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Luis Araujo,

Qingqing Cao,

Raoul Minetti and

Pierluigi Murro

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Center for Relationship Banking and Economics
Department of Economic and Political Sciences
and of Modern Languages
LUMSA University
Via Pompeo Magno, 22, 00192 Rome – Italy
https://sites.google.com/site/cerbelumsa/home

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Luis Araujo
Michigan State University

Qingqing Cao
Michigan State University

Raoul Minetti*
Michigan State University

Pierluigi Murro
Lumsa University

Abstract

We investigate the effects of a credit crunch in an economy where firms can retain a mature technology or adopt a new technology. We show that firms' collateral eases firms' access to credit and investment but can also inhibit firms' innovation. When this occurs, a contraction in the price of collateral assets squeezes collateral-poor firms out of the credit market but fosters the innovation of collateral-rich firms. The analysis reveals that the credit and asset market policies adopted during recent credit market crises can boost investment but slow down innovation. We find that the predictions of the model are consistent with the innovation patterns of a large sample of European firms during the 2008-2010 credit crisis.

Keywords: Credit Crunch, Technological Change, Collateral.
JEL Codes: E44; G21; G01.

*Department of Economics, Michigan State University. E-mail: minetti@msu.edu. Phone: +1-517-355-7349. Address: 486 W. Circle Drive, 110 Marshall-Adams Hall, Michigan State University, East Lansing, MI 48824-1038. During the preparation of the manuscript we have benefited from several comments and conversations. In particular, we wish to thank Giorgio Gobbi, Luigi Guiso, Maurizio Iacopetta, Matteo Iacoviello, Nobuhiro Kiyotaki, Rowena Pecchenino, Susan Chun Zhu and seminar participants at Bank of France, Bank of Portugal, Boston College, Einaudi Institute for Economics and Finance, Fed Board of Governors, London School of Economics (FMG/ESRC Conference), North Carolina State University, Stockholm School of Economics (Finance Department), University of Kentucky, University of Michigan Ross Business School (Finance Department), Chicago Fed "Summer Workshop on Money, Banking, Payments and Finance", American Economic Association Meetings, Midwest Meetings in Economic Theory and in Macroeconomics, SKEMA Workshop on "Credit Frictions and Money" (Nice), OFCE-Sciences Po Workshop on "Finance, Growth and Crises" (Paris). All remaining errors are ours.

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Abstract

We investigate the effects of a credit crunch in an economy where firms can retain a mature technology or adopt a new technology. We show that firms' collateral eases firms' access to credit and investment but can also inhibit firms' innovation. When this occurs, a contraction in the price of collateral assets squeezes collateral-poor firms out of the credit market but fosters the innovation of collateral-rich firms. The analysis reveals that the credit and asset market policies adopted during recent credit market crises can boost investment but slow down innovation. We find that the predictions of the model are consistent with the innovation patterns of a large sample of European firms during the 2008-2010 credit crisis.

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1 Introduction

During the financial crisis that started in 2008, a major drop in the value of collateral assets, especially real estate, triggered a credit contraction, forcing firms to reduce their investments. The literature offers well-established arguments for interpreting these effects of a credit crunch. When entrepreneurs cannot commit to repay lenders, collateral eases their access to credit.[1] Thus, aggregate shocks that erode collateral values depress total investment by hindering firms' access to external finance (Kiyotaki and Moore, 1997; Lorenzoni, 2008; Holmstrom and Tirole, 1997; Den Haan, Ramey and Watson, 2003).

While useful to explain key transmission mechanisms of a credit market crisis, these arguments only yield partial insights into the effects of a credit crunch on technological change. Financial crises appear to have contrasting effects on technological change. The OECD (2009) reviews several pieces of evidence and concludes that credit market crises can certainly damage innovative firms but also be "times of industrial renewal". Field (2011) documents that the Great Depression was a period of major innovations for the U.S. economy.[2] These innovations ranged from Teflon in petrochemicals industries to household appliances, such as the radio and refrigerator, and formed the basis for the post-World War II economic expansion. In South Korea and in Finland, the number of innovative firms boomed during and in the immediate aftermath of the 1990s financial crises (OECD, 2009). And firm-level surveys reveal that while the credit crisis started in 2008 depressed the innovation efforts of firms with difficult access to credit, such as young businesses with little pledgeable wealth, it also stimulated the innovation activity of other firms, especially more established businesses with more pledgeable assets and easier access to credit (see, e.g., Hall, 2011; European Commission, 2012; Voigt and Moncada-Paternò-Castello, 2009; Cincera, Cozza,

[1] Ex post, after entrepreneurs default, lenders can repossess collateral and this compensates for the limited pledgeability of entrepreneurs' output; ex ante, lenders' threat to repossess collateral deters entrepreneurs' misbehavior.

[2] Further back in history, the Long Depression started in 1873 was marked by the introduction of major innovations.

Tübke and Voigt, 2011, and references therein). In Section 2, we will uncover evidence in support of these conclusions by exploring survey data on the innovation activity of about 15,000 European firms during the 2008-2009 credit crisis. The results will suggest that, while the majority of firms responded to the 2008-2009 credit crunch and drop in collateral prices by postponing innovation, a non-negligible number of firms responded to shrinking credit and collateral values by stepping up their innovation plans. Such firms were concentrated in the segment of businesses with large pledgeable assets, while firms with little collateral scaled down their innovation activity.

These observations elicit fundamental questions: Can we build a model economy that captures these contrasting effects of credit market crises on innovation? In such an economy, under what conditions does a credit crunch triggered by a drop in collateral values depress or stimulate innovation? And what policies are more innovation-friendly during a credit crunch? This paper takes a step towards addressing these questions. Building on the above observations, we focus on the innovation propensity within incumbent businesses that rely on collateral-based funding. We posit an economy where entrepreneurs operate a mature technology or innovate and adopt a new technology. Lenders, in turn, acquire information that is essential for repossessing and liquidating productive assets pledged as collateral when entrepreneurs default (as in Diamond and Rajan, 2001, for example). Lenders' information on collateral assets eases entrepreneurs' access to credit but can make lenders reluctant to finance entrepreneurs' innovation. In fact, the assets of the new technology are more illiquid and firm specific and, hence, less pledgeable as collateral than the assets of the mature technology. Furthermore, lenders' information on the assets of the mature technology is (partially) specific and non-transferable to the assets of the new technology. Therefore, expecting that the information they have accumulated on mature collateral assets will go wasted if entrepreneurs switch to the new technology, lenders may hinder entrepreneurs' innovation efforts.

The distribution of firms across collateral values replicates salient features of that obtained in previous general equilibrium models of the credit market (e.g., Holmstrom and Tirole, 1997). Collateral-poor firms lack access to credit because they cannot pledge enough expected returns to lenders. Firms with medium and rich collateral, instead, obtain credit. The novelty consists of firms' technology adoption. When lenders' technological inertia arises, while firms with a medium value of collateral potentially innovate, collateral-rich firms retain the mature technology. In fact, their lenders expect a large depreciation in the value of their information if the mature technology is abandoned in favor of the new technology.

We study the effects of a contraction in the price of collateral assets (e.g., as in Holmstrom and Tirole, 1997, and Kiyotaki and Moore, 1997). Following a drop in the asset price, marginal firms with collateral just sufficient to obtain credit are squeezed out of the credit market because they can no longer pledge enough expected returns to lenders. This tends to reduce total investment and innovation. Consider next collateral-rich firms. The drop in the asset price erodes the value of the information acquired by their lenders on mature collateral assets, mitigating lenders' potential technological inertia. This can foster the innovation of collateral-rich firms. Overall, while the asset price drop depresses total investment, its effect on innovation depends on the relative magnitudes of the drop in the innovation of firms squeezed out of the credit market and the increase in the innovation of collateral-rich firms.

The analysis delivers novel policy implications. We investigate the effects of two unconventional policies implemented by central banks and governments during the recent credit crisis: an intervention in the collateral asset market aimed at sustaining the asset price and a policy of direct lending to collateral-poor firms. We find that both policies boost total investment but may dampen the increase in the innovation of collateral-rich firms after the shock. Notably, the asset market policy turns out to be more taxing for innovators than the direct lending policy.

In the last part of the paper, we revisit the mechanisms of the model under richer structures of the credit sector and the corporate sector. The goal is to assess under what structures of the credit and corporate sectors a credit crunch is more likely to depress or stimulate innovation. In the credit sector, we allow for information-intensive credit relationships between firms and lenders in which lenders obtain more information on firms' collateral assets (Diamond and Rajan, 2001). We find that, following a contraction in the price of collateral assets, the increase in the innovation of collateral-rich firms can entail a reduction in the number of credit relationships. In turn, this can dampen the stimulus to output triggered by innovation. In the corporate sector, we extend the model by allowing for managerial firms and managers' technological inertia due to higher riskiness of the new technology. We then investigate how managers' inertia interacts with lenders' potential technological inertia.

This paper especially relates to two strands of literature. The first investigates the impact of a disruption in the financial structure on aggregate investment (e.g., Gertler and Karadi, 2011; Gertler and Kiyotaki, 2010, 2015). In this literature, we borrow some properties of our modelling strategy, such as the focus on a finite horizon economy, from Holmstrom and Tirole (1997). Den Haan, Ramey and Watson (2003) and dell'Ariccia and Garibaldi (2001) are other related papers in this literature. While in these studies a credit tightening depresses investment, in our economy it depresses investment but may foster technological change. The second strand of literature analyzes the impact of recessions on firms' innovation. Most of this literature neglects the role of the credit market. Caballero and Hammour (2005) and Ramey (2004) are exceptions. Caballero and Hammour (2005) show that, because of credit frictions, production units can be destroyed at an excessive rate during a recession and the subsequent recovery can occur more through a slowdown in the destruction rate than through an increase in the creation rate. Ramey (2004) endogenizes financial managers' project selection and shows that, if managers have empire-building incentives, during downturns they can discard efficient projects to preserve the size of their portfolios. This paper puts forward a view opposite to these studies: while it depresses investment, a credit tightening can mitigate lenders' technological inertia. In this sense, our analysis shares some features with the Shumpeterian view of recessions as moments of creative destruction. For example, in Caballero and Hammour (1994) during recessions innovative production units can more easily enter and displace outdated ones. Relative to this literature, we do not focus on the innovations of newly formed start-ups, but rather on changes in the innovation propensity within incumbent businesses, showing how changes in the value of their collateral can alter the incentives of their lenders to support innovation. Accordingly, we focus on collateralized lending by financial institutions, rather than early-stage private equity or growth funding.

The remainder of the paper unfolds as follows. In Section 2, we provide background empirical evidence for the key mechanisms explored in the model. In Section 3, we present the baseline model. Section 4 solves for the equilibrium. In Section 5, we conduct experiments aimed at mimicking a credit market crisis. Section 6 considers policies. Section 7 studies extensions while Section 8 concludes. The Appendix contains details on the data and the main proofs (baseline model, Sections 3-5) while further details of the derivations are relegated to Supplement A.

2 Empirical Background

As noted, various pieces of evidence point to a possible role of credit market crises in stimulating the start of innovative plans by established firms with large pledgeable collateral, while depressing the access to credit and the innovation ability of collateral-poor firms. To gain further intuition, in this section we exploit information from a large survey of European firms conducted in 2010 with reference to the years 2007-2009. Our data source is the EU-EFIGE data set, collected as part of the EFIGE project (European Firms in a Global Economy: internal policies for external competitiveness) supported by the Directorate General Research of the European Commission and coordinated by the Bruegel Institute. The survey targets a representative sample at the country level of almost 15,000 manufacturing firms with no fewer than 10 employees in seven European countries (Austria, France, Germany, Hungary, Italy, Spain, United Kingdom). The data set includes quantitative and qualitative information on firms' R&D, innovation, labor organization, financing and organizational activities. Questions related to the behavior of firms during the 2008-2010 financial crisis were also included in the survey. We complement the EFIGE data set with firms' balance-sheet information provided by the BvD-Amadeus database.

The EFIGE data set is particularly suitable for our purposes. First, it surveys firms in European countries generally characterized by a strong importance of banking sectors in firm financing. Second, it covers the period of the credit market crisis in Europe started in 2008. The seven countries covered by the EFIGE survey experienced a sizeable credit crunch from 2008 to 2009, with the average credit to non-financial businesses dropping by about 1.2% in real terms from the last quarter of 2008 to the last quarter of 2009 (source: BIS, Credit to the Non-Financial Sector, section on non-financial firms). Third, one of the main goals of the survey was to investigate firms' response to deteriorating credit market conditions from 2008 to 2009. Thus, the survey questionnaire explicitly asked the firms whether from 2008 to 2009 they increased or decreased their activities on a number of relevant margins. Importantly for our purposes, one of the margins investigated in detail by the survey consists of firms' innovation activity. In particular, the survey asks each firm whether from 2008 to 2009 it accelerated or instead postponed innovation plans. It also asks each firm whether it innovated by expanding the range of its products and by conducting non-marginal innovations. Using these questions, we can construct a dummy that takes the value of 1 if a firm accelerated its non-marginal innovation activity, expanding its range of products, and zero if instead the firm postponed innovation plans or maintained its technology unchanged. In addition, our data provide rich information on the availability of collateralizable assets as well as details on banks' "lending technologies", including the emphasis of banks on firms' collateral when extending credit (see the Appendix for more details on the variables).

In Table 1, we use this information in two ways. In Panel A, we explore whether during the credit market crisis (2008-2009) there were significant differences between firms that accelerated their innovation activity and firms that instead postponed their innovation plans. Unsurprisingly, the panel reveals that during the credit crunch about 85% of the firms postponed or maintained unchanged innovation plans. Yet, about 15% of the firms in the sample declare that during the credit crunch they instead accelerated non-marginal innovation plans aimed at expanding their products. Importantly for our purposes, the panel shows that the firms that accelerated innovation plans during the credit crunch were of similar size and age as the firms that postponed innovation but exhibited a significantly larger availability of collateralizable assets, especially fixed assets easily pledgeable as collateral. It further suggests that during the crisis banks' emphasis on collateral tended to be associated with a drop in the innovation activity of firms with little pledgeable assets but with some increase in the propensity to innovate of firms with large pledgeable assets. Finally, the panel indicates stronger importance of credit relationships for the firms that accelerated innovation plans than for those that postponed innovation.

While the 2008-2009 credit crunch was pervasive, some firms suffered from its effects more than others. Further, our theoretical analysis stresses the impact of a drop in the value of collateralizable assets. In Panel B, we then dig deeper into the data and test whether the firms that during the 2008-2009 credit crunch experienced a contraction in the value of their fixed, pledgeable assets

Table 1: European Firms' Innovation during the 2008-2009 Credit Market Crisis

Panel (A) Summary Statistics (means) for Non-marginal Innovation Plans during the 2008-2009 Credit Crunch

		General firms' demographics		Pledgeable collateral assets		Emphasis on collateral			Bank involvement in investment finance and relationship lending	
	Number of firms	Firm age (years)	Number of employees	Total assets (thousand euros)	Fixed assets (thousand euros)	Collateral	Collateral * Tot. ass. > median	Collateral * Tot. ass. ≤ median	Bank highly involved * Collateral	Length credit relation
Accelerate Innovation from 2008 to 2009	2020	35.541	127.224	20479	8119	0.642	0.215	0.183	1912	3.269
Postpone or Stall Innovation from 2008 to 2009	12686	34.323	129.817	14752	5838	0.636	0.209	0.230	2281	3.064
t-test		*-1.616*	*0.048*	*-1.585*	*-1.165*	*-0.368*	*-0.434*	*3.643*	*0.820*	*-2.843*

Panel (B) Innovation Response to Change in Value of Fixed Assets during the 2008-2009 Credit Crunch

	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit	Probit
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
	Engage in Non-marginal Innovation in 2008-2009										Accelerate Non-marginal Innovation in 2008-2009			
			Tot. Ass. > median	Tot. Ass. ≤ median			Tot. Ass. > median	Tot. Ass. ≤ median	Bank highly involved in investm. finance	Bank not involved in investm. finance			Tot. Ass. > median	Tot. Ass. ≤ median
Growth fixed assets	0.064**	0.061**	-0.048	0.062**	0.067***	0.080*	-0.013	0.052***	0.136***	0.051	0.057	0.162***	0.015	0.123***
	(0.029)	(0.031)	(0.031)	(0.029)	(0.020)	(0.048)	(0.025)	(0.020)	(0.049)	(0.051)	(0.041)	(0.038)	(0.041)	(0.043)
Total assets > median (dummy)	0.293***				0.291***				0.289***	0.297***	0.282***			
	(0.033)				(0.038)				(0.038)	(0.048)	(0.049)			
II quartile of tot ass. (dummy)		0.087**				0.027						0.124**		
		(0.042)				(0.018)						(0.049)		
III quartile of tot ass. (dummy)		0.284***				0.265***						0.283***		
		(0.043)				(0.053)						(0.012)		
IV quartile of tot ass. (dummy)		0.400***				0.354***						0.318***		
		(0.041)				(0.036)						(0.031)		
Growth fixed ass. * Tot ass.>median	-0.112***				-0.083***				-0.114**	-0.101	-0.085*			
	(0.024)				(0.027)				(0.058)	(0.083)	(0.050)			
Growth fixed ass. * II q. tot ass.		0.009				-0.028						-0.079		
		(0.067)				(0.116)						(0.098)		
Growth fixed ass. * III q. tot ass.		-0.095***				-0.069						-0.159***		
		(0.036)				(0.059)						(0.051)		
Growth fixed ass. * IV q. tot ass.		-0.124***				-0.129**						-0.126		
		(0.042)				(0.063)						(0.107)		
Age					0.001	0.001	0.001	0.000						
					(0.001)	(0.001)	(0.001)	(0.001)						
Sales					0.000	0.000	0.000	0.000						
					(0.000)	(0.000)	(0.000)	(0.000)						
Labour productivity					-0.009	-0.019	0.013	-0.214**						
					(0.048)	(0.049)	(0.052)	(0.090)						
Industry & Country dummies	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Observations	11231	11231	5606	5625	7196	7196	3983	3212	4063	4994	11206	11206	5598	5604

Note: This table examines the innovation patterns of firms from seven European countries (Austria, France, Germany, Italy, Spain, United Kingdom, Hungary) during the 2008-2009 credit crisis. Panel A reports the number of firms that accelerated or postponed non-marginal innovation plans during the 2008-2009 credit crunch and summary statistics (means) for the two categories of firms. The summary statistics refer to general firms' demographics (firm age and employees), pledgeable collateral assets (total assets and fixed assets), banks' emphasis on collateral, banks' involvement in investment financing, and proxies for relationship lending (duration of main credit relationship). Panel B, columns 1-10, report the effect of the growth rate of the value of fixed assets on the introduction of non-marginal innovations in 2008-2009. Panel B, columns 11-14, report the effect of the growth rate of the value of fixed assets on the decision to accelerate non-marginal innovation plans in 2008-2009. In the regressions, "tot ass.>median" is a dummy that equals 1 if the firms' total assets exceed the median. All regressions in Panel B include country and industry dummies. In columns 5-8 labor productivity is value added per worker. See the Appendix for more details on variables and data. ***, **, * denote significance at the 1%, 5%, and 10% level, respectively.

exhibited a tendency to accelerate or postpone the start of innovation plans. Again, our main interest is whether firms with larger initial collateral responded differently to a drop in the value of their pledgeable fixed assets, accelerating rather than postponing non-marginal innovation plans (see the interaction term in the regressions). We saturate all the regressions in Panel B with a full set of country and two-digit industry dummies. In robustness checks, we further include various firm-level controls, such as proxies for firm size, age and labor productivity (the inclusion of these controls entails a loss of observations).[3] The results in the panel reveal that during the crisis the firms with little assets that experienced a contraction in the value of fixed assets did not engage in non-marginal innovations and indeed postponed innovation plans following such a contraction. By contrast, the firms with initially large assets responded to a contraction in the value of fixed assets by engaging in non-marginal innovations and actually accelerating their innovation plans. For example, in column 1 the estimated coefficient on the change in the value of fixed assets is positive and equal to 0.064 while the interaction term with the dummy for larger-than-median assets is negative and equal to -0.112. In column 2, the estimated coefficient on the change in fixed assets is again positive (equalling 0.061) while the coefficients on the interaction terms with the dummies for the 3rd and 4th asset quartiles are significantly negative (and equal to -0.095 and -0.124, respectively). These findings are confirmed when we reestimate the regressions for different subsamples based on firms' initial asset value, rather than inserting interaction terms (see, e.g., columns 3-4 and 13-14). Further, in columns 9-10 we reestimate the regression in column 1 separately for firms that declare that their banks are significantly involved in the financing of the firm's investments and for firms for which banks have little involvement. We find that, for firms with initially large assets, the tendency to innovate in response to a drop in fixed assets manifested itself especially when they relied on bank finance (compare the interaction terms in columns 9 and 10).

To summarize, consistent with the evidence mentioned in Section 1 and with the conclusions of OECD (2009), these results from the EFIGE survey suggest that during the 2008-2009 European credit crisis, while the majority of firms responded to the contraction in credit and collateral values by scaling down their innovation plans, a non-negligible share of firms responded by stepping up their innovation plans. Such firms were concentrated in the segment of businesses with relatively large availability of assets pledgeable as collateral.

3 The Baseline Model

This section describes the baseline model. Figure 1 illustrates the timing of events while Table 2 summarizes the notation.

3.1 Agents, goods, and technology

Consider a three-date economy ($t = 1, 2, 3$) populated by a unit continuum of entrepreneurial firms and a continuum of investors of measure larger than one. There is a final consumption good, which can be produced and stored, and productive assets of two vintages, mature and new. Entrepreneurs have no endowment while each investor is initially endowed with an amount ω of final good. All agents are risk neutral and consume on date 3.

Each entrepreneur can carry out one indivisible project. On date 1, an entrepreneur can choose an innovative plan for his project that can generate an innovation opportunity on date 2. If the

[3] In untabulated tests, we also experimented with including other firm controls, such as proxies for the human capital of the firm.

innovative plan is chosen and the innovation opportunity arises, the entrepreneur adopts a new technology. Otherwise, the entrepreneur has to retain a mature, less productive technology. Under the mature (new) technology, on date 3 the entrepreneur transforms an amount $i < \omega$ of final good into one unit of mature (new) assets. With probability π the project succeeds and the mature (new) assets yield an output y ($y(1+n)$) of final good; otherwise the project fails and the entrepreneur goes out of business.

In case of failure, a fraction μa of assets can be recovered and redeployed outside the firm. a captures the amount of collateralizable assets of an entrepreneur and is uniformly distributed across entrepreneurs over the domain $[0, 1]$. μ reflects the effort the entrepreneur exerts for the maintenance of the collateralizable assets. This maintenance can be thought as acquiring information on the collateral and its market or also as restraining from looting and asset depreciation.[4] We specify a simple technology for the maintenance of collateral assets: an entrepreneur sustains a per-unit effort cost of $\frac{\zeta\mu^2}{2}$ for achieving a level μ of maintenance.

On date 3, each entrepreneur still in business can reuse one unit of liquidated assets, obtaining an amount $\eta\tilde{y}$ of final good. $\tilde{y}$ is an idiosyncratic output with a positive mass on zero. The expected value of $\tilde{y}$ is θ, which is uniformly distributed across entrepreneurs over the domain $[0, \overline{\theta}]$; η represents the aggregate productivity of liquidated assets.[5]

3.2 Credit sector

Each entrepreneur can enter a credit contract with one investor on date 1. Following an established literature, we allow the lender to exert some control over the entrepreneur's production opportunities (see, e.g., Aghion and Bolton, 1992; Rajan, 1992). Precisely, consider the case in which the entrepreneur has chosen an innovative plan for his project. On date 2, the lender can carry out a costless action that affects the probability of the innovation opportunity: if she carries out this action, the opportunity will arise with probability $1-\sigma^A$; otherwise, the opportunity will arise with a lower probability $1-\sigma^{\bar{A}}$ (where $0 < \sigma^A < \sigma^{\bar{A}} < 1$).

The lender also acquires information on assets as a by-product of her financing activity. As in Diamond and Rajan (2001) and Habib and Jonsen (1999), this enables her (unlike other agents) to obtain value from the liquidation of the entrepreneur's assets. Precisely, the liquidation value the lender recovers in the event of project failure and liquidation of the mature technology is $p\mu a$, where p denotes the asset price; the rest is lost in the form of transaction costs.[6] To capture the idea that the lender has instead lower ability to acquire experience about the assets of a new technology, we assume that the lender recovers less value from new assets than from mature assets (we normalize to zero what she obtains in case of liquidation of the new technology).

3.3 Contractual structure

As in Aghion and Bolton (1992) and Diamond and Rajan (2001), a lender cannot contractually commit to carry out her action that facilitates (increases the probability of) the innovation opportunity because the action is non-verifiable; similarly, the level of collateral maintenance performed

[4] Different classes of models focus on various activities of collateral maintenance and preservation and we do not restrict attention to one particular interpretation. A broad empirical literature shows that borrowers' actions can significantly impair or enhance the actual liquidation value of collateral (see, e.g., Calomiris, Larrain, Liberti and Sturgess, 2016, Udell, 2004, ILO, 2001, and references therein). In macroeconomic settings, firms are often assumed to engage in activities of capital repair (see, e.g., Gertler and Karadi, 2011).

[5] The heterogeneity in entrepreneurs' ability to reuse assets generates a downward sloping asset demand.

[6] Throughout, unless otherwise stated, we let transaction costs be transfers rather than a real resource loss. This is without loss of generality.

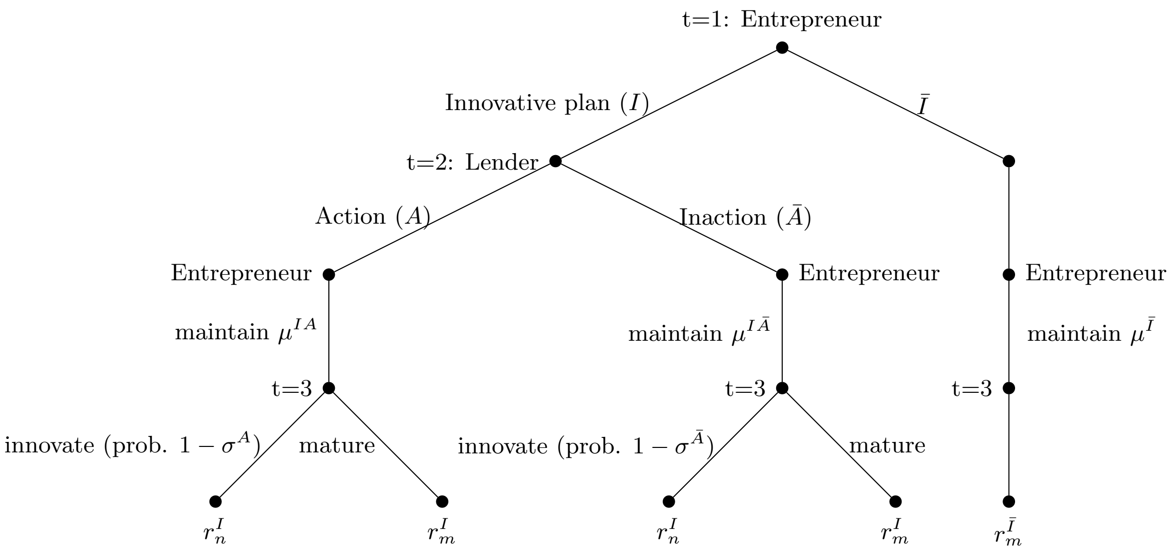

Figure 1: Decisions of entrepreneurs and lenders. The bottom of the tree shows the repayments to the lender in the event of project success.

by an entrepreneur is not verifiable in courts, implying that no contract can be written upon it. Imperfect enforceability also limits agents' commitment to pecuniary transfers and, hence, the design of pecuniary incentives for the lender. Specifically, in the event of project success, only a fraction l of the output is verifiable while the rest accrues privately to the entrepreneur. In the event of project failure and asset liquidation, the lender cannot commit the specific liquidation skills tied to her information about the assets. Thus, as in Diamond and Rajan (2001), she can threaten to withhold her skills during the liquidation, forcing a renegotiation of the allocation of the liquidation proceeds. We denote by λ the bargaining power of the lender in the renegotiation.

Given this contractual structure, on date 1 the contract between a lender and an entrepreneur specifies a loan amount of i and the repayment to the lender in the event of project success, contingent on the technology adopted. Precisely, if the entrepreneur does not choose an innovative plan, the contract specifies the repayment $r_m^{\bar{I}}$ if the mature technology is successfully operated; if the entrepreneur chooses an innovative plan, the contract specifies the repayment $r_m^I(r_n^I)$, if the mature (new) technology is successfully operated. Since on date 1 there is perfect competition among investors, the contract maximizes the entrepreneur's expected return subject to the entrepreneur's limited liability constraints $r_m^I, r_m^{\bar{I}} \leq ly$, $r_n^I \leq l(1+n)y$, and the relevant constraints of the lender.[7,8] These include the lender's participation constraint and the lender's incentive constraint if the entrepreneur wants to incentivize the lender to carry out the action that facilitates innovation.

3.4 Discussion

In the real sector, the difference between the two technologies is that the new technology produces more output ($y(1+n) > y$) but its assets have lower liquidation value ($\mu_n pa < \mu pa$, where for

[7] Since assets purchased in the liquidation market have zero output with positive probability, an entrepreneur is unable to commit such liquidation output to a lender, on top of the output of his project. This feature captures in a reduced form the difficulty to contractually pledge output from distant and unrelated activities.

[8] We do not impose a limited liability constraint for the lender. Implicitly, we are assuming that the lender has more than enough funds to make transfers to the entrepreneur on date 3, if needed. Adding a limited liability constraint would not alter the results.

Table 2: Notation of the Model

Probability of project success	π
Output of mature technology	y
Productivity edge of new technology	n
Collateral assets of firm	a
Investment outlay of project	i
Share of verifiable output	l
Probability of innovation opportunity if lender facilitates	$1-\sigma^{A}$
Probability of innovation opportunity if lender hinders	$1-\sigma^{\bar{A}}$
Aggregate productivity liquidated assets	η
Idiosyncratic productivity liquidated assets	θ
Lender's bargaining power in renegotiation	λ
Maintenance cost of collaterals	ζ
Lender's endowment	ω

Note. The table describes the symbols used in the model.

simplicity we have set $\mu_n = 0$).[9,10] The assets that embody new technologies and R&D results are likely to be firm specific and illiquid, thus having little collateral value (Carpenter and Petersen, 2002; Hall and Khan, 2003; Berlin and Butler, 2002; Rajan and Zingales, 2001). Moreover, lenders typically have less experience in liquidating new vintages of assets than mature ones.

In the credit sector, two features are worth discussion: the control exerted by a lender and the characterization of information as asset liquidation skills. We share with Aghion and Bolton (1992), Rajan (1992), and Bhattacharya and Chiesa (1995), for example, the assumption that a lender carries out an interim action that affects production opportunities. This action has several real world counterparts. In an R&D race, it can consist of concealing the findings of the entrepreneur's internal research from his competitors (Bhattacharya and Chiesa, 1995); it can consist of providing the entrepreneur with advice or information for expanding the firm's technological frontier; if the lender has representatives on the board of the firm, as in the case of German and Japanese banks, it can consist of voting for an innovative strategy. In other circumstances, it can consist of a refinancing (Rajan, 1992): the need for refinancing is likely for a new technology which generally yields little interim cash flow, especially at the R&D stage (Goodakre and Tonks, 1995). Aghion and Bolton (1992) discuss examples of other actions of lenders which can affect innovation opportunities, such as supporting firms' mergers and spin-offs.

We borrow the characterization of information as asset liquidation skills from Diamond and Rajan (2001) and Habib and Jonsen (1999). The critical feature is that the lender acquires more information than the entrepreneur and the other investors. As for the latter, following Diamond and Rajan (2001), our assumption reflects the idea that the lender gathers more information on assets through her financing activity. As for the former, "Because he [the entrepreneur] is a specialist at maximizing the value of the asset in its primary use [...] it is reasonable to assume that he lacks the skill even to identify the asset's next best use or to recognize clearly the occurrence of the bad

[9] μ is an endogenous choice by entrepreneurs. It is positive in equilibrium, as the next section shows. We could also allow new assets to have positive liquidation value ($\mu_n > 0$), though lower than that of mature assets. The results would carry through but the analysis would be more cumbersome.

[10] As a robustness check, in Supplement A we study an alternative setting where the new technology has a higher success probability. We show that all agents' decisions are the same as in the main model.

states" (Habib and Johnsen, 1999, p. 145).

4 Equilibrium

We solve the model in steps. First, we take the asset price as given and study the problems of lenders and entrepreneurs. We solve for the date-2 choice of collateral maintenance by an entrepreneur. We then solve for a lender's choice $\alpha \in \{A, \overline{A}\}$ between action (A) and inaction ($\overline{A}$) on date 2, and her choice whether to finance an entrepreneur. We next solve for the date 1 choice of an entrepreneur whether to engage in an innovative plan and her choice of contract.

4.1 Entrepreneurs' collateral maintenance

When choosing the level of maintenance of the collateral assets, an entrepreneur maximizes

$$E(\mu) - \frac{\zeta\mu^2}{2}pa,$$

where $E(\mu)$ denotes the return that the entrepreneur expects to appropriate in case of liquidation of the mature assets. Lemma 1 characterizes the decision of collateral maintenance. The lemma shows that the maintenance effort increases as the probability of operating the mature technology increases (and therefore the probability of innovation declines).

Lemma 1 (Collateral maintenance).

(i) If an entrepreneur adopts an innovative plan (I), and the lender takes the action that facilitates innovation (A), the collateral maintenance effort is

$$\mu^{IA} = \frac{(1-\pi)(1-\lambda)\sigma^A}{\zeta}.$$

(ii) If an entrepreneur adopts an innovative plan (I), while the lender chooses inaction ($\overline{A}$), the maintenance effort is

$$\mu^{I\bar{A}} = \frac{(1-\pi)(1-\lambda)\sigma^{\bar{A}}}{\zeta}.$$

(iii) If an entrepreneur does not adopt an innovative plan ($\bar{I}$), the maintenance effort is

$$\mu^{\bar{I}} = \frac{(1-\pi)(1-\lambda)}{\zeta}.$$

As $\sigma^A < \sigma^{\bar{A}} < 1$, $\mu^{IA} < \mu^{I\bar{A}} < \mu^{\bar{I}}$.

4.2 Lenders

Let us consider the case in which an entrepreneur chooses an innovative plan on date 1 and let us study the date 2 decision of his lender whether to carry out the action that facilitates innovation. The lender compares her expected return if she facilitates innovation with her expected return if she hinders it. Assuming that she breaks a tie in favour of innovation, she will carry out the action if and only if

$$(1-\sigma^A)\pi r_n^I + \sigma^A\left[\pi r_m^I + \lambda(1-\pi)\mu^{IA}pa\right] \geq (1-\sigma^{\bar{A}})\pi r_n^I + \sigma^{\bar{A}}\left[\pi r_m^I + \lambda(1-\pi)\mu^{I\bar{A}}pa\right].$$

Using the solution of μ^{IA} and $\mu^{I\bar{A}}$, the above inequality can be rewritten as

$$r_n^I - r_m^I \geq \frac{(\sigma^A + \sigma^{\bar{A}})(1-\pi)^2\lambda(1-\lambda)pa}{\pi\zeta}. \tag{1}$$

Inequality (1) is the lender's incentive constraint. The left hand side is the spread between the repayments in the event of successful adoption of the new technology and in the event of successful adoption of the mature one. The right hand side captures the reduction in the expected liquidation proceeds that the lender suffers if she facilitates innovation. This reduction, due to the lender's worse ability to liquidate new assets, is positively related to the liquidation value pa of mature assets. The lender will facilitate innovation if and only if, as in (1), the contract guarantees her a sufficiently higher repayment if the new technology is successfully adopted, compensating the reduction in her expected liquidation proceeds.

Lemma 2 (Credit for innovation)**.** *Conditional on that an entrepreneur takes an innovative plan, there exists a feasible contract that induces a lender to carry out the action for innovation if and only if the entrepreneur's collateral assets satisfy* $a \in [\underline{a}^{IA}(p), \bar{a}(p)]$*, where:*

$$\underline{a}^{IA}(p) = \frac{\zeta[i - \pi ly(1 + n - \sigma^A n)]}{(\sigma^A)^2(1-\pi)^2\lambda(1-\lambda)p}, \tag{2}$$

and

$$\bar{a}(p) = \frac{\zeta[\pi ly(1+n) - i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)p}. \tag{3}$$

The intuition is as follows. The spread $r_n^I - r_m^I$ that can be set in a contract is bounded. In fact, the repayment r_n^I for the new technology is constrained above by the entrepreneur's limited liability constraint. And, for a given r_n^I, the repayment r_m^I for the mature technology is constrained below by the lender's participation constraint. Lemma 2 shows that if $a > \bar{a}(p)$, in (1) the left hand side falls short of the right hand side for any feasible pair (r_n^I, r_m^I). In this region, the lender hinders innovation. Inspection of (3) reveals that a lender is more likely to hinder innovation when the maintenance cost ζ on the assets is lower, when the entrepreneur is rich in collateral (has a high a), and when the asset price p is higher. Intuitively, a lender loses more from the depreciation of her asset liquidation skills when the entrepreneur's collateral maintenance is higher and the asset value pa is higher. Turning to the lower bound $\underline{a}^{IA}(p)$, this stems from the fact that collateral-poor firms ($a < \underline{a}^{IA}(p)$) cannot satisfy a lender's participation constraint and are thus excluded from the credit market. Inspection of (2) reveals that a lender is more likely to provide credit when the maintenance cost ζ on the assets is lower, when an entrepreneur is rich in collateral, and when the asset price is higher. Lemma 2 thus illustrates the dual role of collateral. On the one hand, collateral eases the access to credit. On the other hand, an excess of collateral hinders innovation.

When the lender does not take the action for innovation or when the entrepreneur does not adopt an innovative plan, the lender may still provide credit as long as the entrepreneur has enough collateral assets. Lemma 3 characterizes the lower bound of collateral assets a for the lender to extend credit in these scenarios.

Lemma 3 (Credit under no innovation)**.** *If an entrepreneur adopts an innovative plan but the lender hinders innovation, the lender is willing to provide credit if and only if the collateral assets satisfy* $a \geq \underline{a}^{I\bar{A}}(p)$*, where*

$$\underline{a}^{I\bar{A}}(p) = \frac{\zeta[i - \pi ly(1 + n - \sigma^{\bar{A}} n)]}{(\sigma^{\bar{A}})^2(1-\pi)^2\lambda(1-\lambda)p}.$$

If an entrepreneur does not adopt an innovative plan, the lender is willing to provide credit if and only if the collateral assets satisfy $a \geq \underline{a}^{\bar{I}}(p)$*, where*

$$\underline{a}^{\bar{I}}(p) = \frac{\zeta\,(i - \pi l y)}{(1-\pi)^2 \lambda (1-\lambda) p}.$$

We make the following parametric assumptions:

$$\text{A1:} \quad \frac{i}{\pi l y} < 1 + \frac{n}{1+\sigma^A},$$

$$\text{A2:} \quad \frac{i}{\pi l y} > 1 + n - \sigma^A n.$$

Lemma 4. *Under assumption A1,* $\underline{a}^{IA}(p) < \underline{a}^{I\bar{A}}(p) < \bar{a}(p)$*, and* $\underline{a}^{IA}(p) < \underline{a}^{\bar{I}}(p) < \bar{a}(p)$*. Under assumption A2,* $\underline{a}^{IA}(p) > 0$*.*

Lemma 4 states that if the lender refuses to provide credit when an innovative plan is adopted and she facilitates innovation ($a < \underline{a}^{IA}(p)$), the lender will also refuse to provide credit when the entrepreneur does not adopt an innovative plan ($a < \underline{a}^{I\bar{A}}(p)$) or when the lender hinders innovation ($a < \underline{a}^{\bar{I}}(p)$).

The measure of entrepreneurs who obtain credit and the measure of entrepreneurs whose lenders facilitate innovation depend on the asset price p. For instance, if p is too low, we can have $\underline{a}^{IA}(p) > 1$, in which case no entrepreneur will obtain credit. Below, when studying the equilibrium asset price, we will characterize the conditions under which such degenerate cases do not occur. Until then, we will reason conditionally. For instance, Lemma 2 states that, conditional on a being in the interval $\left[\underline{a}^{IA}(p), \bar{a}(p)\right]$, innovation is feasible.

4.3 Entrepreneurs' innovation decision

Let us now examine entrepreneurs' decisions. Given Lemmas 3 and 4, entrepreneurs with $a < \underline{a}^{IA}(p)$ do not have access to credit. The following lemma characterizes decisions for firms with $a > \underline{a}^{IA}(p)$.

Lemma 5 (Innovation decision)**.** *Assume that* $l < \frac{2\lambda}{1+\lambda}$ *and that assumptions A1 and A2 hold. Let* $a > \underline{a}^{IA}(p)$*.*

(i) If $\frac{i}{\pi l y} \leq 1 + n - \frac{2\lambda n \sigma^A \sigma^{\bar{A}}}{l(1+\lambda)(1+\sigma^A)}$*, there exists* $a^{*A}(p) \equiv \frac{2\zeta \pi n y}{(1-\pi)^2(1-\lambda^2)(1+\sigma^A)p} \leq \bar{a}(p)$ *such that an entrepreneur chooses an innovative plan if* $a \in \left[\underline{a}^{IA}(p), a^{*A}(p)\right]$ *and chooses not to innovate if* $a > a^{*A}(p)$*.*

(ii) If $1 + n - \frac{2\lambda n \sigma^A \sigma^{\bar{A}}}{l(1+\lambda)(1+\sigma^A)} < \frac{i}{\pi l y} < 1 + n - \frac{2\lambda n \sigma^A \sigma^{\bar{A}}}{l(1+\lambda)\left(1+\sigma^{\bar{A}}\right)}$*, an entrepreneur chooses an innovative plan if* $a \in \left[\underline{a}^{IA}(p), \bar{a}(p)\right]$ *and chooses not to innovate if* $a > \bar{a}(p)$*.*

(iii) If $\frac{i}{\pi l y} \geq 1 + n - \frac{2\lambda n \sigma^A \sigma^{\bar{A}}}{l(1+\lambda)\left(1+\sigma^{\bar{A}}\right)}$*, there exists* $a^{*\bar{A}}(p) \equiv \frac{2\zeta \pi n y}{(1-\pi)^2(1-\lambda^2)(1+\sigma^{\bar{A}})p} \geq \bar{a}(p)$ *such that an entrepreneur chooses an innovative plan if* $a \in \left[\underline{a}^{IA}(p), a^{*\bar{A}}(p)\right]$ *and chooses not to innovate if* $a > a^{*\bar{A}}(p)$*.*

In cases (i)-(iii), conditional on the lender facilitating (hindering) innovation, an entrepreneur chooses an innovative plan if $a \leq a^{*A}(p)$ ($a \leq a^{*\bar{A}}(p)$). These cases capture scenarios where some entrepreneurs can deliberately choose not to innovate because the expected return from the mature technology dominates that of the new technology. Observe that cases (i) and (iii) have an empty intersection with assumptions A1 and A2 if $\frac{\sigma^{\bar{A}}(1+\sigma^{A})}{1+\sigma^{\bar{A}}} < \frac{l(1+\lambda)}{2\lambda} < \frac{\sigma^{\bar{A}}}{1+\sigma^{A}}$. We impose this assumption, thus restricting attention to interesting scenarios in which every entrepreneur is willing to innovate if his lender takes the action that facilitates innovation.[11]

4.4 Asset price and firm distribution

We now solve for the asset price.[12] There always exists a degenerate equilibrium in which the asset price is zero.[13] We are interested in non-degenerate equilibria in which the price is positive. The demand $D(p)$ for liquidated assets satisfies

$$D(p) = \left[1 - \underline{a}^{IA}(p)\right] \pi \left(1 - \frac{p}{\eta\bar{\theta}}\right).$$

A measure $1 - \underline{a}^{IA}(p)$ of entrepreneurs obtain credit and become active. Moreover, a share π of active entrepreneurs remain in business. Finally, a share $\left(\eta\bar{\theta} - p\right)/\eta\bar{\theta}$ of the entrepreneurs still in business recover an output no lower than p from reusing assets. The supply of asset $S(p)$ satisfies

$$S(p) = (1-\pi)\int_{\underline{a}^{IA}(p)}^{1} a da.$$

This is given by the probability $1-\pi$ that an entrepreneur fails times the amount of assets a liquidated by a failed entrepreneur, integrated across the active entrepreneurs.

The asset demand is increasing in the probability π of project success (entrepreneurs still in business can reuse liquidated assets) while the supply is decreasing in π (liquidated assets come from failed entrepreneurs). Therefore, the lower π, the lower the net asset demand and the asset price. If the price is too low, it may cause $\underline{a}^{IA}(p)$ to exceed one, completely shutting down entrepreneurs' access to credit. Thus, π cannot be too low. For a similar reason, the upper bound $\eta\bar{\theta}$ on entrepreneurs' ability to reuse assets cannot be too low. Overall, we need to assume[14]

$$\text{A3:} \quad \eta\bar{\theta}\left(\pi - \frac{1}{2}\right) > \frac{\pi}{2}\frac{\zeta\left[i - \pi l y\left(1 + n - \sigma^{A} n\right)\right]}{\left(\sigma^{A}\right)^{2}(1-\pi)^{2}\lambda(1-\lambda)}.$$

Lemma 6 solves for the equilibrium price.

Lemma 6 (Collateral asset price)**.** *Consider the region of parameters where assumptions A1-A3 hold. There exists a unique equilibrium with positive asset demand and supply. In this equilibrium, the asset price is given by*

$$p^{*} = \frac{\eta\bar{\theta}}{2\pi}\left\{\frac{3\pi-1}{2} + \left[\left(\frac{3\pi-1}{2}\right)^{2} - \frac{2\pi}{\eta\bar{\theta}}\frac{\zeta\left[i - \pi l y\left(1+n-\sigma^{A} n\right)\right]}{\left(\sigma^{A}\right)^{2}(1-\pi)\lambda(1-\lambda)}\right]^{\frac{1}{2}}\right\}. \tag{4}$$

[11]The restriction on the parameters is intuitive. For example, regarding l, when the output verifiability (l) is not too high, it is hard to induce the lender to carry out the action for the innovation. Thus, whenever it is possible to induce the lender to facilitate the innovation, the entrepreneur prefers innovating. On the other hand, when the output verifiability (l) is not too low, it is relatively easy to induce the lender to carry out the action for the innovation. Thus, when the lender has no incentive to facilitate innovation, the entrepreneur prefers not to innovate.

[12] We focus on the asset market clearing. In the credit market, investors' supply of funds is infinitely elastic at an expected return of one. In fact, investors are risk neutral and can store their endowment instead of lending it.

[13]This degenerate equilibrium is the result of a coordination failure. If entrepreneurs and lenders believe that the asset price is zero, no project will be funded. This will lead to a zero demand and a zero supply of assets.

[14]The particular lower bound on π we obtain ($\pi > \frac{1}{2}$) is driven by our assumptions on the distribution of collateral assets ($a \sim U[0,1]$) and on the distribution of entrepreneurs' ability to reuse assets ($\theta \sim U\left[0, \bar{\theta}\right]$). We chose these distributions for tractability. However, it should be clear that a lower bound constraint on π applies more generally.

Proposition 1 characterizes the distribution of firms across collateral values.

Proposition 1 (Firm distribution)**.** *Consider the region of parameters where assumptions A1-A3 hold.*

(i) If

$$\eta\bar{\theta} \leq \frac{\zeta[\pi l y(1+n)-i]}{\sigma^{A}\sigma^{\bar{A}}(1-\pi)^{2}\lambda(1-\lambda)}\left[\frac{3\pi-1}{2\pi}-\frac{(1-\pi)\sigma^{\bar{A}}}{2\pi\sigma^{A}}\frac{i-\pi l y\left(1+n-\sigma^{A}n\right)}{\pi l y(1+n)-i}\right]^{-1}, \tag{5}$$

no firm with collateral $a < \underline{a}^{IA}(p^*)$ has access to credit, and all firms with collateral $a > \underline{a}^{IA}(p^*)$ have access to credit and potentially innovate.

(ii) If (5) *does not hold, no firm with collateral $a < \underline{a}^{IA}(p^*)$ has access to credit, all firms with collateral $a \in \left[\underline{a}^{IA}(p^*), \bar{a}(p^*)\right]$ have access to credit and potentially innovate, and all firms with collateral $a > \bar{a}(p^*)$ have access to credit but do not innovate.*

Case (i) in Proposition 1 shows that, if the equilibrium asset price is low (say, because $\eta\bar{\theta}$ is relatively small), then all firms with access to credit potentially innovate. In fact, as noted, lenders hinder the adoption of the new technology only when the collateral asset value is not too low. Figure 2 instead displays the distribution of firms in the case in which the asset price is not too low and $\bar{a}(p^*) < 1$, that is, case (ii) in Proposition 1. This is the interesting case in which a positive measure of collateral-rich firms face lenders' technological inertia and do not innovate.

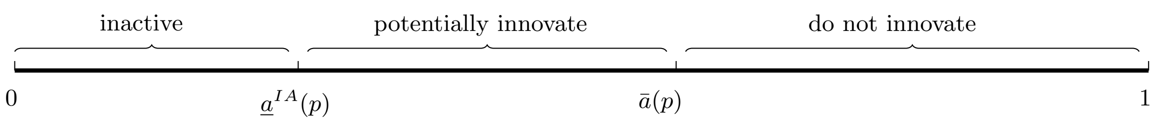

Figure 2: Firm distribution across collateral values

5 Credit Crisis Experiments

We study the effects of a collateral squeeze as in Holmstrom and Tirole (1997) (see also the capital quality shock in Gertler and Karadi, 2011). Precisely, we consider a drop in the aggregate productivity η of liquidated assets and assume that the drop is small so we can evaluate its effects using differential calculus. In practice, as in Holmstrom and Tirole (1997), for example, we perform comparative statics exercises, comparing the equilibrium for different values of η. Throughout, we consider two scenarios. In the first scenario, which occurs in the region of parameters defined in (ii) of Proposition 1 and which is represented in Figure 2, lenders can engage in technological inertia. In the second, which occurs in the region of parameters defined in (i) of Proposition 1, lenders do not engage in technological inertia and all firms with access to credit potentially innovate.

In the credit sector, we focus on the effect on the measure of firms obtaining credit,

$$C = 1 - \underline{a}^{IA}(p^*).$$

In the real sector, we focus on the effect on the asset price p^*, total investment $I = iC$, the measure of innovative firms

$$N = \min\left\{C, \bar{a}(p^*) - \underline{a}^{IA}(p^*)\right\},$$

and output Y.

Proposition 2 (Collateral squeeze and innovation)**.** *Consider the region of parameters in which assumptions A1-A3 hold. A collateral squeeze (reduction of η) reduces the asset price, total investment, and the measure of firms with access to credit. Moreover,*

(i) If (5) *holds, the collateral squeeze reduces the measure of innovative firms; if* (5) *does not hold, it increases the measure of innovative firms.*

(ii) If (5) *holds, the collateral squeeze reduces output; if* (5) *does not hold, it reduces output if and only if*

$$\frac{\partial C}{\partial \eta}\left(\pi y - i\right) + \pi \frac{\partial \left(C \int_{\frac{p^*}{\eta}}^{\bar{\theta}} \frac{\eta \theta}{\bar{\theta}} d\theta \right)}{\partial \eta} > - \frac{\partial N}{\partial \eta} \pi (1 - \sigma^A) n y. \tag{6}$$

The drop in the productivity η of assets induces a fall of the asset price because the demand for liquidated assets shrinks. The measure of firms with access to credit falls with the asset price. In particular, the firms that were "marginal" in the credit market (with collateral in the neighborhood of $\underline{a}^{IA}(p^*)$) are denied credit because they can no longer pledge enough expected returns to a lender. These firms drop out of the credit market and their investment is lost. Their exclusion from the credit market further reduces the net asset demand and feeds back on the asset price. This effect is similar to that in Holmstrom and Tirole (1997).

The new prediction regards collateral-rich firms in the scenario in which lenders' technological inertia arises (case (ii) in Proposition 1). Since the threshold $\overline{a}(p^*)$ above which collateral-rich firms face lenders' technological inertia is negatively related to the asset price, the collateral squeeze induces firms in the neighborhood of $\overline{a}(p^*)$ to potentially innovate. The assumption of a uniform distribution of collateral values implies that the measure of additional collateral-rich firms that potentially innovate outweighs the measure of firms that drop out of the credit market, so the total measure of innovative firms increases. Of course, with a generic distribution, whether the total measure of innovative firms increases or decreases depends on the relative size of these two groups of firms. However, the message of the paper is that in a credit crunch there can be a positive effect on innovation that contrasts with the traditional effect due to tight credit. Notably, in general equilibrium the exclusion of some firms from the credit market is beneficial for the innovation of collateral-rich firms. In fact, when some firms become inactive, the net asset demand drops. This further depresses the asset price, and, given the negative relationship between $\overline{a}(p^*)$ and p^*, it fosters the innovation of collateral-rich firms. This will be crucial for evaluating the impact of policies that sustain the access of collateral-poor firms to credit.

Turning to the effect on output, in the scenario with lenders' technological inertia this effect reflects the competition between two opposite forces: the investment drop due to the exclusion of some firms from the credit market and the increase of innovation of collateral-rich firms.

6 Credit Policies

During the recent financial crisis, central banks and governments (including the Federal Reserve and the U.S. Treasury as well as the ECB and various European governments) engaged in two unconventional credit policies. First, they intervened in asset markets to sustain asset prices – for instance, by purchasing mortgage-backed securities. Second, they directly granted loans to firms and non-bank financial institutions to finance asset holdings at margin requirements lower than those of financial institutions. We are going to see that a consequence of these policies could be that while, as intended, they boost investment, they also tend to freeze the stimulus to innovation triggered by a credit crunch.

Before proceeding, it is useful to compare the decentralized equilibrium with the allocation that would be chosen by a social planner. Lemma 7 shows that in the decentralized equilibrium the measures of active firms and of innovative firms are suboptimally low.

Lemma 7 (Social optimum)**.** *A social planner would choose an allocation in which more entrepreneurs obtain credit than in the decentralized equilibrium. All funded entrepreneurs would choose innovative plans.*

In the social planner's problem, a positive measure of firms with $a < \underline{a}^{IA}(p^*)$ would invest. However, it is not necessarily the case that the planner would want all entrepreneurs to invest, because entrepreneurs with a low value a provide few assets for other entrepreneurs to reuse and produce output. Therefore, they may have a negative social value.

We can think of the asset market policy as consisting of the government subsidizing asset purchases on date 3. Precisely, we posit that the government makes a transfer τ of final good to each entrepreneur who purchases one unit of liquidated assets. The government can finance these subsidies by levying non-distortionary (lump-sum) taxes. For example, on date 3 it may tax investors' revenues, regardless of whether these originate from storage, from loan repayment or from asset liquidation; alternatively, it may tax the output of collateral-rich entrepreneurs without distorting agents' decisions. Since the subsidy affects the asset demand and the equilibrium asset price (see the Appendix), assumption A3 needs to be rewritten as

$$\text{A3}(\tau) : \eta\bar{\theta}\left(\pi - \frac{1}{2}\right) > \frac{\pi}{2}\left[\frac{\zeta\left[i - \pi l y\left(1 + n - \sigma^A n\right)\right]}{\left(\sigma^A\right)^2\left(1-\pi\right)^2\lambda(1-\lambda)} - \tau\right].$$

Note that A3 implies A3(τ) for any positive τ. Proposition 3 illustrates the effects of the asset market policy. Again, we contrast the scenario in which lenders' technological inertia arises for collateral-rich firms (case (ii)) with the scenario in which lenders' inertia does not arise (case (i)).

Proposition 3 (Asset market policy)**.** *Consider the region of parameters in which assumptions A1, A2, and A3(τ) hold. An increase of the transfer τ boosts the asset price and total investment. Moreover,*

(i) If

$$\eta\bar{\theta} \leq \left[\frac{\zeta[\pi l y(1+n) - i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)} - \tau\right]\left[\frac{3\pi - 1}{2\pi} - \frac{(1-\pi)\sigma^{\bar{A}}}{2\pi\sigma^A}\frac{i - \pi l y\left(1 + n - \sigma^A n\right)}{\pi l y(1+n) - i}\right]^{-1}, \quad (7)$$

an increase of the transfer raises the measure of innovative firms and output;

(ii) If (7) *does not hold, an increase of the transfer reduces the measure of innovative firms. The increase in transfer increases output if*

$$\frac{\partial C}{\partial \tau}\left(\pi y - i\right) + \pi\frac{\partial\left(C\int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}}\frac{\eta\theta}{\bar{\theta}}d\theta\right)}{\partial\tau} > -\frac{\partial N}{\partial \tau}\pi(1-\sigma^A)ny.$$

The second policy consists of the government directly lending to firms at margin requirements lower than private lenders. We assume that the government grants credit to firms with

$a \in \left[a_G, \underline{a}^{IA}(p)\right]$, where the policy tool is now the a_G threshold. Similar to the first policy, the government finances any loss by levying lump-sum taxes. As above, assumption A3 needs to be rewritten to account for the new price level:

$$\text{A3}(a_G) : \eta\overline{\theta}\left(\pi - \frac{1}{2}\right) > \frac{\zeta\left[i - \pi l y\left(1 + n - \sigma^A n\right)\right]}{\left(\sigma^A\right)^2(1-\pi)^2\lambda(1-\lambda)}\frac{(2\pi-1)\pi}{3\pi - 1 - (1-\pi)a_G}. \tag{8}$$

Note that A3 implies A3(a_G) for any $a_G < 1$. Proposition 4 studies the effects of direct lending.

Proposition 4 (Direct lending)**.** *Consider the region of parameters in which assumptions A1, A2, and A3(a_G) hold. A decrease of a_G boosts the asset price and total investment. Moreover,*

(i) If

$$\eta\overline{\theta} \leq \frac{\zeta\left[\pi l y(1+n) - i\right]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)}\frac{2\pi}{3\pi - 1 - (1-\pi)a_G}, \tag{9}$$

a decrease of a_G raises the measure of innovative firms and increases output;

(ii) If (9) does not hold, a decrease of a_G increases the measure of innovative firms and output if

$$\eta\overline{\theta} \geq \frac{\zeta[\pi l y(1+n) - i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)}\frac{2\pi(1-\pi)}{\left[3\pi - 1 - (1-\pi)\underline{a}_G\right]^2}.$$

Otherwise, a decrease of a_G reduces the measure of innovative firms; it increases output if

$$\frac{\partial C}{\partial \underline{a}_G}(\pi y - i) + \pi\frac{\partial\left(C\int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}}\frac{\eta\theta}{\bar{\theta}}d\theta\right)}{\partial \underline{a}_G} < -\frac{\partial N}{\partial \underline{a}_G}\pi(1-\sigma^A)ny.$$

The policy of subsidies boosts the asset price, easing the access of collateral-poor firms to credit. However, a higher asset price reduces the collateral threshold above which lenders hinder innovation. Similarly, the direct lending policy promotes the access of collateral-poor firms to credit but, since in general equilibrium this increases the asset demand and the asset price, it reduces the collateral threshold above which lenders hinder innovation. However, unlike in the case of subsidies, the policy directly promotes the access of collateral-poor firms to credit while it exerts an upward pressure on the asset price indirectly. Thus, its chilling effect on innovation is only a possibility, that is, the direct lending policy is more innovation-friendly than the policy of subsidies.

7 Extensions

In what follows, we extend the baseline model to richer structures of the credit and corporate sectors. Our goal is to understand what structures of the credit and corporate sectors are more conducive to the mechanisms investigated in the baseline model and, hence, under what structures credit crunches are more likely to depress or stimulate firms' innovation. In the credit sector, we introduce credit relationships. A growing strand of literature finds beneficial effects of credit relationships during credit crunches (see, e.g., Beck, Degryse, De Haas and van Horen, 2017). Thus, it is natural to examine how credit relationships would affect the collateral channel of innovation isolated in the model. In the corporate sector, we consider managerial firms and examine a form of managers' technological inertia and its interaction with lenders' inertia.

7.1 Credit relationships

Entrepreneurs can establish information-intensive credit relationships with lenders or seek transactional loans with little information content (Berger and Udell, 2002).[15] We now account for this and show that the innovation of collateral-rich firms following a collateral squeeze can entail their switch from relationship to transactional funding. In turn, this may involve an output cost.

In this extension, we posit that there is a date 0 when each entrepreneur chooses whether to establish an information-intensive relationship with his financier on date 1 or seek a transactional loan. Under relationship finance the asset liquidation value achieved for a given collateral maintenance cost is higher, capturing the idea that a relationship lender can acquire better information about the collateral and its market and also help avoid collateral asset depreciation (Diamond and Rajan, 2001). This will enhance the asset liquidation value. Formally, we let the cost for collateral maintenance be lower when an entrepreneur chooses to have a relationship lender ($\zeta = \zeta^R$) than when he chooses to have a a transactional lender ($\zeta = \zeta^T$). Therefore, we now also need to solve for an entrepreneur's funding choice $\zeta \in \{\zeta^R, \zeta^T\}$. The trade-off is immediate. A relationship lender allows to achieve a higher liquidation value of mature assets. Thus, she can offer cheaper financing and also grant credit to entrepreneurs that would not be funded by a transactional lender ($\underline{a}^{IAR}(p) < \underline{a}^{IAT}(p)$). However, a transactional lender is more willing to facilitate innovation because, extracting less value from mature assets, she loses less collateral value in case of adoption of the new technology ($\overline{a}^T(p) > \overline{a}^R(p)$).

Throughout, we maintain the assumptions of the baseline model, with the caveat that they hold for $\zeta \in \{\zeta^R, \zeta^T\}$. The analysis for extreme collateral values is trivial. Collateral-poor firms with $a < \underline{a}^{IAR}(p)$ cannot obtain credit, even if they choose relationship funding. Collateral-rich firms with $a > \overline{a}^T(p)$ cannot innovate, even if they choose transactional funding. Since relationship funding is cheaper, they choose $\zeta = \zeta^R$. The non-trivial case occurs for firms with intermediate collateral ($a \in [\underline{a}^{IAR}(p), \overline{a}^T(p)]$). For those among them with $a \in \left[\underline{a}^{IAR}(p), \overline{a}^R(p)\right]$ relationship funding is innovation-friendly and cheaper. Firms with $a \in \left(\overline{a}^R(p), \overline{a}^T(p)\right]$ face instead a non-trivial choice: transactional funding facilitates innovation but it is more expensive. Specifically, there are two possible cases. In the first case, $\underline{a}^{IAT}(p) > \overline{a}^R(p)$ so some firms with $a \in \left(\overline{a}^R(p), \overline{a}^T(p)\right]$ cannot obtain credit if they want to innovate under transactional funding. We examine this possibility in Supplement B (available from the authors). In the second case, $\underline{a}^{IAT}(p) \leq \overline{a}^R(p)$ so all firms with $a \in \left(\overline{a}^R(p), \overline{a}^T(p)\right]$ can obtain credit if they choose to innovate under transactional funding. Here, we restrict attention to this case by assuming

$$\text{A4}: \frac{i}{\pi l y} \leq 1 + \left[\frac{1}{1+\sigma^A} - \frac{\left(\sigma^{\bar{A}}\zeta^T - \zeta^R\right)\left(\sigma^A\right)^2}{\left(\sigma^{\bar{A}}\zeta^T + \sigma^A\zeta^R\right)\left(1+\sigma^A\right)}\right] n.$$

Note that A4 implies A1 if and only if $\sigma^{\bar{A}} \geq \zeta^T/\zeta^R$. Figure 3 illustrates the distribution of firms. Lemma 8 solves for an entrepreneur's funding choice. For expositional simplicity, we focus here on the interesting scenario in which a positive measure of collateral-rich firms do not innovate under relationship funding, i.e., $\overline{a}^R(p) < 1$ ((5) evaluated at $\zeta = \zeta^R$ does not hold).

Lemma 8 (Funding choice)**.** *An entrepreneur chooses transactional funding if and only if* $a \in \left(\overline{a}^R(p), \overline{a}^T(p)\right]$ *and* $a \leq \frac{2\zeta^R\zeta^T(1-\sigma^A)\pi n y}{(1-\pi)^2(1-\lambda^2)\left[\zeta^T - \zeta^R(\sigma^A)^2\right]p} \equiv \widehat{a}(p)$.

Lemma 8 identifies two credit regimes. In the first, which arises when $\widehat{a}(p) \leq \overline{a}^R(p)$, no entrepreneur chooses transactional funding. We label it "relationship finance" regime. This arises

[15] For evidence, see, e.g., Guiso and Minetti (2010).

when relationship lenders hinder only the innovation of firms with very large collateral or when relationship funding is much cheaper. In the second regime, which arises when $\widehat{a}(p) > \overline{a}^R(p)$, entrepreneurs with intermediate collateral avoid the technological inertia of relationship lenders by choosing transactional funding. We label it "mixed finance" regime. This arises when relationship lenders are very inclined to technological inertia or when their cost advantage is small. In both regimes, collateral-rich firms form credit relationships in which they retain the mature technology.

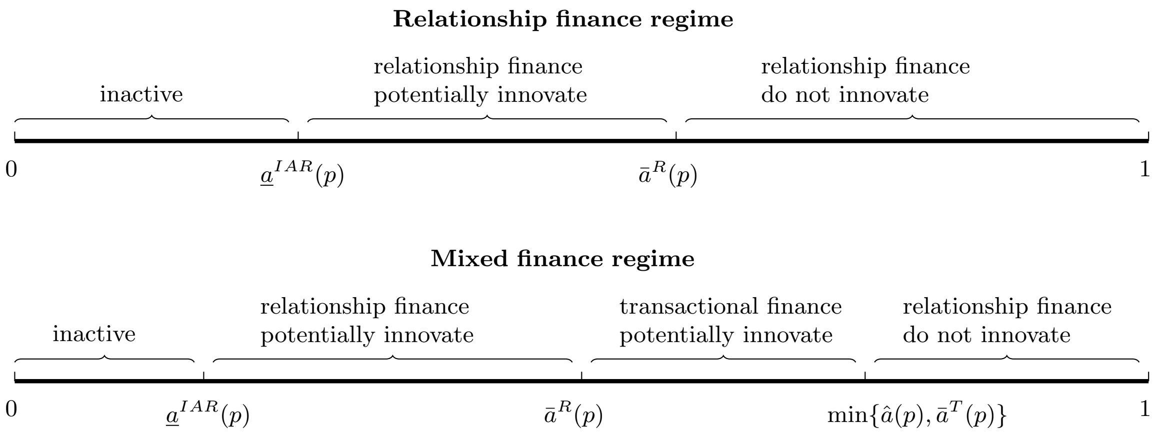

Figure 3: Credit regimes

Lemma 9 characterizes the regions of parameters in which the two regimes arise.

Lemma 9 (Credit regimes)**.** *Credit regimes are characterized by two thresholds*

$$\underline{l} = \frac{2\lambda\left(1-\sigma^A\right)\sigma^{\bar{A}}\zeta^T}{(1+\lambda)\left[\zeta^T - \zeta^R\left(\sigma^A\right)^2\right]},$$

$$\bar{l} = \min\left\{\frac{2\lambda\left[1-\left(\sigma^A\right)^2\right]\sigma^{\bar{A}}\zeta^T}{(1+\lambda)\left[\zeta^T - \zeta^R\left(\sigma^A\right)^2\right]}, \frac{2\lambda\left(1-\sigma^A\right)\left(\sigma^{\bar{A}}\zeta^T + \sigma^A\zeta^R\right)}{(1+\lambda)\left[\zeta^T - \zeta^R\left(\sigma^A\right)^2\right]}\right\}.$$

If $l \leq \underline{l}$ mixed finance is the only regime; if $l \geq \bar{l}$, relationship finance is the only regime. If $l \in \left(\underline{l}, \bar{l}\right)$, the relationship finance regime occurs if $\frac{i}{\pi l y} \leq 1 + n - \frac{\sigma^A n \underline{l}}{l}$, and the mixed regime occurs otherwise.

Proposition 5 describes the distribution of firms in the two credit regimes. The proof is immediate given Lemmas 8 and 9.

Proposition 5 (Firm distribution)**.** *In the region of parameters consistent with the relationship regime, firm distribution is as in the baseline model (Proposition 1), with $\zeta = \zeta^R$. In the region consistent with the mixed regime, firms (i) have no access to credit iff $a < \underline{a}^{IAR}(p)$, (ii) choose relationship funding and potentially innovate iff $a \in \left[\underline{a}^{IAR}(p), \overline{a}^R(p)\right]$, (iii) choose transactional funding and potentially innovate iff $a \in (\overline{a}^R(p), \min\left\{\widehat{a}(p), \overline{a}^T(p)\right\}]$, (iv) choose relationship funding and do not innovate iff $a > \min\left\{\widehat{a}(p), \overline{a}^T(p)\right\}$.*

We now study the effects of a collateral squeeze.

Proposition 6 (Collateral squeeze, credit regimes, and innovation)**.** *In both credit regimes, a collateral squeeze (reduction of η) reduces the asset price, total investment, and the measure of firms with access to credit while it increases the measure of innovative firms and has an ambiguous effect on output. In the mixed regime, it induces firms with collateral in the neighborhood of* $\min\left\{\widehat{a}(p^*), \overline{a}^T(p^*)\right\}$ *to innovate by switching from relationship to transactional funding.*

In the relationship finance regime, collateral-rich firms innovate within their credit relationships. In the mixed regime, instead, since $\min\left\{\widehat{a}(p^*), \overline{a}^T(p^*)\right\}$ is negatively related to the asset price, after the drop in η collateral-rich firms innovate by switching to transactional funding. This can have implications for output. In fact, since the recovery value of collateral assets is higher within credit relationships, the switch to transactional funding increases liquidation costs. If these costs are assumed to be at least partially a real resource loss, this adds to the effects on output of the investment decline and of the increase in innovation.

Discussion. One may argue that some types of lenders, though at a disadvantage in liquidating collateral assets (like the transactional lenders in the above extension), have the ability to boost the success probability of innovations. This might be the case for venture capitalists, which allegedly have less experience on mature, established technologies but have also special expertise in acquiring information about new technologies and asset vintages. Although, as noted, our model does not focus on venture capital finance, we could capture this scenario by assuming that for transactional lenders $\zeta^T > \zeta^R$ and $\sigma^{AT} < \sigma^{AR}$.[16] The analysis and results are similar to the case with only $\zeta^T > \zeta^R$. Higher probability of innovation further reduces entrepreneurs' collateral maintenance when they borrow from transactional lenders, as collateral assets are less likely to be useful. The rankings $\underline{a}^{IAR}(p) < \underline{a}^{IAT}(p)$ and $\bar{a}^R(p) < \bar{a}^T(p)$ are further reinforced. Therefore, under an assumption similar to A4, we again obtain the rankings of thresholds $\underline{a}^{IAR}(p) < \underline{a}^{IAT}(p) < \bar{a}^R(p) < \bar{a}^T(p)$.

The entrepreneurs make decisions on which lender to borrow from and whether to adopt an innovative plan. Again, collateral-poor firms with $a < \underline{a}^{IAR}(p)$ cannot obtain credit, even if they choose relationship funding; collateral-rich firms with $a > \overline{a}^T(p)$ cannot innovate, even if they choose transactional funding. Since relationship funding is cheaper, they choose to borrow from relationship lenders. Firms with $a \in \left(\underline{a}^{IAR}(p), \underline{a}^{IAT}(p)\right)$ can only borrow from relationship lenders and innovate. Firms with $a \in \left[\underline{a}^{IAT}(p), \bar{a}^R(p)\right]$ can borrow from both types of lenders and innovate. The trade-off is that relationship lenders induce lower innovation probability but also lower maintenance costs of mature assets. Assuming the advantage of lower maintenance cost dominates, firms with $a \in \left[\underline{a}^{IAT}(p), \bar{a}^R(p)\right]$ would all choose relationship lenders. Firms with $a \in \left(\bar{a}^R(p), \bar{a}^T(p)\right)]$ face the choice between transactional lenders that facilitate innovation versus relationship lenders that hinder innovation. Similar as in Lemma 8, either the mixed finance regime or the relationship finance regime could occur.

7.2 Managerial firms

In the baseline model, we have considered entrepreneurial firms. In this section, we extend the baseline model to managerial firms and investigate the interaction between lenders' inertia and a form of technological inertia inside borrowing firms. The source of borrowers' inertia is the higher risk of failure that the new technology can entail relative to the mature technology.

We model technological inertia inside borrowing firms building on the extant literature on agency conflicts in managerial firms (see, e.g., Jensen and Meckling, 1976, for a discussion). We now posit that the economy is also populated by a continuum of managers of measure larger than

[16] We assume that $\sigma^{\bar{A}T} = \sigma^{\bar{A}R} = \sigma^{\bar{A}}$, so the probability of innovation is the same when lenders do not take actions.

one. Managers have no endowment and have the same utility as entrepreneurs and investors. In a firm the implementation of a project now requires a manager, who faces an effort (or an opportunity) cost e for working for the firm. On date 2, the manager can carry out a non-verifiable costless action that facilitates innovation: if the manager and the lender both take actions, then the probability of innovation increases from $1-\sigma^{\bar{A}}$ to $1-\sigma^{A}$. To highlight managers' aversion to innovation due to higher riskiness of the new technology, we now let the success probability π_n of the new technology be lower than the success probability π of the mature one (though, consistent with the baseline model, $\pi_n y(1+n) > \pi y$).

A manager's compensation package comprises a wage w if the project succeeds and the firm remains in business, plus a possible bonus w_n in the event the new technology is successfully adopted. In case of project failure, the manager loses his job and obtains zero. With a flat compensation (i.e., $w > 0$, $w_n = 0$), the manager would prefer retaining the mature technology with its higher success probability in order to minimize the risk of losing his job. To prevent this, the entrepreneur needs to pledge part of the higher output of the new technology as a bonus ($w_n > 0$) to the manager. Assuming that he breaks a tie in favor of innovation, the incentive constraint under which the manager prefers facilitating the new technology reads

$$(1-\sigma^{A})\pi_n(w+w_n)+\sigma^{A}\pi w \geq (1-\sigma^{\bar{A}})\pi_n(w+w_n)+\sigma^{\bar{A}}\pi w, \tag{10}$$

or, rearranging,

$$w_n \geq \frac{(\pi-\pi_n)}{\pi_n}w. \tag{11}$$

The manager's bonus reduces the output pledgeable to the lender in case of successful adoption of the new technology. Thus, the entrepreneur now faces a tension between the need to incentivize the lender and the need to incentivize the manager. Lemma 10 solves for the collateral threshold below which a firm has no access to credit and the threshold above which a firm does not innovate. The lemma compares these thresholds with those in the absence of managers' moral hazard (for example, if managers worked for firms but did not affect innovation).

Lemma 10 (Managers' and lenders' inertia)**.** *There exists a feasible contract that induces both a lender and a manager to facilitate innovation if and only if the entrepreneur's collateral assets satisfy* $a \in \left[\underline{a}'^{IA}(p), \overline{a}'(p)\right]$, *where*

$$\underline{a}'^{IA}(p) = \frac{\zeta[i+e-(1-\sigma^{A})\pi_n l(1+n)y-\sigma^{A}\pi l y]}{(\sigma^{A})^2(1-\pi)^2\lambda(1-\lambda)p},$$

$$\bar{a}'(p) = \frac{\zeta[\pi_n l y(1+n)-e-i]}{\sigma^{A}\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)p}.$$

Absent managers' moral hazard, the threshold above which firms do not innovate would equal

$$\overline{a}''(p) \equiv \frac{\zeta[\pi_n l y(1+n)-\frac{\pi_n e}{(1-\sigma^{A})\pi_n+\sigma^{A}\pi}-i]}{\sigma^{A}\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)p} > \overline{a}'(p), \tag{12}$$

while the threshold below which firms do not obtain credit would equal $\underline{a}''^{IA}(p) = \underline{a}'^{IA}(p)$.

Henceforth, we maintain assumptions analogous to A1-A3 to guarantee that in this extended environment a positive measure of firms (but not all firms) obtain credit ($0 < \underline{a}'^{IA}(p) < 1$) and that a positive measure of funded firms potentially innovate ($\underline{a}'^{IA}(p) < \overline{a}'(p)$).

Lemma 10 shows that, for a given asset price, the region of collateral values in which technological inertia arises is now larger ($\overline{a}'(p) < \overline{a}''(p)$). In particular, an entrepreneur with $a > \overline{a}'(p)$ cannot simultaneously satisfy the lender's and the manager's incentive constraints, so that either the lender or the manager do not have the incentive to facilitate the innovation. To complete the analysis, however, we need to account for the general equilibrium effects through the asset price.

Proposition 7 (Firms' innovation)**.** *The measure of innovative firms is lower in the presence of managers' moral hazard than in its absence.*

As shown in Lemma 10, in this extended environment in which both lenders and managers can engage in technological inertia the measure of innovative firms tends to be lower. Since the new technology succeeds with a lower probability ($\pi_n < \pi$), this implies that a larger measure of firms remain in business and a smaller measure of firms fail. The resulting higher net demand for liquidated assets induces a higher asset price, further exacerbating technological inertia (remember that $\overline{a}'(p)$ is negatively related to p). Thus, there is both a direct negative effect and an indirect, general equilibrium negative effect (through asset prices) on the measure of innovative firms.

It is immediate that the results on the effects of a collateral squeeze (drop in η) carry through to this extended environment. Moreover, a given drop in the asset price boosts the measure of innovative firms more than in the baseline model (see the proof of Proposition 7).

8 Conclusion

This paper has studied a credit crunch triggered by a drop in collateral values in an economy where firms can adopt new technologies or retain less productive technologies. In our economy, lenders hinder the innovation of collateral-rich firms to preserve the value of their information on mature technologies. By depressing the price of collateral assets, a negative collateral shock squeezes collateral-poor firms out of the credit market but fosters the innovation of collateral-rich firms. The analysis reveals that credit and asset market policies such as those implemented during the recent credit crisis promote investment but may slow down innovation.

The paper leaves important questions open for future research. First, while the model can help disentangle the effects of a credit crunch on technological change, it cannot offer predictions on their magnitude. A priority is to cast the analysis into a dynamic general equilibrium environment and study the quantitative relevance of the effects. Second, in our economy, following negative collateral shocks collateral-poor firms lose access to credit while collateral-rich firms switch to more productive technologies. Interestingly, this is reminiscent of the finding of Bloom, Floetotto, Jaimovich, Saporta-Eksten and Terry (2012) that during recessions the cross-sectional dispersion of output increases. An objective for future research is to dig deeper into the cross-sectional effects of a credit crunch.

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Appendix

Data Appendix

The data collection for EFIGE was performed through a survey carried out by a professional contractor, with the aim of gathering both qualitative and quantitative information at the firm level. The questionnaire submitted to the firms covers six areas: firm ownership structure; workforce characteristics (skills, type of contracts, domestic vs. migrant workers, training); investment, technological innovation, R&D (and related financing); export and internationalization processes; market structure and competition; financial structure and bank-firm relationships. To ensure statistical representativeness of the collected data, the data set was built so as to fulfill two main criteria. First, the availability of an adequately large target sample of firms, initially set at around 3,000 firms for large countries (France, Germany, Italy, Spain and the UK), and about 500 firms for smaller countries (Austria and Hungary). Second, a proper stratification of the sample in order to ensure representativeness of the collected data ex ante and ex post for each country, considering in particular three dimensions: sector composition, regions and size classes.

As explained in the main text, the EFIGE survey provides information on innovation activities and on the impact of the financial crisis on such activities. In particular, for measuring innovation activities, we use and combine information from three questions: 1) During 2009, has your firm decided to postpone investments in innovation? (Yes/No); 2) Always referring to the last year (2009), the range of products that your firm has decided to offer has (relative to past years): (a) Been widened; (b) Remained the same; (c) Been reduced; 3) On average in the last three years (2007-2009), did the firm carry out product innovation, that is, introduction of a good which is either new or significantly improved with respect to its fundamental characteristics (the innovation should be new to the market)? (Yes/No);

Starting from these questions, we construct two variables: the first "Non-marginal Innovation" that is a dummy variable equal to one if the firm answers affirmatively to question 3), zero otherwise. The second "Accelerate Non-marginal Innovation" that is a dummy variable equal to one if the firm answers No to question 1), a) to question 2) and Yes to question 3), zero otherwise.

Data on fixed and total assets are drawn from firms' balance sheet information (obtained from the BvD-Amadeus database).

Further, in a question of the survey, firms are requested to specify the type of information they normally provide to their main bank in the screening and monitoring process. The question reads out as follows:

Which type of information does the bank normally use/ask to assess your firm's creditworthiness? (a) collateral (0/1); (b) balance sheet information (0/1); (c) interviews with management on firm's policy and prospects (0/1); (d) business plan and firms' targets (0/1); (e) historical records of payments and debt service (0/1); (f) brand recognition (0/1); (g) other (0/1).

Starting from this categorization, following Berger and Udell (2006), we build a dummy variable "Emphasis on Collateral" that equals 1 if the firm answers yes to a), and zero otherwise.

Relationship length is defined as the number of years the firm has been doing business with its main bank. The variable "Bank Involvement in Investments Finance" is based on a question in the survey asking the firms the percentage of investments that was financed with bank credit. We construct a dummy that equals 1 if this percentage is higher than the sample median, and zero otherwise.

Labor productivity of a firm is measured as value added per worker.

Proof of Lemma 1

If an entrepreneur adopts the innovative plan, and the lender exerts action, the entrepreneur chooses maintenance effort to maximize:

$$\max_{\mu^{IA}} \quad (1-\pi)(1-\lambda)\sigma^A \mu^{IA} pa - \frac{\zeta \left(\mu^{IA}\right)^2}{2} pa.$$

From the first order condition, we solve for $\mu^{IA} = \frac{(1-\pi)(1-\lambda)\sigma^A}{\zeta}$.

If an entrepreneur adopts the innovative plan, while the lender chooses inaction, the entrepreneur chooses maintenance effort to maximize:

$$\max_{\mu^{I\bar{A}}} \quad (1-\pi)(1-\lambda)\sigma^{\bar{A}} \mu^{I\bar{A}} pa - \frac{\zeta \left(\mu^{I\bar{A}}\right)^2}{2} pa.$$

Therefore, $\mu^{I\bar{A}} = \frac{(1-\pi)(1-\lambda)\sigma^{\bar{A}}}{\zeta}$.

If an entrepreneur does not adopt an innovative plan, the entrepreneur solves the problem:

$$\max_{\mu^{\bar{I}}} \quad (1-\pi)(1-\lambda)\mu^{\bar{I}} pa - \frac{\zeta \left(\mu^{\bar{I}}\right)^2}{2} pa.$$

Therefore, $\mu^{\bar{I}} = \frac{(1-\pi)(1-\lambda)}{\zeta}$.

Proof of Lemma 2

The incentive compatibility constraint for the lender is

$$(1-\sigma^A)\pi r_n^I + \sigma^A \left[\pi r_m^I + \lambda(1-\pi)\mu^{IA} pa\right] \geq (1-\sigma^{\bar{A}})\pi r_n^I + \sigma^{\bar{A}} \left[\pi r_m^I + \lambda(1-\pi)\mu^{I\bar{A}} pa\right], \tag{13}$$

which implies equation (1). The participation constraint for the lender is

$$(1-\sigma^A)\pi r_n^I + \sigma^A \left[\pi r_m^I + \lambda(1-\pi)\mu^{IA} pa\right] \geq i. \tag{14}$$

Due to limited commitment, the lender can at most pledge l fraction of output. Therefore,

$$r_n^I \leq ly(1+n), \quad \text{and} \quad r_m^I \leq ly.$$

As shown in Figure 4, for the existence of a feasible contract, the point $(r_m^I, r_n^I) = (ly, ly(1+n))$ must lie in the shaded area. Therefore, $(ly, ly(1+n))$ must satisfy two conditions: (i) it must lie above the PC, i.e.,

$$(1-\sigma^A)\pi ly(1+n) + \sigma^A \left[\pi ly + \lambda(1-\pi)\mu^{IA} pa\right] \geq i,$$

from which we can solve for

$$a \geq \frac{\zeta[i - \pi ly(1+n-\sigma^A n)]}{(\sigma^A)^2(1-\pi)^2\lambda(1-\lambda)p} \equiv \underline{a}^{IA}(p);$$

(ii) it is above the intersection of IC and PC, i.e.,

$$\frac{i}{\pi} + \frac{\sigma^A \sigma^{\bar{A}} (1-\pi)^2 \lambda (1-\lambda) pa}{\pi \zeta} \leq ly(1+n),$$

from which we can solve for

$$a \leq \frac{\zeta[\pi ly(1+n) - i]}{\sigma^A \sigma^{\bar{A}} (1-\pi)^2 \lambda(1-\lambda) p} \equiv \bar{a}(p).$$

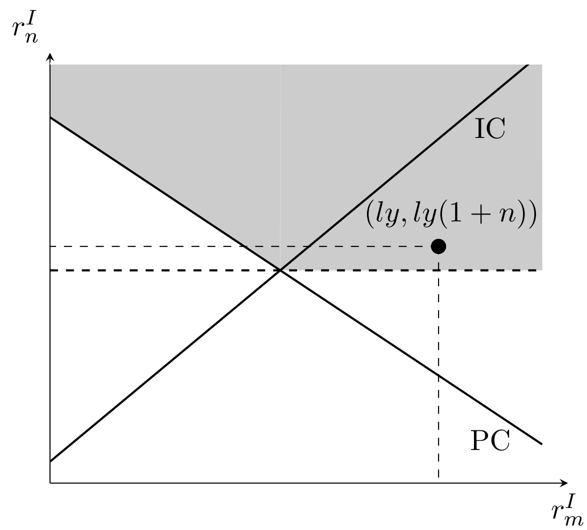

Figure 4: IC and PC of the lender

Proof of Lemma 3

If an entrepreneur adopts an innovative plan but the lender hinders innovation, the lender's participation constraint is

$$(1-\sigma^{\bar{A}})\pi r_n^I + \sigma^{\bar{A}} \left[\pi r_m^I + \lambda(1-\pi)\mu^{I\bar{A}} pa\right] \geq i. \tag{15}$$

Using the fact that $r_n^I \leq ly(1+n)$, and $r_m^I \leq ly$, we can derive $\underline{a}^{I\bar{A}}(p)$ in Lemma 3.

If an entrepreneur does not adopt an innovative plan, the lender's participation constraint is

$$\pi r_m^{\bar{I}} + \lambda(1-\pi)\mu^{\bar{I}} pa \geq i. \tag{16}$$

Using the fact that $r_m^I \leq ly$, we can derive $\underline{a}^{\bar{I}}(p)$ in Lemma 3.

Proof of Lemma 4

To show that $\underline{a}^{IA}(p) < \bar{a}(p)$,

$$\frac{\bar{a}(p)}{\underline{a}^{IA}(p)} > 1 \Leftrightarrow \frac{\sigma^A[\pi ly(1+n) - i]}{\sigma^{\bar{A}}[i - \pi ly(1+n-\sigma^A n)]} > 1 \Leftrightarrow \frac{i}{\pi ly} < 1 + n - \frac{\sigma^A \sigma^{\bar{A}} n}{\sigma^A + \sigma^{\bar{A}}}.$$

The last inequality holds under assumption A1, as $\frac{1}{1+\sigma^A} < 1 - \frac{\sigma^A \sigma^{\bar{A}}}{\sigma^A + \sigma^{\bar{A}}}$, when $\sigma^A, \sigma^{\bar{A}} \in (0,1)$.

To show that $\underline{a}^{IA}(p) < \underline{a}^{I\bar{A}}(p) < \bar{a}(p)$,

$$\frac{\underline{a}^{I\bar{A}}(p)}{\underline{a}^{IA}(p)} > 1 \Leftrightarrow \frac{(\sigma^A)^2[i - \pi ly(1+n-\sigma^{\bar{A}}n)]}{(\sigma^{\bar{A}})^2[i - \pi ly(1+n-\sigma^A n)]} > 1 \Leftrightarrow \frac{i}{\pi ly} < 1 + n - \frac{\sigma^A \sigma^{\bar{A}} n}{\sigma^A + \sigma^{\bar{A}}},$$

and

$$\frac{\bar{a}(p)}{\underline{a}^{I\bar{A}}(p)} > 1 \Leftrightarrow \frac{\sigma^{\bar{A}}[\pi ly(1+n) - i]}{\sigma^A[i - \pi ly(1+n-\sigma^{\bar{A}}n)]} > 1 \Leftrightarrow \frac{i}{\pi ly} < 1 + n - \frac{\sigma^A \sigma^{\bar{A}} n}{\sigma^A + \sigma^{\bar{A}}}.$$

Both inequalities hold under assumption A1, as $\frac{1}{1+\sigma^A} < 1 - \frac{\sigma^A \sigma^{\bar{A}}}{\sigma^A + \sigma^{\bar{A}}}$, when $\sigma^A, \sigma^{\bar{A}} \in (0,1)$.

To prove that $\underline{a}^{\bar{I}}(p) > \underline{a}^{IA}(p)$ and $\underline{a}^{\bar{I}}(p) < \bar{a}(p)$,

$$\frac{\underline{a}^{\bar{I}}(p)}{\underline{a}^{IA}(p)} > 1 \Leftrightarrow \frac{(\sigma^A)^2\,(i - \pi ly)}{i - \pi ly(1+n-\sigma^A n)} > 1 \Leftrightarrow \frac{i}{\pi ly} < 1 + \frac{n}{1+\sigma^A}.$$

and

$$\frac{\bar{a}(p)}{\underline{a}^{\bar{I}}(p)} > 1 \Leftrightarrow \frac{\pi ly(1+n) - i}{\sigma^A \sigma^{\bar{A}}\,(i - \pi ly)} > 1 \Leftrightarrow \frac{i}{\pi ly} < 1 + \frac{n}{1+\sigma^A \sigma^{\bar{A}}}.$$

The last inequality holds under assumption A1, as $\frac{1}{1+\sigma^A} < \frac{1}{1+\sigma^A\sigma^{\bar{A}}}$, when $\sigma^{\bar{A}} \in (0,1)$.

To prove the last part of the lemma,

$$\underline{a}^{IA}(p) > 0 \Leftrightarrow \frac{\zeta[i - \pi ly(1+n-\sigma^A n)]}{(\sigma^A)^2(1-\pi)^2\lambda(1-\lambda)p} > 0 \Leftrightarrow \frac{i}{\pi ly} > 1 + n - \sigma^A n.$$

Proof of Lemma 5

Firms with $a \in \left[\underline{a}^{IA}(p), \underline{a}^{\bar{I}}(p)\right)$ have no option but to innovate in order to obtain credit. For a firm with $a \in \left[\underline{a}^{\bar{I}}(p), \bar{a}(p)\right]$, if it chooses an innovative plan, the lender will facilitate innovation. Such a firm chooses an innovative plan if and only if

$$\begin{aligned}&(1-\sigma^A)\pi\left[(1+n)y - r_n^I\right] + \sigma^A\left[\pi\left(y - r_m^I\right) + (1-\pi)\,(1-\lambda)\mu^{IA}pa\right] - \frac{\zeta\left(\mu^{IA}\right)^2}{2}pa \\ \geq &\pi\left(y - r_m^{\bar{I}}\right) + (1-\pi)(1-\lambda)\mu^{\bar{I}}pa - \frac{\zeta\left(\mu^{\bar{I}}\right)^2}{2}pa. \end{aligned} \tag{17}$$

Using the lenders' participation constraints (14) and (16), and the entrepreneurs' choice of maintenance efforts in Lemma 1, we can get $a \leq \frac{2\zeta\pi ny}{(1-\pi)^2(1-\lambda^2)(1+\sigma^A)p} \equiv a^{*A}(p)$. Under the assumption $l < \frac{2\lambda}{1+\lambda}$ and assumptions A1, we have $a^{*A}(p) > \underline{a}^{\bar{I}}(p)$. To see this,

$$\frac{a^{*A}(p)}{\underline{a}^{\bar{I}}(p)} > 1 \Leftrightarrow \frac{i}{\pi ly} < 1 + \frac{2\lambda}{l(1+\lambda)\,(1+\sigma^A)}.$$

The latter holds when $l < \frac{2\lambda}{1+\lambda}$ and assumptions A1 holds.

For a firm with $a > \bar{a}(p)$, if it chooses an innovative plan, the lender will not facilitate innovation, and innovation opportunities arrive with lower probability. Such a firm chooses an innovative plan if and only if

$$\begin{aligned}&(1-\sigma^{\bar{A}})\pi\left[(1+n)y - r_n^I\right] + \sigma^{\bar{A}}\left[\pi\left(y - r_m^I\right) + (1-\pi)(1-\lambda)\mu^{I\bar{A}}pa\right] - \frac{\zeta\left(\mu^{I\bar{A}}\right)^2}{2}pa \\ \geq &\pi\left(y - r_m^{\bar{I}}\right) + (1-\pi)(1-\lambda)\mu^{\bar{I}}pa - \frac{\zeta\left(\mu^{\bar{I}}\right)^2}{2}pa. \qquad (18)\end{aligned}$$

Using the lenders' participation constraints (15) and (16), and the entrepreneurs' choice of maintenance efforts in Lemma 1, we can get $a \leq \frac{2\zeta\pi ny}{(1-\pi)^2(1-\lambda^2)(1+\sigma^{\bar{A}})p} \equiv a^{*\bar{A}}(p)$. As $\sigma^{\bar{A}} > \sigma^A$, $a^{*\bar{A}}(p) < a^{*A}(p)$. Depending on the ranking of $a^{*A}(p)$, $a^{*\bar{A}}(p)$, and $\bar{a}(p)$, we have the following three cases:

(i) If $\frac{i}{\pi ly} \leq 1 + n - \frac{2\lambda n\sigma^A\sigma^{\bar{A}}}{l(1+\lambda)(1+\sigma^A)}$, then $a^{*\bar{A}}(p) < a^{*A}(p) \leq \bar{a}(p)$. An entrepreneur chooses an innovative plan if $a \in \left[\underline{a}^{IA}(p), a^{*A}(p)\right]$.

(ii) If $1 + n - \frac{2\lambda n\sigma^A\sigma^{\bar{A}}}{l(1+\lambda)(1+\sigma^A)} < \frac{i}{\pi ly} < 1 + n - \frac{2\lambda n\sigma^A\sigma^{\bar{A}}}{l(1+\lambda)\left(1+\sigma^{\bar{A}}\right)}$, then $a^{*\bar{A}}(p) < \bar{a}(p) < a^{*A}(p)$. An entrepreneur chooses an innovative plan if $a \in \left[\underline{a}^{IA}(p), \bar{a}(p)\right]$.

(iii) If $\frac{i}{\pi ly} \geq 1 + n - \frac{2\lambda n\sigma^A\sigma^{\bar{A}}}{l(1+\lambda)\left(1+\sigma^{\bar{A}}\right)}$, then $\bar{a}(p) \leq a^{*\bar{A}}(p) < a^{*A}(p)$. An entrepreneur chooses an innovative plan if $a \in \left[\underline{a}^{IA}(p), a^{*\bar{A}}(p)\right]$.

Proof and Lemma 6

Equating demand and supply gives

$$\left[1 - \underline{a}^{IA}(p)\right]\pi\left(1 - \frac{p}{\eta\bar{\theta}}\right) = \frac{1}{2}(1-\pi)\left[1 - \underline{a}^{IA}(p)^2\right].$$

which can be rewritten as

$$\frac{\pi}{\eta\bar{\theta}}p^2 - \frac{3\pi - 1}{2}p + \frac{\zeta\left[i - \pi ly\left(1 + n - \sigma^A n\right)\right]}{2\left(\sigma^A\right)^2(1-\pi)\lambda(1-\lambda)} = 0.$$

We obtain

$$p^* = \frac{\eta\bar{\theta}}{2\pi}\left\{\frac{3\pi - 1}{2} \pm \left[\left(\frac{3\pi - 1}{2}\right)^2 - \frac{2\pi}{\eta\bar{\theta}}\frac{\zeta\left[i - \pi ly\left(1 + n - \sigma^A n\right)\right]}{\left(\sigma^A\right)^2(1-\pi)\lambda(1-\lambda)}\right]^{\frac{1}{2}}\right\}.$$

We restrict the parameters to ensure that $\underline{a}^{IA}(p) < 1$ and that there is a unique positive equilibrium price. This implies that $\underline{a}^{IA}(p_-) > 1$ and $\underline{a}^{IA}(p_+) < 1$. Substituting for the price, both hold when assumption A3 holds.

Proof of Proposition 1

The proof directly follows from Lemmas 1-6. There are two cases to be considered. First, $\bar{a}(p^*) \geq 1$, which occurs whenever $p^* \leq \frac{\zeta[\pi ly(1+n) - i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)}$, i.e.,

$$\eta\bar{\theta} \leq \frac{\zeta[\pi ly(1+n) - i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)}\left[\frac{3\pi - 1}{2\pi} - \frac{(1-\pi)\sigma^{\bar{A}}}{2\pi\sigma^A}\frac{i - \pi ly\left(1 + n - \sigma^A n\right)}{\pi ly(1+n) - i}\right]^{-1}.$$

In this case, all firms with collateral $a > \underline{a}^{IA}(p^*)$ have access to credit and potentially innovate.

Second, $\bar{a}(p^*) < 1$, which occurs whenever $p^* > \frac{\zeta[\pi ly(1+n)-i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)}$, i.e.,

$$\eta\bar{\theta} > \frac{\zeta[\pi ly(1+n)-i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)}\left[\frac{3\pi-1}{2\pi} - \frac{(1-\pi)\sigma^{\bar{A}}}{2\pi\sigma^A}\frac{i-\pi ly\left(1+n-\sigma^A n\right)}{\pi ly(1+n)-i}\right]^{-1}.$$

In this case, all firms with collateral $a \in \left[\underline{a}^{IA}(p^*), \bar{a}(p^*)\right]$ have access to credit and potentially innovate, and all firms with collateral $a > \bar{a}(p^*)$ have access to credit but do not innovate.

Proof of Proposition 2

Given (4), it is straightforward that $\frac{\partial p^*}{\partial \eta} > 0$. The investment change is computed by multiplying i by the change in the measure of firms obtaining credit, $C = 1 - \underline{a}^{IA}(p^*)$:

$$\frac{\partial I}{\partial \eta} = i\frac{\partial C}{\partial \eta} = -i\frac{\partial \underline{a}^{IA}(p^*)}{\partial p^*}\frac{\partial p^*}{\partial \eta} > 0.$$

If (5) holds, the measure of firms that innovate equals that of firms with access to credit: $C = N$. Hence, $\frac{\partial N}{\partial \eta} > 0$. If (5) does not hold, $N = \bar{a}(p^*) - \underline{a}^{IA}(p^*)$ and

$$\frac{\partial N}{\partial \eta} = -\frac{\bar{a}(p^*) - \underline{a}^{IA}(p^*)}{p^*}\frac{\partial p^*}{\partial \eta}.$$

Assumption A2 implies that $\frac{\partial N}{\partial \eta} < 0$.

Consider now output. If (5) holds, letting L denote the measure of investors,

$$Y = \omega L + C\left[\pi y\left(1+n-n\sigma^A\right) - i\right] + \pi C\int_{\frac{p^*}{\eta}}^{\bar{\theta}}\frac{\eta\theta}{\bar{\theta}}d\theta.$$

The second term is increasing in η because $\frac{\partial C}{\partial \eta} > 0$. To show the third term is also increasing η,

$$\pi C\int_{\frac{p^*}{\eta}}^{\bar{\theta}}\frac{\eta\theta}{\bar{\theta}}d\theta = \pi C\frac{\eta^2\bar{\theta}^2 - p^{*2}}{2\eta\bar{\theta}} = \frac{\eta\bar{\theta}}{2}\pi C\left(1-\frac{p^*}{\eta\bar{\theta}}\right)\left(1+\frac{p^*}{\eta\bar{\theta}}\right) = \frac{\eta\bar{\theta}}{2}D(p^*)\left(1+\frac{p^*}{\eta\bar{\theta}}\right) = \frac{\eta\bar{\theta}}{2}S(p^*)\left(1+\frac{p^*}{\eta\bar{\theta}}\right).$$

It is straightforward to show that $\frac{\partial S(p^*)}{\partial \eta} > 0$ and $\frac{\partial \frac{p^*}{\eta}}{\partial \eta} > 0$. Therefore, the third term is also increasing in η. If (5) does not hold,

$$Y = \omega L + C\left\{\pi\left[1+\frac{N}{C}(1-\sigma^A)n\right]y - i\right\} + \pi C\int_{\frac{p^*}{\eta}}^{\bar{\theta}}\frac{\eta\theta}{\bar{\theta}}d\theta.$$

An increase in η raises output iff

$$\frac{\partial C}{\partial \eta}(\pi y - i) + \pi\frac{\partial\left(C\int_{\frac{p^*}{\eta}}^{\bar{\theta}}\frac{\eta\theta}{\bar{\theta}}d\theta\right)}{\partial \eta} > -\frac{\partial N}{\partial \eta}\pi(1-\sigma^A)ny.$$

The Following Supplement is Not Intended for Publication.

Supplement A. Not for Publication

Proof of Lemma 7 The marginal firm that obtains credit has collateral equal to $\underline{a}^{IA}(p^*)$. The social value of this marginal firm is

$$V = (1-\sigma^A)\left[\pi y(1+n) + (1-\pi)\eta\hat{\theta}\underline{a}^{IA}(p^*)\right] + \sigma^A\left[\pi y + (1-\pi)\eta\hat{\theta}\underline{a}^{IA}(p^*)\right] - i,$$

where $\hat{\theta}$ is the marginal buyer of resale assets. The maintenance costs are assumed to be transfers, so they are not subtracted from the social value. We now show that the social value of the marginal firm is positive. The participation constraint of the marginal firm's lender implies that

$$\begin{aligned}&(1-\sigma^A)\pi ly(1+n) + \sigma^A\left[\pi ly + \lambda(1-\pi)\mu^{IA}p^*\underline{a}^{IA}(p^*)\right]\\ =&(1-\sigma^A)\pi ly(1+n) + \sigma^A\left[\pi ly + \lambda(1-\pi)\mu^{IA}\eta\hat{\theta}\underline{a}^{IA}(p^*)\right] = i.\end{aligned}$$

Therefore,

$$V = (1-\sigma^A)\left[\pi(1-l)y(1+n) + (1-\pi)\eta\hat{\theta}\underline{a}^{IA}(p^*)\right] + \sigma^A\left[\pi(1-l)y + (1-\pi)\eta\hat{\theta}\underline{a}^{IA}(p^*)\left(1-\lambda\mu^{IA}\right)\right] > 0.$$

The last inequality holds both because $l < 1$ (i.e., the social planner would account for the output not pledgeable to investors) and because the social planner would internalize the asset liquidation returns of the new technology (which are a transfer). It follows that in the allocation chosen by the social planner, a positive measure of firms with $a < \underline{a}^{IA}(p^*)$ would invest.

In the social planner's problem, all funded firms will take the innovative plan. This is because (i) since the liquidation costs are a transfer, in the event of project failure the asset liquidation returns of the two technologies are equal; (ii) in the event of project success the output of the new technology exceeds that of the mature since $y(1+n) > y$.

Proof of Proposition 3

The asset demand and supply are

$$D(p) = \left[1-\underline{a}^{IA}(p)\right]\pi\left(1-\frac{p-\tau}{\eta\overline{\theta}}\right) \text{ and } S(p) = \frac{1}{2}(1-\pi)\left[1-\underline{a}^{IA}(p)^2\right].$$

Equating $D(p)$ and $S(p)$ and solving for p,

$$p^*(\tau) = \frac{\tau}{2} + \frac{\eta\overline{\theta}}{2\pi}\left\{\frac{3\pi-1}{2} \pm \left[\left(\frac{3\pi-1}{2}+\frac{\pi\tau}{\eta\overline{\theta}}\right)^2 - \frac{2\pi}{\eta\overline{\theta}}\frac{\zeta\left[i-\pi ly\left(1+n-\sigma^A n\right)\right]}{(\sigma^A)^2(1-\pi)\lambda(1-\lambda)}\right]^{\frac{1}{2}}\right\}$$

To ensure that there exists a unique positive equilibrium price, we need $\underline{a}^{IA}(p_+) < 1$ and $\underline{a}^{IA}(p_-) > 1$. These hold whenever

$$\eta\overline{\theta}\left(\pi-\frac{1}{2}\right) > \frac{\pi}{2}\left[\frac{\zeta\left[i-\pi ly\left(1+n-\sigma^A n\right)\right]}{(\sigma^A)^2(1-\pi)^2\lambda(1-\lambda)} - \tau\right]$$

and the unique price is

$$p^*(\tau) = \frac{\tau}{2} + \frac{\eta\overline{\theta}}{2\pi}\left\{\frac{3\pi-1}{2} + \left[\left(\frac{3\pi-1}{2}+\frac{\pi\tau}{\eta\overline{\theta}}\right)^2 - \frac{2\pi}{\eta\overline{\theta}}\frac{\zeta\left[i-\pi ly\left(1+n-\sigma^A n\right)\right]}{(\sigma^A)^2(1-\pi)\lambda(1-\lambda)}\right]^{\frac{1}{2}}\right\}$$

Clearly, $\frac{\partial p^*}{\partial \tau} > 0$. Thus,

$$\frac{\partial C(\tau)}{\partial \tau} = -\frac{\partial \underline{a}^{IA}(p^*)}{\partial p^*}\frac{\partial p^*(\tau)}{\partial \tau} > 0.$$

If (7) holds, the measure of innovative firms equals that of firms with access to credit. Hence, $\frac{\partial N(\tau)}{\partial \tau} > 0$. To show that $\partial Y/\partial \tau > 0$, note that if (7) holds,

$$Y = \omega L + C\left[\pi y\left(1 + n - n\sigma^A\right) - i\right] + \pi C \int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta.$$

The second term increases in τ because $\frac{\partial C}{\partial \tau} > 0$. It remains to show that the third term also increases in τ. If $\partial(p^* - \tau)/\partial \tau \leq 0$, then it immediately follows that $\pi C \int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta$ increases in τ. If $\partial(p^* - \tau)/\partial \tau > 0$, note that

$$\pi C \int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta = \pi C \frac{\eta^2\bar{\theta}^2 - (p^*-\tau)^2}{2\eta\bar{\theta}} = \frac{\eta\bar{\theta}}{2}\pi C\left(1 - \frac{p^*-\tau}{\eta\bar{\theta}}\right)\left(1 + \frac{p^*-\tau}{\eta\bar{\theta}}\right)$$
$$= \frac{\eta\bar{\theta}}{2} D(p^*)\left(1 + \frac{p^*-\tau}{\eta\bar{\theta}}\right) = \frac{\eta\bar{\theta}}{2} S(p^*)\left(1 + \frac{p^*-\tau}{\eta\bar{\theta}}\right).$$

Because $\frac{\partial S(p^*)}{\partial \tau} = \frac{\partial S(p^*)}{\partial p^*}\frac{\partial p^*}{\partial \tau} > 0$, $\frac{\eta\bar{\theta}}{2} S(p^*)\left(1 + \frac{p^*-\tau}{\eta\bar{\theta}}\right)$ increases in τ, and so does $\pi C \int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta$. Therefore, whether $\partial(p^* - \tau)/\partial \tau \leq 0$ or not, we have shown that the third term is also increasing in τ.

If (7) does not hold, $N = \overline{a}^{IA}(p^*) - \underline{a}(p^*)$ and

$$\frac{\partial N(\tau)}{\partial \tau} = -\frac{\overline{a}(p^*) - \underline{a}^{IA}(p^*)}{p^*}\frac{\partial p^*(\tau)}{\partial \tau} < 0.$$

Output equals

$$Y = \omega L + C\left\{\pi\left[1 + \frac{N}{C}(1 - \sigma^A)n\right]y - i\right\} + \pi C \int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta.$$

An increase in τ raises output iff

$$\frac{\partial C}{\partial \tau}(\pi y - i) + \pi \frac{\partial\left(C \int_{\frac{p^*-\tau}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta\right)}{\partial \tau} > -\frac{\partial N}{\partial \tau}\pi(1 - \sigma^A)ny.$$

Proof of Proposition 4

The asset demand and supply are

$$D(p) = (1 - \underline{a}_G)\pi\left(1 - \frac{p}{\eta\bar{\theta}}\right) \text{ and } S(p) = \frac{1}{2}(1 - \pi)\left(1 - \underline{a}_G^2\right).$$

Equating

$$p^*(\underline{a}_G) = \frac{\eta\bar{\theta}}{2\pi}\left[3\pi - 1 - (1 - \pi)\underline{a}_G\right].$$

We let $\underline{a}^{IA}(p^*) < 1$, which holds whenever

$$\eta\bar{\theta}\left(\pi - \frac{1}{2}\right) > \frac{\zeta\left[i - \pi l y\left(1 + n - \sigma^A n\right)\right]}{\left(\sigma^A\right)^2 (1-\pi)^2 \lambda(1-\lambda)} \frac{(2\pi - 1)\,\pi}{3\pi - 1 - (1-\pi)\, a_G}.$$

Clearly, $\frac{\partial p^*(\underline{a}_G)}{\partial \underline{a}_G} < 0$, and

$$\frac{\partial C(\underline{a}_G)}{\partial \underline{a}_G} = \frac{\partial\left(1 - \underline{a}_G\right)}{\partial \underline{a}_G} = -1 < 0.$$

If (9) holds, the measure of innovative firms equals that of firms with access to credit. Hence, $\frac{\partial N}{\partial \underline{a}_G} < 0$. To show that $\partial Y / \partial \underline{a}_G < 0$, note that

$$Y = \omega L + C\left[\pi y\left(1 + n - n\sigma^A\right) - i\right] + \pi C \int_{\frac{p^*}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta.$$

The second term decreases in $\underline{a}_G$ because $\frac{\partial C}{\partial \underline{a}_G} < 0$. To show that the third term decreases in $\underline{a}_G$, note that

$$\pi C \int_{\frac{p^*}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta = \pi C \frac{\eta^2\bar{\theta}^2 - p^{*2}}{2\eta\bar{\theta}} = \frac{\eta\bar{\theta}}{2}\pi C\left(1 - \frac{p^*}{\eta\bar{\theta}}\right)\left(1 + \frac{p^*}{\eta\bar{\theta}}\right) = \frac{\eta\bar{\theta}}{2} D(p^*)\left(1 + \frac{p^*}{\eta\bar{\theta}}\right) = \frac{\eta\bar{\theta}}{2} S(p^*)\left(1 + \frac{p^*}{\eta\bar{\theta}}\right).$$

Because $\frac{\partial S(p^*)}{\partial \underline{a}_G} = \frac{\partial S(p^*)}{\partial p^*}\frac{\partial p^*}{\partial \underline{a}_G} < 0$ and $\partial p^* / \partial \underline{a}_G < 0$, the third term decreases in $\underline{a}_G$.

If (9) does not hold, $N = \overline{a}(p^*) - \underline{a}_G$ and

$$\frac{\partial N(\underline{a}_G)}{\partial \underline{a}_G} = \frac{\partial\left[\overline{a}(p^*(\underline{a}_G)) - \underline{a}_G\right]}{\partial \underline{a}_G} = -\frac{\zeta[\pi l y(1+n) - i]}{\sigma^A \sigma^{\bar{A}} (1-\pi)^2 \lambda(1-\lambda) p^*(\underline{a}_G)^2} \frac{\partial p^*(\underline{a}_G)}{\partial \underline{a}_G} - 1.$$

This is positive iff

$$-\frac{\zeta[\pi l y(1+n) - i]}{\sigma^A \sigma^{\bar{A}} (1-\pi)^2 \lambda(1-\lambda) p^*(\underline{a}_G)^2} \frac{\partial p^*(\underline{a}_G)}{\partial \underline{a}_G} > 1.$$

Plugging in $\frac{\partial p^*(\underline{a}_G)}{\partial \underline{a}_G}$,

$$\eta\bar{\theta} < \frac{\zeta[\pi l y(1+n) - i]}{\sigma^A \sigma^{\bar{A}} (1-\pi)^2 \lambda(1-\lambda)} \frac{2\pi(1-\pi)}{\left[3\pi - 1 - (1-\pi)\,\underline{a}_G\right]^2}.$$

Output equals

$$Y = \omega L + C\left\{\pi\left[1 + \frac{N}{C}(1 - \sigma^A) n\right] y - i\right\} + \pi C \int_{\frac{p^*}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta.$$

An increase in $\underline{a}_G$ reduces output iff

$$\frac{\partial C}{\partial \underline{a}_G}(\pi y - i) + \pi \frac{\partial\left(C \int_{\frac{p^*}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}} d\theta\right)}{\partial \underline{a}_G} < -\frac{\partial N}{\partial \underline{a}_G}\pi(1 - \sigma^A) n y,$$

which always holds if $\partial N / \partial \underline{a}_G < 0$, as the left-hand-side is negative.

Proof of Lemma 8

An entrepreneur cannot innovate under relationship funding and can innovate under transactional funding iff $a \in \left(\overline{a}^R(p), \overline{a}^T(p)\right]$. In this case, the condition under which an entrepreneur chooses transactional funding is

$$(1-\sigma^A)\pi\left[(1+n)y - r_n^{IT}\right] + \sigma^A\left[\pi\left(y - r_m^{IT}\right) + (1-\pi)(1-\lambda)\mu^{IAT}pa\right] - \frac{\zeta^T\left(\mu^{IAT}\right)^2}{2}pa$$
$$\geq \pi\left(y - r_m^{\bar{I}R}\right) + (1-\pi)(1-\lambda)\mu^{\bar{I}R}pa - \frac{\zeta^R\left(\mu^{\bar{I}R}\right)^2}{2}pa. \tag{19}$$

The repayments r_m^{IT} and r_n^{IT} that guarantee zero profits to a transactional lender when the innovation can occur satisfy

$$(1-\sigma^A)\pi r_n^{IT} + \sigma^A\left[\pi r_m^{IT} + \lambda(1-\pi)\mu^{IAT}pa\right] = i,$$

whereas the repayment $r_m^{\bar{I}R}$ that guarantees zero profits to a relationship lender when the innovation cannot occur satisfies

$$\pi r_m^{\bar{I}R} + \lambda(1-\pi)\mu^{\bar{I}R}pa = i.$$

Using the above two equations to substitute into (19), we obtain

$$a \leq \frac{2\zeta^R\zeta^T(1-\sigma^A)\pi n y}{(1-\pi)^2(1-\lambda^2)\left[\zeta^T - \zeta^R\left(\sigma^A\right)^2\right]p} \equiv \widehat{a}(p).$$

Proof of Lemma 9

A mixed finance regime occurs when $\widehat{a}(p) > \overline{a}^R(p)$, which can be rewritten as

$$\frac{i}{\pi l y} > 1 + n - \frac{2\zeta^T\left(1-\sigma^A\right)\sigma^A\sigma^{\bar{A}}\lambda n}{(1+\lambda)\left[\zeta^T - \zeta^R\left(\sigma^A\right)^2\right]l}.$$

Assumptions 1, 2 and 4 restrict that $1+n-\sigma^A n < \frac{i}{\pi l y} < \min\left\{1+\frac{n}{1+\sigma^A}, 1+\left[\frac{1}{1+\sigma^A} - \frac{\left(\sigma^{\bar{A}}\zeta^T - \zeta^R\right)\left(\sigma^A\right)^2}{\left(\sigma^{\bar{A}}\zeta^T + \sigma^A\zeta^R\right)\left(1+\sigma^A\right)}\right]n\right\}$.

(i) If $1+n-\frac{2\zeta^T\left(1-\sigma^A\right)\sigma^A\sigma^{\bar{A}}\lambda n}{(1+\lambda)\left[\zeta^T-\zeta^R\left(\sigma^A\right)^2\right]l} \leq 1+n-\sigma^A n$, that is, $l \leq \frac{2\lambda\left(1-\sigma^A\right)\sigma^{\bar{A}}\zeta^T}{(1+\lambda)\left[\zeta^T-\zeta^R\left(\sigma^A\right)^2\right]} = \underline{l}$, then entrepreneurs with $a \in \left(\overline{a}^R(p), \min\left\{\widehat{a}(p), \overline{a}^T(p)\right\}\right)$ choose transactional funding and set a contract that induces the lender to choose the action that facilitates innovation.

(ii) If $1+n-\frac{2\zeta^T\left(1-\sigma^A\right)\sigma^A\sigma^{\bar{A}}\lambda n}{(1+\lambda)\left[\zeta^T-\zeta^R\left(\sigma^A\right)^2\right]l} \geq \min\left\{1+\frac{n}{1+\sigma^A}, 1+\left[\frac{1}{1+\sigma^A} - \frac{\left(\sigma^{\bar{A}}\zeta^T-\zeta^R\right)\left(\sigma^A\right)^2}{\left(\sigma^{\bar{A}}\zeta^T+\sigma^A\zeta^R\right)\left(1+\sigma^A\right)}\right]n\right\}$, that is, $l \geq \min\left\{\frac{2\lambda\left[1-\left(\sigma^A\right)^2\right]\sigma^{\bar{A}}\zeta^T}{(1+\lambda)\left[\zeta^T-\zeta^R\left(\sigma^A\right)^2\right]}, \frac{2\lambda\left(1-\sigma^A\right)\left(\sigma^{\bar{A}}\zeta^T+\sigma^A\zeta^R\right)}{(1+\lambda)\left[\zeta^T-\zeta^R\left(\sigma^A\right)^2\right]}\right\} = \bar{l}$, mixed finance regime never occurs.

(iii) If $1+n-\sigma^A n < 1+n-\frac{2\zeta^T\left(1-\sigma^A\right)\sigma^A\sigma^{\bar{A}}\lambda n}{(1+\lambda)\left[\zeta^T-\zeta^R\left(\sigma^A\right)^2\right]l} < \min\left\{1+\frac{n}{1+\sigma^A}, 1+\left[\frac{1}{1+\sigma^A} - \frac{\left(\sigma^{\bar{A}}\zeta^T-\zeta^R\right)\left(\sigma^A\right)^2}{\left(\sigma^{\bar{A}}\zeta^T+\sigma^A\zeta^R\right)\left(1+\sigma^A\right)}\right]n\right\}$, that is, $l \in \left(\underline{l}, \bar{l}\right)$, there are two regimes of parameters consistent with assumptions 1, 2, and 4. When $\frac{i}{\pi l y} \leq 1+n-\frac{2\zeta^T\left(1-\sigma^A\right)\sigma^A\sigma^{\bar{A}}\lambda n}{(1+\lambda)\left[\zeta^T-\zeta^R\left(\sigma^A\right)^2\right]l}$, the relationship regime occurs, and the mixed regime occurs otherwise.

Proof of Proposition 6

The proof for the effects in the relationship regime and for the effects on the asset price, investment, and the measure of firms with access to credit in the mixed regime are as in case (ii) of Proposition 2.

Here we first present the proof for the effects of the shock on the measure of innovative firms and on output in the mixed finance regime, which are similar to those in case (ii) of Proposition 2. In the mixed finance regime, the measure of firms that innovate is

$$N_m = \min\left\{\widehat{a}(p^*), \overline{a}^T(p^*)\right\} - \underline{a}^{IAR}(p^*).$$

Hence,

$$\frac{\partial N_m}{\partial \eta} = \begin{cases} -\frac{\widehat{a}(p^*)-\underline{a}^{IAR}(p^*)}{p^*}\frac{\partial p^*}{\partial \eta} & \text{if } \overline{a}^T(p^*) \geq \widehat{a}(p) \\ -\frac{\overline{a}^T(p^*)-\underline{a}^{IAR}(p^*)}{p^*}\frac{\partial p^*}{\partial \eta} & \text{if } \overline{a}^T(p^*) < \widehat{a}(p^*) \end{cases}.$$

The existence of the mixed financing regime implies that $\min\left\{\widehat{a}(p^*), \overline{a}^T(p^*)\right\} - \underline{a}^{IAR} > 0$. Thus, it is always the case that $\frac{\partial N_m}{\partial \eta} < 0$.

Output is given by

$$Y_j = \omega L + C\left\{\pi\left[1 + \frac{N_j}{C}(1-\sigma^A)n\right]y - i\right\} + \pi C\int_{\frac{p^*}{\eta}}^{\bar{\theta}} \frac{\eta\theta}{\bar{\theta}}d\theta,$$

where $j \in \{r, m\}$ identifies the relationship or mixed credit regime. $\frac{\partial Y_j}{\partial \eta} > 0$ iff

$$\frac{\partial C}{\partial \eta}(\pi y - i) + \pi\frac{\partial\left(C\int_{\frac{p^*}{\eta}}^{\bar{\theta}}\frac{\eta\theta}{\bar{\theta}}d\theta\right)}{\partial \eta} > -\frac{\partial N_j}{\partial \eta}\pi(1-\sigma^A)ny.$$

We then study credit relationships. In the relationship regime, their measure (R_r) equals that of active firms (C):

$$R_r = C = 1 - \underline{a}^{IAR}.$$

Thus,

$$\frac{\partial R_r}{\partial \eta} = \frac{\partial C}{\partial \eta} = \frac{\underline{a}^{IAR}(p^*)}{p^*}\frac{\partial p^*}{\partial \eta} > 0.$$

In the mixed regime,

$$R_m = C - \left[\min\left\{\widehat{a}(p^*), \overline{a}^T(p^*)\right\} - \overline{a}^R(p^*)\right] = 1 - \underline{a}^{IAR}(p^*) - \left[\min\left\{\widehat{a}(p^*), \overline{a}^T(p^*)\right\} - \overline{a}^R(p^*)\right].$$

Hence,

$$\frac{\partial R_m}{\partial \eta} = \begin{cases} \frac{\underline{a}^{IAR}(p^*)+\overline{a}^T(p^*)-\overline{a}^R(p^*)}{p^*}\frac{\partial p^*}{\partial \eta} & \text{if } \overline{a}^T(p^*) \leq \widehat{a}(p^*) \\ \frac{\underline{a}^{IAR}(p^*)+\widehat{a}(p^*)-\overline{a}^R(p^*)}{p^*}\frac{\partial p^*}{\partial \eta} & \text{if } \overline{a}^T(p^*) > \widehat{a}(p^*) \end{cases}.$$

Therefore, $\frac{\partial R_m}{\partial \eta} > 0$. Next, we study how the measure of relationships changes relative to that of active firms. One can show that

$$\frac{\partial\left(\frac{R_m}{C}\right)}{\partial \eta} = \frac{C - R_m}{C^2}\frac{1}{p^*}\frac{\partial p^*}{\partial \eta} > 0.$$

Proof of Lemma 10

Introducing managers into the model does not change the optimal maintenance efforts of entrepreneurs (μ^{IA}, $\mu^{I\bar{A}}$, and $\mu^{\bar{I}}$) in Lemma 1, because maintenance generates positive expected payoff only when the mature technology is used and the project fails.

A manager's participation constraint is

$$(1-\sigma^A)\pi_n(w+w_n)+\sigma^A\pi w \geq e, \tag{20}$$

while the lowest w_n satisfying (10) is

$$w_n = \frac{\pi-\pi_n}{\pi_n}w. \tag{21}$$

Using (20) and (21),

$$w_n = \frac{(\pi-\pi_n)e}{\pi_n\pi}$$

and $w=\frac{e}{\pi}$. Thus, the compensation in case of successful adoption of the new technology is $w+w_n=\frac{e}{\pi_n}$. Next, consider the lender. The incentive compatibility constraint for the lender is

$$(1-\sigma^A)\pi_n r_n^I + \sigma^A\left[\pi r_m^I + \lambda(1-\pi)\mu^{IA}pa\right] \geq (1-\sigma^{\bar{A}})\pi_n r_n^I + \sigma^{\bar{A}}\left[\pi r_m^I + \lambda(1-\pi)\mu^{I\bar{A}}pa\right].$$

That is,

$$\pi_n r_n^I - \pi r_m^I \geq \frac{(\sigma^A+\sigma^{\bar{A}})(1-\pi)^2\lambda(1-\lambda)pa}{\zeta}.$$

The participation constraint for the lender is

$$(1-\sigma^A)\pi_n r_n^I + \sigma^A\left[\pi r_m^I + \lambda(1-\pi)\mu^{IA}pa\right] \geq i. \tag{22}$$

Due to limited commitment, the lender can at most pledge l fraction of output. We also need to take into account the payment to managers. Therefore,

$$r_n^I \leq ly(1+n)-(w+w_n) = ly(1+n)-\frac{e}{\pi_n},$$

$$r_m^I \leq ly - w = ly - \frac{e}{\pi}.$$

Following the same logic as the proof of Lemma 2, one can show that the two threshholds become

$$\underline{a}'^{IA}(p) = \frac{\zeta[i+e-(1-\sigma^A)\pi_n l(1+n)y-\sigma^A\pi ly]}{(\sigma^A)^2(1-\pi)^2\lambda(1-\lambda)p},$$

$$\bar{a}'(p) = \frac{\zeta[\pi_n ly(1+n)-e-i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)p}.$$

Consider now the scenario in which the manager cannot prevent the innovation. The manager's participation constraint under innovation is

$$(1-\sigma^A)\pi_n w+\sigma^A\pi w \geq e,$$

from which

$$w = \frac{e}{(1-\sigma^A)\pi_n+\sigma^A\pi}.$$

Therefore, the pledgeable returns to the lender are

$$r_n^I \le ly(1+n) - w = ly(1+n) - \frac{e}{(1-\sigma^A)\pi_n + \sigma^A\pi},$$

$$r_m^I \le ly - w = ly - \frac{e}{(1-\sigma^A)\pi_n + \sigma^A\pi}.$$

The lender's IC and PC are the same as the case with moral hazard. Therefore, one can solve for

$$\overline{a}''(p) \equiv \frac{\zeta[\pi_n ly(1+n) - \frac{\pi_n e}{(1-\sigma^A)\pi_n+\sigma^A\pi} - i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)p},$$

and

$$\underline{a}''^{IA}(p) = \underline{a}'^{IA}(p).$$

One can show that

$$\overline{a}''(p) = \frac{\zeta[\pi_n ly(1+n) + \frac{\sigma^A(\pi-\pi_n)}{(1-\sigma^A)\pi_n+\sigma^A\pi} - e - i]}{\sigma^A\sigma^{\bar{A}}(1-\pi)^2\lambda(1-\lambda)p} > \overline{a}'(p).$$

Proof of Proposition 7

The difference between the asset demand $D'(p)$ in the presence of managerial moral hazard and the demand $D''(p)$ in its absence is

$$D'(p) - D''(p) = \left[\overline{a}''(p) - \overline{a}'(p)\right]\left(1-\sigma^A\right)\left(\pi - \pi_n\right)\left(1 - \frac{p}{\eta\overline{\theta}}\right) > 0,$$

while the difference in the supply is

$$S'(p) - S''(p) = -\left\{\frac{[\overline{a}''(p)]^2}{2} - \frac{[\overline{a}'(p)]^2}{2}\right\}\left(1-\sigma^A\right)\left(\pi-\pi_n\right) < 0.$$

Thus, the equilibrium price is higher in the presence of moral hazard: $p' > p''$. The difference in the measure of innovative firms is (assuming $\overline{a}''(p) < 1$, which holds if $\eta\overline{\theta}$ is large enough)

$$\begin{aligned} N'(p') - N''(p'') &= \left[\overline{a}'(p') - \underline{a}'^{IA}(p')\right] - \left[\overline{a}''(p'') - \underline{a}''^{IA}(p'')\right] \\ &< \left[\overline{a}'(p') - \underline{a}'^{IA}(p')\right] - \left[\overline{a}'(p'') - \underline{a}'^{IA}(p'')\right] \\ &< 0. \end{aligned}$$

The first inequality holds because $\overline{a}'(p'') < \overline{a}''(p'')$ and $\underline{a}'^{IA}(p'') = \underline{a}''^{IA}(p'')$. The second inequality holds because $p' > p''$ and $\left[\overline{a}'(p) - \underline{a}'^{IA}(p)\right]$ is decreasing in p.

Robustness check: new technology has a higher probability of success.

Our model assumes that the new technology is more productive than the mature technology ($n > 0$). In this section, we study an alternative setting where the new technology has a higher success probability. We show that all agents' decisions are the same as the main model when parameters are chosen in a specific way. Suppose the new technology has the same output y as the mature technology but a higher probability of success $\pi_n > \pi$. We show that the lenders' and entrepreneurs' problems are equivalent to those in the main model, when π_n is chosen in a specific way.

Entrepreneurs' maintenance effort. The maintenance efforts μ^{IA}, $\mu^{I\bar{A}}$, and $\mu^{\bar{I}}$ are the same as in Lemma 1, because mature assets are only useful when the mature technology is adopted and therefore the value of π_n is irrelevant.

The lender's decision whether to take an action to innovate. The lender's IC (13) and PC (14) become

$$(1-\sigma^A)\pi_n r_n^I + \sigma^A \left[\pi r_m^I + \lambda(1-\pi)\mu^{IA} pa\right] \geq (1-\sigma^{\bar{A}})\pi_n r_n^I + \sigma^{\bar{A}} \left[\pi r_m^I + \lambda(1-\pi)\mu^{I\bar{A}} pa\right]. \quad (23)$$

That is,

$$\pi^n r_n^I - \pi r_m^I \geq \frac{(\sigma^A + \sigma^{\bar{A}})(1-\pi)^2 \lambda(1-\lambda) pa}{\zeta}. \quad (24)$$

The participation constraint for the lender is

$$(1-\sigma^A)\pi_n r_n^I + \sigma^A \left[\pi r_m^I + \lambda(1-\pi)\mu^{IA} pa\right] \geq i. \quad (25)$$

Due to limited commitment, the lender can at most pledge l fraction of output. Therefore,

$$r_n^I \leq ly, \quad \text{and} \quad r_m^I \leq ly.$$

Now let $\tilde{r}_n^I = \frac{\pi_n}{\pi} r_n^I$. Substitute for r_n^I in (24) and (25), we get

$$\pi \tilde{r}_n^I - \pi r_m^I \geq \frac{(\sigma^A + \sigma^{\bar{A}})(1-\pi)^2 \lambda(1-\lambda) pa}{\zeta},$$

and

$$(1-\sigma^A)\pi \tilde{r}_n^I + \sigma^A \left[\pi r_m^I + \lambda(1-\pi)\mu^{IA} pa\right] \geq i,$$

which are identical as (1) and (14) in Lemma 2. The limited commitment constraint yields that

$$\tilde{r}_n^I \leq l \frac{\pi_n}{\pi} y, \quad \text{and} \quad r_m^I \leq ly.$$

Therefore, if $\frac{\pi_n}{\pi} = 1 + n$, the lender's problem is exactly the same as that in Lemma 2. Similarly, the lender's participation constraint when she hinders innovation is the same as that in (15), and her participation constraint when the entrepreneur does not take an innovative plan is the same as that in (16).

The entrepreneur's decision whether to adopt an innovative plan. The entrepreneur chooses an innovative plan if and only if

$$\begin{aligned}
&(1-\sigma^A)\pi_n \left(y - r_n^I\right) + \sigma^A \left[\pi \left(y - r_m^I\right) + (1-\pi)(1-\lambda)\mu^{IA} pa\right] - \frac{\zeta \left(\mu^{IA}\right)^2}{2} pa \\
\geq &\pi \left(y - r_m^{\bar{I}}\right) + (1-\pi)(1-\lambda)\mu^{\bar{I}} pa - \frac{\zeta \left(\mu^{\bar{I}}\right)^2}{2} pa.
\end{aligned}$$

Again, let $\tilde{r}_n^I = \frac{\pi_n}{\pi} r_n^I$ and $\frac{\pi_n}{\pi} = 1 + n$, this constraint becomes

$$\begin{aligned}
&(1-\sigma^A)\pi \left[(1+n)y - \tilde{r}_n^I\right] + \sigma^A \left[\pi \left(y - r_m^I\right) + (1-\pi)(1-\lambda)\mu^{IA} pa\right] - \frac{\zeta \left(\mu^{IA}\right)^2}{2} pa \\
\geq &\pi \left(y - r_m^{\bar{I}}\right) + (1-\pi)(1-\lambda)\mu^{\bar{I}} pa - \frac{\zeta \left(\mu^{\bar{I}}\right)^2}{2} pa,
\end{aligned}$$

which is identical as (17). Similarly, conditional on that the lender hinders innovation, we can get an identical incentive constraint for the entrepreneur as in (18).