger differences by long term debt. We find that this is not the case; if anything, the differences across firms are stronger for debt due in less than one year.

TABLE 14
POST-1994 ESTIMATES

	(1)	(2)	(3)
leverage × ffr shock	-0.51	-0.55	-0.64
	(0.50)	(0.44)	(0.45)
leverage	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)
ffr shock			-0.05
			(1.54)
Observations	185752	185752	185752
R^2	0.120	0.131	0.116
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Notes: Results from estimating variants of the baseline specification

$$\Delta \log k_{jt} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\text{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, ε_t^{m} is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Only data after 1994 is used in the estimation. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shocks ε_t^{m} so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

leverage firms hold low debt because they are permanently riskier, which leads to higher costs of investment finance.

We argue that permanent heterogeneity in financial positions does not drive our results by estimating the specification

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta(\ell_{jt-1} - \mathbb{E}_j[\ell_{jt}])\varepsilon_t^{\text{m}} + \mathbf{\Gamma}' Z_{jt-1} + \varepsilon_{jt},$$

where $\mathbb{E}_j[\ell_{jt}]$ is the average leverage of firm j in our sample.[32] Permanent heterogeneity in leverage is differenced out of the interaction $(\ell_{jt-1} - \mathbb{E}_j[\ell_{jt}])\varepsilon_t$. Table 19 shows that our benchmark results are stable if we only use within-firm variation in leverage.

Heterogeneity in Other Observable Firm Characteristics Table 20 shows that our main results are not driven by firms' sales growth, realized future sales growth, or size. It

[32] Our sample selection focuses on firms with at least forty quarters of data to precisely estimate the average leverage $\mathbb{E}_j[\ell_{jt}]$.

Table 15
Alternative Time Aggregation

	(1)	(2)	(3)
leverage × ffr shock (sum)	-0.89***	-0.79***	-0.79***
	(0.33)	(0.28)	(0.29)
ffr shock (sum)			1.02
			(0.82)
Observations	236296	236296	236296
R^2	0.106	0.118	0.103
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Notes: Results from estimating variants of the baseline specification $\Delta \log k_{jt} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. The high-frequency shocks are aggregated to the quarterly frequency simply by summing all shocks within a quarter. Standard errors are two-way clustered by firms and time. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates).We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

expands the baseline specification as:

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta_\ell \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \beta_y y_{jt} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + \varepsilon_{jt},$$

where y_{jt} is lagged sales growth, realized future sales growth in one year, or lagged size. In each case, the coefficient on leverage ℓ_{jt-1} remains stable. Hence, firm-level shocks or characteristics that are correlated with these additional variables do not drive the heterogeneous responses by leverage.[33]

Heterogeneity in Other Unobservable Firm Characteristics Table 21 provides evidence that unobservable factors do not drive the heterogeneous responses by leverage either. We instrument leverage ℓ_{jt-1} in our baseline specification (3) with past leverage (ℓ_{jt-5} or ℓ_{jt-9}). If unobserved factors drive both leverage and the response to monetary policy, and

[33]Our result that large firms are more sensitive to monetary policy shocks is broadly consistent with Kudlyak and Sanchez (2017), who find that, in Compustat, large firms are also more responsive to the 2007 financial crisis.

TABLE 16

HETEROGENEOUS RESPONSES BY LEVERAGE, EXTENSIVE MARGIN

	(1)	(2)	(3)
leverage × ffr shock	-5.41***	-5.01***	-4.78***
	(1.39)	(1.26)	(1.31)
ffr shock			4.31
			(4.47)
Observations	239523	239523	239523
R^2	0.210	0.215	0.201
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Notes: Results from estimating variants of the baseline specification

$$\mathbb{1}\{\frac{i_{jt}}{k_{jt}} \geq 1\%\} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

these factors are more weakly correlated with lagged leverage, we would expect these instrumental variables coefficients to be smaller than our baseline results. Instead, Table 21 shows that the estimated coefficients increase in this instrumental variables specification. This result is consistent with measurement error creating attenuation bias in our baseline specification (3).

Relationship Between Leverage and Credit Ratings Table 22 shows that the negative relationship between leverage and credit rating documented in Figure 3 holds in a regression context, conditional on firm controls.

Heterogeneity by Other Measures of Financial Position Table 23 computes heterogeneous responses by other measures of financial position – size, cash flows, and dividend payments.

Table 17
Net Leverage

	(1)	(2)	(3)
net leverage × ffr shock	-1.01**	-0.81**	-0.74*
	(0.43)	(0.36)	(0.37)
net leverage	-0.01***	-0.01***	-0.01***
	(0.00)	(0.00)	(0.00)
ffr shock			1.25
			(0.94)
Observations	233182	233182	233182
R^2	0.110	0.119	0.106
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Notes: Results from estimating variants of the baseline specification

$$\Delta \log k_{jt} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage net of current assets, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized net leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Table 18
Decomposition of Leverage

	(1)	(2)	(3)	(4)	(5)
ST debt × ffr shock	-4.53		-4.65		
	(11.18)		(16.49)		
LT debt × ffr shock		-1.50	-1.71		
		(11.91)	(3.86)		
leverage × ffr shock				-4.47	
				(12.48)	
other liab × ffr shock				-2.52	
				(6.85)	
liabilities × ffr shock					-10.71***
					(1.04)
Observations	238070	238070	238070	238050	238050
R^2	0.225	0.224	0.225	0.225	0.224
Firm controls	yes	yes	yes	yes	yes

Notes: Results from estimating variants of the baseline specification

$$\Delta \log k_{jt} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1} \varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Column (1) measures leverage using short term debt, column (2) with long term debt, column (3) with total debt, column (4) with other liabilities (such as trade credit), and column (5) with total liabilities. Standard errors are two-way clustered by firms and quarters. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized each components of leverage over the entire sample, so its units are in standard deviations relative to the mean.

Table 19
Within-Firm Variation in Leverage

	(1)	(2)	(3)
leverage × shock	-0.95**	-0.77**	-0.75**
	(0.42)	(0.36)	(0.35)
ffr shock			1.38
			(1.00)
Observations	239523	239523	239523
R^2	0.106	0.118	0.103
Firm controls	no	yes	yes
Time sector FE	yes	yes	no
Time clustering	yes	yes	yes

Results from estimating

$$\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta(\ell_{jt-1} - \mathbb{E}_j[\ell_{jt}])\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt},$$

where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\mathbb{E}_j[\ell_{jt}]$ is the average leverage of firm j in the sample, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarter. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Table 20
Interaction With Other Firm-Level Covariates

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
leverage × ffr shock	-0.59***		-0.59		-0.67		-0.58
	(0.07)		(2.64)		(6.66)		(1.69)
sales growth × ffr shock		-0.08	-0.09				
		(0.19)	(2.87)				
future sales growth × ffr shock				-0.39	-0.37		
				(4.72)	(2.80)		
size × ffr shock						0.21**	0.25
						(0.08)	(2.30)
Observations	238070	238070	238070	226086	226086	238070	238070
R^2	0.133	0.131	0.133	0.135	0.137	0.131	0.133
Firm controls	yes	yes	yes	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes	yes	yes	yes

Notes: Results from estimating variants of the baseline specification $\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta y_{jt}\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, y_{jt} is the firm's lagged sales growth, future sales growth, or lagged size, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Columns (2) and (4) additionally include an interaction between leverage ℓ_{jt-1} and the monetary policy shock $\varepsilon_t^{\mathrm{m}}$. Standard errors are two-way clustered by firms and quarter. We have normalized the sign of the monetary shocks $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Table 21
Instrumenting Leverage with Past Leverage

	(1)	(2)
leverage × ffr shock	-0.74	-2.36**
	(1.27)	(0.94)
Observations	230112	221326
R^2		
Firm controls, Time-Sector FE	yes	yes
Instrument	4q lag	8q lag

Notes: Results from estimating and IV strategy for the baseline specification $\Delta \log k_{jt+1} = \alpha_j + \alpha_{st} + \beta \ell_{jt-1}\varepsilon_t^{\mathrm{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, ℓ_{jt-1} is leverage, $\varepsilon_t^{\mathrm{m}}$ is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Leverage in $t-4$ and $t-8$ are used as instruments for leverage in $t-1$. Standard errors are two-way clustered by firms and time. We have normalized the sign of the monetary shock $\varepsilon_t^{\mathrm{m}}$ so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage x_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Table 22
Low-Leverage Firms Have Higher Credit Ratings

	(1)	(2)	(3)	(4)
leverage	-0.09***	-0.04***	-0.09***	-0.04***
	(0.01)	(0.01)	(0.02)	(0.01)
sales_growth	-0.01***	-0.00***	-0.01**	-0.00
	(0.00)	(0.00)	(0.00)	(2.21)
size $(t-1)$	0.28***	0.11***	0.28***	0.11
	(0.02)	(0.03)	(0.02)	(2.48)
share current assets	0.01	0.04***	0.02	0.04
	(0.01)	(0.01)	(0.01)	(5.33)
Observations	49201	49166	49201	49166
R^2	0.261	0.826	0.282	0.828
Firm controls	yes	yes	yes	yes
Firm FE	no	yes	no	yes
Time sector FE	no	no	yes	yes

Notes: Results from estimating variants of the baseline specification $\mathbb{1}\{\texttt{rating}_{it} \geq A\} = \alpha_i + \alpha_{st} + \mathbf{\Gamma}' Z_{it-1} + e_{it}$, where $\mathbb{1}\{\texttt{rating}_{it} \geq A\}$ is an indicator variable for whether the firm's credit rating is above AA, α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Standard errors are two-way clustered by firms and quarter. We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

Table 23
Interaction With Other Measures of Financial Positions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
leverage × ffr shock	-0.74**		-0.73**		-0.76**		-0.74**
	(0.28)		(0.28)		(0.29)		(0.28)
size × ffr shock		0.35	0.37***				
		(0.31)	(0.07)				
cash flows × ffr shock				0.24	0.28		
				(0.54)	(1.34)		
$\mathbb{I}\{\text{dividends} > 0\}\times$ ffr shock						0.13	0.39
						(0.58)	(4.83)
Observations	239523	239523	239523	237890	237890	239232	239232
R^2	0.118	0.115	0.118	0.120	0.122	0.116	0.118
Firm controls	yes	yes	yes	yes	yes	yes	yes
Time sector FE	yes	yes	yes	yes	yes	yes	yes
Time clustering	yes	yes	yes	yes	yes	yes	yes

Notes: Results from estimating variants of the baseline specification $\Delta \log k_{jt} = \alpha_j + \alpha_{st} + \beta y_{jt-1}\varepsilon_t^{\text{m}} + \mathbf{\Gamma}' Z_{jt-1} + e_{jt}$, where α_j is a firm fixed effect, α_{st} is a sector-by-quarter fixed effect, y_{jt} is the firm's size (measured by log of current assets), cash flows, or an indicator for whether the firm pays dividends. ε_t^{m} is the monetary shock, and Z_{jt-1} is a vector of firm-level controls containing leverage, sales growth, size, current assets as a share of total assets, and an indicator for fiscal quarter. Columns (2) and (4) additionally include an interaction between leverage ℓ_{jt-1} and the monetary policy shock ε_t^{m}. Standard errors are two-way clustered by firms and time. We have normalized the sign of the monetary shocks ε_t^{m} so that a positive shock is expansionary (corresponding to a decrease in interest rates). We have standardized leverage ℓ_{jt} over the entire sample, so its units are in standard deviations relative to the mean.

B Model Appendix

B.1 Proof of Proposition 1

We prove Proposition 1 in steady state; extending the proof to include transition dynamics is straightforward. To clarify the economic mechanisms, we work with a simple version of the model that abstracts from capital-quality shocks ($\sigma_\omega = 0$), has zero recovery value of debt ($\alpha = 0$), and has no exogenous exit shocks ($\pi_d = 0$). The proof in the full model follows the same steps with more complicated notation.

Default Threshold As discussed in the main text, firms only default when they have no feasible choice which satisfies the non-negativity constraint on dividends, i.e., there is no (k', b') such that $x - k' + \mathcal{Q}(z, k', b')b' \geq 0$. Define the default threshold $\underline{x}(z) = \min_{k',b'} k' - \mathcal{Q}(z, k', b')b'$. Note that the largest feasible dividend payment of a firm is $x - \underline{x}(z)$. If $x \geq \underline{x}(z)$, then $\arg\min_{k',b'} k' - \mathcal{Q}(z, k', b')b'$ is a feasible choice and the firm will not default. On the other hand, if $x < \underline{x}(z)$, then $d \leq 0$ for all (k', b'), violating feasibility.

With this notation in hand, the Bellman equation of a continuing firm in this simple case is

$$v(z, x) = \max_{k',b'} x - k' + \mathcal{Q}(z, k', b')b' + \beta \mathbb{E}\left[v(z', x')\mathbb{1}\{x' > \underline{x}(z')\}|z, k', b'\right] \text{ s.t. } d \geq 0, \quad (18)$$

where $\underline{x}(z')$ is the default threshold.

Although the continuation value is kinked at the default point, it is never optimal for a firm to choose this point (see Clausen and Strub (2017) and the discussion in Arellano et al. (2016)). Hence, the first order conditions are necessary at the optimum.

Unconstrained Firms Define the *unconstrained capital accumulation rule* $k^*(z)$ as

$$k^*(z) = \underset{k'}{\operatorname{argmax}} -k' + \beta \mathbb{E}\left[\iota(z', k') + (1 - \delta)k'|z\right],$$

where $\iota(z, k) = \max_n zk^\theta n^\nu - wn$. After some algebra, one can show that the expression in the main text solves this maximization problem (extending the expression to the full model).

We will now fully characterize the decision rules for firms that can afford the unconstrained capital accumulation rule while have zero probability of default in all future states. We first claim that such a firm is indifferent over any choice of debt b' which leaves the firm unconstrained. To show this, note that since the firm has no default risk it borrows at the risk-free rate β. In this case, the first order condition for borrowing b' is $\beta = \beta$, which is obviously true for any value of b'.

Following Khan, Senga and Thomas (2016), we resolve this indeterminacy by defining the *maximum borrowing policy* $b^*(z)$ as the maximal borrowing b' the firm can do while having zero probability of default in all future states.[34] To derive the maximum borrowing policy $b^*(z)$, first note that if the firm if the firm invests $k^*(z)$ and borrows $b^*(z)$ in the current period, its dividends in the next period are

$$\iota(z', k^*(z)) + (1-\delta)k^*(z) - b^*(z) - \xi - k^*(z') + \beta b^*(z'),$$

for a given realization of z'. The requirement that the firm has zero probability of default in all future states then implies that

$$b^*(z) = \min_{z'} \iota(z', k^*(z)) + (1-\delta)k^*(z) - k^*(z') + \beta b^*(z').$$

Hence, $b^*(z)$ is the largest amount of borrowing the firm can do and be guaranteed to satisfy the non-negativity constraint on dividends.[35]

By construction, if a firm can follow the unconstrained capital accumulation policy $k^*(z)$ and the maximum borrowing policy $b^*(z)$ while satisfying the non-negativity constraint on dividends in the current period, it will also satisfy the non-negativity constraint in all future periods. Moreover, following $k^*(z)$ is indeed optimal for such firms because it solves the associated first-order condition of these firms. Hence, a firm is *unconstrained* and follows

[34] Khan, Senga and Thomas (2016) refer to this object as the "minimum savings policy."

[35] To derive this expression, first re-arrange the non-negativity constraint on dividends conditional on a realization of the future shocks as an inequality with b' on the left-hand side. This results in a set of inequalities for each possible realization of the future shocks. The min operator ensures that all of these inequalities are satisfied.

these decision rules if and only if $d = x - k^*(z) + \beta b^*(z)$, i.e.,

$$x > \underline{x}(z) \equiv k^*(z) - \beta b^*(z).$$

Constrained Firms Consider again the constrained Bellman equation (18). We will show that firms with $x \in [\underline{x}(z), \overline{x}(z)]$ pay zero dividends. Invert the default threshold $\underline{x}(z)$ so that the firm defaults if $z' < \underline{z}(k', b')$. The Bellman equation (18) can then be written as

$$v(z,x) = \max_{k',b'} x - k' + \mathcal{Q}(z,k',b')b' + \beta \int_{\underline{z}(k',b')}^{\overline{z}} v(z',x')g(z'|z)\mathrm{d}z' \text{ s.t. } d \geq 0, \tag{19}$$

where $g(z'|z)$ is the density of z' conditional on z, $\overline{z}$ is the upper bound of the support of z, and $\mathcal{Q}_3(z,k',b')$ is the derivative of the debt price schedule with respect to b'.

Letting $\lambda(z,x)$ be the Lagrange multiplier on the $d \geq 0$ constraint, the first order condition for b' is

$$\begin{aligned}
&(1+\lambda(z,x))(\mathcal{Q}(z,k',b') + \mathcal{Q}_3(z,k',b')b') = \\
&\quad \beta \left[\int_{\underline{z}(k',b')}^{\overline{z}} (1 + \lambda(z',k',b')g(z'|z)\mathrm{d}z' + g(\underline{z}(k',b')|z)v(\underline{z}(k',b'), \hat{x}'(k',b'))\frac{\partial \underline{z}(k',b')}{\partial b'} \right],
\end{aligned}$$

where $\hat{x}'(k',b') = \max_{n'} \underline{z}(k',b')(k')^{\theta}(n')^{\nu} - wn' + (1-\delta)k' - b' - \xi$ and $\lambda(z',k',b') = \lambda(z',x')$ for the x' implied by (z',k',b'). The left hand side of this expression measures the marginal benefit of borrowing. The marginal resources the firm receives on borrowing is the debt price, adjusting for the fact that the marginal cost of borrowing changes on existing debt. The firm values those marginal resources using the Lagrange multiplier. The right hand side of this expression measures the discounted marginal cost of borrowing. In states of the world in which the firm does not default, it must give up one unit of resources, which it values using the next period's Lagrange multiplier. In addition, marginal borrowing implies that the firm defaults in additional future states.

Note that the debt price schedule is $\mathcal{Q}(z,k',b') = \beta \int_{\underline{z}(k',b')}^{\overline{z}} g(z'|z)\mathrm{d}z'$, which implies that

$\mathcal{Q}_3(z,k',b') = -\beta g(\underline{z}(k',b')|z)\frac{\partial \underline{z}(k',b')}{\partial b'}$. Plugging this into the first order condition gives

$$\beta(1+\lambda(z,x))(\int_{\underline{z}(k',b')}^{\overline{z}} g(z'|z)\mathrm{d}z' - \beta g(\underline{z}(k',b')|z)\frac{\partial \underline{z}(k',b')}{\partial b'} =$$
$$\beta\left[\int_{\underline{z}(k',b')}^{\overline{z}}(1+\lambda(z',k',b')g(z'|z)\mathrm{d}z' + g(\underline{z}(k',b')|z)v(\underline{z}(k',b'),\hat{x}'(k',b'))\frac{\partial \underline{z}(k',b')}{\partial b'}\right]. \quad (20)$$

We will now show that constrained firms set $d = 0$. We do so by contradiction: suppose that a constrained firm sets $d > 0$, implying that $\lambda(z,x) = 0$.

First consider a firm that has zero probability of default in the next period, i.e., $\underline{z}(k',b') = \underline{z}$ and $\frac{\partial \underline{z}(k',b')}{\partial b'} = 0$. In this case, the first order condition (20) can be simplified to

$$0 = \int_{\underline{z}}^{\overline{z}} \lambda(z',k',b')g(z'|z)\mathrm{d}z'.$$

Since the firm is constrained, $\lambda(z',k',b') > 0$ for some positive mass of realizations of z', leading to a contradiction.

Now consider a firm that has some positive probability of default, implying that $\underline{z}(k',b') > \underline{z}$ and $\frac{\partial \underline{z}(k',b')}{\partial b'} > 0$. In this case, the first order condition (20) can be rearranged to

$$0 = \int_{\underline{z}(k',b')}^{\overline{z}} \lambda(z',k',b')g(z'|z)\mathrm{d}z' + \frac{\partial \underline{z}(k',b')}{\partial b'}g(\underline{z}(k',b')|z)(b'+v(z',k',b')),$$

where $v(z',k',b') = v(z',x')$ for the x' implied by (z',k',b'). By construction, risky constrained firms engage in strictly positive borrowing $b' > 0$. This implies that the right hand side is strictly greater than zero, leading to a contradiction.

B.2 Equilibrium Definition

Distribution of Firms We need to derive the evolution of the distribution of firms in order to precisely define an equilibrium. The distribution of firms in production is composed of incumbents who do not default and new entrants who do not default. Mathematically, this distribution $\hat{\mu}_t(z,x)$ is given by

$$\hat{\mu}_t(z,x) = \int \left(\pi_d \chi^1(x_t(z,\omega,k,b)) + (1-\pi_d)\chi_t^2(z, x_t(z,\omega,k,b))\right) \mathrm{d}\mu_t(z,\omega,k,b) \\ + \overline{\mu}_t \int \left(\pi_d \chi^1(x_t(z,\omega,k_0,0)) + (1-\pi_d)\chi_t^2(z, x_t(z,\omega,k_0,0))\right) g(\omega)\mathrm{d}\omega\mathrm{d}\mu^{\text{ent}}(z), \tag{21}$$

where $x_t(z,\omega,k,b) = \max_n p_t z(\omega k)^\theta n^\nu - w_t n + q_t(1-\delta)\omega k - b - \xi$ is the implied cash-on-hand x of a firm with state (z,ω,k,b) and $g(\omega)$ is the PDF of capital quality shocks.

The evolution of the distribution of firms $\mu_t(z,\omega,k,b)$ is given by

$$\mu_{t+1}(z',\omega',k',b') = \int (1-\pi_d)\chi_t^2(z, x_t(z,\omega,k,b)) 1\{k_t'(z, x_t(z,\omega,k,b)) = k'\} \\ \times \mathbb{1}\{\frac{b_t'(z, x_t(z,\omega,k,b))}{\Pi_{t+1}} = b'\} p(\varepsilon | e^{\rho \log z + \varepsilon} = z') g(\omega') \mathrm{d}\varepsilon \mathrm{d}\mu_t(z,\omega,k,b) \\ + \overline{\mu}_t \int (1-\pi_d)\chi_t^2(z, x_t(z,\omega,k_0,0)) 1\{k_t'(z, x_t(z,\omega,k_0,0)) = k'\} \\ \times \mathbb{1}\{\frac{b_t'(z, x_t(z,\omega,k_0,0))}{\Pi_{t+1}} = b'\} p(\varepsilon | e^{\rho \log z + \varepsilon} = z') g(\omega') \mathrm{d}\varepsilon \mathrm{d}\mu^{\text{ent}}(z), \tag{22}$$

where $p(\varepsilon | e^{\rho \log z + \varepsilon} = z')$ denotes the density of draws ε such that $e^{\rho \log z + \varepsilon} = z'$.

Equilibrium Definition An **equilibrium** of this model is a set of $v_t(z,x)$, $k_t'(z,x)$, $b_t'(z,x)$, $n_t(z,x)$, $\mathcal{Q}_t(z,k',b')$, Π_t, Δ_t, Y_t, q_t, $\mu_t(z,\omega,k,b)$, $\hat{\mu}_t(z,x)$, $\Lambda_{t,t+1}$, w_t, C_t, and I_t such that

(i) Production firms optimization: $v_t(z,x)$ solves the Bellman equation (10) with associated decision rules $k_t'(z,x)$, $b_t'(z,x)$, and $n_t(z,x)$.

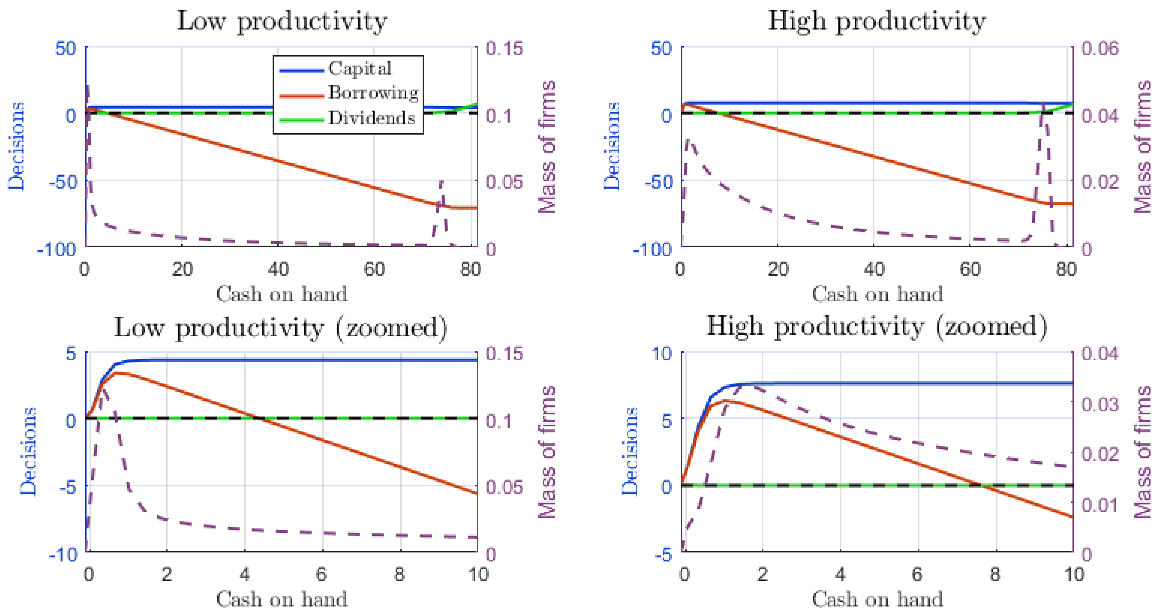
(ii) Financial intermediaries price default risk according to (11).

(iii) New Keynesian block: Π_t, p_t, and q_t satisfy (12) and (14).

(iv) The distribution of firms in production $\hat{\mu}_t(z,x)$ satisfies (21) and the distribution $\mu_t(z,\omega,k,b)$ evolves according to (22).

(v) Household block: the stochastic discount factor is given by $\Lambda_{t,t+1} = \beta \frac{C_{t+1}^{-\sigma}}{C_t^{-\sigma}}$. The wage must satisfy $w_t = \Psi C_t$. The stochastic discount factor and nominal interest rate are

FIGURE 10: Steady State Decision Rules



Notes: Left column plots decision rules and stationary distribution of firms conditional on idiosyncratic productivity one standard deviation below the mean. Right column plots the same objects conditional on productivity one standard deviation above the mean. The left y-axis measures the decision rules (capital accumulation, borrowing, and dividend payments) as a function of cash-on-hand x. The right y-axis measures the stationary distribution of firms. Top row plots these functions over the entire space of cash on hand. Bottom row plots these functions for low levels of cash on hand only.

linked through the Euler equation for bonds, $1 = \mathbb{E}_t\left[\Lambda_{t,t+1}\frac{R_t^{\text{nom}}}{\Pi_{t+1}}\right]$.

(vi) Market clearing: aggregate investment is implicitly defined by $K_{t+1} = \Phi(\frac{I_t}{K_t})K_t + (1-\delta)K_t$, where $K_t = \int k\mathrm{d}\mu_t(z,\omega,k,b)$. Aggregate consumption is defined by $C_t = Y_t - I_t - \xi$.[36]

B.3 Analysis of Calibrated Model

In this appendix, we analyze firms' decision rules in our calibrated steady state and show that the financial heterogeneity in our model is broadly comparable to that in the data.

Firms' Decision Rules Figure 10 plots the investment, borrowing, and dividend payment decisions of firms. The top row of the figure plots the decision rules over the entire state space.

[36] We normalize the mass of firms in production to 1, so ξ is the total resources lost from the fixed operating costs.

Firms with cash-on-hand x below the default threshold $\underline{x}_t(z)$ do not operate. Once firms clear this default threshold, they lever up to increase their capital to its optimal scale $k_t^*(z)$. Once capital is at its optimal level $k_t^*(z)$, firms use additional cash-on-hand to pay down their debt until they reach the unconstrained threshold $\overline{x}_t(z)$. Unconstrained firms set $k' = k_t^*(z)$ and $b' = b_t^*(z)$, which do not depend on cash on hand x. Only unconstrained firms pay positive dividends.

The curvature in the policy functions over the region with low cash on hand x reflects the role of financial frictions in firms' decisions. Without frictions, all non-defaulting firms would borrow the amount necessary to reach the optimal scale of capital $k_t^*(z)$. However, firms with low cash-on-hand x would need to borrow a substantial amount, increasing their risk of default and therefore borrowing costs. Anticipating these higher borrowing costs, low cash on hand x firms accumulate capital below its optimal scale.

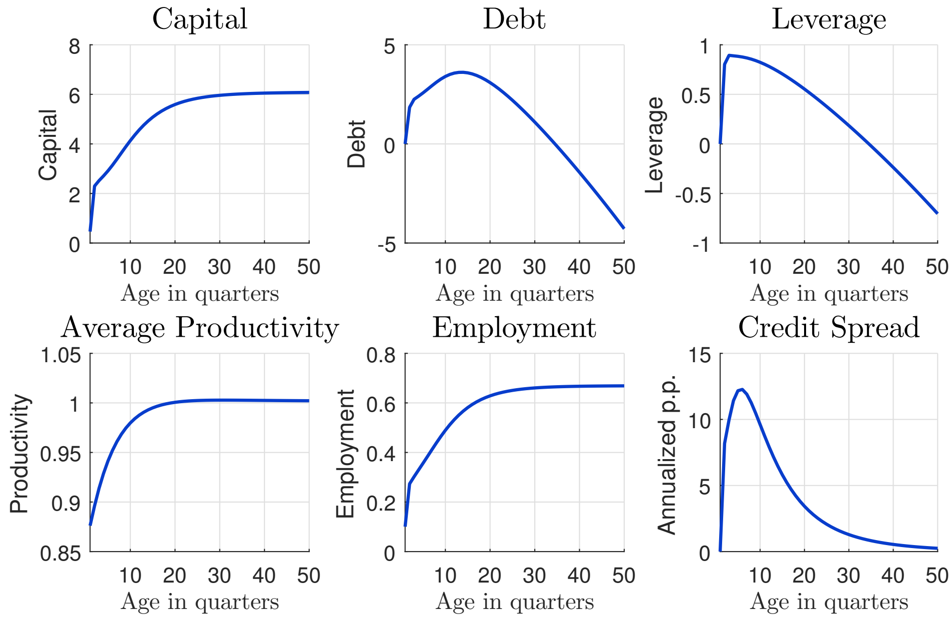
The right axis of Figure 10 plots the stationary distribution of firms. 53.1% of firms pay a risk premium, i.e., are "risky constrained." These firms are in the region with curved policy functions described above. 43% of firms are constrained but do not currently pay a risk premium, i.e., are "risk-free constrained." These firms have achieved their optimal scale of capital $k_t^*(z)$ and have linear borrowing policies. The remaining 3.9% of firms are unconstrained. Due to our assumed debt accumulation policy, unconstrained firms pay out any cash on hand $x > \overline{x}_t(z)$ as dividends.

Figure 10 makes clear that there are two key sources of financial heterogeneity in the model. First, reading the graphs from left to right captures heterogeneity due to lifecycle dynamics; young firms accumulate debt in order to reach their optimal level of capital $k_t^*(z)$ and then pay down that debt over time. Second, moving from the left to the right column captures heterogeneity due to idiosyncratic productivity shocks; a positive shock increases the optimal scale of capital $k_t^*(z)$, again leading firms to first accumulate and then decumulate debt.[37,38]

[37] A third source of financial heterogeneity are the capital quality shocks, which simply generate variation in firms' cash on hand x.

[38] Buera and Karmakar (2017) study how the aggregate effect of an interest rate shock depends on these two sources of heterogeneity in a simple two-period model.

FIGURE 11: Lifecycle Dynamics in Model

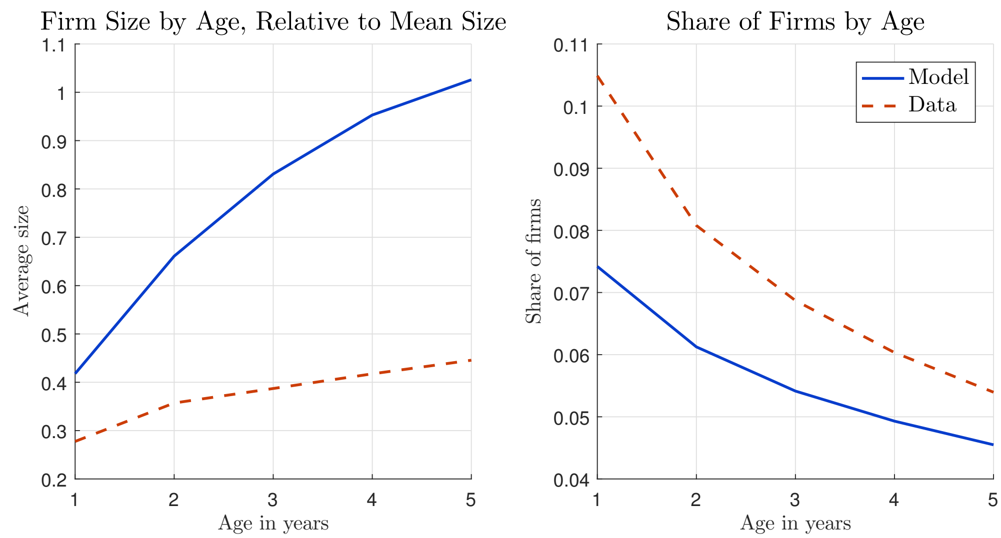


Notes: Average capital, debt, leverage, productivity, employment, and credit spread conditional on age in steady state.

Comparing Lifecycle Dynamics to the Data Figure 11 plots the dynamics of key variables over the firm lifecycle. New entrants begin with a low initial capital stock k_0 and, on average, a low draw of idiosyncratic productivity z. As described above, young firms take on new debt in order to finance investment, which increases their default risk and credit spreads. Over time, as firms accumulate capital and productivity reverts to its mean, they reach their optimal capital stock $k_t^*(z)$ and begin paying down their debt.

Figure 12 shows that these lifecycle dynamics are in line with key features of the data. The left panel plots the average size of firms by age. In the data, young firms are substantially smaller than average and take many years to catch up. Qualitatively, our model captures this prolonged growth process; however, quantitatively, growth in our model is too rapid because we do not include other frictions to firm growth such as capital adjustment costs or customer accumulation. The right panel of Figure 12 plots the share of firms in the economy in different age groups. The curve is downward-sloping because firms exit over time. In the model, the only source of curvature is state-dependent exit due to default. Although the

Figure 12: Comparison of Lifecycle Dynamics to the Data



Notes: Left panel plots the average employment of firms by age, relative to the average employment in the population. Right panel plots the share of firms by age. Model: steady state of the calibrated model; Data: computed from the Business Dynamics Statistics (BDS).

model underpredicts the overall level of the curve, it provides a good match of the slope.

Investment and Leverage Heterogeneity in the Data Table 24 shows that our model is broadly consistent with key features of the distributions of investment and leverage not targeted in the calibration. The top panel analyzes the distribution of investment rates in the annual Census data reported by Cooper and Haltiwanger (2006). We present the corresponding statistics in our model for a selected sample – conditioning on firms that survive at least twenty years to mirror the selection into the LRD – and in the full sample. Although we have calibrated the selected sample to match the dispersion of investment rates, the mean and autocorrelation of investment rates in the selected sample are also reasonable. The mean investment rate in the full sample is higher than the selected sample because the full sample includes young, growing firms.

The middle and bottom panels of Table 24 compare the model-implied distribution of investment rates and leverage to quarterly Compustat data. We mirror the sample selection into Compustat by conditioning on firms that survive for at least ten years. According to Wilmer et al. (2017), the median time to IPO has ranged from roughly six to eight years

Table 24

Investment and Leverage Heterogeneity

Moment	Description	Data	Model (selected)	Model (full)
Investment heterogeneity (annual LRD)				
$\mathbb{E}\left[\frac{i}{k}\right]$	Mean investment rate	12.2%	8.83%	20.6%
$\sigma\left(\frac{i}{k}\right)$	SD investment rate (calibrated)	33.7%	31.8%	38.5%
$\rho\left(\frac{i}{k}, \frac{i}{k_{-1}}\right)$	Autocorr investment rate	0.058	-0.26	-0.26
Leverage heterogeneity (quarterly Compustat)				
$\sigma\left(\frac{b}{k}\right)$	SD leverage ratio	36.4%	76.4%	77.0%
$\rho\left(\frac{b}{k}, \frac{b}{k_{-1}}\right)$	Autocorr leverage ratio	0.94	0.92	0.95
Joint investment and leverage (quarterly Compustat)				
$\rho\left(\frac{i}{k}, \frac{b}{k}\right)$	Corr. of leverage and investment	-0.08	-0.16	-0.02

Notes: Statistics about the cross-sectional distribution of investment rates and leverage ratios in steady state. Data for investment heterogeneity are drawn from Cooper and Haltiwanger (2006). Model (selected) for investment heterogeneity corresponds to firms alive for longer than twenty years in a panel simulation, time aggregated to the annual frequency. Model (full) corresponds to the full sample of firms in a panel simulation, time aggregated to the annual frequency. Data for leverage heterogeneity drawn from quarterly Compustat data. Model (selected) for leverage heterogeneity corresponds to firms alive for longer than ten years in a panel simulation. Model (full) correpsonds to the full sample of firms in a panel simulation.

over the last decade.[39] Our model provides a close match of the persistence of leverage and its correlation with investment in the selected sample. However, the standard deviation of leverage ratios is about twice as large as in the data.

Table 25 shows that the model generates a positive measured investment-cash flow sensitivity, consistent with the data. Following Gomes (2001), we compute investment-cash flow sensitivity using the regression

$$\frac{i_{jt}}{k_{jt}} = \alpha_j + \alpha_t + a_1 \frac{\mathtt{CF}_{jt-1}}{k_{jt}} + a_2 \mathtt{q}_{jt-1} + \varepsilon_{jt}, \tag{23}$$

where $\mathtt{CF}_{jt}$ is cash flow and $\mathtt{q}_{jt}$ is Tobin's q. The coefficient a_1 captures the statistical comovement of investment with cash flow, conditional on the fixed effects and Tobin's q. In the model, we identify cash flow as the firm's cash on hand x and Tobin's q as the ratio of the market value of the firm to the book value of its capital stock, k. In quarterly Compustat, we identify cash flow as earnings before tax, depreciation, and amortization (EBITDA) and

[39]Our results are robustness to sensitivity analysis around this cutoff.

Table 25
Measured Investment-Cash Flow Sensitivity

	Without cash flow		**With cash flow**	
	Data	*Model*	*Data*	*Model*
Tobin's q	0.01***	0.06	0.01***	0.02
cash flow			0.02***	0.08
R^2	0.097	0.065	0.106	0.086

Notes: Results from estimating the regression (23). Data refers to quarterly Compustat data. We measure cash flow as earnings before tax, depreciation, and amortization (EBITDA) and Tobin's q as the market to book value of the firm. Model refers to simulating a panel of firms from the calibrated model, conditional on surviving at least ten years. We measure cash flow as the firm's cash-on-hand x and Tobin's q as the ratio of market value to the book value of capital, k.

Tobin's q as the market to book value of the firm.

The model's implications for regression (23) are consistent with two key features of the data. First, the coefficient on cash flow a_1 is positive, indicating that increases in cash flows are associated with increases in investment. Second, the inclusion of cash flow as a regressor in (23) significantly increases the R^2 of the regression, indicating that cash flow has predictive power for investment. However, the quantitative magnitude of the cash flow coefficient is larger in the model than the data.