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FINANCING VENTURES

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## Financing Ventures

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### **ABSTRACT**

The relationship between venture capital and growth is examined using an endogenous growth model incorporating dynamic contracts between entrepreneurs and venture capitalists. At each stage of financing, venture capitalists evaluate the viability of startups. If viable, venture capitalists provide funding for the next stage. The success of a project depends on the amount of funding. The model is confronted with stylized facts about venture capital; viz., statistics by funding round concerning the success rates, failure rates, investment rates, equity shares, and IPO values. Raising capital gains taxation reduces growth and welfare.

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# 1 Introduction

“I think the development of the venture capital system has been an example of something which is a successful improvement in risk-bearing. It doesn’t exactly remove the risks at the beginning, but at least creates greater rewards at a slightly later stage and therefore encourages, say, small companies to engage in technologically risky enterprises. If you like innovation, you expect 50 percent to 60 percent failure. In a sense, if you don’t get that, you’re not trying hard enough. Venture capital has done much more, I think, to improve efficiency than anything.” Kenneth J. Arrow, *The Region*, December 1995

The importance of venture capital in the U.S. economy has skyrocketed over the past 50 years. Investment by venture capitalists was roughly \$303 million in 1970. This soared to \$54 billion by 2015 (both numbers are in \$2009). The rise in venture capital (VC) financing is shown in the right-hand-side panel of Figure 1. While the share of VC funding in total investment is still relatively small, around 2 percent in 2015, its punch far exceeds its weight. The fraction of public firms that have been backed at some time by venture capitalists is now around 20 percent, compared with just 4 percent in 1970—see the left-hand-side panel of Figure 1. (See the Data Appendix for the sources of all data used in the paper.) Such firms presently account for about 20 percent of market capitalization. The capitalization line lies below the fraction-of-firms line because VC-backed companies tend to be more recent entrants that are younger and smaller in size, whereas their non-VC-backed counterparts tend to be established incumbents. Today venture capitalists are significant players in job creation and technological innovation. Public firms that were once backed by venture capitalists currently make up a significant fraction of employment and an even larger share of R&D spending, as opposed to virtually nothing in 1970, as the left-hand-side panel of Figure 2 makes clear. The right-hand side of the figure displays their enormous contribution to the generation of patents, both in raw and quality-adjusted terms. The employment share of VC-backed firms is far less than the R&D (and patents) share.

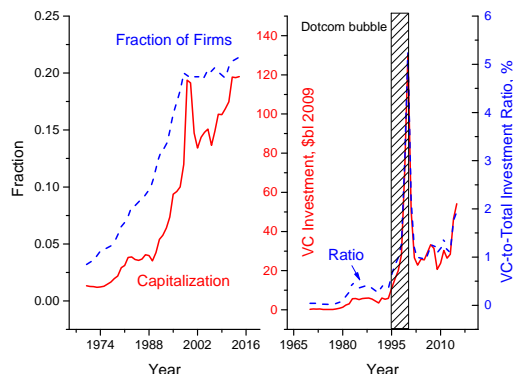


Figure 1: The rise of venture capital, 1970 to 2015. The right-hand-side panel shows investment by venture capitalists. The left-hand-side panel plots both the fraction of public firms financed by venture capitalists and the share of VC-backed public firms in market capitalization.

This is because VC-backed companies are more R&D intensive than their non-VC-backed counterparts. For instance, Google (a VC-backed company) has far fewer employees than General Motors (a non-VC-backed company), but Google invests a lot more in R&D than General Motors.

The VC industry has been an incubator of numerous technological giants in the information and communication technology sector as well as the biotechnology sector, plus an array of star innovators in the service industry. Former VC-backed firms are household names. Table 1 lists the top 30 VC-backed public companies by market capitalization. Figure 3 plots the relative significance of the words “banks” and “venture capital,” as reflected by their usage in English language books. As shown, the term venture capital was virtually unused in 1930. The relative significance of venture capital vis-à-vis banks has increased considerably since then.

To address the importance of VC in the U.S. economy, an endogenous growth model is developed. At the heart of the growth model is a dynamic contract between an entrepreneur and a venture capitalist. The venture capitalist invests in the entrepreneur’s startup as an active participant. The venture capitalist provides seed money for initial research. The project then enters a funding-round cycle. At the beginning of each funding round the

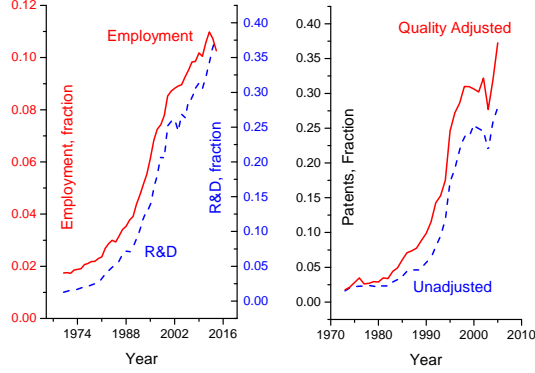


Figure 2: The share of VC-backed firms in employment, R&D spending, and patents. The data in the left-hand-side panel are from 1970 to 2014, while that in the right-hand-side panel spans 1973 to 2005.

TOP 30 VC-BACKED COMPANIES					
1	Apple Inc	11	Amgen Inc.	21	Fedex Corp.
2	Cisco Systems Inc.	12	Yahoo Inc.	22	Juniper Networks Inc.
3	Microsoft Corp.	13	Genentech Inc.	23	Nextel Communications Inc.
4	Alphabet Inc.	14	Celgene Corp.	24	Gap Inc.
5	Facebook Inc.	15	Ebay Inc.	25	Viacom Inc.
6	Oracle Corp.	16	Compaq Computer Corp.	26	Veritas Software Corp.
7	Amazon.Com Inc.	17	Starbucks Corp.	27	Salesforce.Com Inc.
8	Sun Microsystems Inc.	18	Micron Technology Inc.	28	Alexion Pharmaceuticals Inc.
9	Gilead Sciences Inc.	19	Applied Materials Inc.	29	Adobe Systems Inc.
10	Dell Inc.	20	Regeneron Pharmaceuticals	30	Twitter Inc.

Table 1: The table shows the top 30 VC-backed companies by market capitalization. These companies are identified by matching firm names in VentureXpert and CompuStat.

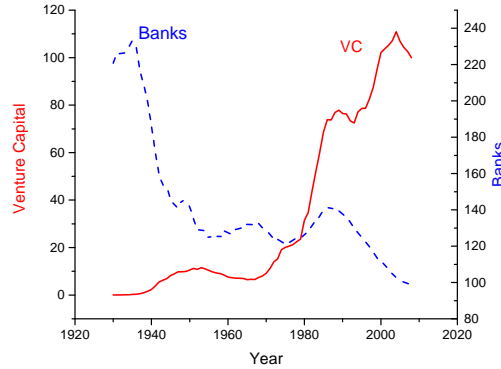


Figure 3: Banks and venture capital, 1930-2008. The figure plots the use of the words “banks” and “venture capital,” relative to all words in English language books, using the Google Ngram Viewer. For each series, the value in 2008 is normalized to 100.

venture capitalist evaluates the worthiness of the project. Those projects that pass the evaluation are given funds for development. The contract is designed so that it is not in the entrepreneur’s interest to divert funds away from their intended purpose. The venture capitalist can imperfectly monitor at a cost the entrepreneur’s use of funds, which helps to ensure incentive compatibility. Those ventures that are successful during a fund round are floated on the stock market.

The contract specifies for each funding round the evaluation strategy to gauge the project’s worthiness, the amount of VC invested in development, the level of monitoring to avoid malfeasance, and the shares of each party in the proceeds from a potential IPO. The agreement is optimal, from both the entrepreneur’s and venture capitalist’s perspectives, given the economic environment that the two parties work within. The predicted features of the contract are compared with some stylized facts about venture capital: (i) the success and failure rates by funding round, (ii) investment by funding round, (iii) the value of an IPO by duration of the incubation period, and (iv) the venture capitalist’s share of equity by funding round.

Despite the importance of VC, the majority of U.S. firms are not financed through this channel. Hurst and Pugsley (2011) show that the great majority of new businesses do not

to plan to innovate or grow. Only roughly 10 percent of all new businesses reported that they plan to develop proprietary technology, processes, or procedures in the future (Table 8) and by the fourth year of their life, only 2.7 percent have or are applying for a patent (Table 6). So, the analysis includes a traditional sector that produces the majority of output using capital that can be thought of as being financed through regular banks.

Some thought experiments are conducted to show the importance of efficiency in evaluating, developing, and monitoring startups. The analysis debases these efficiencies to approximate the efficacy of traditional methods of finance. A question arises: If VC is more efficient than traditional methods of finance, then why didn't growth rise with birth of VC? Presumably other things might have changed. On this, it has been suggested that ideas are now harder find. A thought experiment is presented where ideas were more abundant in the past, finance was less efficient, but economic growth was more or less the same as today. It is then found that without VC today's economic growth would have dropped from 1.8 to 1.4-1.5 percent.

The key participants in a VC partnership receive the majority of their compensation in the form of stock options and convertible equity. As such, in the United States they are subject primarily to capital gains taxation. The analysis examines how innovative activity is affected by the capital gains tax rate. The rates of taxation on VC-funded startups vary widely across countries and with it so do the levels of VC activity. The calibrated model matches this cross-country relationship. The impact that taxes on startup have on growth is then examined. Economic growth would fall from 1.8 to 1.62 percent, if VC-funded startups in the United States are taxed at the German rate. This leads to a large drop in welfare. To highlight the role that venture capital may play in generating differences in growth across countries, a comparison is undertaken between France with the United States.

Dynamic contract models have now been used for some time to study consumption/savings cum effort decisions with moral hazard. An early example is Phelan and Townsend (1991), with Karaivanov and Townsend (2014) being representative of more recent work. Dynamic contract frameworks that focus on firms, and VC in particular, are rarer. Bergemann and

Hege (1998), Clementi and Hopenhayn (2006), Cole, Greenwood, and Sanchez (2016) and Smith and Wang (2006) develop contracting structures that share some similarities with the one presented here. Clementi and Hopenhayn (2006) and Smith and Wang (2016) model long-term credit relationships between entrepreneurs and lenders. Lenders cannot monitor the borrower. These analyses stress the efficiency of long-term contracts. Since they do not focus on VC, they do not formulate the incubation period where a lender supplies funding for research and development while evaluating the worthiness of the startup and monitoring the use of funds.

In Bergemann and Hege (1998) a venture capitalist also learns about a project’s type, good or bad, over time. Their research yields some valuable insights about how to model the VC staging process. Unlike in the current analysis, however, a venture capitalist cannot invest in evaluating a project in each funding round to learn about its type, good or bad. As noted by Lerner (1998), the Bergemann and Hege (1998) analysis implies that a venture capitalist’s belief that a venture is bad must rise over time as the project fails to go to market. An important real-world feature about stage financing is that it permits a venture capitalist to produce information during a funding round about a project’s worth by evaluating it. While this evaluation process is costly it allows the venture capitalist to cut bad projects more speedily ensuring, to quote Lerner (1998, p. 737), that the “lemons ripen faster than plums.” By investing in this additional information acquisition, the odds that a project is good can rise over funding rounds. This works to generate an upward-sloping investment profile by funding round, something the Bergemann and Hege (1998) framework does not yield. While the Bergeman and Hege (1998) model shares features with the current analysis, their structure is linear in nature. While facilitating analytical results, this renders corner solutions, which makes the framework impossible to match the U.S. data. (For example, in their setting investment is either zero or at its assumed upper bound, while monitoring is only done toward the end of contract.) Also since their analysis is partial equilibrium, it is silent about the impact of VC on the performance of the economy at large.

VC is taken to be a competitive industry, as in Bergemann and Hege (1998). It is also



similar to Cole, Greenwood, and Sanchez’s (2016) and Smith and Wang’s (2006) assumption that financial intermediation, more generally, is competitive. This is certainly true today, albeit not historically speaking. According to the National Venture Capital Association, in 2016 there were 898 VC organizations with average assets under management of \$243.6 million. Among these VC organizations, only 68 managed \$1 billion or more. In contrast, 334 VC organizations managed \$50 million or less. The share of total assets under management is 14.7 percent for the largest five U.S. VC firms and 2.3 percent for the largest five U.S. VC funds. By comparison, the largest five U.S. banks control 44.6 percent of the industry’s total assets.

The current analysis is done within the context of an endogenous growth model. Cole, Greenwood, and Sanchez (2016) focus on the impact that financial intermediation, more broadly defined, has on cross-country technological adoption and income levels. As in Akcigit, Celik, and Greenwood (2016), the current work has a distribution of competitive firms operating in general equilibrium. This distribution is continually shifting rightward with technological progress in the economy. A new entrepreneur decides how far to push his productivity relative to the frontier; this is somewhat reminiscent of Parente (1994). The position of the frontier is determined by a classic Romer (1986) type externality. The last three papers noted have no startups. None of the above papers compares the predictions of their models with the VC process in the United States. And none of them examines how innovative activity is affected by the rate of capital gains taxation.

There is, of course, work on VC that does not take a dynamic contract perspective. Silveira and Wright (2016) build a canonical search model of the process where entrepreneurs are matched with venture capitalists, something abstracted from here. Upon meeting, the parties bargain in Nash fashion over each one’s investment and how to split the proceeds. Jovanovic and Szentes (2013) focus on a setting where the incubation period for a project is unknown. Unlike entrepreneurs, venture capitalists have deep pockets and can weather supporting a project over a prolonged period of time, if they so choose. A contract specifies the initial investment by the venture capitalist and some fixed split of the profits. The

analysis focuses on characterizing and measuring the excess return earned by venture capitalists, due to the latter's scarcity. A tractable stylized Schumpeterian model of VC that has analytical solutions is developed by Opp (2018). He estimates that the welfare benefits of VC are worth 1 to 2 percent of aggregate consumption, despite the fact that VC investment is highly procyclical, which operates to trim the estimates. In his analysis, entrepreneurs do not choose how far to launch their endeavor ahead of the pack. Also, the likelihood of success does not depend on the level of development funding. Since the innovation process is essentially static, there is no investment over time in learning about the project's quality. Given the static nature of R&D investment, he does not model the stage-financing process; i.e., the success rates, failure rates, investment rates, equity shares, and values of an IPO by funding round.

## **2 Empirical Evidence on Venture Capital and Firm Performance**

How does VC affect firm growth and technological innovation? The VC industry is a successful incubator of high-tech and high-growth companies. VC-backed public companies have higher R&D-to-sales ratios than their non-VC-backed counterparts. Following an IPO, they also grow faster in terms of employment and sales. VC-backed companies are embraced as "golden geese" by the investors. They are valued higher than their non-VC-backed counterparts around the time of an IPO. In addition, VC is a potent apparatus for financing technological innovation. VC funding is positively associated with patenting activity by firms. Those industries where VC funding is high tend to have higher levels of employment and sales growth.

## 2.1 Venture Capital and Firm Growth

Regression analysis is now conducted to evaluate the performance of VC-backed and non-VC-backed firms along four dimensions for years following an IPO: the R&D-to-sales ratio, the growth rate of employment, the growth of sales revenue, and the (natural logarithm of the) market value of firms. The results are presented in Table 2. The regressions are based on an unbalanced panel of U.S. public companies between 1970 and 2014. To compare VC-backed companies with their non-VC-backed counterparts, a VC dummy is entered as an independent variable that takes the value of 1 if the company is funded by VC before its IPO. In all regressions, industry dummies, year dummies, and a year dummy for the IPO are included. In addition, a cross term is added between the VC dummy and the number of years since the firm's IPO.

As shown by the first row of regression coefficients, VC-backed companies are more R&D intensive and grow faster than their non-VC-backed counterparts. On average the R&D-to-sales ratio of a public VC-backed company is higher than its non-VC-backed counterpart by 5.2 percentage points, and it grows faster—by 4.9 percentage points in terms of employment and 7.0 percentage points in terms of sales revenue. These superior performances translate into higher market values: VC-backed companies are valued 37.3 percent higher than their non-VC-backed counterparts. The difference in performance, however, gradually dwindles over the years, as shown by the negative signs of the regression coefficients in the second row. As a consequence, the performances of VC- and non-VC-backed public companies tend to converge in the long run, though the speed of convergence is fairly low, as revealed by the magnitude of the regression coefficients in the second row.

## 2.2 Venture Capital and Innovation

The role of VC in encouraging technological innovation is now gauged at an annual periodicity; specifically, the impact of VC funding on patent performance is evaluated at the firm level and at the industry level for employment and sales growth. The data contains all com-

VC- VERSUS NON-VC-BACKED PUBLIC COMPANIES

<i>Dependent variable</i>	<i>R&amp;D / Sales</i>	<i>Employment growth</i>	<i>Sales growth</i>	<i>ln(Firm value)</i>
VC (= 1, if backed by VC)	0.0521*** (0.00169)	0.0490*** (0.00206)	0.0696*** (0.00270)	0.373*** (0.0141)
VC $\times$ years since IPO	-0.000780*** (0.000132)	-0.00304*** (0.000165)	-0.00406*** (0.000215)	-0.0110*** (0.00110)
ln(employment)	-0.0133*** (0.000248)	-0.00567*** (0.000254)	-0.00641*** (0.000335)	0.851*** (0.00170)
+ controls				
Observations	84,116	148,834	149,672	168,549
R-squared	0.383	0.084	0.108	0.737

Table 2: All specifications include year dummies, industry dummies (at the 4-digit SIC), and a year dummy for the IPO. Standard errors are in parentheses and significance at the 1 percent level is denoted by \*\*\*.

panies funded by venture capitalists between 1970 and 2015. These VC-funded patentees are identified by matching firm names in VentureXpert and PatentsView.

**Firm-Level Regressions.** In the firm-level regressions, the primary independent variable is (the natural logarithm of) annual VC funding, while the dependent variable is a measure of patenting performance 3 years after the firm receives the funding. The primary independent variable may suffer from both measurement error and selection issues. So, an instrumental variable (IV) is used in some of the regressions. Inspired by Kortum and Lerner (2000), the IV is based on the deregulation of pension funds in 1979, as highlighted in Section 15. The deregulation of pension funds reduced the fundraising costs of VC and led to increasing VC investment in all industries. In addition, industries that relied more on external finance enjoyed a stronger boost in VC funding.<sup>1</sup> Hence, a cross term between a “deregulation dummy” and a variable reflecting the industry’s (in which the firm operates) dependence on external finance is introduced as an IV. The deregulation dummy takes the value of 1 after 1979. The dependence on external finance is a Rajan-Zingales type measure that reflects the extent to which outside funds are used in the industry for expenditures

<sup>1</sup> This is revealed by the first stage results of the IV regressions. Though the first stage results are not presented due to space limitations, they can be sent upon request.

on property, plant and equipment, R&D, advertising, and employee training. In all of the regressions, controls are added for the number of patents held by the firm at the beginning of the year, the age of the firm, and the total amount of private- and federally-funded R&D of the industry in which the firm operates. Additionally, both a year dummy and an industry dummy (at 2-digit SIC) are entered. Last, since both innovation and VC activities are remarkably clustered in California and Massachusetts, a “cluster dummy” for a firm headquartered in California and Massachusetts is included.

The results of the regression analysis are reported in Table 3. Panel A of Table 3 conducts the analysis along the extensive margin; that is, whether the firm obtains any patents 3 years after receiving VC funding. In regressions (1) and (2), the dependent variable is a dummy that takes the value of 1 if the firm files any successful patent applications at the U.S. Patents and Trademark Office (USPTO) within the 3 years following funding. Regressions (3) and (4) focus on “breakthrough” patents, a measure pioneered by Kerr (2010). Breakthrough patents refer to those in the right tail of the citation distribution. Here the dependent variable in regressions (3) and (4) is a dummy variable that takes the value of 1 if the firm files any patents in the top 10 percent of the citation distribution in its cohort (i.e., those patents with the same technological class and same application year) within the 3 years following funding. Panel B of Table 3 turns to the intensive margin. In regressions (5) and (6) the dependent variable is (the natural logarithm of) the number of patents within the 3 years ensuing the firm’s funding. The (natural logarithm of the) number of patents is weighted by citations in regressions (7) and (8).

As shown by the positive regression coefficients of VC funding in Panel A, a firm is more likely to file a patent and come up with a breakthrough patent the larger is the funding from a venture capitalist, although the impact of VC funding is somewhat smaller in spurring breakthrough patents than ordinary patents. According to the IV estimates in regressions (6) and (8), a 10 percent increase in VC funding will induce a boost, in the 3 years subsequent to funding, of 7.9 percent in patenting and 7.5 percent in quality-adjusted patenting. In addition, across all the regressions in Table 3, the estimates are consistently

# VC FUNDING AND PATENTING

<i>Panel A: Firm-Level Regressions, Extensive Margin Analysis</i>				
<i>Dependent variable</i>	$1\{\text{Patent} > 0\}$		$1\{\text{"Breakthrough patent"} > 0\}$	
	Probit	IV	Probit	IV
	(1)	(2)	(3)	(4)
$\ln(\text{firm VC funding})$	0.126*** (0.0123)	0.610*** (0.0932)	0.125*** (0.0118)	0.525*** (0.123)
+ controls				
Observations	7,589	7,589	7,589	7,589
<i>Panel B: Firm-Level Regressions, Intensive Margin Analysis</i>				
<i>Dependent variable</i>	$\ln(\text{Patent})$		$\ln(\text{Patent, quality adj})$	
	OLS	IV	OLS	IV
	(5)	(6)	(7)	(8)
$\ln(\text{firm VC funding})$	0.137*** (0.0107)	0.792*** (0.233)	0.182*** (0.0173)	0.748** (0.369)
+ controls				
Observations	5,538	5,538	4,958	4,958
R-squared	0.244		0.135	

Table 3: See the main text for a description of the dependent and independent variables. Standard errors are in parentheses. \*\*\* denotes significance at the 1 percent level, \*\* at the 5 percent level.

higher in the IV regressions.

**Impact of Venture Capital on Industry Growth.** How does VC affect growth at the industry level? Attention is now turned to evaluating the impact of VC funding on the growth of industries between 1970 and 2011. The main explanatory variable is the (natural logarithm of the) amount of VC funding each industry receives in each year. The dependent variables are the average annual growth rate of employment and sales for the 3 year period after an industry receives VC funding.<sup>2</sup> In all the regressions, controls are added for logged employment in each industry, year dummies, and industry dummies (at 2-digit SIC). An instrumental variable (IV) is applied to address the issues of measurement errors and selection bias in the OLS regressions. As detailed earlier, the IV is a cross term between the deregulation dummy and a variable reflecting the industry’s dependence on external

<sup>2</sup> The employment and sales information is based on the NBER-CES Manufacturing Industry Database available at <https://www.nber.org/nberces/>.

VC FUNDING AND INDUSTRY GROWTH				
<i>Dependent variable</i>	<i>Employment growth</i>		<i>Sales Growth</i>	
	OLS	IV	OLS	IV
	(1)	(2)	(3)	(4)
ln(industry VC funding)	0.00338*** (0.000748)	0.00608*** (0.00178)	0.00495*** (0.000958)	0.00898*** (0.00228)
ln(employment)	-0.00646*** (0.00161)	-0.00817*** (0.00189)	-0.00476** (0.00207)	-0.00730*** (0.00243)
+ controls				
Observations	1,909	1,909	1,909	1,909
R-squared	0.285		0.334	

Table 4: See the main text for a description of the dependent and independent variables. Standard errors are in parentheses. \*\*\* denotes significance at the 1 percent level.

finance.

As demonstrated in Table 4, increasing VC funding in an industry in a given year is associated with a higher growth rate of employment and sales in the subsequent 3 years. According to the IV regressions (2) and (4), a one-standard-deviation increase in logged industry-level VC funding is associated with increases of 1.3 and 1.9 percentage points in annual employment and sales growth following funding. As complementary evidence on the cyclicity of VC activities, Khan and Petratos (2016) document that VC-backed firm entry (the number of startups) and exit (the number of IPOs and M&As) are respectively almost three and five times as volatile as business fixed investment.

### 3 The Setting

At the center of the analysis is the interplay between an entrepreneur and a venture capitalist, which is governed by an incentive-compatible financial contract. Entrepreneurs have ideas, but no money, while venture capitalists have expertise and money, but no ideas. Each period new entrepreneurs bring ideas of their choosing to a venture capitalist to obtain funding. The parties sign a partnership agreement that has finite duration. Most VC enterprises are operated as partnerships. The share of corporate venture programs in total U.S. VC

investment is low, averaging just 9 percent between 1995 and 2015. Also, corporate VC faces many of same challenges as VC partnerships; viz., the uncertainty about a project's quality, the decision about how much to invest at each stage of the development process based on limited information, and the moral hazard problem connected with lending.

At the time the contract is signed, the venture capitalist provides seed money to research initially the idea. After this initial research is finished, the project enters a funding-round cycle that may last for many periods. Some ideas brought by entrepreneurs to the venture capitalist are good, others are bad. Only a good idea has a payoff, and even then this might not happen. Neither party knows whether an idea is good or bad. So, at the beginning of each funding round the venture capitalist evaluates the project at a cost in an attempt to detect whether the venture is bad. Bad projects are terminated. Projects that aren't known to be bad are given development money. The probability of success within a funding round is an increasing function of the level of investment in development undertaken by the entrepreneur. How much of the money the entrepreneur actually uses for development is private information. The venture capitalist can imperfectly monitor development investment at a cost in an attempt to detect any malfeasance. When malfeasance is detected, the venture capitalist drops the venture. If successful, the project will be floated on the stock market or sold to another firm, which yields a reward that will be a function of the idea's type. The reward is split between the entrepreneur and venture capitalist as specified by the partnership agreement. Any profits from floating a VC-funded enterprise are subject to capital gains taxation. All revenue from capital gains taxation is rebated back to the populace in lump-sum transfer payments. If the project is not successful, then it enters another funding round, provided the contract has not expired, and the funding cycle goes on. At the time a contract expires, an unsuccessful surviving project can be sold by the venture capitalist for scrap. The timing of events within a generic funding round is shown in Figure 4.

The analysis focuses on a balanced-growth path. The aggregate level of productivity in the VC sector is denoted by  $\mathbf{x}$ , which represents the aggregate state of the economy. Along



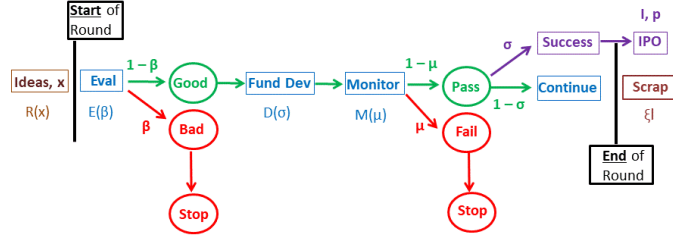


Figure 4: The timing of events within a typical funding round. The research underlying the idea occurs at the very beginning of the funding cycle, or round 0, and is shown to the left of generic funding round. A surviving project can be sold for scrap at the end of the contract, or at the end of round  $T$ , as shown to the right of the typical funding round.

a balanced-growth path,  $\mathbf{x}$  will grow at the gross rate  $\mathbf{g}_\mathbf{x} > 1$  so that

$$\mathbf{x}' = \mathbf{g}_\mathbf{x} \mathbf{x}.$$

The gross growth rate of aggregate productivity,  $\mathbf{g}_\mathbf{x}$ , is an endogenous variable in equilibrium. It will be a function of the efficiency of the VC system. The gross growth rate in wages,  $\mathbf{g}_w$ , will be a function of the growth rate of aggregate productivity,  $\mathbf{g}_\mathbf{x}$ . The discussion now proceeds by detailing the stages portrayed in Figure 4.

### 3.1 The Research Stage—Starting a New Venture

Each period an inflow of new entrepreneurs in the amount  $\epsilon$  approach venture capitalists to obtain funding for their ideas. An entrepreneur incurs an opportunity cost in the amount  $w\sigma$  to run a project, where  $w$  is the wage rate for labor. The component  $\sigma$  of this cost is distributed across potential entrepreneurs according to the non-normalized distribution

function,  $O(o)$ . This distribution function  $O(o)$  is assumed to be Pareto so that

$$O(o) = 1 - (v/o)^\nu, \text{ with } \nu, v > 0. \quad (1)$$

Only those potential entrepreneurs who expect the payoff from a startup to exceed their opportunity cost,  $wo$ , will approach a venture capitalist for funding. This criterion determines the number of funded entrepreneurs,  $e$ .

A new entrepreneur is free to choose the type of startup,  $x$ , that he wants to develop. In particular, when deciding on the project, the entrepreneur picks  $x$  subject to a research cost function of the form

$$i = R\left(\frac{x}{\mathbf{x}}\right) = w\left(\frac{x}{\mathbf{x}}\right)^\iota / \chi_R,$$

where  $i \geq 0$  is the initial investment in researching the project. The entrepreneur can choose how far ahead the productivity of his firm,  $x$ , is from the average level of productivity in the VC sector,  $\mathbf{x}$ . The more ambitious he is, or the higher  $x$  is relative to  $\mathbf{x}$ , the greater will be the research cost, which rises in convex fashion. The cost of research,  $R(x/\mathbf{x})$ , rises with the current level of wages,  $w$ , which will be a function of the aggregate state of the economy,  $\mathbf{x}$ . (Think about  $R(x/\mathbf{x})/w$  as representing the cost in terms of labor.) This structure provides a mechanism for endogenous growth in the model.

### 3.2 The Evaluation Stage

Out of the pool of *new* entrepreneurs, the fraction  $\rho$  will have good ideas, implying that the fraction  $1 - \rho$  have bad ones. The venture capitalist can potentially discover a bad project by evaluating it. Assume that the venture capitalist can detect within each funding round a bad project with probability  $\beta$ , according to the cost function,  $E(\beta; \mathbf{x})$ , where  $E$  is an increasing, convex function in  $\beta$ . Specifically,

$$E(\beta; \mathbf{x}) = w\left(\frac{1}{1 - \beta} - 1\right)\beta / \chi_E.$$

The productivity of the evaluation process is governed by  $\chi_E$ . Note that the marginal cost of evaluating starts at zero when  $\beta = 0$  and goes to infinity as  $\beta$  approaches 1. The cost of evaluating rises with the level of wages,  $w$ . Think about  $\chi_E$  as capturing the efficiency of investment in evaluation. Projects that are detected to be bad are thrown out.

### 3.3 The Development Stage

Ventures that pass the evaluation stage are given development funding. The level of funding depends upon the common prior (held by the entrepreneur and venture capitalist) that the project is good, which evolves across funding rounds. The odds of success during a funding round depend on the entrepreneur's investment in development. In particular, a probability of success,  $\sigma$ , can be secured by undertaking development investment in the amount  $D(\sigma; \mathbf{x})$ , where  $D$  is an increasing, convex function in  $\sigma$ . The development cost function  $D(\sigma; \mathbf{x})$  is given the form

$$D(\sigma; \mathbf{x}) = w \left( \frac{1}{1 - \sigma} - 1 \right) \sigma / \chi_D.$$

The development cost function  $D(\sigma; \mathbf{x})$  has a similar form to that for  $E(\beta; \mathbf{x})$ .

There is also a fixed cost,  $\phi_t$ , connected with developing a startup project in round  $t$ . This fixed cost rises with the level of wages in the economy. In particular,

$$\phi_t = w_1 \mathbf{g}_w^{t-1} \phi(t),$$

where  $w_1$  represents the round-1 wage rate and  $\mathbf{g}_w > 1$  is the gross growth rate in wages (which will be a function of  $\mathbf{g}_x$ ). Additionally, the fixed cost changes by the round of the project, as reflected by the function  $\phi(t)$ . The shape of the function  $\phi(t)$  will be parameterized using a polynomial that is pinned down from the U.S. VC funding-round data.

### 3.4 The Monitoring Stage

The venture capitalist provides in a funding round the amount  $D(\sigma; \mathbf{x})$  for development. The entrepreneur may decide to spend some smaller amount  $D(\tilde{\sigma}; \mathbf{x}) \leq D(\sigma; \mathbf{x})$  and siphon off the difference,  $D(\sigma; \mathbf{x}) - D(\tilde{\sigma}; \mathbf{x})$ . The entrepreneur uses the difference in funds for his own consumption. By diverting funds the entrepreneur reduces the odds of success in the current funding round; i.e.,  $\tilde{\sigma} \leq \sigma$ . The venture capitalist can dissuade this fraud by engaging in monitoring. Assume that the venture capitalist can pick the odds  $\mu$  of detecting fraud in a venture during round  $t$  according to the strictly increasing, convex cost function,  $M_t(\mu; \mathbf{x})$ , where

$$M_t(\mu; \mathbf{x}) = w_1 \mathbf{g}_w^{t-1} \left( \frac{1}{1-\mu} - 1 \right) \mu / \chi_{M,t}.$$

This flexible monitoring technology is borrowed from Cole, Greenwood, and Sanchez's (2016). It implies that the more the venture capitalist invests in auditing, the higher the odds that he will detect any irregularities. The cost of monitoring rises with wages in the economy. Additionally, monitoring costs change by the round of the project, as reflected by the term  $\chi_{M,t}$ ; again,  $\chi_{M,t}$  represents the productivity of this auditing process in round  $t$ . Presumably, as the venture capitalist becomes more familiar with the project,  $\chi_{M,t}$  will rise with  $t$ . This feature implies that the incentive problem will become less severe over time and helps to generate an upward-sloping funding profile. A polynomial for  $\chi_{M,t}$  will be fit to the U.S. VC funding-round data.

While motivated by the prototypical costly-state-verification paradigms of Townsend (1979) and Williamson (1986), the monitoring technology employed here is different. In those frameworks, getting monitored is a random variable—in Williamson (1986) only those entrepreneurs declaring a bad outcome are monitored, while in Townsend (1979) some fraction of such entrepreneurs are. The audit will detect any fraud with certainty. By contrast, here everybody gets monitored, but the detection of any fraud is a probabilistic event. Also, as will be discussed, a venture capitalist will always monitor his investment, unlike in Bergemann and Hege (1998). According to Bernstein, Giroud, and Townsend (2016) and

Lerner (1998), venture capitalists devote a considerable amount of time to overseeing their investments—this fact is returned to in Section 9.

### 3.5 The Success Stage—Floated Firms

A startup of type  $x$  turns into a going concern with productivity  $x$ , if successful. A successful VC-backed firm produces output,  $o$ , according to the production process

$$o = x^\zeta k^\kappa l^\lambda, \text{ with } \zeta + \kappa + \lambda = 1, \quad (2)$$

where  $k$  and  $l$  are the amounts of capital and labor used in production. This structure is borrowed from Akcigit, Celik, and Greenwood (2016). It results in the firm earning pure profits that are linear in its productivity,  $x$ . The lure of capturing these profits is what motivates entrepreneurs and venture capitalists. Labor is hired at the wage rate,  $w$ , and capital at the rental rate,  $r$ . The firm's per period net takings are

$$\begin{aligned} T(x; \mathbf{x}) &= \max_{k,l} \{x^\zeta k^\kappa l^\lambda - rk - wl\} \\ &= x(1 - \kappa - \lambda) \left[ \left( \frac{\kappa}{r} \right)^\kappa \left( \frac{\lambda}{w} \right)^\lambda \right]^{1/\zeta}. \end{aligned} \quad (\text{P1})$$

Clearly, as wages rise, which will be a function of the aggregate state of the economy,  $\mathbf{x}$ , net takings will shrink for a given level of the firm's productivity,  $x$ . Operating firms last stochastically in accordance with the time-invariant survival rate,  $\mathfrak{s}$ .

A successful VC-backed project is sold for  $I(x; \mathbf{x})$ , either through an IPO or an M&A, just before production starts. The (gross) reward for a successful IPO is

$$I(x; \mathbf{x}) = \sum_{t=1}^{\infty} (\mathfrak{s}\delta)^{t-1} T(x; \mathbf{g}_{\mathbf{x}}^{t-1} \mathbf{x}), \quad (3)$$

where  $\delta$  is the market discount factor. If the startup is successful, the entrepreneur must pay the venture capitalist the amount  $p$ . So the entrepreneur will reap the amount  $I(x; \mathbf{x}) - p$ ,

which is taxed at the capital gains rate,  $\tau$ . If a project is not successful, it moves back to the evaluation stage, assuming that the contract has not expired. An ongoing project that has not been successful by the time the contract expires at end of round  $T$  can be sold by the venture capitalist for scrap value. The scrap value for a project in the current period is  $\xi I(x; \mathbf{x})$ , where  $0 < \xi < 1$ .

## 4 The Financial Contract

The financial contract between the entrepreneur and the venture capitalist is cast now. VC is a competitive industry so the entrepreneur shops around to secure the financial contract with the best terms. Venture capitalists cover the cost of research, evaluation, development, and monitoring. They raise the money to do this from savers, to whom they promise a gross rate of return of  $1/\delta$ . There are no profits on VC activity in equilibrium. The profits that accrue to the entrepreneur are subject to the rate of capital gains taxation,  $\tau$ . The analysis presumes that there is a maximum of  $T$  rounds of potential funding. The timing of events for the contract is shown in Figure 4. The research for the idea is done at the start of the funding-round cycle or in round zero. At the beginning of a generic funding round, the venture capitalist evaluates projects and purges the ones that are found to be bad. Good projects are then given an injection of cash for development. The venture capitalist monitors the use of these funds. If malfeasance is detected, the project is terminated. Some projects will be successful. These are floated in the next period on the stock market. The unsuccessful projects then start another funding round, assuming the number of funding rounds doesn't exceed  $T$ . At the end of round  $T$ , any unsuccessful surviving projects can be sold by the venture capitalist for scrap.

Let  $\beta_t$  represent the odds of detecting a bad project in round  $t$  and  $\sigma_t$  denote the probability of success for a good project. Now suppose that a unit measure of new entrepreneurs approaches a venture capitalist for funding. As the funding rounds progress, the numbers of good and bad projects will evolve as shown in Table 5. For example, of the entrepreneurs ini-

EVOLUTION OF PROJECT TYPES ACROSS FUNDING ROUNDS		
<i>Round</i>	<i>Number good</i>	<i>Number bad</i>
1	$\rho$	$(1 - \rho)(1 - \beta_1)$
2	$\rho(1 - \sigma_1)$	$(1 - \rho)(1 - \beta_1)(1 - \beta_2)$
3	$\rho(1 - \sigma_1)(1 - \sigma_2)$	$(1 - \rho)(1 - \beta_1)(1 - \beta_2)(1 - \beta_3)$
$\vdots$	$\vdots$	$\vdots$
$t$	$\rho \prod_{j=1}^{t-1} (1 - \sigma_j)$	$(1 - \rho) \prod_{j=1}^t (1 - \beta_j)$

Table 5: The table shows how the number of good and bad projects change across funding rounds assuming that the venture capitalist starts with a unit mass of ventures.

tially applying for funding, the number  $\rho$  will have good projects and  $1 - \rho$  will have bad ones. In round 1 the venture capitalist will evaluate the applicants and eliminate  $(1 - \rho)\beta_1$  bad projects, so that  $(1 - \rho)(1 - \beta_1)$  bad ones will still remain. Of the good projects, the number  $\rho\sigma_1$  will be successful. So, at the beginning of the second round there will be  $\rho(1 - \sigma_1)$  good projects in the pool. After the second-round evaluation,  $(1 - \rho)(1 - \beta_1)(1 - \beta_2)$  bad projects will still be around. Table 5 specifies how the number of good and bad projects evolves over funding rounds. As can be seen, the number of good and bad projects in funding-round  $t$  are given by  $\rho \prod_{j=1}^{t-1} (1 - \sigma_j)$  and  $(1 - \rho) \prod_{j=1}^t (1 - \beta_j)$ , respectively.

The odds of a project being good in round  $t$  are

$$\Pr(\text{Good}|\text{Round} = t) = \frac{\rho \prod_{j=1}^{t-1} (1 - \sigma_j)}{\rho \prod_{j=1}^{t-1} (1 - \sigma_j) + (1 - \rho) \prod_{j=1}^t (1 - \beta_j)}. \quad (4)$$

As time goes by, more and more bad projects are purged from the pool. The number of goods projects will also fall due to the successes. Thus, the odds of being good can rise or fall with the funding round, depending on which type of projects are exiting the pool the fastest, at least theoretically. Without the evaluation technology the odds of a project being good must decline by funding round, since then  $\beta_j = 0$  for all  $j$ . By this account, the venture capitalist should invest less in a startup as funding rounds progress, something at odds with the data as discussed by Lerner (1998). The introduction of the evaluation technology admits the possibility that “lemons ripen faster than plums.”

The optimal contract between the entrepreneur and the venture capitalist will specify

for the length of the relationship: (i) the precision of evaluation, as given by the  $\beta_t$ 's; (ii) the investments in development as reflected by the  $\sigma_t$ 's; (iii) the exactness of monitoring as measured by the  $\mu_t$ 's; and (iv) the payments that an entrepreneur who finds success in round  $t$  must make to the intermediary, or the  $p_t$ 's. The agreement is formulated in sequence space as opposed to a recursive representation; e.g., Clementi and Hopenhayn (2006). Note that for a recursive representation to be valid it must also satisfy its underlying sequence space problem. The optimal contract is summarized by the outcome of the following maximization problem:

$$C(x; \mathbf{x}) = \max_{\{\beta_t, \sigma_t, \mu_t, p_t\}} (1 - \tau) \sum_{t=1}^T \rho \Pi_{j=1}^{t-1} (1 - \sigma_j) \delta^t \sigma_t [I(x; \mathbf{g}_{\mathbf{x}}^t \mathbf{x}) - p_t], \quad (\text{P2})$$

subject to:

1. The round- $t$  incentive constraints

$$\begin{aligned} & \Pr(\text{Good} | \text{Round} = t) \times (1 - \tau) \times \{\delta \sigma_t [I(x; \mathbf{g}_{\mathbf{x}}^t \mathbf{x}) - p_t] \\ & + (1 - \sigma_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_{\mathbf{x}}^i \mathbf{x}) - p_i]\} \\ & \geq (1 - \mu_t) \max_{\tilde{\sigma}_t} \left( D(\sigma_t) - D(\tilde{\sigma}_t) \right. \\ & + \Pr(\text{Good} | \text{Round} = t) \times (1 - \tau) \times \{\delta \tilde{\sigma}_t [I(x; \mathbf{g}_{\mathbf{x}}^t \mathbf{x}) - p_t] \\ & \left. + (1 - \tilde{\sigma}_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_{\mathbf{x}}^i \mathbf{x}) - p_i]\} \right), \end{aligned} \quad (5)$$

for  $t = 1, \dots, T$ , where  $\Pr(\text{Good} | \text{Round} = t)$  is given by (4);



## 2. The round-0 zero-profit condition

$$\begin{aligned}
& \rho \sum_{t=1}^T \Pi_{j=1}^{t-1} (1 - \sigma_j) \delta^t \sigma_t p_t + \rho \Pi_{j=1}^T (1 - \sigma_j) \delta^T \xi I(x; \mathbf{g}_x^T \mathbf{x}) \\
& - \sum_{t=1}^T [\rho \Pi_{j=1}^{t-1} (1 - \sigma_j) + (1 - \rho) \Pi_{j=1}^t (1 - \beta_j)] \delta^{t-1} [D(\sigma_t) + \phi_t + M_t(\mu_t)] \\
& - \sum_{t=1}^T [\rho \Pi_{j=1}^{t-1} (1 - \sigma_j) + (1 - \rho) \Pi_{j=1}^t (1 - \beta_j)] \delta^{t-1} E(\beta_t) - R\left(\frac{x}{\mathbf{x}}\right) = 0.
\end{aligned} \tag{6}$$

The objective function in (P2) reflects the fact that VC is a competitive industry. A contract must maximize the expected return for the entrepreneur, subject to the two constraints (5) and (6). The term  $I(x; \mathbf{g}_x^t \mathbf{x}) - p_t$  gives the payoff to the entrepreneur should the enterprise be floated in round  $t$ . The payoff could come from executing stock options or convertible shares. It is taxed at the capital gains rate,  $\tau$ . The maximized value of objective function,  $C(x; \mathbf{x})$ , specifies the worth of the financial contract for the entrepreneur. This expected discounted payoff is a function of the entrepreneur's idea,  $x$ .

Equation (5) is the incentive compatibility constraint for a round- $t$  project. The left-hand side gives the expected return to the entrepreneur when he undertakes the level of development investment linked with  $\sigma_t$ . The term  $\Pr(\text{Good} | \text{Round} = t)$  represents the Bayesian odds of having a good project at the beginning of round  $t$ , conditional on the entrepreneur still dealing with the venture capitalist. The right-hand side gives the return when the entrepreneur deviates and picks the level of development linked with  $\tilde{\sigma}_t$ . The level of development represented by  $\tilde{\sigma}_t$  maximizes the value of the deviation. The return from deviating will only materialize if the entrepreneur is not caught cheating, which has the odds  $1 - \mu_t$ ; if caught cheating, which occurs with probability  $\mu_t$ , then the contract is terminated and the entrepreneur receives nothing. The incentive constraint has a dynamic element to it. If the entrepreneur invests less in development today, he lowers the odds that a good project will be successful in the current period. He increases the probability that a success,

if it happens, will occur in the future; thus, an intertemporal tradeoff is involved.

The last equation, or (6), is the zero-profit constraint. The first two terms are the expected present value of the cash that the venture capitalist expects to receive. This includes any scrap value. The remaining terms are the venture capitalist's expected costs. Observe that there is a fixed cost,  $\phi_t$ , connected with operating a startup project in round  $t$ . Last, the venture capitalist must cover the initial research cost,  $R(x/\mathbf{x})$ . Since VC is a competitive industry, the expected present value of the cash inflow exactly offsets the expected present value of the cash outflow.

Now, it is easy to see that the ability of the venture capitalist to monitor the entrepreneur is important. Focus on the incentive constraint (5). If  $\mu_t = 1$ , say because the cost of monitoring is zero, then the left-hand side of the constraint will always exceed the right-hand side. This transpires no matter what the solution for  $\tilde{\sigma}_t$  is, as dictated by the right-hand side of (5). In this situation, the first-best solution to problem (P2) can be obtained. Alternatively, suppose  $\mu_t = 0$ , because the cost of monitoring is infinite. Then, the incentive-compatible contract specifies that  $\sigma_t = \tilde{\sigma}_t$ . To see this, pull the  $D(\sigma_t)$  term over onto the left-hand side of (5). Note that the terms on the left- and right-hand sides are then the same, except that they involve  $\sigma_t$  on the left and  $\tilde{\sigma}_t$  on the right. But  $\tilde{\sigma}_t$  maximizes the right-hand side, implying that the right-hand side must then equal the left-hand side. This can only be the case if  $\sigma_t = \tilde{\sigma}_t$ , which greatly limits the contract and may result in an allocation far from first-best. So if no monitoring is done, then the incentive constraint holds tightly. Why can't the incentive constraint be slack? Suppose it is slack, implying that the associated Lagrange multiplier is zero. Then, no monitoring will be done because it would have no benefit and is costly. But, as just discussed, when  $\mu_t = 0$ , the constraint must hold tightly—a contradiction. Therefore, the incentive constraint (5) always binds.

**Lemma 1** *(Always monitor) The incentive constraint (5) holds tightly for all funding rounds with  $0 < \mu_t < 1$ .*

**Remark 1** *(One-shot versus multi-shot deviations) The incentive constraints in (5) prevent one-shot deviations from occurring in any funding round. Lemma 4 in the Theory Appendix*

establishes that this is equivalent to using a single consolidated round-0 incentive constraint with multi-shot deviations.

**Remark 2** (*Self financing*) *If an entrepreneur has any funds, he should invest them all. This does not change the generic form of the contract problem. The entrepreneur's funds can merely be subtracted from the expected present value of the fixed costs, or the  $\phi_t$ 's, in (6). (See Cole, Greenwood, and Sanchez (2016, Lemmas 1 and 6)). What matters is how much the entrepreneur borrows, net of his own investment. The entrepreneur's funds can be incorporated in problem (P2) by simply transforming the fixed costs.*

## 5 The Choice of Idea

The entrepreneur is free to pick the type of venture,  $x$ , that he pitches to the venture capitalist. He selects the one that maximizes his expected discounted profits. Therefore,  $x$  will solve

$$V(\mathbf{x}) = \max_x C(x; \mathbf{x}), \tag{P3}$$

where the value of the entrepreneur's contract, or  $C(x; \mathbf{x})$ , is specified by problem (P2). The shape of the  $C(x; \mathbf{x})$  function determines the value of  $x$  picked by the entrepreneur. So if better intermediation increases the marginal return from  $x$ , then VC will increase growth. Note that the cost of researching  $x$ , or  $R(x/\mathbf{x})$ , is embedded in the zero-profit condition (6) connected with problem (P2). This problem will give a decision rule of the form

$$x = X(\mathbf{x})\mathbf{x}.$$

The function  $V(\mathbf{x})$  gives an entrepreneur's expected discounted payoff from a startup.

## 6 The Inflow of New Startups

Recall that an entrepreneur incurs an opportunity cost in the amount  $w\mathfrak{o}$  to run a project. Therefore, only those new entrepreneurs with  $w\mathfrak{o} \leq V(\mathbf{x})$  will choose to engage in a startup. Now,  $\mathfrak{o}$  is distributed according to the cumulative distribution function  $O(\mathfrak{o})$ . Therefore,  $O(V(\mathbf{x})/w)$  entrepreneurs will approach the venture capitalist for funding. Consequently, the number of new entrants,  $\mathfrak{e}$ , is given by

$$\mathfrak{e} = O(V(\mathbf{x})/w). \quad (7)$$

## 7 The Non-VC-Funded Sector

Most firms are not funded by venture capitalists. To capture this, suppose there are always  $\mathfrak{m}$  firms operating that were not funded by VC. All firms in the non-VC-funded sector are same. These non-VC-funded firms produce using a production function that is identical to a VC-funded firm with one exception: their productivity differs. Specifically, they produce in line with

$$o = z^\zeta k^\kappa l^\lambda, \text{ with } \zeta + \kappa + \lambda = 1,$$

where  $z$  represents their productivity. Suppose that

$$z = \omega \mathbf{x}, \text{ with } \omega < 1.$$

Thus, firms in the non-VC-funded segment of the economy are on average less productive than the ones in the VC segment, but will be dragged along by the latter. Average productivity in the VC sector is defined in Section 8. For more micro-founded theories about how ideas diffuse through an economy (either by buying or imitating them) see Akcigit, Celik, and Greenwood (2016), Jovanovic and MacDonald (1994), Lucas and Moll (2014), and Perla and Tonetti (2014).

The non-VC-funded firm's profit maximization problem is

$$\max_{k,l} \{z^\zeta k^\kappa l^\lambda - rk - wl\}. \quad (8)$$

One can think about these firms as raising the funds for capital through traditional intermediation at the gross interest rate  $1/\delta$ . VC-funded firms also raise capital this way after they are floated. On this, Midrigan and Xu (2014) argue that producing establishments can quickly accumulate funds internally and thus rapidly grow out of any borrowing constraints. Therefore, modeling producing firms as having frictionless access to capital markets may not be grossly at variance with reality—Moll (2014) discusses how the ability to self-finance is tied with the degree of persistence in technology shocks.

## 8 Balanced-Growth Equilibrium

The analysis focuses on analyzing a balanced-growth path for the model. Along a balanced-growth path, the rental rate on capital,  $r$ , is some fixed number. In particular, the rental rate on capital will be

$$r = 1/\delta - \mathfrak{d}, \quad (9)$$

where  $\delta$  is the market discount factor and  $\mathfrak{d}$  is the depreciation factor on capital. In balanced growth, the market discount factor,  $\delta$ , is given by

$$\delta = \widehat{\delta} \mathbf{g}_w^{-\varepsilon}, \quad (10)$$

where  $\widehat{\delta}$  is the representative agent's discount factor and  $\varepsilon$  denotes his coefficient of relative risk aversion.<sup>3</sup>

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<sup>3</sup> That is, in the background there is a representative consumer/worker who inelastically supplies one unit of labor and has a utility function (in period 1) of the form

$$\sum_{t=1}^{\infty} \widehat{\delta}^{t-1} c_t^{1-\varepsilon} / (1-\varepsilon),$$

The idea distribution for VC-backed firms will now be characterized. To this end, let  $\mathbf{n}_t$  represent the number of VC-backed firms that are operating with an idea,  $x_{-t}$ , that was generated  $t$  periods ago. Attention will now be turned to specifying the number  $\mathbf{n}_t$ . Now, no firms will operate in the VC-backed sector with productivity level  $x$ , since this type is not operational yet. Each period,  $\epsilon$  new entrepreneurs will be funded by the venture capitalist. Hence,  $\mathbf{n}_1 = \epsilon\rho\sigma_1$  firms will operate with an idea generated one period ago,  $x_{-1}$ . Likewise, there will be  $\mathbf{n}_2 = \epsilon\rho\sigma_1\mathfrak{s} + \epsilon\rho(1 - \sigma_1)\sigma_2$  firms operating with a two-period-old idea,  $x_{-2}$ . So, the number of firms operating with an idea,  $x_{-t}$ , from  $t \leq T$  periods ago is

$$\mathbf{n}_t = \epsilon \sum_{i=1}^t \rho \prod_{j=1}^{i-1} (1 - \sigma_j) \sigma_i \mathfrak{s}^{t-i}, \text{ for } t = 1, \dots, T. \quad (11)$$

The venture capitalist only funds entrepreneurs for  $T$  periods. Consequently, the number of operational firms with an idea from more than  $T$  periods ago is

$$\mathbf{n}_{T+j} = \mathfrak{s}^j \mathbf{n}_T, \text{ for } j \geq 1. \quad (12)$$

The total number of operational VC-backed firms,  $\mathbf{n}$ , is given by

$$\mathbf{n} = \sum_{t=1}^T \mathbf{n}_t + \sum_{t=T+1}^{\infty} \mathbf{n}_t = \sum_{t=1}^T \mathbf{n}_t + \frac{\mathbf{n}_T \mathfrak{s}}{1 - \mathfrak{s}}.$$

In a stationary equilibrium the distribution function over VC-funded firms using an age- $t$  idea will remain constant; that is,  $\mathbf{n}'_t = \mathbf{n}_t$ . It is easy to see from (11) that this will be true provided that  $\epsilon$  and the  $\sigma_i$ 's are constant.

In balanced growth the wage rate,  $w$ , will grow at some constant gross rate,  $\mathbf{g}_w$ . To determine this growth rate, note that a VC-funded firm with productivity level  $x$  will hire labor in the amount

$$l(x; w) = \left(\frac{\kappa}{r}\right)^{\kappa/\zeta} \left(\frac{\lambda}{w}\right)^{(\zeta+\lambda)/\zeta} x, \quad (13)$$

---

where  $c_t$  is his period- $t$  consumption.

where again  $w$  and  $r$  are the current wage and rental rates, respectively. For a non-VC-funded firm, just replace the  $x$  with a  $z$  in the above formula. In general equilibrium, the labor market must clear each period. Suppose that there is one unit of labor available in aggregate. To calculate the aggregate demand for labor, sum over all operating firms' demands for labor, both in the VC- and non-VC-backed sectors. Equilibrium in the labor market requires that

$$\sum_{t=1}^T \mathbf{n}_t l(x_{-t}; w) + \sum_{t=T+1}^{\infty} \mathbf{n}_t l(x_{-t}; w) + \mathbf{m} l(z; w) = 1,$$

where  $\mathbf{m}$  is the measure of firms in the non-VC-funded sector. Along a balanced-growth path, the productivity of the latest idea will grow at rate  $\mathbf{g}_\mathbf{x}$ . Therefore, the above condition can be recast as

$$\sum_{t=1}^T \mathbf{n}_t l(x_{-1} \mathbf{g}_\mathbf{x}^{1-t}; w) + \sum_{t=T+1}^{\infty} \mathbf{n}_t l(x_{-1} \mathbf{g}_\mathbf{x}^{1-t}; w) + \mathbf{m} l(\omega \mathbf{x}; w) = 1.$$

Using equations (12) and (13), this can be expressed as

$$\left(\frac{\kappa}{r}\right)^{\kappa/\zeta} \left(\frac{\lambda}{w}\right)^{(\zeta+\lambda)/\zeta} [x_{-1} (\sum_{t=1}^T \mathbf{n}_t \mathbf{g}_\mathbf{x}^{1-t} + \frac{\mathbf{n}_T \mathfrak{s} \mathbf{g}_\mathbf{x}^{-T}}{1 - (\mathfrak{s}/\mathbf{g}_\mathbf{x})}) + \mathbf{m} \omega \mathbf{x}] = 1.$$

The solution for wages,  $w$ , obtained from the above labor-market clearing condition, is

$$w = \lambda \left(\frac{\kappa}{r}\right)^{\kappa/(\zeta+\lambda)} \underbrace{[x_{-1} (\sum_{t=1}^T \mathbf{n}_t \mathbf{g}_\mathbf{x}^{1-t} + \frac{\mathbf{n}_T \mathfrak{s} \mathbf{g}_\mathbf{x}^{-T}}{1 - (\mathfrak{s}/\mathbf{g}_\mathbf{x})}) + \mathbf{m} \omega \mathbf{x}]}_{=\mathbf{n}\mathbf{x}}^{\zeta/(\zeta+\lambda)}, \quad (14)$$

where aggregate productivity in the VC sector,  $\mathbf{x}$ , is

$$\mathbf{x} \equiv \frac{x_{-1} [\sum_{t=1}^T \mathbf{n}_t \mathbf{g}_\mathbf{x}^{1-t} + \mathbf{n}_T \mathfrak{s} \mathbf{g}_\mathbf{x}^{-T} / (1 - (\mathfrak{s}/\mathbf{g}_\mathbf{x}))]}{\sum_{t=1}^T \mathbf{n}_t + \mathbf{n}_T \mathfrak{s} / (1 - \mathfrak{s})} = \frac{x_{-1} [\sum_{t=1}^T \mathbf{n}_t \mathbf{g}_\mathbf{x}^{1-t} + \mathbf{n}_T \mathfrak{s} \mathbf{g}_\mathbf{x}^{-T} / (1 - (\mathfrak{s}/\mathbf{g}_\mathbf{x}))]}{\mathbf{n}}.$$

As can be seen, wages rise with the aggregate state of the economy,  $\mathbf{x}$ , which grows at rate

$\mathbf{g}_x$ . Therefore, wages will grow at the gross growth rate  $\mathbf{g}_x^{\zeta/(\zeta+\lambda)}$ , so that

$$\frac{w'}{w} \equiv \mathbf{g}_w = \mathbf{g}_x^{\zeta/(\zeta+\lambda)}.$$

Attention is now turned to determining the growth rate in aggregate productivity,  $\mathbf{g}_x$ . All new entrepreneurs will pick the same type of project,  $x$ . Now

$$\mathbf{g}_x = \mathbf{x}'/\mathbf{x} = x'/x.$$

Recall that

$$x = X(\mathbf{x})\mathbf{x},$$

and

$$\mathbf{x} = x_{-1} \left[ \sum_{t=1}^T \mathbf{n}_t \mathbf{g}_x^{1-t} + \frac{\mathbf{n}_T \mathfrak{s} \mathbf{g}_x^{-T}}{1 - (\mathfrak{s}/\mathbf{g}_x)} \right] / \mathbf{n}.$$

Therefore,

$$\mathbf{g}_x = \frac{x}{x_{-1}} = \frac{X(\mathbf{x})\mathbf{x}}{x_{-1}} = X(\mathbf{x}) \left[ \sum_{t=1}^T \mathbf{n}_t \mathbf{g}_x^{1-t} + \frac{\mathbf{n}_T \mathfrak{s} \mathbf{g}_x^{-T}}{1 - (\mathfrak{s}/\mathbf{g}_x)} \right] / \mathbf{n}. \quad (15)$$

This is a nonlinear equation in  $\mathbf{g}_x$ .

It is easy to see that the aggregate capital stock and output grow at the same rate as wages. The demand for capital by a type- $x$  VC-backed firm is

$$k(x; w) = \left(\frac{\kappa}{r}\right)^{(1-\lambda)/\zeta} \left(\frac{\lambda}{w}\right)^{\lambda/\zeta} x.$$

From this it is easy to deduce that  $k(\mathbf{g}_x x; \mathbf{g}_w w) = \mathbf{g}_w k(x; w)$ . The same is true for a non-VC-backed firms; just replace  $x$  with  $z$  to get  $k(\mathbf{g}_x z; \mathbf{g}_w w) = \mathbf{g}_w k(z; w)$ . Let the aggregate capital stock in the current period be represented by  $\mathbf{k}$  and that for next period by  $\mathbf{k}'$ . Then  $\mathbf{k}' = \sum_{t=1}^{\infty} \mathbf{n}_t k(\mathbf{g}_x x_{-t}; \mathbf{g}_w w) + \mathbf{m} k(\mathbf{g}_x z; \mathbf{g}_w w) = \mathbf{g}_w [\sum_{t=1}^{\infty} \mathbf{n}_t k(x_{-t}; w) + \mathbf{m} k(z; w)] = \mathbf{g}_w \mathbf{k}$ , so that the aggregate capital stock grows at gross rate  $\mathbf{g}_w$ . A similar argument can be used to show that aggregate output grows at the same rate.



**Definition** (*Balanced-Growth Path*) For a given subjective discount factor and coefficient of relative risk aversion,  $\hat{\delta}$  and  $\varepsilon$ , a balanced-growth path consists of (i) a financial contract,  $\{\beta_t, \sigma_t, \mu_t, p_t\}$ , between entrepreneurs and the venture capitalist; (ii) a set of labor inputs for VC- and non-VC-funded firms,  $l(x; w)$  and  $l(z; w)$ ; (iii) values for the contract, an IPO, and a startup,  $C(x; \mathbf{x})$ ,  $I(x; \mathbf{x})$ , and  $V(\mathbf{x})$ ; (iv) a project type,  $x$ , for new entrepreneurs; (v) an inflow of new entrepreneurs,  $\mathbf{e}$ ; (vi) a rental rate for capital,  $r$ , and a market discount factor,  $\delta$ ; (vii) an idea distribution for VC-funded firms,  $\{\mathbf{n}_t\}_{t=1}^{\infty}$ ; (viii) a wage rate,  $w$ ; and (ix) a gross growth rate of aggregate productivity,  $\mathbf{g}_x$ , such that:

1. The financial contract,  $\{p_t, \sigma_t, \mu_t, \beta_t\}$ , solves problem (P2), given the function  $I(x; \mathbf{x})$  and  $x$ ,  $\mathbf{g}_x$ , and  $\mathbf{x}$ . The solution to this problem gives the expected return to a new entrepreneur from the contract,  $C(x; \mathbf{x})$ .
2. The VC-funded firm maximizes its profits, given  $x$ ,  $r$ , and  $w$ , as specified by problem (P1). This determines the value of its IPO,  $I(x; \mathbf{x})$ , as presented in (3). The solution to the firm's maximization problem gives the rule for hiring labor (13). Analogously, a non-VC-funded firm maximizes its profits, given  $z$ ,  $r$  and  $w$ , as specified by problem (8).
3. A new entrepreneur picks the project type,  $x$ , to solve problem (P3), given the value of the contract,  $C(x; \mathbf{x})$ , as a function of  $x$  and  $\mathbf{x}$ . This determines the expected value of a startup,  $V(\mathbf{x})$ .
4. The inflow of new entrepreneurs,  $\mathbf{e}$ , is regulated by (1) and (7), taking as given the value of the startup,  $V(\mathbf{x})$ .
5. The rental rate on capital,  $r$ , and the market discount factor,  $\delta$ , are governed by (9) and (10), given  $\mathbf{g}_w$ .
6. The idea distribution for VC-funded firms,  $\{\mathbf{n}_t\}_{t=1}^{\infty}$ , is specified by (11) and (12).
7. The market-clearing wage rate,  $w$ , is given by (14) and grows at the gross rate  $\mathbf{g}_w = \mathbf{g}_x^{\zeta/(\zeta+\lambda)}$ .
8. Aggregate productivity in the VC sector,  $\mathbf{x}$ , grows at the gross rate  $\mathbf{g}_x$  specified by (15).

The lemma below establishes that the setup will have a balanced-growth path.

**Lemma 2** (*Balanced Growth*) Let  $x' = \mathbf{g}_x x$  and  $\mathbf{x}' = \mathbf{g}_x \mathbf{x}$  for all time. If  $\beta_t, \sigma_t, \mu_t, p_t$  and  $C(x; \mathbf{x})$  solve the contract specified by (P2) for  $(x, \mathbf{x})$ , then  $\sigma'_t = \sigma_t, \mu'_t = \mu_t, \beta'_t = \beta_t$ ,

$\tilde{\sigma}'_t = \tilde{\sigma}_t$ ,  $p'_t = \mathbf{g}_w p_t$ , and  $C(x'; \mathbf{x}') = \mathbf{g}_w C(x; \mathbf{x})$  will solve it for  $(x', \mathbf{x}')$ . Likewise, if it is optimal in (P3) to pick  $x$  for  $\mathbf{x}$ , then it is optimal to choose  $x' = \mathbf{g}_x x$  for  $\mathbf{x}'$ . The gap between the frontier,  $x$ , and average productivity in the VC sector,  $\mathbf{x}$ , as measured by  $x/\mathbf{x}$ , is time invariant. The inflow of new entrepreneurs,  $\mathbf{e}$ , is a constant, so that  $\mathbf{e}' = \mathbf{e}$ .

**Proof.** See Theory Appendix. ■

## 9 Calibration

As discussed in Section 15, VC partnerships are of a limited duration, usually between 7 to 10 years. So, the analysis assumes that an entrepreneur's contract with a venture capitalist has 7 potential funding rounds each lasting 1.5 years. Thus, partnerships are structured to last at most 10.5 years. The decreasing returns to scale parameter in the production function (2) is taken from Guner, Ventura, and Xu (2008), which requires setting  $\zeta = 0.20$ . The exponents for the inputs are picked so that capital earns 1/3 of nonprofit income and labor receives 2/3. The survival rate of a firm is selected so that on average a publicly listed firm lives 25 years, as in the U.S. economy. The depreciation rate on capital,  $1 - \mathfrak{d}$ , is taken to be 7 percent. Last, Henrekson and Sanandaji (2016) report that the key personnel connected with VC startups are taxed in the United States at a 15 percent capital gains rate. So, set  $\tau = 0.15$ .<sup>4</sup>

The model has 17 remaining parameters, each marked with an asterisk in Table 6, that will be calibrated to match 22 data targets, listed in Table 7. For the most part, the model's parameter values are *jointly* determined as a function of the data targets. Still, some data targets play a much more central role in identifying a parameter, as discussed now. Over the period 1948 to 2015, U.S. GDP per hours worked grew at 1.8 percent per year. This fact is targeted in the calibration procedure. The parameter governing the efficiency of doing research,  $\chi_R$ , is important for determining the economy's growth rate. The long-run interest

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<sup>4</sup> The capital gains tax rate has varied across time in the United States. The 15 percent rate was instituted under President Bush in 2003. The maximum rate rose to 20 percent in 2012 under President Obama.

rate is set to 4 percent, a typical value. A standard value of 2 is assigned for the coefficient of relative risk aversion. The market discount factor is the reciprocal of the equilibrium interest rate, and it will change as the growth rate of the economy,  $\mathbf{g}_w$ , changes. At the calibrated equilibrium, the representative agent's annual discount factor is determined by the formula to  $\hat{\delta} = (1 - 0.04)/(1.018)^{-2}$ ; cf. (10). This yields a yearly interest rate of 4 percent.

To calibrate the elasticity of the research cost function,  $\iota$ , the following firm-level regression is run using VentureXpert data:

$$\ln(\text{IPO VALUE}) = \underset{(0.154)}{0.390^{**}} \times \ln(\text{VC FUNDING}) + \text{CONTROLS, obs.} = 1,145, \quad (16)$$

where the controls are the logarithm of the firm's employment, the firm's age at IPO, a 2-digit SIC industry dummy variable, the logarithm of the aggregate level of VC funding, and a cluster dummy for whether the venture capitalist was located in California or Massachusetts. Three instrumental variables are also used: the capital gains tax rate (which varies across states and time), dependence on external finance (which varies across industries), and the deregulation dummy. The coefficient shows the impact of a firm's VC funding on its IPO value and is used to identify a value for  $\iota$ , as discussed next.

To identify  $\iota$ , the impact of a change in firm-level VC funding on its IPO value is calculated for the model. This calculation is broken down into two steps. First, the elasticity of  $I(x; \mathbf{x})$  with respect to  $x$  is computed. Second, the elasticity of VC funding with respect to  $x$  is totted up numerically. This is done in partial equilibrium to match the results of the firm-level regression. The ratio of these two elasticities gives the elasticity of IPO value with respect to VC funding. Thus, the following object is computed for the model:

$$\text{IPO VALUE ELASTICITY} = \frac{d \ln \text{IPO} / d \ln x}{d \ln(\text{VC FUNDING}) / d \ln x}.$$

Ideally, this should have a value of 0.390.

Another key elasticity in the model is the shape parameter,  $\nu$ , for the Pareto distribution governing the opportunity cost of entrepreneurship. This regulates the inflow of entrepreneurs. Henrekson and Sanandaji (2016) report that a one percent increase in a country's effective tax rate on VC activity leads to a one percent decline in the VC investment-to-GDP ratio. This elasticity is targeted to recover the shape parameter,  $\nu$ . This parameter can be selected after calibrating the remaining parameters because the scale parameter,  $v$ , can be adjusted, given the choice for  $\nu$ , such that the number of entrepreneurs is constant. This normalization for  $v$  implies that all the other moments used in the calibration will not change.

The process for the efficiency of round- $t$  monitoring,  $\chi_{M,t}$ , is taken to be a cubic:

$$\chi_{M,t} = \log(a_0 + a_1 \times t + a_2 \times t^2 + a_3 \times t^3).$$

This requires specifying four parameters, namely  $a_0$ ,  $a_1$ ,  $a_2$  and  $a_3$ . Additionally, the monitoring parameters are selected to match the venture capitalist's share of equity by funding round (this pattern is taken up below). The more efficient monitoring is, the higher will be the venture capitalist's share of equity, as will be seen in Section 10.

The time profile for the fixed cost,  $\phi(t)$ , is governed by the quartic

$$\phi(t) = \exp(b_0 + b_1 \times t + b_2 \times t^2 + b_3 \times t^3 + b_4 \times t^4).$$

Five parameters,  $b_0$ ,  $b_1$ ,  $b_2$ ,  $b_3$ , and  $b_4$ , govern this specification. The pattern of VC investment by funding round (discussed below) determines these parameters.

Bernstein, Giroud, and Townsend (2016) estimate the impact on investment of a venture capitalist's time cost for monitoring. To do this, they examine the effect of changes in airline routes that reduce the commuting time a venture capitalist spends visiting a startup. They find that the introduction of a new airline route (the treatment) leads to a 4.6 to 5.2 percent increase in VC investment. The average reduction in travel time is significant. The lead investor visits the company site roughly 20 times per year and spends approximately 12

hours traveling and 5 hours at the company per visit, which amounts to 100 contact hours annually.<sup>5</sup> On average, a treatment saves roughly 2 hours per trip, or 40 hours per year of a venture capitalist's time. Accordingly, the treatments correspond to fairly large reductions in monitoring costs: a reduction of 2 hours per trip translates into a 12.4 percent reduction in monitoring costs. Bernstein, Giroud, and Townsend (2016) argue that most of the resources spent by a venture capitalist on monitoring is time. So, assume that monitoring is done using labor in the model.

The size of this micro-level elasticity depends in the model, among other things, on the quality of the projects, captured by,  $\rho$ . As the share of good projects rises, the success rate for ventures increases while the failure rate falls. The payoff from investing in research and development hence rises. So, does the return from monitoring because more funds are being invested. Therefore, the size of the treatment effect moves up with  $\rho$ . Therefore matching, in partial equilibrium, the Bernstein, Giroud, and Townsend's (2016) treatment effect helps to tie down the fraction of good ideas,  $\rho$ .

Next, projects that are funded by venture capitalists have an average success rate per funding round of 2.0 percent and a failure rate of 3.2 percent. The calibration procedure attempts to match these two statistics. To construct these statistics for the model, note that the success rate in funding-round  $t$  is just the number of IPOs divided by the mass of surviving firms:

$$\text{SUCCESS RATE}_t = \frac{\text{IPOs}_t}{\text{SURVIVING FIRMS}_t} = \frac{\sigma_t \rho \Pi_{j=1}^{t-1} (1 - \sigma_j)}{\rho \Pi_{j=1}^{t-1} (1 - \sigma_j) + (1 - \rho) \Pi_{j=1}^t (1 - \beta_j)}.$$

The analogous definition for the failure rate in round  $t$  is

$$\text{FAILURE RATE}_t = \frac{\text{FAILURES}_t}{\text{SURVIVING FIRMS}_t} = \frac{\beta_t (1 - \rho) \Pi_{j=1}^{t-1} (1 - \beta_j)}{\rho \Pi_{j=1}^{t-1} (1 - \sigma_j) + (1 - \rho) \Pi_{j=1}^t (1 - \beta_j)}.$$

Not surprisingly, the development efficiency parameter,  $\chi_D$ , is instrumental for determining

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<sup>5</sup> The time spent visiting the company is quoted in the unpublished version of Bernstein, Giroud, and Townsend (2016).

the average success rate, while the evaluation efficiency parameter,  $\chi_E$ , impinges heavily on the average failure rate—this is discussed in Section 10.

Puri and Zarutskie (2012, Table I) report that ratio of employment in a VC-backed firm to a non-VC-backed one is 58.14. This is a calibration target. For the model, the employment ratio is

$$\text{EMPLOYMENT RATIO} = \frac{\left(\frac{\kappa}{r}\right)^{\kappa/\zeta} \left(\frac{\lambda}{w}\right)^{(\zeta+\lambda)/\zeta} \mathbf{n}\mathbf{x}/\mathbf{n}}{\left(\frac{\kappa}{r}\right)^{\kappa/\zeta} \left(\frac{\lambda}{w}\right)^{(\zeta+\lambda)/\zeta} \mathbf{m}\omega\mathbf{x}/\mathbf{m}} = \frac{1}{\omega}.$$

This ratio pins down the productivity of a non-VC-backed firm relative to a VC-backed one, or  $\omega$ .

Data on the scrap value of unsuccessful ventures are, unfortunately, not readily available. So, the parameter  $\xi$  governing the scrap value of a firm is identified by attempting to match the observed cash multiple for VC investments. The cash multiple is the ratio of the venture capitalist’s cash receipts to disbursements, and is used as a crude measure of the ex post return on a VC investment. A venture capitalist’s receipts will include the scrap value on those unsuccessful projects that are still surviving at the end of the contract.

## 9.1 Model Fit, Targeted Observations

The upshot of the calibration procedure is now discussed. The parameter values resulting from the calibration procedure are presented in Table 6, which also gives the basis for their identification. First, the model matches the average success and failure rates very well, as shown in Table 7. And, the model replicates perfectly the ratio of VC-backed employment to non-VC backed employment. The IPO elasticity is duplicated. And the model matches exactly the Henrekson and Sanandaji (2016) tax rate elasticity. The monitoring-cost treatment effect lies within the range of estimates reported by Bernstein, Giroud, and Townsend (2016).

Next, note how investment in a project by a venture capitalist increases with the funding round (see the top panel of Figure 5). This time profile is a calibration target. Given the limited life span of a VC partnership, there is considerable pressure to bring a project

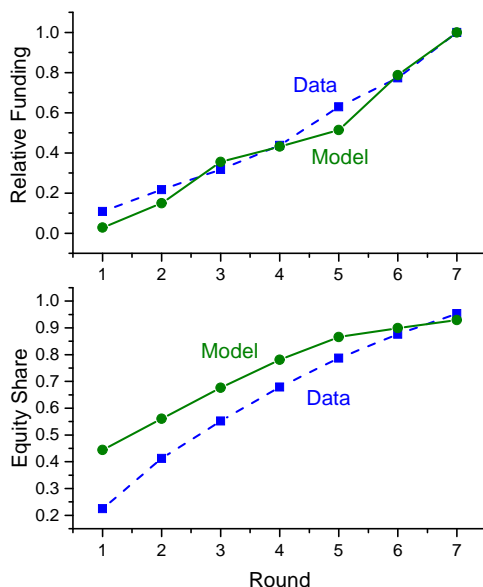


Figure 5: Investment and equity share by funding round—data and model. The upper panel shows the venture capitalist’s investment by funding round. Funding in the last round is normalized to 1.0. The lower panel charts the venture capitalist’s share of equity by funding round.

to fruition as quickly as possible. This is true in the model too, which displays the same increasing profile of funding. Two features help to generate this. The first is that bad projects get purged over time through the evaluation process. The second is that the cost of monitoring drops as the venture capitalist becomes more familiar with the project, which reduces the incentive problem. Without these features, funding would fall over time. Last, since investment increases over time, one would expect that the venture capitalist’s share of the enterprise will too. The bottom panel of Figure 5 illustrates this. The model does very well on this account. Again, the calibration procedure focuses on this feature of the data.

## 9.2 Model Fit, Non-Targeted Observations

The time profiles for the success and failure rates are *not* targeted in the calibration procedure. As shown in the middle panel of Figure 6, in the data the odds of success decline by

PARAMETER VALUES		
<i>Parameter value</i>	<i>Description</i>	<i>Identification</i>
Firms		
$\kappa = 1/3 \times 0.80$	Capital's share	Standard
$\lambda = 2/3 \times 0.80$	Labor's share	Standard
$1 - \mathfrak{d} = 0.07$	Depreciation rate	Standard
$\mathfrak{s} = 0.96$	Firm survival rate	Expected life of Compustat firms
$\chi_R = 4.7^*$	Research efficiency, $x$	Growth rate
$\iota = 2.56^*$	Research cost elasticity, $x$	Regression (16)
$\nu = 0.025^*$	Pareto shape parameter	H&S (2016) tax elasticity
$v = 0.57$	Pareto scale parameter	Normalization
Consumers		
$\varepsilon = 2$	CRRA	Standard
$\widehat{\delta} = 0.994$	Discount factor	4% risk-free rate
VC		
$T = 7$	Number of funding rounds	Partnership length (10.5 years)
$\rho = 0.21^*$	Fraction of goods ideas	BG&T (2016) treatment effect
$\chi_D = 0.0335^*$	Development efficiency, $\sigma$	Average success rate
$\chi_E = 0.0360^*$	Evaluation efficiency, $\beta$	Average failure rate
$a = \{-1.12, -0.12, 0.321, -0.018\}^*$	Monitoring efficiency, $\mu$	Equity share by round
$b = \{-0.89, 0.80, 0.25, -0.12, 0.013\}^*$	Fixed costs, $\phi$	VC funding by round
$\tau = 0.15$	Capital gains tax rate	H&S (2016)
$\xi = 0.375^*$	Scrap value fraction	Cash multiple
Non-VC-funded		
$m = 40^*$	Number non-VC firms	Relative empl. non-VC firms
$\omega = 1/58^*$	Relative prod of non-VC firms	Relative size of non-VC firms

Table 6: The parameter values used in the baseline simulation. The parameters marked with an asterisk are fit using the data targets in Table 7.



CALIBRATION TARGETS

<i>Target</i>	<i>Data</i>	<i>Model</i>
Economic growth	1.80%	1.78%
Cash Multiple	5.5	5.6
Success Rate	2.0%	2.0%
Failure Rate	3.2%	3.3%
VC funding	Figure 5	
Equity Share	Figure 5	
IPO Value Elasticity—firm level	0.39	0.39
Tax Elasticity of VC Inv/GDP	-1.0	-1.0
Monitoring-Cost Treatment	4.6 to 5.2%	4.9%
VC Employment Share	5.5%	4.8%
Employment ratio	58.1	58.1

Table 7: All data sources are discussed in the Data Appendix.

funding round or with the passage of time. While the model captures the average success across funding rounds very well, it has some difficulty mimicking the declining time profile. Failure rates also decline with time, and the model does very well on this dimension. Now turn to the bottom panel of Figure 6. Observe that the value of an IPO drops with the incubation time for the project. In the model, as time passes, the value of a project declines because aggregate productivity in the VC sector catches up with the productivity of the entrepreneur’s venture; “the thrill is gone,” so to speak. It is a bit surprising that the framework can match almost perfectly this feature of the data, which is not targeted.

## 10 Thought Experiments

The analysis stresses the ability of a venture capitalist to evaluate, develop, and monitor startup projects. The importance of these three factors is now investigated one by one. Then, an experiment is conducted where the fraction of good ideas is varied. This sets the stage for the final experiment where the efficiency of venture capital is debased, to approximate earlier non-VC forms of finance, while the fraction of good ideas is boosted, to represent periods of time when ideas may have been easier to harvest.

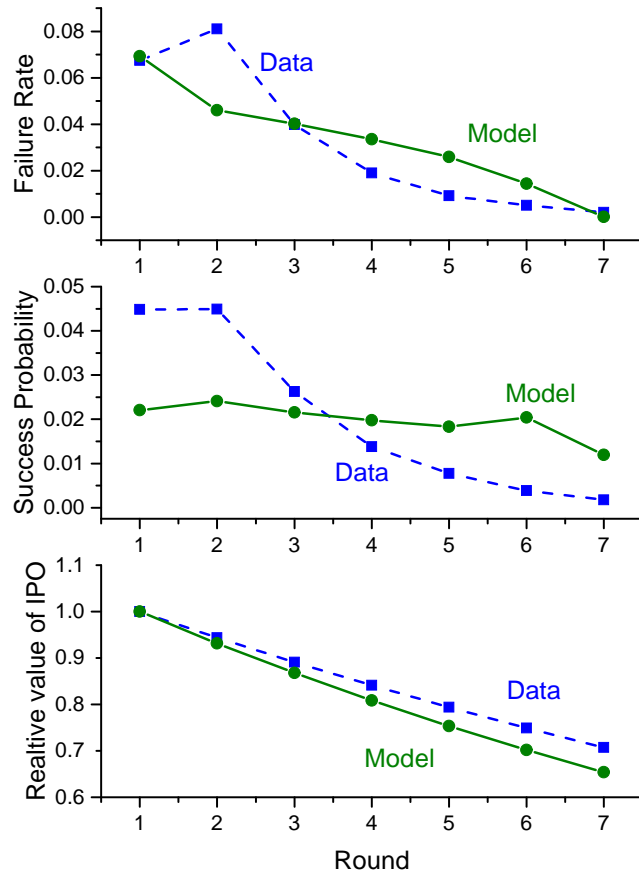


Figure 6: The odds of success and failure by funding round and the value of an IPO by the duration of funding—data and model. The value of an IPO that occurs during first funding round is normalized to 1.0. None of these profiles is targeted in the calibration.

## 10.1 Changes in Monitoring Efficiency, $\chi_{M,t}$

How important is the venture capitalist's ability to monitor the use of funds by entrepreneurs? Figure 7 shows the general equilibrium impact of improving the efficiency of monitoring in the model. To undertake this thought experiment, the monitoring efficiency profile,  $\{\chi_{M,1}, \dots, \chi_{M,7}\}$ , is changed by a scalar, which takes the value of 1 for the baseline calibration. Monitoring efficiency is measured in terms of the percentage deviation of this scalar from its baseline value. As monitoring efficiency improves, there is an increase in the average odds of detecting fraud across funding rounds (see the top panel). The venture capitalist's share of equity rises, on average, because it is now easier to ensure that funds are not diverted. Compliance with the contract can still be guaranteed when the entrepreneur is given a lower share of an IPO. The venture capitalist must still earn zero profits, however. Part of the increased return to the venture capitalist is soaked up by letting the new entrepreneur be more ambitious about his choice of technique, which raises the initial cost of research,  $R(x/\mathbf{x})$ ; the rest of the increased return is absorbed by increased investment in development. As a result, VC-backed firms have a higher level of productivity and are more successful. This results in a higher share of employment for VC-backed firms (as shown in the middle panel). Additionally, the economy's growth rate moves up, which results in a welfare gain (measured in terms of consumption; see the bottom panel).<sup>6</sup>

## 10.2 Changes in Evaluation Efficiency, $\chi_E$

The importance of efficiency in evaluation is examined now. The results are displayed in Figure 8, where  $\chi_E$  is measured in terms of percentage deviations from the baseline equilibrium. As evaluation becomes more efficient, the odds of detecting a bad project increase. Hence, the average failure rate across funding rounds moves up (see the top panel). The success rate rises, both due to the purging of bad projects and the resulting increased

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<sup>6</sup> See Akcigit, Celik, and Greenwood (2016, Section 5.1) for details on how the welfare gain is computed. In the current work, the initial level of consumption across balanced-growth paths is held fixed, though, as opposed to aggregate productivity.

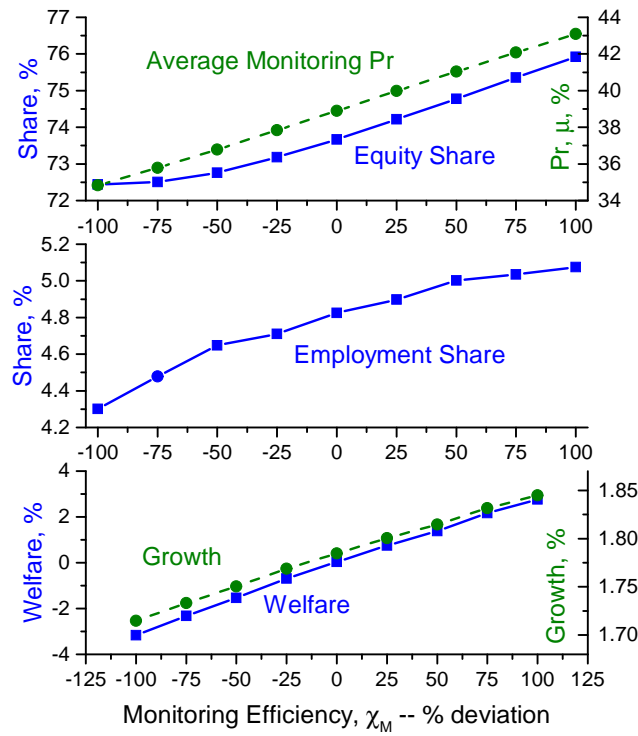


Figure 7: Efficiency in monitoring,  $\chi_{M,t}$ . The top panel shows how the average probability of detecting fraud and the venture capitalist's share of equity vary with efficiency in monitoring. The middle panel illustrates how the share of VC-backed firms in employment responds. Growth and welfare are displayed in the bottom panel. Monitoring efficiency is measured in terms of the percentage deviation from the baseline equilibrium.

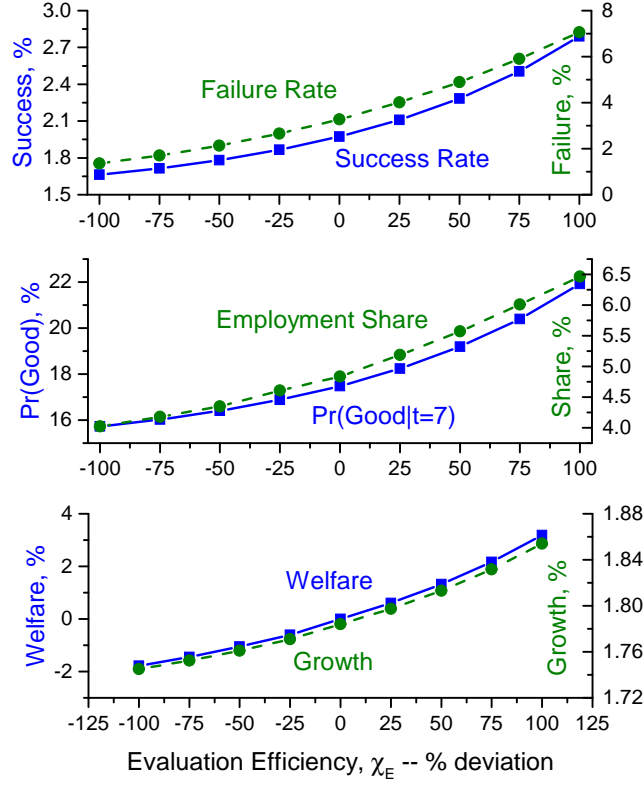


Figure 8: Efficiency in evaluation,  $\chi_E$ . The top panel shows how the average failure and success rates across funding rounds vary with efficiency in evaluation. The middle panel illustrates how the odds of a project being good in the seventh round and the employment share of VC-backed firms respond. Growth and welfare are illustrated in the bottom panel. Evaluation efficiency is measured in terms of the percentage deviation from the baseline equilibrium.

VC investment in development. The purging of bad projects dominates the exit of good ones so that the fraction of good projects in the last round increases with  $\chi_E$  (as the middle panel illustrates). The fact that it is more profitable to invest in research and development is reflected by an upward movement in the share of VC-backed firms in employment. Economic growth and welfare move up in tandem as evaluation efficiency improves (see the bottom panel).

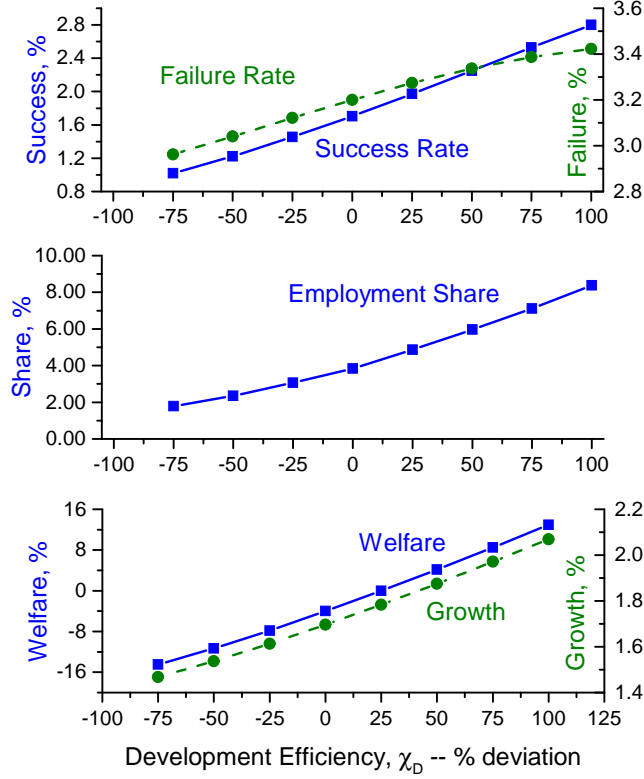


Figure 9: Efficiency in development,  $\chi_D$ . The top panel shows how the average failure and success rates across funding rounds vary with efficiency in development. The middle panel illustrates how the share of VC-backed firms in employment responds. Growth and welfare are illustrated in the bottom panel. Development efficiency is measured in terms of the percentage deviation from the baseline equilibrium.

### 10.3 Changes in Development Efficiency, $\chi_D$

The impact of changes in development efficiency is studied next. Again,  $\chi_D$  is measured in terms of percentage deviations from the baseline calibration. As it becomes less expensive to develop a project, the odds of success improve. The failure rate also rises because fewer good projects remain in the pool over time. VC-backed firms' share of employment picks up, as it is more profitable to fund a project. Last, economic growth and welfare rise with development efficiency.

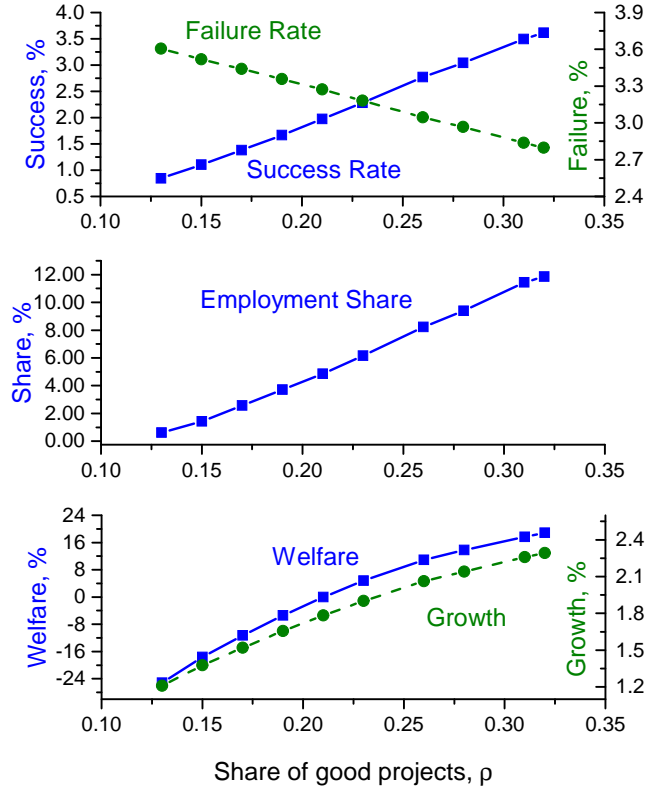


Figure 10: The fraction of good ideas,  $\rho$ . The top panel shows how the average failure and success rates across funding rounds vary with the fraction of good ideas. The middle panel illustrates how the share of VC-backed firms in employment responds. Growth and welfare are illustrated in the bottom panel.

## 10.4 Changes in the Fraction of Good Ideas, $\rho$

Finally, how does the abundance of ideas affect things? To gauge this, in Figure 10 the fraction of good ideas,  $\rho$ , is varied. Not surprisingly, when the fraction of good ideas increases, the success rate rises and the failure rate falls. Additionally, the share of employment comprised by innovating firms moves up. This, of course, leads to an increase in economic growth and welfare.

## 10.5 Ideas and Venture Capital

Venture capitalists lend development and evaluation expertise to startups that alternative forms of finance, such as angel investors, banking, and more recently crowdfunding, do not. Arguably, venture capitalists are also better at monitoring projects. Venture capitalists are highly skilled: 58 percent of them have an MBA degree, 33 percent studied engineering or science in college, 7 percent have a Ph.D. in science, and 8 percent hold a JD degree. In addition, they graduated from prestigious universities: 37% attended an Ivy League university, 19 percent went to Harvard, and 14 percent to Stanford.<sup>7</sup>

Wealthy people have always been willing to lend seed money to startups, as discussed in Section 15. This is what angel investors do today. The sheer size of financing needed as a startup evolves goes well beyond an angel investor's pockets. The average investment per deal of an angel investor was \$510,000 in 2014. In contrast, the average venture capitalist invests \$4 million and \$14 million in seed-stage and later-stage deals. These investments are 8 times and 28 times larger than those of angel investors. VC organizations feature substantially higher levels of professionalism and specialization than angel investors: all the roles of a VC organization (e.g., evaluation, development, and monitoring) are rolled up into one single angel investor.

Puri and Zarutskie (2012) track the performance of VC- and non-VC-financed firms using the Longitudinal Business Database (LBD). They identify firms in the LBD as VC-financed if they can be matched to the VentureSource and VentureXpert databases. They match each VC-financed firm to a non-VC-financed firm based on four characteristics: age, 4-digit SIC code, geographical region, and employment size. They find that VC-financed and non-VC-financed firms are observationally identical at the time the former first receive VC financing. Based on this comparison, they report that the average ratio of the success rate of non-VC-financed firms to the success rate of observationally identical VC-financed firms is 0.30.<sup>8</sup>

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<sup>7</sup> Source: Zarutskie, Rebecca. 2010. "The Role of Top Management Team Human Capital in Venture Capital Markets: Evidence from First Time Funds," *Journal of Business Venturing*, 25 (1): 155-172.

<sup>8</sup> Venture capitalists could match with better firms based on unobservable characteristics. Given that startups are very young with little in terms of employment and patents, it might be difficult to control empirically for this selection effect. To the extent that such selection effects are important, the results in this



To approximate more traditional forms of finance in the model, the efficiency of development, evaluation, and monitoring are all debased in an equiproportional manner to render the same average success-odds ratio for a startup as Puri and Zarutskie (2012) find. In order for this ratio to be comparable with its empirical counterpart, this recalibration is done in partial equilibrium. The 0.30 ratio is reproduced by reducing in tandem development, evaluation, and monitoring efficiency to 55 percent of their original values.<sup>10</sup> The upshot of this exercise is shown in Table 8. Alternative forms of finance have a much lower success rate (1.1 versus 2.0 percent) than do VC-financed projects. The ratio of 1.1/2.0 is larger than 0.30 because there are general equilibrium effects, inducing a drop in wages, that partially offset the reduction in financing efficiency. The financier's share of the project declines considerably. Since monitoring is less efficient, a larger share of the project must be given to the entrepreneur to ensure that he will invest all of the development funds. The drop off in the success rate and the financier's share of equity lead to less research and development in the debased VC-backed firms. The IPO value of a startup drops a lot, by 43.7 percent (which is not shown in the table). This is in the ballpark of the 31.1 percent drop predicted by the firm-value regression in Table 2 for a non-VC-backed firm (relative to a VC-backed one). As a result, there is less employment in VC-backed firms. Growth also drops. This generates a large welfare loss. In a similar vein, Kortum and Lerner (2000) report that a dollar of VC investment is worth 3 times as much as a dollar on non-VC investment in generating patents. So, as an alternative experiment, simply reduce development efficiency by one third. As can be seen, the results for the two experiments are fairly similar.

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section constitute an upper bound for the effect of VC financing.

<sup>9</sup> This number is based on Table VI.B (p. 2271) of Puri and Zarutskie (2012). First, Puri and Zarutskie's cumulative success rates are first differenced to get the yearly rates. Second, the success-odds ratio (of non-VC-financed firms to VC-financed firms) is calculated year by year. Third, an average is taken over the years. Only acquisitions are considered to be successes in this calculation, because Puri and Zarutskie (2012) don't report yearly IPO numbers for non-VC-financed firms. This is presumably because IPOs are virtually non-existent for non-VC-financed firms. This implies that the estimated success ratio is conservative in nature.

<sup>10</sup> The results are quite similar when only development efficiency is debased.

## IDEAS AND VC

<i>Variable</i>	<i>Debasings VC</i>				
	<i>Baseline</i>	<i>KL</i>	<i>PZ</i>	<i>With more abundant ideas</i>	
		<i>KL</i>	<i>PZ</i>	<i>KL</i>	<i>PZ</i>
Share of good ideas, $\rho$	0.210	0.210	0.210	0.294	0.266
Monitoring efficiency, $\chi_M$	0.125	0.125	0.067	0.125	0.067
Evaluation efficiency, $\chi_E$	0.036	0.036	0.019	0.036	0.019
Development efficiency, $\chi_D$	0.034	0.011	0.018	0.011	0.018
Success probability, %	2.0	0.9	1.1	1.6	1.7
Monitoring probability, %	38.8	32.2	32.8	35.2	34.3
VC equity share, %	73.6	62.6	69.4	67.4	70.7
Empl share innovative firms, %	4.9	1.7	2.1	4.3	4.3
Growth rate, %	1.8	1.4	1.5	1.8	1.8
Welfare loss, %	0.0	-15.1	-11.3	0.2	0.3

Table 8: KL and PZ refer to Kortum and Lerner (2000) and Puri and Zarutskie (2012), respectively.

Since non-VC methods of finance are less efficient in encouraging innovation, should one expect lower growth in the past? Not necessarily, because other things have changed. For example, Bloom et al. (2018) suggest that ideas are “getting harder and harder to find.” If so, ideas would have been easier to harvest in the past. To implement this notion here select  $\rho$  so that the economy’s growth rate remains the same in the above two experiments as in the baseline model. To do this, the fraction of good ideas must be increased by either 6 or 8 percentage points. Still, good ideas are fairly rare. The employment share of innovative firms remains close to that in the baseline economy. Economic welfare is slightly higher. The experiment suggests that the advent of venture capital would not show up in economic growth if at the same time ideas became hard to find. In fact, without venture capital growth would have fallen from 1.8 percent to around 1.4 to 1.5 percent.

## 11 Capital Gains Taxation

Most VC-funded firms in the United States are setup as partnerships. CEOs, central employees, founders, and investors are paid in terms of convertible equity and stock options. These financial assets payoff only under certain well-specified contingencies and serve to align the

incentives of key participants.<sup>11</sup> Interestingly, the returns on convertible equity and stock options are taxed in the United States at the capital gains rate, which is 15 percent. The IRS lets companies assign artificially low values to these instruments when they are issued. So, effectively, participants are only subject to taxation at the time of an acquisition/IPO. In other countries the rate of taxation on VC-funded startups is much higher. Figure 11 illustrates for a cross section of countries how VC investment as a percentage of GDP falls with the tax rate on VC profits. The data are from Henrekson and Sanandaji (2016). To obtain the tax rates on VC profits, they asked the local offices of PricewaterhouseCoopers in 22 countries to calculate the effective tax rate for a representative VC startup. This way of computing the tax effective rates is well suited for the current analysis because it takes into account tax avoidance (i.e., the use of legitimate methods in the tax code for minimizing taxes paid). So, for example, PricewaterhouseCoopers calculate that is 30 percent in France, 47.5 percent in Germany, and 72 percent in Italy. Using this data in a regression analysis, Henrekson and Sanandaji (2016, Table 4) report a strong negative correlation between the tax rates on VC profits and VC investment as a percentage of GDP. The elasticity of the tax rate on VC activity is about -1.0, as mentioned earlier. This feature of the data is matched in the model by calibrating the shape parameter for Pareto distribution, which governs the inflow of entrepreneurs. So, the response of VC activity to taxes is the same in the data and model.

The model can be used as a laboratory to gauge the effect of taxation on other key variables, such as growth and welfare, which is shown in Figure 12. As the tax rate on VC profits rises, not surprisingly economic growth declines. An increase in the tax rate from -15 percent (a subsidy) to 50 percent, causes economic growth in the model to fall from 1.90 percent to 1.58 percent. The effects on growth might appear small, but lowering the tax rate from 50 percent to 15 percent produces a long-run welfare gain of 9.4 percent, when ignoring transitional dynamics. Going further from 15 percent to -15 percent generates an

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<sup>11</sup> Celik and Tian (2018) analyze how established firms with better corporate governance (as proxied by the equity share of institutional investors) also tend to remunerate executives more in terms of incentive pay than do other firms, which leads to higher levels of innovation.

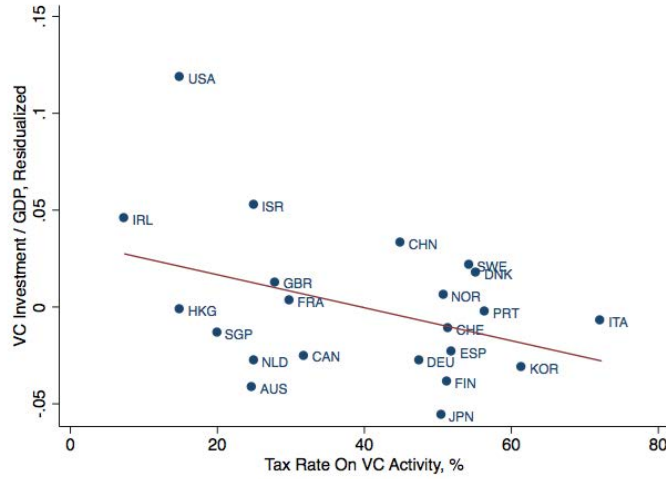


Figure 11: The conditional cross-country relationship between the tax rate on VC profits and the VC-investment-to-GDP ratio. The numbers are expressed as percentages. The conditioning variables are similar to those used in Henrekson and Sanandaji (2016). See the Data Appendix for a list of the controls.

additional welfare gain of 5.5 percent, all measured in terms of consumption.

## 12 What about Growth?

Is the recent rise in VC investment reflected in growth statistics? The answer to this question is nuanced. On the one hand, at the country level VC investment appears to be positively linked with economic growth. Figure 13 illustrates for a sample of 40 countries the conditional relationship between VC investment-to-GDP ratio and the growth rate of real GDP per capita. These countries cover 99 percent of world VC investment and 86 percent of world GDP between 2005 and 2014. A country is included in the sample if its share of world VC investment is not less than 0.03 percent and the information for the control variables is available.<sup>12</sup> The vertical axis is the median growth rate of per capital real GDP in each country for the period 2005 to 2014, residualized against the following control variables: the

<sup>12</sup> An exception is Bermuda, which accounted for 0.15 percent of world VC investment. Bermuda is excluded because it is a tax haven. Companies set up offices there, while undertaking virtually no business activity, just to avoid corporate income taxation.

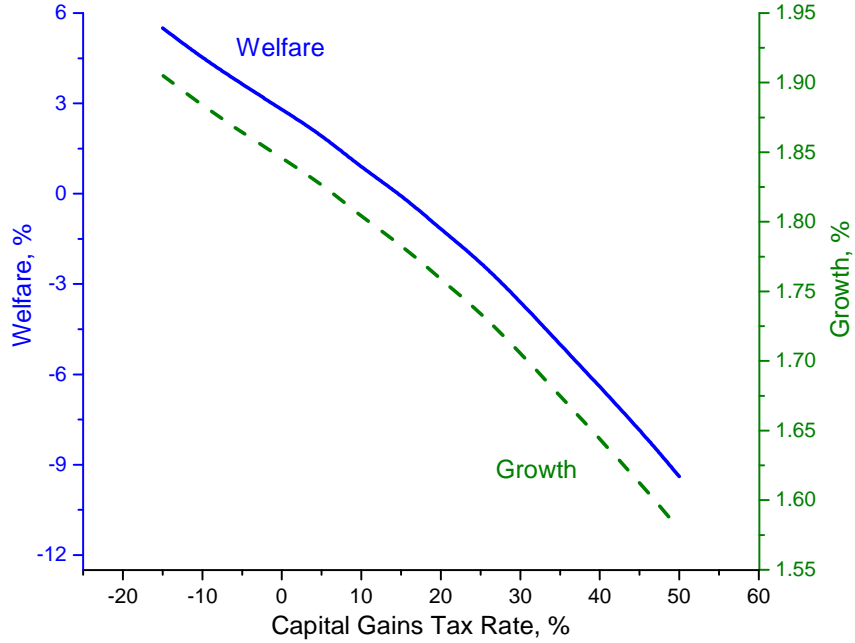


Figure 12: Impact of VC profit taxation on economic growth and welfare.

initial levels of real GDP per capita, a human capital index, and the ratio of domestic private credit to GDP. The first two controls are the main factors demonstrated in the empirical literature to be important for economic growth. Pioneered by King and Levine (1993a, 1993b), the last control variable has been the most widely used measure for the financial development level of a country. The horizontal axis is the median VC investment-to-GDP ratio (in natural logarithm) between 2001 and 2005 for a country.<sup>13</sup> As depicted in Figure 13, a higher VC investment-to-GDP ratio in a country predicts faster economic growth in the subsequent decade. This relationship is statistically significant at the one percent level—see the Data Appendix.

## 12.1 A Comparison between France and the United States

To illustrate how the model can be used to understand the role that venture capital plays in creating divergences in growth across countries, a comparison of France versus the United

<sup>13</sup> In light of the remarkable volatility of VC investment, the median value between 2001 and 2005 is used.

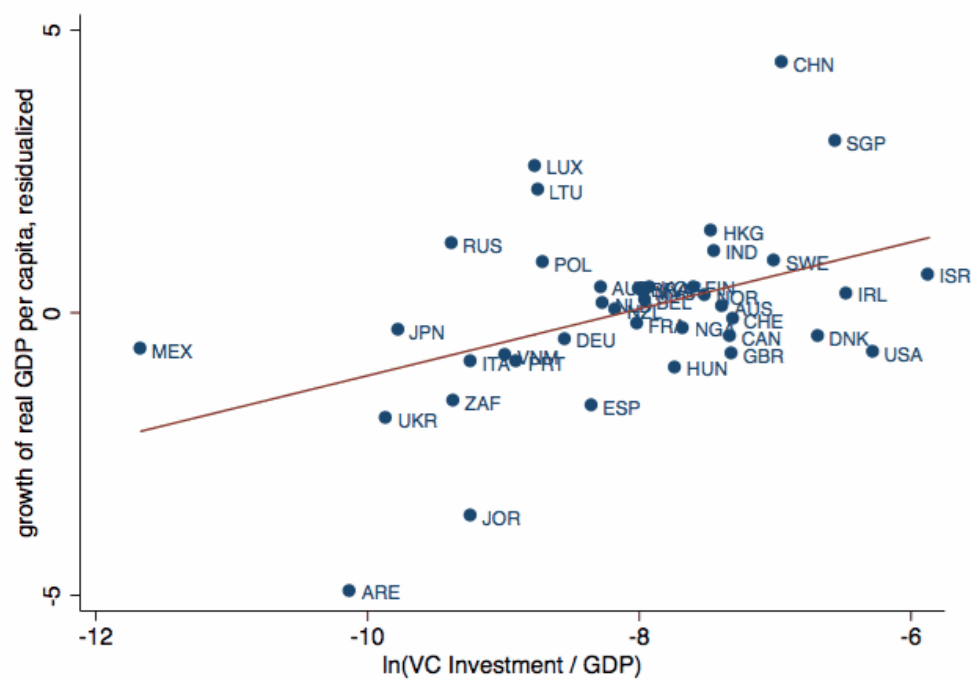


Figure 13: The conditional cross-country relationship between economic growth and VC investment, 2005-2014.

States is undertaken. To do this, four key parameters, namely  $\chi_D$ ,  $\chi_E$ ,  $\chi_M$ , and  $\tau$ , are calibrated so that the model resembles the French economy. Since these parameters do not encompass all of the differences between France and the United States, the baseline model for France will not explain the entire discrepancy between the French (1.3 percent) and U.S. (1.8 percent) growth rates.

First, the tax rate on VC activity, or  $\tau$ , for France is set at 30 percent, the number reported by Henrekson and Sanandaji (2016). Second, Greenwood, Sanchez, and Wang (2013) estimate that the French financial sector is 23 percent less efficient than in the United States. Their estimate applies best to the efficiency of evaluation and monitoring undertaken by financial intermediaries, or  $\chi_E$  and  $\chi_M$ —the functional form they use for the cost of monitoring is a close cousin of functional forms used here for evaluation and monitoring costs. Third, the last parameter is  $\chi_D$ , which represents the efficiency of VC firms in developing projects. As mentioned in Section 10, VC firms in the United States employ highly skilled individuals. For France,  $\chi_D$  is calibrated so that its VC-investment-to-GDP ratio is 35 percent of the U.S. one.

Taking stock of things, three factors will then contribute to the divide in French-U.S. growth due to differences in their financial systems: (i) financial intermediaries' capabilities to acquire information about projects' worthiness and to tackle agency problems (as captured by  $\chi_E$  and  $\chi_M$ ); (ii) the ability of intermediaries to lend expertise to develop projects (as reflected by  $\chi_D$ ); (iii) differences in tax rates that affect the profitabilities of intermediaries investing in startups ( $\tau$ ). The results of the exercise are presented in Table 9. To begin with, the rate of growth in the baseline French economy is 1.44 percent, which is about 70 percent of the actual gap between French and U.S. growth. Factors excluded from the analysis account for the remaining 30 percent. Next, the ranking in importance of the three factors considered is (ii) > (iii) > (i).

There would be only a tiny gain from French intermediaries improving their capabilities to screen projects and monitor the use of funds. This would close 6 percent of the difference between French and U.S. growth. Lowering French taxes on startups to the U.S. level would

FRANCE-U.S. COMPARISON

<i>Variable</i>	<i>Mon.</i>	<i>Eval.</i>	<i>Dev.</i>	<i>Taxes</i>	<i>VC Inv</i>	<i>Growth %</i>	<i>Gap filled</i>
	$\frac{\chi_M^{US}}{\chi_M^M}$	$\frac{\chi_E^{US}}{\chi_E^E}$	$\frac{\chi_D^{US}}{\chi_D^D}$	$\tau$	$\frac{\frac{VC\ Inv}{GDP}}{(\frac{VC\ Inv}{GDP})^{US}}$	$100 \times g_w$	$\frac{\Delta g_w}{g_w^{US} - g_w^{FR}}$
US Baseline	1.00	1.00	1.00	0.15	1.00	1.78	0*
FR Baseline	0.77	0.77	0.49	0.30	0.25	1.44	0.70**
$\Delta \chi_M^{FR} \& \chi_E^{FR}$	1.00	1.00	0.49	0.30	0.35	1.47	0.06
$\Delta \chi_D^{FR}$	0.77	0.77	1.00	0.30	0.59	1.66	0.44
$\Delta \tau^{FR}$	0.77	0.77	0.49	0.15	0.51	1.53	0.18

Table 9: The impact of changes in evaluation, development, and monitoring efficiencies, as well as taxes, on the French growth rate. The entry with the asterisk signifies that there is no gap for the United States, while the one with the double asterisk represents the ratio of the U.S.-France growth gap under the baseline calibration to the actual gap in the data..

make up 18 percent of the gap. While this is a significant effect, tax reform would be a daunting task for France to undertake. Last, increasing the ability of French intermediaries to develop startups has the biggest impact, filling 44 percent of the divide. These are services that traditional financial intermediaries barely provide. Venture capitalists sit on the boards of directors of their portfolio companies and are deeply engaged in the management. They provide strategic and operational guidance, they connect the entrepreneurs with investors and customers, and they are pivotal in the hiring decisions for the board members and key employees. Venture capitalists spend an average of 18 hours per week assisting their portfolio companies out of a total reported work week of 55 hours. Last, (ii) and (iii) are likely to be related. Financiers are more likely to acquire the skills and talent to develop startups when the latter is profitable, a factor omitted from the analysis.

## 13 Conclusion

Venture capital is important for economic growth. Funding by venture capitalists is positively associated with patenting activity. VC-backed firms have higher IPO values when they are floated. Following flotation they have higher R&D-to-sales ratios. VC-backed firms also



grow faster in terms of employment and sales.

An endogenous growth model of the VC process is constructed and taken to the data. In the framework, entrepreneurs bring ideas to venture capitalists for funding. Venture capitalists provide seed money to research the ideas. After this projects enter a funding-round cycle. During each round, projects are: (i) evaluated to assess their ongoing viability; (ii) those that pass are then provided with VC to develop the project; (iii) the use of funds is monitored is done to ensure that there is no malfeasance; and (iv) successful projects are floated on the stock market or sold to other businesses. The evaluation plan, development funding, the monitoring strategy, and the equity share of the venture capitalist are governed by a dynamic contract between the entrepreneur and a venture capitalist. The contracts between entrepreneurs and venture capitalists are optimal, given the economic environment they operate within. The model is capable of matching several stylized facts of the VC process by funding round. In particular, it mimics the funding-round profiles for the success and failure rates of projects, the injections of VC for development, the venture capitalist's share of equity, and the value of an IPO by the time it takes to go to market. This is done while matching the share of VC-backed firms in total employment, the average size of a VC-backed firm relative to a non-VC-backed one, the elasticity of IPO value with respect to VC funding, the cross-country elasticity of VC investment with respect to profit taxes, and the impact of monitoring costs on VC investment.

The key personnel involved with starting up the enterprises funded by venture capitalists are rewarded in the form of convertible equity and stock options. In the United States, venture capitalists are subject only to capital gains taxation. The rate at which VC-funded startups are taxed in the United States is low relative to other developed countries. Does this promote innovative activity? The analysis suggests that raising the tax on VC-funded startups from the U.S. rate of 15 percent to the Norwegian rate of roughly 50 percent would shave 0.2 percentage points off growth and lead to a long-run consumption-equivalent welfare loss of 9.4 percent.

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## 14 Data Appendix

### 14.1 Figures

- *Figure 1: The rise of venture capital, 1970 to 2015.* Investment by venture capitalists is obtained from the VentureXpert database of Thomson ONE. The fraction of public firms backed by VC companies is created by matching firm names in VentureXpert and CompuStat; the latter are available from Wharton Research Data Services.<sup>14</sup>
- *Figure 2: The share of VC-backed companies in employment, R&D spending, and patents.* The employment and R&D shares of VC-backed public companies are calculated by matching firm names in VentureXpert and CompuStat, as in Figure 1. The share of patents for VC-backed public companies is computed by matching firm names in VentureXpert and the NBER Patent Data Project.<sup>15</sup>
- *Figure 5: Investment and equity share by funding round.* Investment in each funding round is based on the VC-funded deals in Crunchbase between 1981 and 2015. Crunchbase has better funding-round information than VentureXpert. The vertical axis is the mean of funding in a round across all deals, from round 1 (i.e., series A) to round 7 (i.e., series G). Funding is converted into millions of constant \$2009 using the GDP deflator. The mean duration of a funding round in Crunchbase is 1.4 years, which is taken to 1.5 years here. The share of equity transferred to the venture capitalist in each funding round is calculated as the ratio of VC funding in each round to the post-money

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<sup>14</sup> Source link: <https://wrds-web.wharton.upenn.edu/wrds/index.cfm?>

<sup>15</sup> Source link: <https://sites.google.com/site/patentdatapoint/Home>

valuation of the company after the VC investment. For each funding round the mean equity share across all deals is calculated. The vertical axis is the cumulated share of equity transferred to the venture capitalist.

- *Figure 6: The odds of success and failure by funding round and the value of an IPO by the duration of funding.* The underlying data source is Puri and Zarutskie (2012, Table VI.B, p. 2271). The success rate refers to firms that have an IPO or that are acquired by another firm. The acquisitions in Puri and Zarutskie (2012) are converted into successes by multiplying by 0.629. This is based on the fact that the cash multiple for acquisitions is 37.1 percent lower than for IPOs, as reported in Achleitner et al. (2012). In addition, the success and failure rates by funding round are obtained by interpolating the original annual data using a cubic spline to get a periodicity of 1.5 years. Puri and Zarutskie (2012, Table V) classify a firm “as having failed if it disappears from the LBD in its entirety.” The value of an IPO, as a function of the duration of VC funding, derives from regression (2) in Table 11 (discussed in Section 14.3).
- *Figure 11: The cross-country relationship between the tax rate on VC activity and the VC investment-to-GDP ratio.* The source for the cross-country data is Henrekson and Sanandaji (2016, Table 1). The VC investment-to-GDP ratio on the vertical axis is residualized against the following control variables: GDP per capita, the Barro and Lee (2013) human capital index, the ratio of R&D to GDP, the ratio of market capitalization of all listed firms to GDP, and the “distance to frontier score” of the World Bank (a measure of the ease of doing business in a country).
- *Figure 13: Economic growth and VC investment.* VC investment and the growth rate of real GDP per capita are based on VentureXpert of Thomson ONE and the World Development Indicators of the World Bank, respectively. The growth rate of real GDP per capita on the vertical axis is residualized against the following control variables: the initial levels of real GDP per capita, the Barro and Lee (2013) human capital index, and the ratio of domestic private credit to GDP. The Barro and Lee (2013) human capital index is a measure of educational attainment in a country. The data for the domestic private credit-to-GDP ratio was gathered from the Global Financial

VC INVESTMENT AND GROWTH: CROSS-COUNTRY REGRESSIONS	
<i>Dependent Variable</i>	<i>Growth of GDP pc., %</i>
ln(VC Investment/GDP)	0.718*** (0.223)
+ control	
Observations	40
R-squared	0.602

Table 10: The control variables are the initial levels of real GDP per capita, the Barro and Lee (2013) human capital index, and the ratio of domestic private credit to GDP. Standard errors are in parentheses. \*\*\* denotes significance at the 1 percent levels.

Development Database of the World Bank. The regression results are reported in Table 10.

## 14.2 Tables

- *Table 1: Top 30 VC-Backed Companies.* As in Figure 1, the list of VC-backed public companies is gathered by matching firm names in VentureXpert and CompuStat.
- *Table 2: VC- versus Non-VC-Backed Public Companies.* The VC-backed public companies are singled out by matching firm names in VentureXpert and CompuStat. Since the R&D-to-sales ratios and growth rates can be very volatile across firms, the top and bottom 5 percent of the outliers are trimmed in this regression. The results are robust to changing the trimming threshold (at the 1 percent versus 5 percent level).
- *Table 3: VC Funding and Patenting, Firm-Level Regressions.* The VC-funded patentees are identified by matching firm names in VentureXpert and PatentsView.<sup>16</sup> The dependence on external finance measure is motivated by Rajan and Zingales (1998). In calculating the dependence on external finance, 30 percent of selling, general, and administrative expenses is taken as intangible investment. The industry levels of private- and federally-funded R&D are collected from the Business R&D and Innovation Survey

<sup>16</sup> Source link of PatentsView: <http://www.patentsview.org/download/>.

by the National Science Foundation.<sup>17</sup> A truncation adjustment for citations is made following Bernstein (2015). The industry dummies in this regression are at the 2-digit SIC level.

- Table 7: The sources for the data targets are: Economic growth–BEA; cash multiple–Gompers et al. (2016, Table 12); success rate, failure rate, VC employment share and employment ratio–Puri and Zarutskie (2012, Tables I and VI.B); VC funding and equity share–Crunchbase; IPO value elasticity (firm level)–Regression (16); tax elasticity of VC Investment/GDP–Henrekson and Sanandaji (2016); Monitoring-cost treatment–Bernstein et al. (2016, Tables IAVI & IAVII).
- *Table 4: VC Funding and Industry Growth, Industry-Level Regressions.* The employment and sales information is based on the NBER-CES Manufacturing Industry Database.<sup>18</sup> The industry panel is based on the 4-digit SIC. The industry dummies in this regression are at 2-digit SIC level.

### 14.3 Duration of VC Funding and the Value of an IPO

The relationship between the firm’s value at an IPO and the number of years it received funding from the venture capitalist is examined using regression analysis. The regressions are based on public companies funded by venture capitalists between 1970 and 2015. These VC-backed companies are identified by matching firm names in CompuStat and VentureXpert. The dependent variable in the regressions is the natural logarithm of the market value of the firms at IPO (in \$2009). A three-year average is used for market value because of the notorious volatility of share prices following an IPO. IPOs are excluded when they take more than 11 years for the firms to go public after receiving the first VC funding. This is for two reasons: (i) the sampling period is formulated to be consistent with the model where the maximum duration for each VC investment is 10.5 years, and (ii) only 4.5 percent of the

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<sup>17</sup> Source link of BRDIS: <https://www.nsf.gov/statistics/srvyindustry/#tabs-2>.

<sup>18</sup> Source link of NBER-CES Manufacturing Industry Database: <https://www.nber.org/nberces/>.

VC FUNDING AND YEARS TO GO PUBLIC		
<i>Dependent variable</i>	$\ln(\text{Firm value at IPO, real})$	
	1	2
<b>years btw first VC funding and IPO</b>	-0.0470*** (0.0161)	-0.0385*** (0.0146)
firm age at IPO		-0.0246*** (0.00495)
# of employees at IPO (log)		0.709*** (0.0375)
year dummy for IPO	N	Y
industry effect	N	Y
Observations	1,042	1,006
R-squared	0.008	0.627

Table 11: Standard errors are in parentheses. \*\*\*, \*\*, and \* denote significance at the 1, 5 and 10 percent levels.

observations occur after 11 years with the data being very noisy. The main explanatory variable is the number of years between the firm’s first VC funding and the date of its IPO. The findings are shown in Table 11. The first coefficient in regression (2) is used in Figure 6 to plot the decline in the value of an IPO across successive funding rounds.

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## 15 Appendix on The Rise of Venture Capital as Limited Partnerships

Financing cutting-edge technologies has always been problematic.<sup>19</sup> It is difficult to know whether new ideas are viable, if they will be saleable, and how best to bring them to market. Also, it is important to ensure that entrepreneurs' and investors' incentives are aligned. Traditional financial institutions, such as banks and equity/securities markets, are not well suited to engage in this sort of underwriting. Historically, the introduction of new technologies was privately financed by wealthy individuals. Investors were plugged into networks of inventive activity in which they learned about new ideas, vetted them, and drew on the expertise needed to operationalize them. These financiers are similar to today's "angel investors."

The Brush Electric Company provided such a network for inventors and investors in Cleveland around the turn of the 20th century. Electricity was one of the inventions born during the Second Industrial Revolution. Individuals linked with the Brush Electric Company network spawned ideas for arc lighting, liquefying air, smelting ores electrically, and electric cars and trolleys, among other things. The shops at Brush were a meeting place for inventors; they could develop and debug new ideas with help from others. Investors connected with the Brush network learned about promising new ideas from the scuttlebutt at the shops. They became partners/owners in the firms that they financed. Interestingly, in the Midwest at the time, prolific inventors (those with more than 15 patents) who were principals in companies were much more likely to keep their patents or assign them to the companies where they were principals as opposed to other inventors, who typically sold them to businesses where they had no concern. This aligned the incentives of innovators and investors.

World War II and the start of the Cold War ushered in new technologies, such as jets, nuclear weapons, radars, and rockets. There was a splurge of spending by the Defense

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<sup>19</sup> This section draws *heavily* on Lamoreaux, Levenstein, and Sokoloff (2007) for the period prior to World War II and on Kenney (2011) for the period after.

Department. A handful of VC firms were formed to exploit the commercialization of scientific advances. American Research and Development (ARD), founded by General Georges Doriot and others, was one of these. ARD pulled in money from mutual funds, insurance companies, and an initial public stock offering. The founders knew that it was important for venture capitalists to provide advice to the fledging enterprises in which they were investing. In 1956 ARD invested \$70,000 in Digital Equipment Corporation (DEC) in exchange for a 70 percent equity stake. ARD's share was worth \$38.5 million when DEC went public in 1966, which represented an annual return of 100 percent. While this investment was incredibly successful, the organizational form of ARD did not come to dominate the industry. The compensation structure of ARD made it difficult for the company to retain the VC professionals needed to evaluate startups and provide the guidance necessary for success.

An alternative organizational form came to emblemize the industry; viz., the limited partnership. This form is exemplified by the formation of Davis and Rock in 1961. These partnerships allowed VC professionals to share in the gains from startups along with the entrepreneurs and investors. Limited partnerships served to align venture capitalists' interests with those of entrepreneurs, investors, and key employees. Money was put in only at the beginning of the partnership. The general partners received management fees as a salary plus a share of the capital gains from the investments, say 40 percent, with the limited partners earning 60 percent. The limited partners had no say in the decisions of the general partners. The partnerships were structured for a limited length of time, say 7 to 10 years. The returns from the partnership were paid out to the investors only when the partnership was dissolved—there were no dividends, interest payments, etc. Therefore, the returns upon dissolution were subject only to capital gains taxation at the investor level. The VC industry also rewarded founders, CEOs, and key employees using stock options. Thus, they too were subject to capital gains taxation and not taxation on labor income. The short time horizon created pressure to ensure a venture's rapid success.

Banks and other financial institutions are not well suited to invest in cutting-edge new ventures. While banks are good at evaluating systematic lending risk, they have limited

ability to judge the skill of entrepreneurs, the worth of new technologies, and the expertise to help commercialize them. The Glass-Steagall Banking Act of 1933 prohibited banks from taking equity positions in industrial firms—the act was repealed in 1999. Allstate Insurance Company created a private placements program in the 1960s to undertake VC-type investments. It abandoned the program because it could not compensate the VC professionals enough to retain them. The Employee Retirement Income Security Act of 1974 prevented pension funds (and dissuaded other traditional fiduciaries) from investing in high-risk ventures. The act was reinterpreted in the 1980s to allow pension funds to invest in VC-operating companies, which provided a fillip for the VC industry.

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## 16 Theory Appendix

Proofs for Lemmas 2 and 4 are supplied in turn here. Lemma 2 establishes the existence of a balanced-growth path. Lemma 4 shows that solving the contract problem (P2) subject to a sequence of one-shot incentive constraints is equivalent to solving it subject to a single consolidated round-0 incentive constraint that allows for multi-shot deviations. This is proved using Lemma 3 as an intermediate step.

### 16.1 Balanced Growth

**Lemma 2** (*Balanced Growth*) *There exists a balanced-growth path of the form outlined in Section 8.*

**Proof.** Suppose that  $\{p_t, \sigma_t, \mu_t, \beta_t\}$  solves the old problem for  $x$  and  $\mathbf{x}$ . It will be shown that  $\{\mathbf{g}_w p_t, \sigma_t, \mu_t, \beta_t\}$  solves the new one for  $x' = \mathbf{g}_x x$  and  $\mathbf{x}' = \mathbf{g}_x \mathbf{x}$ . First, observe that if  $x' = \mathbf{g}_x x$  and  $\mathbf{x}' = \mathbf{g}_x \mathbf{x}$ , then  $I(x'; \mathbf{g}_x^t \mathbf{x}') = \mathbf{g}_w I(x; \mathbf{g}_x^t \mathbf{x})$ . This occurs because  $T(x'; \mathbf{x}') = \mathbf{g}_w T(x; \mathbf{x})$ . This can be seen from (P1) because  $x$  will rise by  $\mathbf{g}_x$  and wages by  $\mathbf{g}_w$ . If  $p'_t = \mathbf{g}_w p_t$ , then it is immediate from the objective function in (P2) that  $C(x'; \mathbf{x}') = \mathbf{g}_w C(x; \mathbf{x})$ . Now, consider the incentive constraint (5). At the conjectured solution, the left-hand side will inflate by the factor  $\mathbf{g}_w$ . So will the right-hand side because  $D(\sigma'_t) - D(\tilde{\sigma}'_t) = \mathbf{g}_w [D(\sigma_t) - D(\tilde{\sigma}_t)]$ , since all costs are specified as a function of  $w$ . Therefore, the new solution still satisfies the incentive constraint. Move now to the zero-profit constraint (6). Again, the left-hand side will inflate by the factor  $\mathbf{g}_w$ , since  $p'_t = \mathbf{g}_w p_t$ ,  $\phi'_t = \mathbf{g}_w \phi_t$ ,  $D(\sigma'_t) = \mathbf{g}_w D(\sigma_t)$ ,  $M_t(\mu'_t) = \mathbf{g}_w M_t(\mu_t)$ ,  $E(\beta'_t) = \mathbf{g}_w E(\beta_t)$ , and  $R(x'/\mathbf{x}') = \mathbf{g}_w R(x/\mathbf{x})$ . This is trivially true for the right-hand side. Hence, the zero-profit constraint holds at the new allocations. It is easy to deduce from the right-hand side of (5) that the old solution for  $\tilde{\sigma}_t$  will still hold. This can be seen by using the above argument while noting that  $D_1(\tilde{\sigma}'_t) = \mathbf{g}_w D_1(\tilde{\sigma}_t)$ . To sum up, at the conjectured new solution, the objective function and the constraints all scale up by the same factor of proportionality  $\mathbf{g}_w$ . By cancelling out this factor of proportionality, the new problem reverts back to the old one. Likewise, it is easy to deduce that if  $x$  solves problem (P3) for  $\mathbf{x}$ , then  $x' = \mathbf{g}_x x$  solves it when  $\mathbf{x}' = \mathbf{g}_x \mathbf{x}$ . This occurs because problem (P3) also scales up by the factor of proportionality  $\mathbf{g}_w$ . When  $x/\mathbf{x}$  remains constant along a balanced-growth path, then the initial research cost of the project will rise at the same rate as wages,  $\mathbf{g}_w$ . Additionally,  $V(\mathbf{x})$  will grow the same rate as wages,  $w$ , so from (7) it is apparent that  $\epsilon$  will remain constant. ■

## 16.2 One-Shot Deviations versus Multi-Shot Deviations

This is an intermediate step toward solving Lemma 4. To this end, it will be shown that if the incentive constraint (5) holds for round  $t$ , when the entrepreneur has not deviated up to and including round  $t - 1$ , then it will also hold when he follows some arbitrary path of deviations up to and including round  $t - 1$ . Let  $\alpha_t$  represent that the probability that a

project is good at round  $t$  as defined by (4). These odds evolve recursively according to

$$\alpha_{t+1} = \frac{(1 - \sigma_t)\alpha_t}{(1 - \sigma_t)\alpha_t + (1 - \beta_{t+1})(1 - \alpha_t)},$$

where  $\alpha_1 = \rho/[\rho + (1 - \rho)(1 - \beta_1)]$ . For use in proving Lemma 3, note that  $\alpha_{t+1}$  is increasing in  $\alpha_t$  and decreasing in  $\sigma_t$ . This implies that if the entrepreneur deviates in round  $t$ , so that  $\tilde{\sigma}_t < \sigma_t$ , he will be more optimistic about the future, as  $\alpha_{t+1}$  will be higher. This increases the value of the  $\alpha$ 's for future rounds as well. With this notation, the round- $t$  incentive constraint (5) then reads

$$\begin{aligned} & \alpha_t(1 - \tau)\{\delta\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \sigma_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i]\} \\ & \geq (1 - \mu_t) \max_{\tilde{\sigma}_t} \left( D(\sigma_t) - D(\tilde{\sigma}_t) \right. \\ & \left. + \alpha_t(1 - \tau)\{\delta\tilde{\sigma}_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \tilde{\sigma}_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i]\} \right). \end{aligned}$$

**Lemma 3** *If the incentive constraint (5) holds for round  $t$ , when the entrepreneur has not deviated up to and including in round  $t - 1$ , then it will also hold when he follows some arbitrary path of deviations up to and including in round  $t - 1$ .*

**Proof.** Suppose that the entrepreneur deviates in some manner before round  $t$ . Let  $\hat{\alpha}_t$  be the prior associated with this path of deviation. Since the  $\tilde{\sigma}$ 's will be less than the  $\sigma$ 's, it follows that  $\hat{\alpha}_t > \alpha_t$ . Let  $\hat{\sigma}_t$  be the *optimal* round- $t$  deviation associated with  $\hat{\alpha}_t$ . Now,

$$\begin{aligned} & \alpha_t(1 - \tau)\{\delta\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \sigma_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i]\} \\ & \geq (1 - \mu_t) \left( D(\sigma_t) - D(\hat{\sigma}_t) \right. \\ & \left. + \alpha_t(1 - \tau)\{\delta\hat{\sigma}_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \hat{\sigma}_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i]\} \right), \end{aligned}$$

because  $\tilde{\sigma}_t$  is maximal when the prior is  $\alpha_t$ , while  $\hat{\sigma}_t$  is not. Next, replace  $\alpha_t$  with  $\hat{\alpha}_t$  to get

$$\begin{aligned} & \hat{\alpha}_t \{ \delta \sigma_t [I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \sigma_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i] \} \\ & \geq (1 - \mu_t) \left( D(\sigma_t) - D(\hat{\sigma}_t) \right. \\ & \quad \left. + \hat{\alpha}_t \{ \delta \hat{\sigma}_t [I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \hat{\sigma}_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i] \} \right), \end{aligned}$$

since  $\hat{\alpha}_t > \alpha_t$ . Last, if the prior is  $\hat{\alpha}_t$ , then  $\hat{\sigma}_t$  is maximal, so the above equation can be rewritten as

$$\begin{aligned} & \hat{\alpha}_t (1 - \tau) \{ \delta \sigma_t [I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \sigma_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i] \} \\ & \geq (1 - \mu_t) \max_{\hat{\sigma}_t} \left( D(\sigma_t) - D(\hat{\sigma}_t) \right. \\ & \quad \left. + \hat{\alpha}_t (1 - \tau) \{ \delta \hat{\sigma}_t [I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \hat{\sigma}_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i] \} \right). \end{aligned}$$

Hence the round- $t$  incentive constraint hold when for some arbitrary path of deviations up to and including in round  $t - 1$ . ■

### 16.3 The Consolidated Round-0 Incentive Constraint

The consolidated round-0 incentive constraint is

$$\begin{aligned}
(1 - \tau) \sum_{t=1}^T \rho \Pi_{j=1}^{t-1} (1 - \sigma_j) \delta^t \sigma_t [I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] \\
\geq \max_{\{\tilde{\sigma}_t\}_{t=1}^T} \left\{ \sum_{t=1}^T \delta^{t-1} [\rho \Pi_{j=1}^{t-1} (1 - \tilde{\sigma}_j) + (1 - \rho) \Pi_{j=1}^t (1 - \beta_j)] \right. \\
\quad \times (1 - \mu_t) [D(\sigma_t) - D(\tilde{\sigma}_t)] \\
\quad \left. + (1 - \tau) \sum_{t=1}^T \rho \Pi_{j=1}^{t-1} (1 - \tilde{\sigma}_j) \delta^t \tilde{\sigma}_t [I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] \right\}.
\end{aligned} \tag{17}$$

**Lemma 4** (*Equivalence of contracts*) *A contract  $\{\beta_t, \sigma_t, \mu_t, p_t\}$  solves problem (P2) subject to the sequence of one-shot incentive constraints (5) if and only if it solves (P2) subject to the consolidated round-0 incentive constraint (17).*

**Proof (by contradiction).** (*Necessity*) Suppose that an allocation satisfies the one-shot incentive compatibility constraints (5) but that it violates the consolidated one (17). This implies that at some round in the problem with the consolidated constraint it pays to deviate and pick a  $\tilde{\sigma}_t \neq \sigma_t$ . Pick the last round of deviation (which may be  $T$ ). It must be true that  $\tilde{\sigma}_t$  solves the maximization problem

$$\begin{aligned}
(1 - \mu_t) \max_{\tilde{\sigma}_t} \left( D(\sigma_t) - D(\tilde{\sigma}_t) \right. \\
\quad \left. + \hat{\alpha}_t (1 - \tau) \{ \delta \hat{\sigma} [I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \tilde{\sigma}_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1} (1 - \sigma_j) \delta^{i+1-t} \sigma_i [I(x; \mathbf{g}_x^i \mathbf{x}) - p_i] \} \right),
\end{aligned}$$

where  $\hat{\alpha}_t$  is the prior associated with the path of  $\sigma$ 's up to round  $t - 1$ , which may include previous deviations. But, from Lemma 3, this is less than the value of sticking with the

contract or

$$\hat{\alpha}_t(1 - \tau)\{\delta\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \sigma_t) \sum_{i=t+1}^T \Pi_{j=t+1}^{i-1}(1 - \sigma_j)\delta^{i+1-t}\sigma_i[I(x; \mathbf{g}_x^i \mathbf{x}) - p_i]\},$$

when the round- $t$  one-shot incentive constraint (5) holds, as assumed. Thus, a contradiction emerges.

(*Sufficiency*) Suppose  $\{\sigma_t\}_{t=1}^T$  satisfies the consolidated incentive constraint, but violates the one-shot incentive constraint at round  $k$ . Then, using (4) and (5), it follows that

$$\begin{aligned} & \rho \Pi_{j=1}^{k-1}(1 - \sigma_j)\delta^{k-1}(1 - \tau)\{\delta\sigma_k[I(x; \mathbf{g}_x^k \mathbf{x}) - p_k] + (1 - \sigma_k) \sum_{t=k+1}^T \Pi_{j=k+1}^{t-1}(1 - \sigma_j)\delta^{t+1-k}\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t]\} \\ &= (1 - \tau) \sum_{t=k}^T \rho \Pi_{j=1}^{t-1}(1 - \sigma_j)\delta^t\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] \\ &< \delta^{k-1}(1 - \mu_k) \left( [\rho \Pi_{j=1}^{k-1}(1 - \sigma_j) + (1 - \rho) \Pi_{j=1}^k(1 - \beta_j)] [D(\sigma_k) - D(\tilde{\sigma}_k)] \right. \\ & \left. + \rho \Pi_{j=1}^{k-1}(1 - \sigma_j)(1 - \tau)\{\delta\tilde{\sigma}_k[I(x; \mathbf{g}_x^k \mathbf{x}) - p_k] + (1 - \tilde{\sigma}_k) \sum_{t=k+1}^T \Pi_{j=k+1}^{t-1}(1 - \sigma_j)\delta^{t+1-k}\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t]\} \right). \end{aligned} \tag{18}$$

The left-hand side gives the payoff in the contract at the optimal solution from round  $k$  on, when using the consolidated incentive constraint, while the right-hand side represents the payoff from a one-shot deviation at round  $k$ .

Now the objective function for the contract can be written as

$$(1 - \tau) \sum_{t=1}^{k-1} \rho \Pi_{j=1}^{t-1}(1 - \sigma_j)\delta^t\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t] + (1 - \tau) \sum_{t=k}^T \rho \Pi_{j=1}^{t-1}(1 - \sigma_j)\delta^t\sigma_t[I(x; \mathbf{g}_x^t \mathbf{x}) - p_t].$$

Evaluate this at the optimal solution for the contract when using (17) instead of (5). Next, in this objective function, replace the payoff from round  $k$  on, as represented by the left-hand side of (18), with the payoff from the one-shot deviation as given by the right-hand side.



This deviation increases the value of the objective function for the entrepreneur under the contract with the time-0 incentive constraint, which contradicts its optimality. ■