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Venture Capital and Career Concerns

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Venture Capital and Career Concerns

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Dedicated to my dear wife Elayne, and to my sons Benjamin and Thomas.

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Venture Capital and Career Concerns

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This dissertation examines the effect of career concerns on the pattern of investments selected by venture capital fund managers. I propose a simple model in which managers strategically adjust the variance of their portfolio to maximize the probability of raising a follow-on fund. The model demonstrates that career concerns can encourage venture capital fund managers to inefficiently select investments that are too conservative. The influence of these career incentives declines following good initial fund performance, leading to a positive correlation between early fund performance and late fund risk-taking.

Using a unique data set of company-level cash flows from 181 venture capital funds, I demonstrate that the intra-fund patterns of investment in venture capital broadly match the predictions of the model. First, I show that the characteristics of career concerns in the venture capital industry are consistent with the assumptions which drive the model. Funds who perform well in their initial investments raise a new fund more quickly, and the size of their next fund is concave with respect to the existing fund's performance. Second, using a maximum likelihood methodology I show that venture capital fund managers select more risky portfolio companies following good performance and tend to be less diversified.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Venture capitalists frequently claim that the best investment opportunities are often extremely risky ventures, which offer a small possibility of an extremely high return.[1] However, it is common to observe venture capital investments in firms that, at first glance, appear to compete in relatively modest markets, which are unlikely to produce high returns. For example, venture capitalists have recently funded a bottler of iced tea, an on-site car wash service and a pizza delivery service in the United Kingdom.[2] Notably, all of these investments were made by venture capitalists operating their first fund. Certainly these particular firms may have been attractive investment opportunities, but their contrast with the type of high-risk firms usually associated with venture capital motivates a broader look at how the economic incentives facing venture capital funds impact the riskiness of their portfolio and the types of firms in which they invest.

[1] "I don't know how to write a business plan; I can only tell you how we read them. We start at the back and if the numbers are big, we look at the front to see what kind of business it is." - Tom Perkins, founding partner of Kliener, Perkins, Caufield & Byers.

[2] These portfolio companies were identified using VentureXpert, not the sample used in the remainder of the paper. The company descriptions are taken from the database or from examination of the portfolio company's website.

This dissertation offers a theoretical model and empirical evidence that suggests concern about the ability to attract future investors motivates inexperienced venture capital fund managers to tilt their portfolio towards more conservative investments. The strength of these career concerns changes over the course of a fund. Managers with strong early performance demonstrate sufficient skill to guarantee themselves a new fund and are thus free to choose investments that maximize fund value, while poorly performing managers continue to cater to risk-averse career incentives. This stands in contrast to the results in other asset classes, such as mutual funds and hedge funds, where authors have attributed an increase in portfolio risk of *poorly* performing managers to their concerns about future fund flows. (Brown, Harlow and Starks(1996), Chevalier and Ellison (1997) and Brown, Goetzmann and Park (2001)).

Venture capital fund managers, referred to as general partners (GPs), receive finite capital commitments from their investors, the fund's limited partners (LPs). GPs select portfolio companies in which to invest the fund's capital over an investment period of three to five years, after which they must again face the scrutiny of investors to raise a discrete follow-on fund. GPs are rewarded for performance implicitly through the ability to raise a new and potentially larger fund, and explicitly through a convex compensation provision known as carried interest.

The implicit career incentives of venture capitalists differ from those of investment managers in other asset classes in two important ways. First, as demonstrated empirically by Kaplan and Schoar (2005) and confirmed in this paper, the positive relationship between venture capital fund performance and the size of the next fund is concave, with most of the relationship driven by the failure of some GPs to raise any follow-on fund. Thus, career concerns in venture capital tend to discourage risk-taking. Second, because venture capital funds have a limited amount of capital and attracting new capital is time consuming, GPs often secure commitments for a follow-on fund while still making investment decisions for the current fund. With commitments for the next fund in hand, high-performing GPs are less affected by career concerns, and thus able to maximize the value of the current fund.

I formalize this intuition with a simple, two-period model of a venture capital fund in which a GP chooses investments to maximize the expected payoff from raising a follow-on fund and continuing his or her career managing venture capital. In each period the GP must choose between an efficient investment opportunity, and two lower-NPV alternatives. The alternative investments allow the GP to strategically choose their portfolio variance by increasing or decreasing the probability of realizing a "moderate" return with a corresponding adjustment to the probability of extremely high and low returns.[3] The tension in the model is that so long as the loss in NPV isn't too

[3] With the skewed distribution of venture capital returns, "moderate" returns may in fact be very high. The intention is to model the trade-off between extremely risky gambles, and those which offer a higher probability for more modest success. A useful analogy might be to consider a baseball player in a slump who swings less aggressively, trading off the possibility of hitting home runs in hopes of hitting more doubles and triples to raise his batting average.

great, the GP's optimal strategy is to select the alternative investment whose probability distribution places the most weight on outcomes which will result in a new fund.

The model highlights several additional features of implicit compensation in the venture capital markets, that may generalize to other settings. First, investors in the model are rational. They update their beliefs about GP skill after observing realized returns each period. Second, the value of a follow-on venture capital career is not a smooth function of investor's beliefs about a GP's skill. A large jump occurs as the GP crosses the threshold of just being able to convince investors to finance a follow-on fund. Relative to this jump, the investor's perception of "moderate" returns as evidence of skill determines the GP's choice of portfolio risk. When "moderate" returns are not sufficiently indicative of skill, the GP essentially faces a convex payoff function. Only extremely high returns will result in a new fund; thus, the model produces the typical intuition that career concerns promote risk-taking. However, when "moderate" returns are sufficiently indicative of skill, the GP faces concave incentives and will correspondingly choose the least risky portfolio.

There is reason to suspect that the venture capital industry represents a case in which career concerns discourage risk-taking. Industry participants describe encountering funds that earn the majority of their returns from one or two home run investments. In evaluating the manager of such a fund it is difficult to determine whether high returns should be attributed to skill or luck. Given these concerns and the high skewness of venture capital returns, GPs may well be willing to trade off some probability of extremely high returns for an increased probability of relatively good returns.

In addition to characterizing the direction in which career concerns influence portfolio risk, the model generates predictions on how the influence of career concerns evolves over the course of the fund. By allowing for early fund raising, the model generates a pattern of investments, similar to the effect noted in the mutual fund literature. This allows some GPs (those who have performed well in their initial investment) to escape the influence of career concerns and simply choose the efficient investment in the second period. The empirical implication is that a GP's early fund performance should be positively related to the riskiness of the portfolio selected with the fund's remaining capital. This effect should be concentrated among less experienced GPs.

In an extension of the model, I consider the effect of career concerns on the optimal explicit compensation contract. When agents endogenously determine the explicit compensation contract at the beginning of the fund, the convexity of the compensation function is designed to mitigate the risk-taking incentives of career concerns. Under model parameters where career concerns promote risk-taking, the optimal explicit compensation is concave. In contrast, when implicit career concerns discourage risk-taking, the optimal explicit compensation contact is convex. In practice the explicit compensation of venture capital GPs consists of a flat management fee and a convex option-like provision known as carried interest. The model suggests that the carried interest provision can be interpreted as a response to career concerns that encourage inefficiently low risk investments.

I test the model using a unique proprietary data set covering the investments of 181 venture capital funds. The data was obtained from Neuberger Berman, a global alternative asset management firm with over 30 years of venture capital experience. Unlike commercial data sets, this data includes the quarterly cash flows and valuations for every portfolio company investment of a large sample of venture capital funds. To my knowledge this is the first venture capital data set in the literature to contain detailed cash flow information at the portfolio company-level.

Despite access to a particularly well suited data set, estimating the relationship between fund performance and the volatility of subsequent investments remains challenging. Unlike public investments, for which we observe the time series of i.d.d. returns, private investments generate a single observable return when the fund exits.[4] I implement a maximum likelihood approach that identifies the effects of previous fund performance on the volatility of subsequent investments using the common variation in the difference between the realized return and predicted mean return across the sample of portfolio

[4] The difficulty created by this distinction becomes clear in comparison to the mutual fund literature, where estimating the relationship between previous performance and subsequent risk-taking relies on the time series volatility of daily mutual fund returns. The volatility of daily returns can be taken as directly proportional to the volatility of the mutual fund manager's 6-month or 1-year portfolio strategy, given that the returns are assumed to be i.i.d.

companies.[5] The approach takes the volatility of each investment as a latent variable. The resulting model is similar to the feasible generalized least squares approach to regression with heteroskedasticity.[6] However, in this instance the parameter estimates in the variance equation are the objects of interest, rather than an intermediate step necessary to correct for heteroskedasticity.

My main finding is that following good performance early in a fund, GPs pursue a more risky investment strategy with their remaining capital relative to their poor performing colleagues. This is accomplished by investing in more volatile portfolio companies and by allocating their remaining capital amongst a smaller number of investments (diversifying less). These effects are particularly concentrated among inexperienced GPs. For a GP operating their first fund, three years into the fund's life an increase of 10% in the reported internal rate of return of the fund corresponds with a 14% higher variance of future portfolio company investments. The same increase in performance corresponds to a 5% increase in the initial size of portfolio company investments, resulting in less diversification. In addition, I confirm that the characteristics of implicit compensation conform with the assumptions of my model. The size of the next fund is concave, with the effect largely driven by the GPs who fail to raise a new fund. The speed at which GPs raise a new fund is also related

[5]The actual identification is slightly more subtle as the maximum likelihood approach jointly estimates the parameters for the mean and variance. However, the difference between the predicted mean and realized return captures the intuition for how the parameters related to variance enter the likelihood equation.

[6]The approach differs from the textbook FGLS approach by allowing the mean return to be linearly related to the variance, and by allowing for truncation at -100% return.

to performance, with a 10% increase in the fund's internal rate of return resulting in a factor increase of 1.02 to 1.03 for the speed at which GPs raise a new fund. Finally, I show that extent to which the GP's current performance is based on a small number of very successful investments (as opposed to a large number of moderate successes) is negatively related to their ability to raise a follow-on fund. This corresponds to the model's prediction that career concerns discourage risk taking when "moderate" success is relatively more informative about GP skill.

This paper relates to the growing literature investigating the incentives of venture capital and private equity fund managers. Chung, et al. (2012) use fund-level data from Prequin to estimate that implicit pay-for-performance in a first-time venture capital fund is of a similar order of magnitude to the explicit pay-for-performance derived from the carried interest option. This study expands upon their work by linking implicit pay-for-performance to the investment decisions of managers. In a closely related study, Ljungqvist, Richardson and Wolfenzon (2007) use a sample of portfolio company investments made by buyout private equity funds to investigate a manager's propensity to risk shift in response to implicit incentives. This study differs from theirs in that they model implicit compensation as a convex function of performance. Their intuition is that GPs that have performed poorly will be unable to raise a new fund unless they "catch up" by choosing volatile investments. Empirically, I show that in venture capital implicit incentives are concave in performance and discourage risk taking. However, my results do not rule out the possibility that a small number of funds may perform poorly enough in early investments that they may expect to fail to raise a new fund without dramatically improving performance. These funds, which may seek out more risk, do not appear to be prevalent in my sample.[7]

The remainder of this dissertation is organized as follows. Chapter 2 describes the stylized model, which motivates the empirical tests. Chapter 3 describes the data from the fund-of-fund samples and presents the main empirical results concerning implicit incentives and portfolio risk. Chapter 4 concludes.

[7] Such a non-monotonic relationship would be consistent with the model of Zwiebel (1995), who shows that under relative performance evaluation high and low talent managers may pursue risky strategies, while managers with an average level of talent may prefer to behave conservatively.

Chapter 2

A Model of Venture Capital

2.1 Model Setup

The model represents a venture capital fund as a sequence of two investment periods, after which a successful GP will continue their career by raising a new fund. The timeline of the model is depicted in Fig. 2.1. At $t = 1$ and $t = 2$ the GP invests the fund's capital in investment opportunities. The GP chooses investments in each period while trying to maximize the expected value of the implicit compensation they will earn from performing well enough to raise a follow-on fund and continue their career as a venture capitalist. Fund-raising for the follow-on fund can take place at $t = 2$ or at $t = 3$. Raising committed capital for a follow-on fund prior to exhausting the capital of the current fund is typical feature of the venture capital industry. Allowing early fund-raising in the model at $t = 2$ allows comparison of the investment decisions of funds who are able to secure early commitments for a follow-on fund, with those who are still subject to career concerns.

2.1.1 Investments

The model represents changes in the variance of a GP's investment portfolio as deviations relative to a standard investment. The standard investment yields a payoff $c_{std} \in \{0, X, 2X\}$ according to the following pdf:

$$Pr\left[c_{std} = C_{std}\right] = \begin{cases} \alpha t_i + \frac{p}{2} & C_{std} = 2X \\ (1-\alpha)\, t_i + \frac{p}{2} & C_{std} = X \\ 1 - t_i - p & C_{std} = 0 \end{cases} \tag{2.1}$$

t_i is a parameter measuring the skill of the GP, which positively affects the likelihood of both a modest and very high payoff. Parameters α and p jointly determine the extent to which the likelihood of each payoff is determined by skill or luck. These parameters play an important role in the model because investors, rationally updating their beliefs about the GP skill, will be more likely to invest a new fund when the observed outcomes of the current fund are heavily dependent on skill. The parameter α represents the extent to which a very high outcome ($2X$) is more skill dependent than a modest outcome (X). At the extreme, when α is 1, the investors learn nothing from observing $c_{std} = X$, and thus will maintain the same beliefs about the skill held prior to observing the result of the current investment. Similarly, both the outcomes $c_{std} = X$ and $c_{std} = 2X$ become less informative about GP skill as p, the component of each outcome attributable to luck, increases. When p is very high, good outcomes are not very informative about the GP's skill, but the outcome $c_{std} = 0$ is very indicative that the GP is poorly skilled.

In each period the GP has a choice between taking the standard investment, or selecting one of two alternative investments. The alternative investments allow the GP increase or decrease risk, which, under many parameter values, improves the probability of raising a new fund. For example, for some parameter values, the only outcome that would result in a new fund is $c_2 = 2X$; thus, the GP may benefit from taking a more risky investment, which improves the chance of a very high outcome.[1] However, the ability to act strategically comes at a cost, as both alternative investments offer a smaller NPV than the standard investment. The alternative that places less weight on the extreme outcomes, which I will refer to as the safe investment, has the following pdf:

$$Pr\left[c_{safe} = C_{safe}\right] = \begin{cases} \alpha\left(t_i - \epsilon\right) + \frac{p}{2} - \gamma & C_{safe} = 2X \\ \left(1-\alpha\right)\left(t_i - \epsilon\right) + \frac{p}{2} + 2\gamma & C_{safe} = X \\ 1 - \left(t_i - \epsilon\right) - p - \gamma & C_{safe} = 0 \end{cases} \tag{2.2}$$

The investment with higher variance than the standard investment, referred to as the risky investment has the following pdf:

$$Pr\left[c_{risky} = C_{risky}\right] = \begin{cases} \alpha\left(t_i - \epsilon\right) + \frac{p}{2} + \gamma & C_{risky} = 2X \\ \left(1-\alpha\right)\left(t_i - \epsilon\right) + \frac{p}{2} - 2\gamma & C_{risky} = X \\ 1 - \left(t_i - \epsilon\right) - p + \gamma & C_{risky} = 0 \end{cases} \tag{2.3}$$

The alternative investments differ in volatility by adding, or subtracting, γ to the extreme outcomes 0 and $2X$, and adjusting the probability of the

[1] The solution is complicated by the fact that investors rationally anticipate the GP's investment decisions. While relative to the standard investment the risky investment results in a high probability of realizing $c_2 = 2X$, this outcome becomes less informative about GP skill and may no longer be sufficient to raise a new fund. The solution provided in Appendix A considers these effects and the resulting mixed strategies in detail.

X accordingly. This adjustment alone does not lower the NPV of the alternative investments relative to the standard investment. To evaluate the ability of career concerns to create agency conflicts it is assumed that the GP is less talented at choosing or operating these alternative investments, such that the effect of their skill is reduced by an amount ϵ. This way of modeling a negative effect of deviating from the standard investment opportunity is meant to suggest that GPs have a competitive advantage in certain types of investments. Deviating from these investment to pursue a portfolio with a more favorable distribution for raising a new fund is likely to reduce the effect of GP skill on the investment outcome. In practice LPs frequently express their concern that poorly performing GPs are straying from the fund's stated investment plan into markets where the GP's background is unlikely to provide sufficient competitive advantage. Figure 2.2 plots the pdf of each type investment the for an average GP under certain parameter values.

2.1.2 General Partner Skill

GP skill can be interpreted as both the ability to select portfolio companies with good prospects and the ability to exert a monitoring influence, making it more likely a given portfolio company will succeed. In the model there are two types of GPs, good and bad, which are in equal proportion in the population. Neither the GP nor LP have private information about the GP's type and both will update their beliefs according to Bayes' rule, given the performance of the fund's investments. The skill of each GP is given by a parameter t_i, where bad and good types have skill $t_{bad} = t$ and $t_{good} = t + \Delta t_g$ respectively, with $\Delta t_g > 0$. initially:

$$E[t_i] = t + \frac{\Delta t_g}{2} \tag{2.4}$$

2.1.3 Compensation and Career Concerns

Both the GP and LP are assumed to be risk neutral with the discount rate normalized to 0. In the base version of the model, the GP's pay for managing the current fund is assumed to be a constant, paid at the beginning of the fund, and not sensitive to performance. This simplification allows the model isolate the effects of implicit career concerns.

Implicit compensation represents the expected value the GP will receive from raising and operating follow-on funds. For simplicity the value of these future wages is summarized by a constant, F, which only accrues to GPs who successfully raise a new fund. The outside option of a GP who is unable to raise a new fund is normalized to zero. Investors will be willing to finance a follow-on fund whenever the expected value of a GP's skill meets or exceeds the expected skill of a GP drawn randomly from the population. The resulting relationship between performance and implicit compensation for GP i is the following step function:

$$V_{i,\text{ GP career}} = \begin{cases} F & \Pr[t_i = t + \Delta t_g] \geq 1/2 \\ 0 & \Pr[t_i = t + \Delta t_g] < 1/2 \end{cases} \tag{2.5}$$

The choice to represent the career concerns as a step function is motivated by empirical findings that suggest that the relation between fund performance and the size of follow-on fund is concave, and that the concavity is largely driven by the failure of some GPs to raise a new fund. Empirical results in Section 3.2 suggest that the concave relation holds in this study's sample. Modeling this relationship as a step function is a tractable method of obtaining the important feature of the data: that crossing over the threshold required to raise a new fund is far more valuable than the marginal increase in fund size thereafter.

Note that in the timeline depicted in Fig. 2.1 the venture capitalist can raise a follow-on fund after realizing only one investment. This closely follows the fund-raising environment faced by venture capital GPs. Raising a follow-on fund is a time-consuming process that often starts long before the committed capital for the current fund has been fully invested. Aside from raising the largest fund possible, the goal for the GP is to have a seamless transition from one fund to the next, so that they are not forced to ration capital. In the model there is no explicit penalty for waiting for two periods to raise a follow-on fund. However, the functional form of implicit compensation guarantees that raising a new fund after one period is, at least, weakly preferred to waiting for the result of the second investment. Good performance in the second investment will not increase the size of the follow-on fund, but for some parameters, a bad result could cause investors' perception of the GP's skill to fall below the threshold required to raise a new fund.

2.2 Model Results

The model's main results demonstrate the connection between implicit incentives, the timing of fund-raising and the pattern of investment in venture capital funds. A detailed solution to the model is given in Appendix A.

Result 1. *In the first period the GP will select the safe investment. Following a successful first investment,* $c_1 \geq X$*, the GP will immediately raise a new fund and select a standard investment in the second investment period.*

Proof. See Appendix A. □

Result 1 demonstrates how career concerns affect early investment decisions and fade following good performance early in the fund. Early in the fund there is a strong incentive to select safe investments because any success will be sufficient to improve the LP's beliefs about GP skill. Because fund-raising can be conducted before the second investment is made, successful GPs have the opportunity to lock-in a follow-on fund; thus, their second investment decision is not constrained by career concerns. The critical assumption is that there is little benefit to demonstrating talent through additional success, while the failure of subsequent investments could prevent the GP from raising a new fund.[2]

[2] This result will hold in the case where the GP is able to raise a larger fund with additional good performance, so long as the increase in fund size is not high enough to outweigh the potential losses from poor performance.

When $c_1 = 0$ the GP cannot immediately raise a new fund. They must face a choice between taking the standard investment, which would maximize the value of the current fund and selecting one of the alternative investments, which may increase the probability of an outcome which would allow him to raise a new fund at $t = 3$. Result 2 demonstrates that unless the loss of NPV for the alternative investments is particularly bad, the GP will always select one of the alternative investments, provided they do not face a situation where they cannot raise a new fund regardless of the outcome of the second investment.

Result 2. *There exists $\bar{\epsilon} > 0$, such that for $\epsilon \leq \bar{\epsilon}$, in any equilibrium which contains positive probability of the GP raising a new fund following $c_1 = 0$, the GP will always pursue one of the lower NPV, alternative strategies with some positive probability.*

- *For any pure strategy equilibrium in which the GP selects the risky investment following $c_1 = 0$, the outcome $c_2 = 2X$ must be sufficiently informative about the GP's type for the investors to grant a new fund, while the outcome $c_2 = X$ must not be sufficient to raise a new fund. This requires that:*
  - *α, the relative effect of skill on the probability of very high returns, is large.*
  - *p, the extent to which positive returns depend on luck, is moderate*
  - *$t + \frac{\Delta t_g}{2}$, the average GP skill level, is moderate.*

- *For any pure strategy equilibrium in which the GP selects the safe investment following* $c_1 = 0$*, the outcome* $c_2 = X$ *must be sufficiently informative about the GP's type for the investors to grant a new fund, while the outcome* $c_2 = 2X$ *may or may not be sufficient to raise a new fund. This requires that:*
  - α*, the relative effect of skill on the probability of very high returns, is low.*
  - p*, the extent to which positive returns depend on luck, is low*
  - $t + \frac{\Delta t_g}{2}$*, the average GP skill level, is low.*

Proof. See Appendix A. □

Figure 2 depicts the regions described in Result 2 for a representative set of model parameters. The first part of the result suggests there are only two conditions when the GP will play a pure strategy of selecting the standard investment. The first is when there is no chance of raising a new fund. This occurs when $t + \frac{\Delta t_g}{2}$ is high, and adverse effect of learning that the initial investment was a failure cannot be overcome by a successful investment. The second condition under which the GP will select the standard investment is when the reduction probability of a high outcome due to ϵ is so severe that it swamps the effect of taking safe or risky projects. For moderate levels of ϵ, as depicted in figure 2, when it is feasible to raise a new fund for some outcome of c_2, the GP will always select one of the alternative investments with some positive probability.

The model suggests that the effect of the current fund's early performance on risk-taking toward the end of the fund is determined by the characteristics of venture capital investments. The model predicts that if very high outcomes are highly attributable to skill, while moderate outcomes are more dependent on luck (i.e. α is close to one), then we would expect that venture capitalists should exhibit the same "gambling for salvation" behavior that has been observed in the mutual fund and hedge fund literature. If, instead, moderate success is likely to be rewarded with a new fund, then venture capitalists performing poorly in the first should select safer investments of the sort described in the introduction.

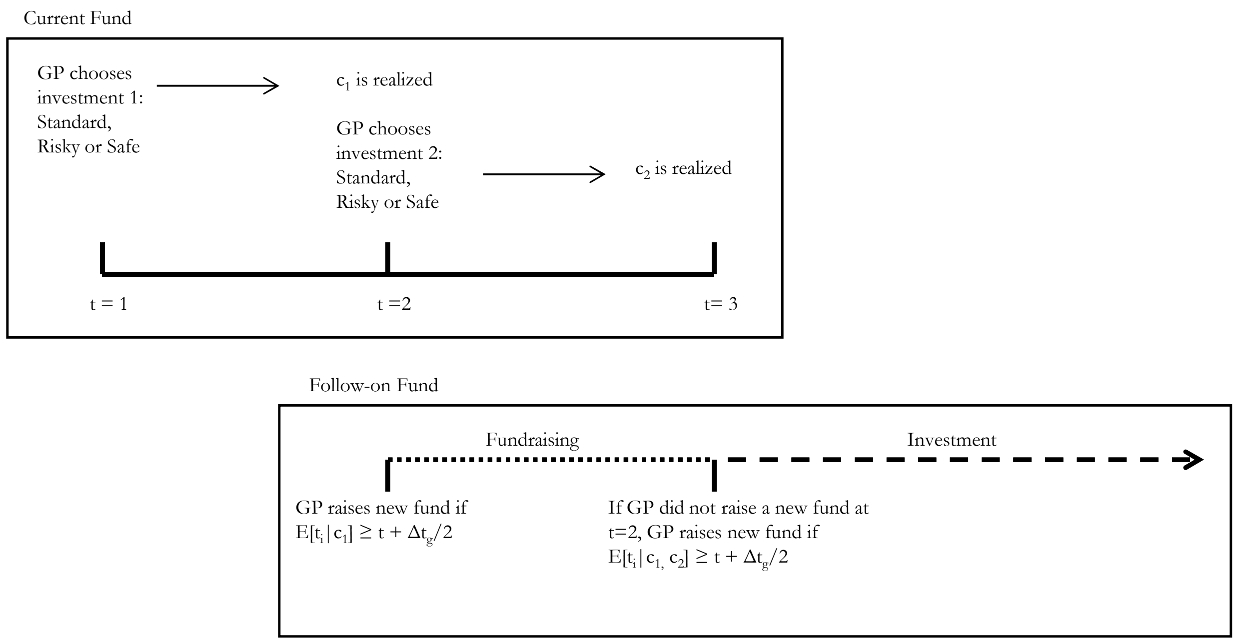

Figure 2.1: Model Timeline.

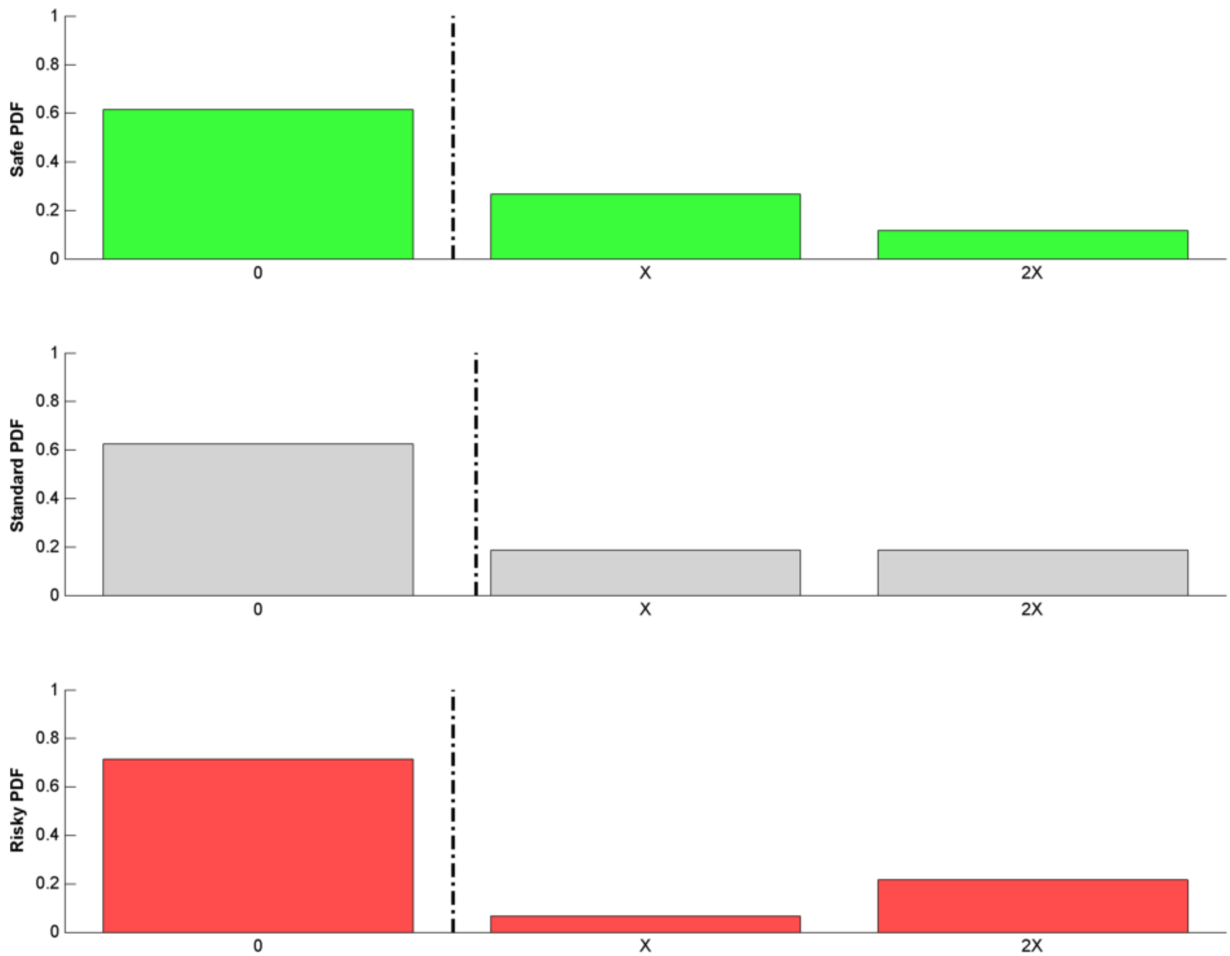

Figure 2.2: Distribution of investment returns for the average GP at model parameters: $\alpha = 0.5$, $t = 0.05$, $\Delta t_g = 0.05$, $p = 0.30$, $\gamma = 0.05$, $\epsilon = 0.04$

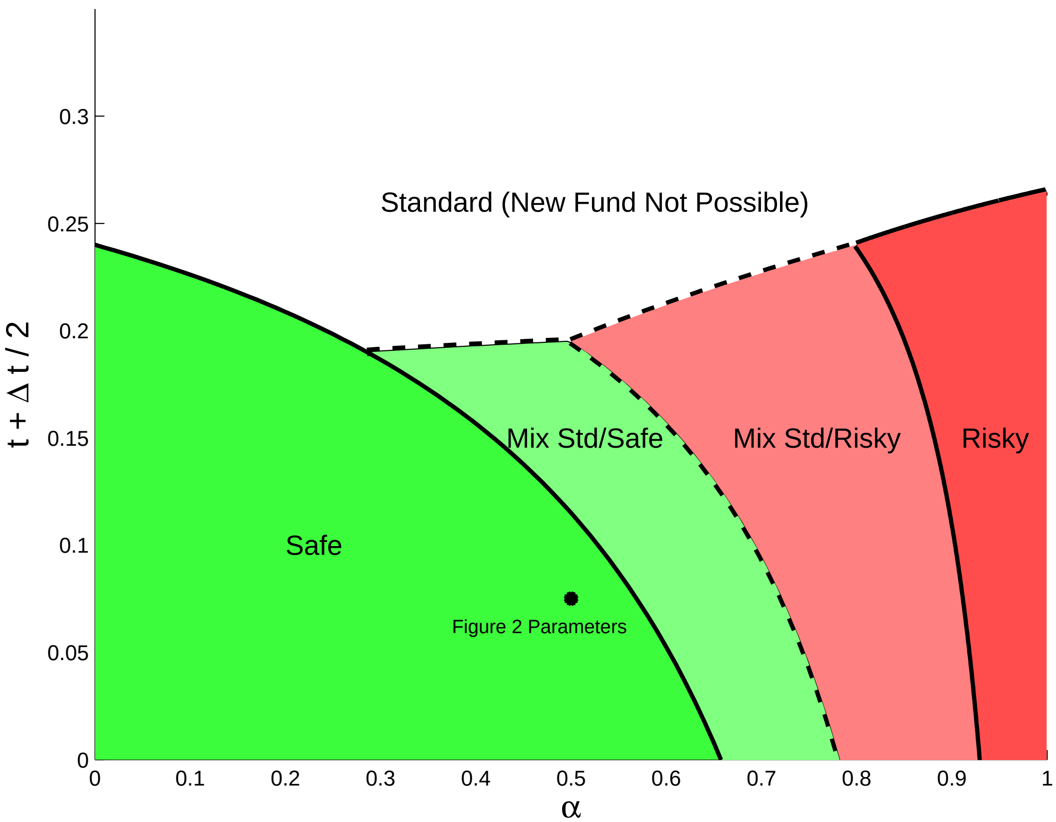

Figure 2.3: Equilibrium Period 2 Strategy Following $c_1 = 0$ for $p = 0.30$, $\gamma = 0.05$, $\epsilon = 0.02$

2.3 Model Extension - Endogenous Explicit Compensation

This section extends the model to consider the functional form of the GP's payoff when explicit compensation is determined endogenously. I assume that at the beginning of the fund the GP proposes a contract that determines how the cash flows from the current fund will be divided. The LP is assumed to be competing among a large group of potential LPs such that he will accept any division of cash flows in which he expects to break even in equilibrium.

I assume that the proposed compensation must be a function of the aggregate performance of the fund, $f(C_1 + C2)$. While this assumption is largely made to simplify the exposition of the model, it can be justified on the grounds that there may exist several frictions, which lie outside of the model, that would prevent the agents from writing contracts which are a function of C_1 and C_2 separately (i.e. $f(C_1, C2)$). For example, there may be an un-modeled moral hazard problem that requires the GP to expend costly effort monitoring all of the investments for a long time after they are made. A compensation function that gives more weight to the performance of one investment may distort the incentives to efficiently allocate monitoring effort. In addition, this corresponds to the contracts we observe in practice, which compensate GPs on the aggregate return of the fund.

In addition I include several standard assumptions regarding the division of the fund's cash flows. First, I assume limited liability for both the GP and the LP. Second, I assume that the compensation function for the GP must be monotonically increasing in the aggregate performance of the fund. The remaining primitives of the model remain identical to the base model considered in the previous chapter.

Claim 1. *Without loss of generality, the wage function for the GP can be decomposed into a management fee $A \geq 0$, and a monotonically increasing performance sensitive function $W_{GP}\left[C_1 + C_2\right]$.*

Proof. See Appendix B. □

Claim 1 follows trivially from the limited liability constraint and the monotonicity assumption for total GP compensation. The compensation observed in practice consists of a fixed management fee, typically 2% of committed capital, and a performance sensitive portion which is based on the aggregate cash flow of the fund.

The following results characterize the equilibria when explicit compensation is used to achieve a first-best investment outcome and the GP selects the standard investment in each period. The purpose is to provide an additional implication of the model that can be compared with the compensation terms common in the venture capital industry.

This section does not address all of the possible equilibrium that do not achieve the first best investment policy. The case where when explicit compensation is insufficient to overcome the effects of implicit career concerns is covered in the base model. In such an equilibrium the shape of the explicit compensation function is largely irrelevant, and many possible compensation functions are admissible.[3]

I consider the optimal compensation function in two regions. The first corresponds to the parameters in the base model where implicit compensation would result in inefficiently safe investment following $C_2 = 0$. This corresponds to the area to the left in Figure 2.3. The second case corresponds the the area in the right in Figure 2.3, where implicit compensation alone would lead the GP to inefficiently select the risky investment following $C_2 = 0$.

2.3.1 Case 1: Career Concerns Encourage Safe Investment

Result 3. *For parameter values where career concerns alone would promote inefficient safe investment following $C_2 = 0$, there exists a level of career concerns $\bar{F}$ such that for $F < \bar{F}$ the first-best equilibrium is implementable and has the following properties:*

A) *There exists a function $W_{GP}[C_1 + C_2]$ which implements the efficient equilibrium that is convex in the region $C_1 + C_2 \in [0, 2X]$. In addition there exists $\bar{\epsilon}$, such that for $\epsilon < \bar{\epsilon}$ all possible $W_{GP}[C_1 + C_2]$ which implements*

[3] There exist additional equilibria where the explicit compensation is sufficient to prevent some inefficient investment, but insufficient to reach the first best. Detailing all of these equilibria is impractical, as with three investment choices at four decision nodes there are $3^4 = 81$ possible combination of investments, many of which are implementable over a small portion of the parameter space, all with different restrictions on the compensation function. Instead the model focuses on the extreme outcomes. The base model focused on the outcome when explicit compensation is unable to undo any of the effects of career concerns; the extended model focuses on the optimal compensation that can be implemented to achieve the first-best equilibrium.

the efficient equilibrium must be convex in the region $C_1 + C_2 \in [0,\ 2X]$.

B) *There exists a GP compensation function that implements the efficient equilibrium in which the performance sensitive component is of the form:*

$$W_{GP}\left[C_1 + C_2\right] = \begin{cases} 0 & \text{if } C_1 + C_2 \leq X \\ \left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right) F & \text{if } C_1 + C_2 = 2X \\ \left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)\left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right) F & \text{if } C_1 + C_2 = 3X \\ \left[\left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)^2 - \left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right)\right]\left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right) F & \text{if } C_1 + C_2 = 4X \end{cases} \tag{2.6}$$

Proof. See Appendix B. □

Result 3 demonstrates that when career concerns alone would generate inefficiently safe investment, an equilibrium exists with an explicit compensation function that shares many of the features of the management fee and carried interest option observed in practice.

The compensation function can be decomposed into positive constant A, which, like the management fee in practice, is not sensitive to performance. Similar to the carried interest option observed in practice, the performance-sensitive portion of the equilibrium payout function, $W_{GP}\left[C_1 + C_2\right]$ is convex in the low end of the function's support.

Result 3.B characterizes the compensation function that will produce the first-best investment choices under the broadest range of parameters. The shape of this compensation function is plotted in Figure 2.4. The upper panel plots the implicit compensation resulting from career concerns. The middle panel plots the explicit compensation. The lower panel plots the combined compensation function facing the GP. Note that the effect of the explicit compensation is to "smooth out" the effect of the large jump as the GP crosses the threshold of raising a new fund. Result 3.B demonstrates that the ability of agents to "undo" the effect of career concerns through explicit compensation contracts is limited.

2.3.2 Case 2: Career Concerns Encourage Risky Investment

Result 4. *For parameter values where career concerns alone would promote inefficient risky investment following $C_2 = 0$, if there exists a compensation function which implements the first-best equilibrium, the equilibrium must have the properties:*

A) *There exists a function $W_{GP}[C_1 + C_2]$ which implements the efficient equilibrium that is concave in the region $C_1 + C_2 \in [0,\ 2X]$. In addition there exists $\bar{\epsilon}$, such that for $\epsilon < \bar{\epsilon}$ all possible $W_{GP}[C_1 + C_2]$ that implements the efficient equilibrium must be concave in the region $C_1 + C_2 \in [0,\ 2X]$.*

B) $W_{GP}[X] >= \frac{\gamma - \alpha\epsilon}{\gamma + \epsilon} F$

Proof. See Appendix B. □

Result 4 characterizes the behavior of the equilibrium compensation function when career concerns alone would result in the GP selecting the risky investment. The important observation is that the efficient equilibrium, if it exists, can always be implemented by a concave compensation function. This stems from the fact that following $C_2 = 0$, the GP will only raise a new fund when $C_2 = 2X$, thus explicit compensation must be concave in this region to make the standard investment incentive compatible in the second period. In the second part of Result 3 we demonstrated a general functional form for the compensation function in the safe case, and that the general form includes $W_{GP}[0] = 0$. No such general form exists for the risky case because the first period incentive compatibility constrains are not simply linear functions of the second period constraints. However, it is shown in Appendix B that $W_{GP}[0] > 0$, thus the shape of $W_{GP}[C_1 + C_2]$ is clearly very different from result from Case 1.

2.3.3 Implications of the Extended Model

The optimal compensation results from the extended model provide additional support for the claim that career concerns tend to discourage risk-taking in venture capital markets. To implement the first-best equilibrium, agents facing career concerns that discourage risk-taking, can always use a convex compensation function, which is similar to the carried interest option used in practice. In contrast, the model suggests that if career concerns encouraged risk-taking, we should expect that venture capitalists would be compensated by a concave function.

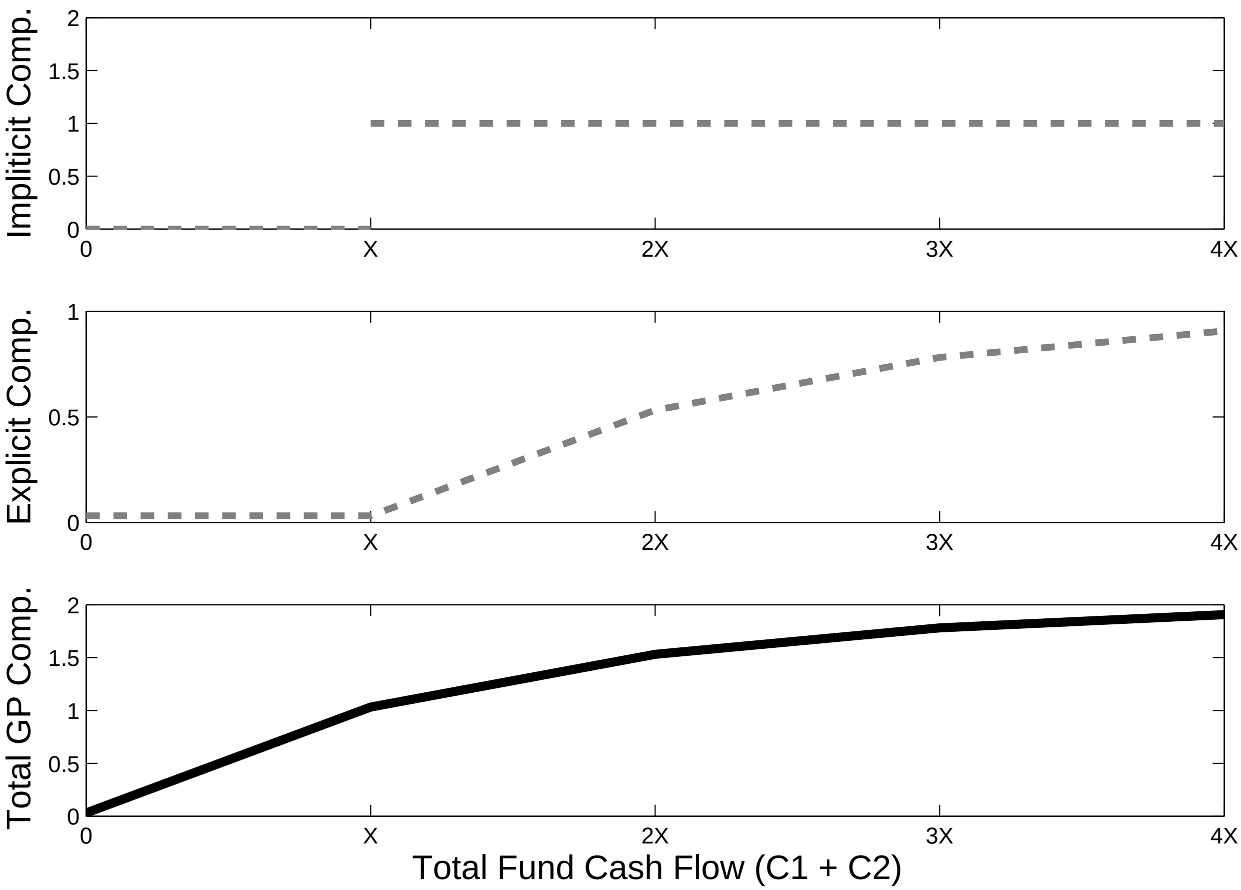

Figure 2.4: GP Compensation.

Chapter 3

Empirical Test of the Model

3.1 Data

The empirical tests of the model's implications use a unique data set consisting of all the individual portfolio company investments of 181 venture capital funds. The data was provided by Neuberger Berman, a global alternative asset management firm which manages approximately $11 billion in private equity commitments which are invested through its fund-of-funds business. The sample includes venture capital funds that received an investment from the firm between 1981 and 2003. I exclude secondary investments (those which were purchased from an existing LP), investments in sidecar funds and funds with less then five portfolio companies.

Table 3.1 gives the descriptive statistics of the funds and their underlying portfolio companies. Panel A describes the moments of the data at the fund-level. The GP of the median fund in the sample has operated 3 previous funds, with the largest having operated 26 previous funds.[1] 29 of the funds,

[1] This count includes all previous funds for a GP, including geographic and industry focused funds. The count was gathered from VentureXpert and the fund-of-fund's records. In many cases the previous experience was imputed from the series number of the funds (i.e. the GP of the fictional fund ACME VII LLP would be assumed to have six previous funds)

16%, are managed by a GP operating their first fund. Fund size is measured as the capital committed to the fund in millions with a median value of $118 million. Unlike many other investment vehicles, venture capital funds don't immediately collect funds from investors. Instead, the fund receives commitments from the LPs, which are called by the GP over the investment period as required.

I measure the performance of individual investments and performance of the fund's entire portfolio using a modified internal rate of return. This is an alternative to the typical internal rate of return, which is consistent across the 7% of the portfolio companies and 52% of the fund-quarter observations that exhibit more than one change in cash flow sign.[2] To calculate the MIRR, I discount all negative cash flows back to the initial investment date using the five-year treasury rate in the month prior to the initial investment. The intuition behind using long-term treasury rates is that the resulting discounted cash flow represents the amount that the fund would have been required to set aside in a risk-free security in the event they could perfectly anticipate the expected follow-on investment needs. This variation of MIRR avoids throwing out the observations with multiple sign changes over the cash flows, while minimizing the impact of assumptions about discount rates, re-investment rates, etc. The median final MIRR of funds in the sample is 13.9%. I also

[2]Cash flows with multiple sign changes result in multiple or non-existent internal rates of return. Variations on the modified IRR method are recommended in widely-used introductory finance textbooks such as Parrino and Kidwell (2009) and Ross, Westerfield and Jordan (2010). The results presented are robust to using Modified IRR only when an IRR does not exist.

report Total Value to Paid-in (TVPI), a multiple commonly used in the private equity industry. TVPI is formed by taking the un-discounted sum of cash flows returned from an investment plus the valuation of any unrealized claim, and dividing by the total cash flow in to the investment. The median fund TVPI for the sample is 1.9. Kaplan and Schoar (2005) has performance data on 577 venture capital funds taken from the Venture Economics database over a the period from 1980 to 2001. Compared to the Venture Economics sample, the funds in this sample are somewhat larger, with more experienced GPs, and exhibit better performance.

A natural concern about this sample is that selection bias may influence the results of my tests. While I acknowledge that the results may be interpreted as pertaining predominantly to the larger venture capital funds represented in the sample, sample selection is unlikely to significantly affect the results for several reasons. The first reason is that the tests that are the focus of this paper are cross-sectional. For selection bias to have an effect, the provider of the data would need to express a bias toward the type of funds for which the effect of performance in the fund's early investments is more important than in the population of funds. However, this seems more likely to be the case for smaller funds, not the larger ones represented in the sample. In addition, there is some heterogeneity in fund size. 46.4% of the venture capital funds in the sample are smaller than the $103 million mean venture capital fund size in the Kaplan and Schoar (2005) Venture Economics sample. Lastly, although all the funds in the sample share the common characteristic that they were selected by the firm providing the data, the firm administers separate accounts for some institutional clients who may have different investment objectives. As a result, there may be some heterogeniety in the criteria which was used to select funds into the sample.

Panel B also contains summary statistics on the follow-on funds raised by GPs in the sample. 84% of funds in the sample raise a follow-on fund. The dates and size of the follow-on fund are gathered from the sample itself when possible, or from VentureXpert, which contains information on the first closing date and committed capital of selected funds. There are eight funds for which I am able to confirm that the GP raised a new fund, but do not have sufficient information on the date or size of the new fund. These funds are excluded from the analysis of follow-on fund-raising. The median new fund was raised after 3.4 years of operating the current fund. The median increase in fund size, measured as a ratio of the capital committed to the current fund, is 1.5.

Panel C of Table 3.1 lists the summary statistics at the portfolio company-level. The data consists of the quarterly valuations and cash flows between each venture capital fund to its portfolio company investments, obtained from the quarterly reports of venture capital funds to their LPs. Because this sample has the actual cash flows and exit dates, I can calculate the return of each individual investment, which represents a significant advantage over VentureXpert and other commercial data sources.[3] The median initial investment is

[3]For example Cochrane (2005) merges the VentureXpert data with the SDC Platinum

$2 million. Venture capital investments are often staged in multiple rounds of funding. Size increase represents the factor increase in capital invested in each portfolio company over follow-on rounds. The amount of follow-on funding offered to portfolio companies is right skewed with a mean of 1.5 and a median of 0.2. Holding period represents the amount of time in which each portfolio company is held, and is calculated using only realized investments. Fund Age lists the age of the fund in years when each investment was made. The median investment is made 1.8 years from the closing of the fund.[4] Holding period represents the amount of time in years between the fund's initial investment and exit from the portfolio company. The holding period is calculated using only investments that have been fully realized (i.e. the fund has exited the investment). The 5.3% of investments which are not fully realized represent both active operating companies and assets like patents, which are still held under a portfolio company name, but for which no buyer has yet been found. Previous academic work on private equity has taken different approaches to handling these long lived, still active investments. Kaplan and Schoar (2005) use the reported valuation of these assets, adding them to the final value of the fund, while Gottschalg and Phallipou (2009) write off their value. For estimates of portfolio company performance presented in this paper, I take the

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IPO and merger databases. He is only able to obtain the final value of 2/3 of the firms that eventually IPO, 1/4 of the firms that are acquired and none of the firms which have another outcome such as a liquidation.

[4]The maximum value for Fund Age at the time of investment is surprisingly high 13.9 years. This represents a small tail of outliers as the 95th percentile of investments is 5.5 years. All the results presented in the paper are qualitatively unchanged if the investments made after 5.5 years are excluded.

Kaplan and Schoar approach. However, the results are robust to excluding all unrealized investments.

Note that the mean and median MIRR are slightly negative and the median TVPI is less then one. This indicates that the median portfolio company investment returned less capital than was invested in the firm. However, because of the skewness of returns and the properties of aggregating across multi-year portfolio investments, the result is not inconsistent with the positive aggregate portfolio returns given in Panel A.[5] Finally, note that the returns are right skewed as the mean TVPI and MIRR payoff is higher then the median. This skewness is also evident in Figure 3.1 which plots the histogram of individual portfolio company returns. Note that the highest bin, accounting for nearly 30% of the observations, is the -100% - 80% MIRR bin.

Table 3.2 shows the properties of funds in the sample by the vintage year in which the fund was raised and the comparison sample of funds listed in VentureXpert. The observations of the sample are concentrated in the late 1980's and late 1990's. However, this variation appears to represent the general trend in venture capital investment, rather then an artifact of this sample. The last column expresses the capital committed to funds in the sample as a percentage relative to the universe of funds contained in VentureXpert, the leading commercial source of portfolio company-level data. To obtain the

[5]For example, consider a fund investing in three equal sized investments that all last two years. Two investments are a total loss (-100% MIRR), while the other is sold for three times the original investment (73% MIRR). The mean MIRR among portfolio companies is -63.5%, while the MIRR of the portfolio is 0%.

VentureXpert sample I select all funds identified as venture capital funds with five or more portfolio company investments. I then exclude all funds run by organizations other than private equity firms (e.g. corporate venture capital, insurance agency affiliate funds, etc.) The size of the sample is relatively large, representing 41% of the commited capital in VentureXpert funds, with a tendency to tilt toward larger funds.

3.2 Implicit Incentives

In the first series of tests, I establish the relation between early fund performance and the size and timing of the follow-on fund. Observations of follow-on funds are obtained from instances when the GP's next fund is also in the sample, from VentureXpert or from a search of Factiva for news articles related to a follow-on fund. Combining these sources I'm able to identify 152 instances were the GP was able to raise a follow-on fund. The following analysis excludes eight observations where I identify the existence of a follow-on fund, but am unable to locate specific information regarding its size or closing date.

3.2.1 Concavity of Implicit Incentives

A key assumption of the model is that the implicit career incentives of venture capitalists are concave with respect to the performance of the current fund, with most of the effect occurring at the extensive margin when crossing the threshold required to raise a new fund. This assumption about the functional form of implicit incentives drives the risk-averse behavior of GPs who still face uncertainty about their ability to raise a new fund. Table 3.3 and Table 3.4 test this assumption by comparing the response of the GP's career outcomes to performance.

Table 3.3 reports results from a probit regression that estimates the relation between current fund performance and the existence of a follow-on fund. The dependent variable is an indicator for whether the GP raises a follow-on fund. The explanatory variable of interest is the MIRR of the GP's current fund, measured three years into the fund's life.[6] This measure is formed using the complete portfolio of all investments selected by the GP prior to the third year of the fund. The holding value reported by GP in the quarterly report to LPs is used to value unrealized investments. Prior experience of the GP is represented by the natural logarithm of the number of previous funds raised. If the effect of current fund performance on the ability of the GP to raise a new fund reflects changes in investors' belief about the skill of the GP, the effect is likely to be larger for inexperienced GPs about whom investors have very weak prior beliefs.

Model 1 of Table 3.3 reports results of a specification which includes dummy variables for the vintage year of each fund. This results in the exclusion of 28 observations for which these vintage year dummies perfectly predict the existence of a follow-on fund. Model 2 presents results with vintage year dummies excluded.[7] In both models the coefficient on MIRR is positive and significant. The interaction between MIRR and experience is negative, suggesting that the additional probability of raising a new fund with performance declines with experience. The marginal effects of MIRR, which are reported at the bottom of Table 3.3, are economically significant, particularly for inex-

[6]Results obtained using the MIRR taken at two and four years into the current fund produce very similar results to those which appear in Table 3.3.

[7]Results are presented with and without vintage year dummy variables to demonstrate the robustness of the result. Probit models with fixed effects, such as the one considered in Model 1, offer a control for unobserved heterogeneity across vintage years, but the resulting estimates are known to be inconsistent in the econometric sense. See Greene (2008) p.800 for a discussion.

perienced GPs. For a GP with no previous experience, a 1% increase in MIRR results in an additional 1.3% probability of raising a new fund. The results suggest that the ability of a GP to raise a follow-on fund is positively related to early fund performance.

Table 3.4 proxies for the expected value of a continued career as a venture capitalist (F in the model) with the increase in fund size from the current fund to the follow-on fund. The increase in fund size is calculated as the ratio of capital committed to a follow-on fund, divided by the committed capital of the current fund. I regress the increase in fund size against $MIRR_{t-1}$, the MIRR of the current fund calculated in the quarter before the follow-on fund is raised. Because we may expect that small funds have more opportunity to grow than large funds, the natural logarithm of fund size is included as a control variable, as is the natural logarithm of the number of previous funds raised by the GP.

Models 1 and 2 of Table 3.4 present the results using all funds in the sample. GPs who failed to raise a follow-on fund are assigned a size increase of zero. These observations use the MIRR calculated five years after the start of the current fund. Model 1 reports ordinary least-squares results. Model 2 uses a Tobit analysis to account for the censoring effect when no follow-on fund is raised. The marginal effect of MIRR is reported in the lower portion of the table for GPs with zero and three previous funds and other variables set to their sample means. In both models the relation between fund size and current performance is statistically and economically significant. The results from Model 2 indicate that at the sample mean the marginal effect of an additional 1% increase in MIRR results in 0.75% positive change in the size increase from the current fund. The results also demonstrate that the relation between current fund performance and follow-on fund size is concave, but the decrease in slope with higher fund performance is modest. In both cases the squared term is significant at the 10% level, and roughly one-twentieth of the magnitude of the linear term on MIRR. The standard deviation of MIRR in the quarter prior to the closing of a follow-on fund is 81.9%. The Tobit result suggests that for a GP with no previous experience, a one standard deviation increase in MIRR reduces marginal effect of performance on fund size by roughly 5% relative to the marginal effect at the mean (0.75 vs. 0.721). Measured this way the concavity has modest economic significance.

Model 3 presents the results of an ordinary least-squares regression that only includes managers who successfully raised a new fund. The intuition behind this estimate is to examine whether the relationship between follow-on fund size and performance is primarily driven by the extensive margin (the ability to raise a fund, or not, demonstrated in Table 3.3) rather than the intensive margin (an increase in fund size conditional on raising a new fund). When the GPs who failed to raise a new fund are dropped, the marginal effect associated with MIRR is insignificant and the point estimate is small. This suggests that the relationship between current fund performance and follow-on fund size is very weak conditional on raising a new fund. The results in Table 3.3 and Table 3.4 provide evidence that the model's assumption that career incentives are largely driven by the jump as a GP crosses the performance threshold required to raise a new fund is a plausible representation of the empirical features of the data.

3.2.2 Timing of Implicit Incentives

The evidence in the previous section shows that implicit career incentives are largely determined by the discrete impact of crossing the threshold required to raise a new fund. Conditional on raising a new fund, the additional marginal benefit for performance is small. Given these conditions, it is intuitive that a GP will raise a follow-on as soon as his track record of investment permits. This intuition is formalized by Result 1 of the model. In this section I examine the empirical relationship between current fund performance and the speed at which GPs raise a follow-on fund. I employ a Cox proportional hazard model. This semi-parametric approach allows me to avoid specifying a functional form for the baseline hazard model, while retaining an easy-to-interpret parametric form for the proportional effects of the explanatory variables.[8] In the Cox model, the functional form of the hazard rate is given by:

$$\lambda\left(t_i, x_i\right) = e^{x_i'\beta}\lambda_0\left(t_i\right) \tag{3.1}$$

$\lambda\left(t_i, x_i\right)$ represents the hazard rate at which firms with characteristics x_i at time t_i raise a new fund. $\lambda_0\left(t_i\right)$ represents the baseline hazard rate at

[8]The Cox proportional hazard model is a common model of duration spells. Examples of its use in the venture capital literature include Hellman and Puri (2000, 2002) and Lerner, Shane and Tsai (2003).

which GPs raise a new fund t_i periods into their current fund.

The dependent variable is the duration of time from the first closing of the current fund until the first closing of a follow-on fund, measured in years. As in the previous analysis the independent variable of interest is $MIRR_{t-1}$. The interaction effect with the age of the fund is included because over time, as investments are realized, the MIRR is likely to be more informative about the GP's skill. In addition, I examine the interaction effects of the GP's previous experience. As experience increases, the effect of MIRR on the speed of raising a new fund may diminish as investors have stronger priors about the GP's skill. Finally, to control for exogenous changes in the market appetite for investing in venture capital, I include the count of the number of funds listed in VentureXpert raised in the year prior to the current quarter. The analysis is stratified by vintage year to control for unobserved heterogeneity across time.[9]

Table 3.5 presents the results from the duration model. The coefficients presented in the upper section of the table represent the estimates of β from Eq. 3.1. I report the proportional increase in the hazard rate associated with a 10% increase in $MIRR_{t-1}$. This increase must be evaluated at a particular value of fund age and GP experience because the measure includes all the interaction effects associated with a change in $MIRR_{t-1}$. Results are reported

[9] Stratification by vintage year allows for different baseline hazard functions for each vintage year, while requiring the coefficient estimates to be the same across years. As a result, nothing is identified from the four vintage years that contain only one venture capital fund.

for a GP who is in the third year of the current fund (the median follow-on fund is raised 3.4 years into the current fund). To compare the effect of experience, I calculate the marginal effect separately for a GP raising his first fund, and a GP with three previous funds (the sample median).

The results indicate that the performance of the current fund has a strong positive impact on the rate at which the GP will raise a new fund. The coefficient in all models on $MIRR_{t-1}$ is positive and statistically significant at the 10% level or higher. In Model 1, an increase of 10% in $MIRR_{t-1}$ results in a statistically significant increase in the hazard rate of raising a new fund in year 3 by a factor of 1.01. Model 2 takes into account the additional effect of GP experience. The marginal effect of $MIRR_{t-1}$ is slightly higher in Model 2, 1.02 - 1.03. However, the interaction term between $MIRR_{t-1}$ and GP experience is not significant, nor is the difference in the marginal impact of $MIRR_{t-1}$ between a new GP and one with three years of experience.

3.3 Portfolio Risk

Having established that GPs with positive early performance are more likely to raise a new fund, it remains to be shown that these GPs will pursue more risky strategies relative to their poor-performing peers. This section empirically tests the model's prediction about the intra-fund pattern of investments by looking at the relationship between initial fund performance and the characteristics of the GP's subsequent investments. I explicitly evaluate two channels by which the GP can select a higher variance portfolio. In Section 3.3.1 I demonstrate a positive correlation between early fund performance and the individual variance of subsequent portfolio company investments selected by the GP. Section 3.3.2 demonstrates a similar relation between early fund performance and the size of subsequent investments (implying less diversification).[10] Section 3.3.4 provides additional evidence that these individual channels effect the variance of the fund's aggregate portfolio.

3.3.1 Portfolio Company Volatility

This section investigates whether the performance of previous investments is related to the volatility of subsequent investments. This corresponds to the intuition from the model that, absent career concerns, GPs will seek out more volatile investments because they offer the highest expected returns.

[10] Portfolio variance may also be increased by selecting more correlated investments. Given the nature of the data developing a powerful test to investigate this channel remains difficult and may motivate further study.

To investigate this hypothesis it is necessary to provide a test that evaluates differences in variance across portfolio company investments. This analysis is challenging with venture capital investments because we do not observe a time series of returns as we would with public securities. We do observe the time series of valuations reported by the GP, but these are updated infrequently, and the resulting measures will almost certainly be noisy and heavily biased toward low variance.

To evaluate the effect of past performance on the expected mean and variance of portfolio company investments, I evaluate the following empirical model using maximum likelihood estimation.

$$MIRR_{i,j} = \max\left[-100\% \ , \ \beta_0 + \beta_1 \cdot IRR_{NASDAQ} + \nu_t + \alpha_i^{mean} + \epsilon_{i,j}\right] \quad (3.2)$$

$$\epsilon_{i,j} \sim \mathcal{N}(0, \sigma_{i,j}^2) \quad (3.3)$$

$$\sigma_{i,j}^2 = e^{\phi_0 + \phi_1 \cdot \sigma_{NASDAQ}^2 + \delta X_{i,j} + \alpha_i^{var}} \quad (3.4)$$

The subscript i is used to index individual GPs, while the subscript j represents individual portfolio company investments. Each observation is the MIRR realized for one portfolio company investment.[11] The variance of each investment is treated as a latent variable, which is imputed by maximizing the likelihood function derived in Appendix B. In addition, the model accounts

[11]Each observation in Eq. 3.2 is the final realized MIRR of *one portfolio company*. The main explanatory variable in $X_{i,j}$ of Eq. 3.4 is the MIRR of the *fund* calculated from its previous investments.

for truncation at -100% return with a correction that is analogous to a Tobit model. The expected return is driven by the cumulative return of an equal-weighted index of the smallest decile of NASDAQ stocks available from CRSP, calculated over the holding period of the investment, and the variance of the portfolio company investment. In addition, the mean equation contains two sets of dummy variables. Vintage year dummies, represented by ν_t, capture unobserved heterogeneity in the average return of venture capital investments over time. GP dummy variables, α_i^{mean} and α_i^{var}, capture unobserved differences across venture capital fund managers in the mean and variance equation respectively.

The variance is modeled as an exponential function of a linear combination of characteristics $X_{i,j}$, which include past performance, age of the fund, GP experience and the interactions of these variables.[12] As in previous analysis, performance of the current fund is measured using $MIRR_{t-1}$, the return to the GP's current fund measured the quarter prior to the portfolio company investment. The model predicts that current fund performance should be related to the variance of investments late in the fund, but not early in the fund. Thus the analysis considers only investments made after the fund has been operating for two years. In addition, the specification includes a control for the volatility of public markets over the holding period. σ^2_{NASDAQ} represents the variance of the cross section of cumulative returns of firms in the smallest

[12] This is similar in spirit to the multiplicative heteroskedasticity model of Harvey(1976). Results from a linear model, where variance is modeled as a purely linear function of past performance and other covariates are qualitatively similar to the multiplicative specification.

decile of the NASDAQ, calculated over the holding period of each portfolio company investment.

Table 3.6 presents the results from four different variations of the model. The first column of each model presents the estimates in the mean equation, while the second column lists the coefficient estimates of the variance equation. Panel A presents results with vintage year and GP dummy variables included in the mean equation. Panel B presents results with additional GP dummy variables included in the variance equation.

The main coefficients of interest are the coefficients on $MIRR_{t-1}$ and Fund Age. The model suggests both effect should be positive. For each model, the marginal effect of $MIRR_{t-1}$ is calculated separately at the bottom of the table. The results in Model 1 suggest that a 10% increase in $MIRR_{t-1}$ in the third year of the fund is associated with a 0.156 increase in the variance of subsequent portfolio company investment. This represents an economically significant 14.1% increase relative to the portfolio company variance across the entire sample.[13] Model 2 includes additional interactions with GP experience. The interaction term is positive, but not statistically significant. Similarly the difference in marginal effect of $MIRR_{t-1}$ across levels of experience is not statistically significant, with a p-value of only 0.534.

Models 3 and 4 in Panel B repeat the analysis with additional GP dummy variables included in the mean and variance equation. The benefit

[13]The mean variance is derived from the 105.3% standard deviation given in Table I.

of this specification is that it controls for unobserved heterogeneity in the investments style of different GPs. The results are similar to those in Panel A. In Model 3, a 10% increase in $MIRR_{t-1}$ results in a 0.152 increase in the variance of each portfolio company investment. This represents a 14% increase relative to the sample portfolio company variance. The marginal effects of $MIRR_{t-1}$ in Model 4 are larger than in Model 2 and the difference in marginal effect of $MIRR_{t-1}$ across different levels of experience flips sign, but remains statistically insignificant.

While the model doesn't explicitly address the change in career concerns with experience, its a trivial extension to suggest that career concerns should decline as GPs develop a longer track record, and their type becomes well known. In Model 4, the difference in the marginal effect across different levels of experience is negative, as suggested by the theory, and quite large, however it remains statistically insignificant. This may partially be an effect of the limited power in the sample. Alternatively, it may be that career concerns remain a strong influence for private equity firms with significant experience. While GP is presented in the model as a single agent, funds are typically administered by a group of individuals from a single private equity firm. It is common to see some turnover among individuals serving as general partners from fund to fund, administered by the same private equity firm. It is not uncommon for private equity firms with significant experience to have some unseasoned general partners who may still be subject to career concerns. Finally, the skills required to be a successful venture capitalist may change over time.

Experienced GPs may need to demonstrate their skill in new environments in order to raise new funds. There are several examples of successful venture capitalists from late 90's who have faced criticism for their failure to invest in social media.[14] To the extent that these GPs may find it difficult to raise capital for web and social media focused funds, their investment choices in these sectors may be subject to large implicit career incentives despite their long history investing in venture capital.

3.3.2 Portfolio Company Size

In addition to investing in more risky portfolio companies, general partners can increase the aggregate risk of their portfolio by making larger investments in a smaller number of firms. Table 3.7 estimates the effect of previous performance on the size of portfolio company investments. The dependent variable is the size of the initial investment in each portfolio company divided by the total size of the fund, then multiplied by 100. As in previous analysis, the main variables of interests are $MIRR_{t-1}$, Fund Age and the number of previous funds raised by the GP. The model suggests the effect should be present in the last half of the fund, thus as with the previous table the analysis only considers investments made after two years into the fund. An additional concern in this analysis is that the very last investment of the fund may be determined simply by the amount of the capital remaining, rather then the dynamics of compensation and career concerns. To mitigate this effect I iden-

[14]See Tam and Fowler (August 29, 2011) for a recent example.

tify the last quarter in which each fund makes a new investment and remove all the investments in this quarter from the analysis. This reduces the number of observations to 3,122.

The first two models of Table 3.7 include fund fixed effects, while the Model 3 adds additional fixed effects for the year each portfolio company investment was made. The effect of $MIRR_{t-1}$ is positive and significant in each model. The coefficient in Model 1 suggest that a 10% increase in $MIRR_{t-1}$ is associated with a 0.066% increase in the expected size of each subsequent investment relative to the size of the fund. The economic significance of this result is modest, given that the mean initial investment in year 3 is 2.4% of the fund's capital. Models 2 and 3 demonstrate that the economic effect is much stronger for GPs who are operating their first fund. In both cases the interaction term between $MIRR_{t-1}$ and previous experience is negative, but it is only statistically significant in Model 3. Model 3 suggests that for a GP with no previous experience a 10% increase in $MIRR_{t-1}$ is associated with a 0.094% increase in the expected size of each subsequent investment relative to the size of the fund. This represents a 5% increase over the mean initial investment. This result, that investments are larger as a percentage of fund capital, suggests that GPs pursue less diversification following good performance of early investments. For GP who has operated three previous funds the marginal effect is less then half as large.

3.3.3 Portfolio Diversification

This section examines the propensity of venture capital GPs to diversify their portfolio after observing the performance of their early investments. This section considers diversification along two dimensions - industry and geography. The intuition of the model suggests GPs who perform poorly in their initial investments choose a more conservative strategy. This could be interpreted as selecting a more diversified portfolio, which is less subject to the risks that may be common among a particular industry or region. However, while industry and geographic diversification are easily observed in the data, the scope for GPs to change the diversity of their portfolio along these dimensions may be more limited than their ability to decrease risk through other channels, such as those documented in the previous sections. Many GPs attract financing by claiming that they have competitive advantage investing in a particular industry.[15] Selecting investments outside the fund's core industries may signal to investors that the GP does not have such a competitive advantage. Similarly, the ability of the GP to diversify across regions may be difficult due to the importance of monitoring portfolio company investments; the literature has noted that venture capitalists tend to invest in companies in close geographic proximity to their headquarters (See Tian 2011). The costs of deviating from the optimal geographic strategy might be too high, especially for the less experienced venture capitalists, who tend to operate smaller funds.

[15]Examples of such claims are an information advantage, which can be used to better evaluate investments, or access to proprietary deal flow.

Diversification is measured using Herfindahl-Hirschman Indexes (HHI) formed on the share of invested capital amongst industry and region:

$$HHI = \sum_{n=0}^{N} \left(\frac{\text{Capital Invested in Region (Industry)}_n}{\text{Total Invested Capital}} \right)^2$$

The industry definitions provided with the data are relatively narrow. To create more meaningful industries for this analysis, each of the industry categories provided with the data were mapped to the closest Fama-French 49 industries.[16] As provided, the data categorizes portfolio companies into geographic regions. To facilitate more meaningful comparisons "West Coast" and "Northeast" were split to give portfolio company investments headquartered in California and Massachusetts their own categories. A summary of the distribution of the number of portfolio companies across industry and regions is provided in Figure 3.2 and Figure 3.3.

Table 3.8 presents results from a probit analysis of the effect of previous performance on the probability that GPs select an investment that increases diversification (decreases the Herfindahl index). The dependent binary variable takes a value of one when the Herfindahl index following the investment is lower then the Herfindahl index prior to the investment.

$$\Delta HHI = HHI_{post-investment} - HHI_{pre-investment}$$

[16]The analysis repeated using the original (more narrow) industry classifications produced no significant results.

$$\text{Diversifying Investment} = \begin{cases} 1 & \text{if } \Delta HHI < 0 \\ 0 & \text{if } \Delta HHI \geq 0 \end{cases}$$

The advantage of using a binary variable rather than the raw change in HHI is that the magnitude of the change in HHI for any given investment is partially a function of size and diversification of the fund's portfolio prior to the investment.[17] As with the previous analysis, the first two years of investments are excluded, leaving 3,355 observations. 61% of investments increase diversity across industry, while 53% of investments increase diversity across region.

Models 1 and 2 report the results using diversification among industries, while Models 3 and 4 present results for diversification among geographic regions. The interior of the table reports the linear coefficients associated with each variable. The lower portion of the table reports the marginal effect of $MIRR_{t-1}$.

In Model 1 the marginal effect of $MIRR_{t-1}$ is negative, but statistically insignificant. Model 2, which includes additional interactions of $MIRR_{t-1}$ and previous GP experience, produces similar insignificant results. The only consistently significant relationship is that fund age is negatively related to diversification among industry. This may be somewhat mechanical as late in the fund when the GP has invested in multiple industries it is more likely that any subsequent investment is likely to be in an industry which already exists

[17] Analysis performed using the raw change in HHI from each investment as the dependent variable, and analysis using the quarterly change in HHI produce similar, largely insignificant results.

in the portfolio. Model 3 and 4, which estimate the relation between previous performance and diversification along region, produce entirely insignificant results.

The results suggest that GPs do not alter their strategy with respect to industry or region in response to early performance. This corresponds with the intuition that costs to altering their portfolio risk through industry or region diversification may be more costly than altering portfolio risk by selecting individual investments that have lower variance or by making a larger number of smaller investments.

3.3.4 Aggregate Portfolio Risk

Table 3.9 examines the intra-fund pattern of investment by simply sorting funds based on their performance at given points in the fund's life. Funds are assigned into cohorts representing two year periods (e.g all funds in 1981-82).[18] Funds are then ranked according an adjusted MIRR at two and four years. Using the adjusted MIRR, which is formed by subtracting the cohort median MIRR from the fund's MIRR, is intended to account for differences in venture capital market conditions over time. Funds that have less than 20% of their committed capital remaining or that make less than three investments after the sort are eliminated prior to ranking. I examine the aggregate performance of the portfolio of investments each type of fund makes after the sort.

[18]Two year cohorts are chosen to make cohorts large enough to derive more meaningful rankings.

Each observation represents the final realized performance from one fund's entire post-sort portfolio of investments, which is also adjusted by subtracting the median post-sort performance of other funds in the same cohort. The model suggests that the High MIRR group should pursue a more risky strategy, as these GPs are less likely to face problems when raising a new fund.

Panel A of Table 3.9 shows that funds that performed well in their early investment continue to out-perform in their latter investments, though the difference of 56% is insignificant, with a p-value of 0.216. The difficulty in having power to compare means stems from the large variance of both groups. However, we observe a significantly higher standard deviation across the ex-post portfolios of funds that performed well early on. An F-test of the 365% difference in standard deviation is significant at the 1% level. Because the F-test for equality of variance is known to be particularly sensitive to distributional assumptions Table 3.9 also report the p-value based on Levene (1960)'s test of equality of variance. Levene's test, which is more robust to distributional assumptions than the F-test. shows the difference to be significant at the 10% level. The exceptionally large difference between groups is partially driven by a large outlier in the high group. When the outlier is omitted, the difference in mean falls to 12% and the difference in standard deviation falls to 20%. The difference in standard deviation remains significant the 1% level for the F-test, but becomes insignificant under Levene's test. Sorting the sample at 4 years produces results which are less sensitive to outliers. The difference in mean favors the high group, with an 18% difference in return. The large difference in standard deviation among both groups is significant at the 15% level under Levene's test, with the better performing funds pursuing more risky strategies.

While these results fit with the model's intuition about declining implicit incentives following positive early performance, there may be other explanations for this pattern. For example, the results could reflect a world in which each GP pursues a constant strategy, with the more risky strategies naturally resulting in higher expected returns. If this was the case, sorting on early performance would naturally be similar to sorting on the GPs who pursued riskier strategies. This explanation suggests that the standard deviation of the pre-sort portfolio (the investments made prior to the sort) should also be higher for the funds that perform well in their early investments. Table 3.9 shows no evidence of this effect. At two years, the difference in volatility across the pre-sort portfolios is -8% with a p-value of 0.606 under Levene's test. This suggests that the volatility of portfolios the two groups chose prior to the sort were relatively similar. However, we observe a statistically significant -7% difference in standard deviation across ex-ante portfolios at the 4 year point. This suggests that the low-performing group may have invested in higher variance portfolios early in the fund. While the results in Table 3.9 follow from the model's implications, the results are clearly sensitive to outliers. In part this may be due to the low power of the test, which must rely on a small number of observations. However, the results support the conclusions of main analysis given in Tables VI and VII, that there exists a positive correlation between early fund performance and risk-taking later in the fund.

3.4 Additional Results

3.4.1 Spending Rate

This section presents results on the relation between the early performance of a fund and the rate at which the GP invests the fund's capital. While this relation is not strictly a feature of the model, the model's prediction that GPs who have performed well in their initial investments are willing to take more risk could be interpreted to suggest that they are likely to spend their capital more quickly, perhaps with a lower standard of due diligence. In addition, GP's ability to raise a new fund may be tied to the amount of the current fund that has been spent. Typically the LPs of the current fund discourage GPs from raising a new fund until a significant portion of the existing fund has been invested, for fear that the GP may otherwise allocate the best new investment opportunities to the follow-on fund. For example, two of the limited partnership agreements for funds in the sample contain an explicit clause requiring a GP to have spent 70% of the capital in the current fund prior to raising a new fund. While the majority of limited partnership agreements do not contain such specific targets, the lead investors in a GP's follow-on funds are often LPs from the current fund, who may refuse to commit to a new fund until a significant percentage of the existing fund has been invested.

Figure 3.4 plots the average cumulative investment of capital over the life of venture capital funds in the sample. The darker shaded portion at the bottom of the plot represents the capital spent on initial investments in portfolio companies. As in the previous analysis of portfolio company investment size, *initial investment* is defined as capital invested in a portfolio company over the first three quarters. The lighter shaded area represents total investment of capital, which includes all rounds of financing in each portfolio company. On average, 56% of fund capital is spent making initial investments in portfolio companies, while the remaining 44% is reserved for follow-on funding of existing investments. The plot demonstrates how investments in new portfolio companies largely take place over the first five years of the fund's life.

To evaluate the relation between early performance and the spending rate of the GP, I estimate a Cox proportional hazard model in which the dependent variable is the length of time until the GP has spent a given percentage of capital. Focusing on the time to reach a given threshold of capital spent avoids three problems inherent with linking performance to spending rate variables such as capital-spent-per-quarter. First, the amount of capital-spent-per-quarter includes noise related to the capital needs of existing portfolio companies that is unrelated to the managers incentives, particularly toward the end of the fund. Because crossing a threshold of capital invested is essentially a cumulative measure, the quarter-by-quarter variation in spending rates is less important. Second, as demonstrated in Figure 3.4, the capital-spent-per-quarter declines over the course of a fund with a trend that appears to be non-linear. Finally, the maximum which can be spent in a given quarter is 100% of the remaining capital, such that the error term will be truncated in a linear regression, resulting in some bias in the coefficients.[19]

[19]Both the non-linear trend in spending rate and the truncation of the error term could

Table 3.10 presents the results with the cutoff percentage of committed capital ranging from 70% - 90%. As in previous analysis, the marginal effect of previous performance, measured by $MIRR_{t-1}$, is the main effect of interest. For each cutoff percentage of capital invested, I consider a specification with $MIRR_{t-1}$ by itself and a specification with $MIRR_{t-1}$ interacted with the number of funds the GP has previously operated. The upper portion of the table presents the coefficients from each model. The lower portion of table presents the median time to reach the given threshold of percentage capital invested, and the proportional change in the likelihood of reaching the threshold given a 10% increase in $MIRR_{t-1}$.

Models 1 and 2 use the time until 70% of capital is spent as the dependent variable. In Model 1, the coefficient of $MIRR_{t-1}$ is positive and significant at the 1% level. The sample median time until 70% of a fund's committed capital is spent is 4.25 years. Evaluated at 4.25 years, a 10% increase in $MIRR_{t-1}$ increases the odds of reaching the 70% threshold in the next year by a factor of 1.05. Thus the effect of previous performance on the spending rate of GPs is economically and statistically significant. Model 2 when additional interaction terms involving the number of previous funds operated by the GP are included. For a GP who has operated three previous funds, a 10% increase in $MIRR_{t-1}$ increases the likelihood to reach the 70% threshold within the next year by 1.04, which is significant at the 1%

be addressed using an appropriate econometric model. I've chosen the duration model as it is less complex.

level. Interestingly, the point estimate for the marginal effect on GPs with no previous experience is 0.92, but not statistically significant, with a p-value of 0.305. This suggests that the spending rates of less experienced GPs are not significantly different from zero. The difference between the marginal effects of $MIRR_{t-1}$ at different levels of experience is significant at the 10% level.

Models 3 through 6 present the same analysis using thresholds of 80% and 90% of fund capital. The coefficient estimates and the marginal effects of $MIRR_{t-1}$ are consistent with the results in Models 1 and 2, and of similar magnitudes. Together the results suggest that GPs with good initial performance are more likely to spend the fund's capital more quickly, however this effect is concentrated among more experience GPs. The career concerns hypothesis alone would predict that the effect would be stronger among less experience GPs. The stronger results for more experienced GPs is likely to be related to the necessity to spend capital prior to raising follow on funds.

3.4.2 Concentration of Returns

This section examines the relationship between the concentration of fund returns and follow-on fundraising results. The concentration of fund returns is defined as the extent to which fund performance is driven by a small number of successful investments. Anecdotally, LPs suggest that it is particularly difficult to evaluate the talent of a GP whose current fund performance is entirely attributable to one or two "home runs". This fits directly with one of the implications of the model. Under parameters where moderately successful investments are indicative of skill, but very successful investments are largely attributed to luck, the model predicts the GP will select inefficiently safe investments, consistent with the evidence presented in Section 3.3. Thus we would expect, for the same level of aggregate returns, a GP whose success is driven by a small number of very successful investments will face more difficulty raising a follow-on fund than a GP whose performance is driven by a large number of moderately successful investments. To evaluate this relationship, this section considers the effect of the concentration of returns on the size and speed of raising a follow-on fund, similar to the analysis in Section 3.2.

To measure the concentration of returns I form a Herfindahl-Hirshman Index (HHI) based on the individual contribution of each investment to the aggregate performance of the fund.[20] However, the measure of fund performance used in previous sections, $MIRR$, cannot be decomposed in a convenient way. Instead I form the HHI based on Total-Value over Put-In (TVPI), a multiple which is commonly used in the private equity industry.[21] For any investment TVPI is formed by taking the current value of the investment, adding all cash flows that the investment has paid out in the past, and then dividing by the total capital put into the investment.

[20]The Herfindahl-Hirshman Index is being used in a different context here than in Section 3.3.3. Previously the HHI was formed using the share of the fund's capital allocated to different industries and regions as a measure of diversification. Here the HHI is being formed based on performance of individual investments. An HHI of 1.0 in this context suggests that one of the fund's investments was successful, while the remaining investments were all total failures.

[21]TVPI has also been used as a performance measure in the private equity literature, for example Kaplan and Schoar (2005).

$$TVPI = \frac{\text{Current Value} + \text{Cash Paid-Out}}{\text{Cash Paid-In}} \tag{3.5}$$

The advantage of using TVPI is that the average TVPI, weighted by the capital put into each investment, equals the TVPI of the fund.

$$TVPI^{fund} = \sum_{n=0}^{N} \left(\frac{\text{Cash Paid-In}^n}{\text{Cash Paid-In}^{fund}} \right) TVPI^n \tag{3.6}$$

Thus a Herfindahl index can easily be formed based on the relative contribution of each investment to the TVPI of the fund. The share of aggregate TVPI attributable to investment n at time t is simply:

$$S^n_{TVPI} = \frac{\left(\frac{\text{Capital Paid-In}^n}{\text{Capital Paid-In}^{fund}} \right) TVPI^n}{TVPI^{fund}_{t-1}} \tag{3.7}$$

Note that substituting for $TVPI^n$ and $TVPI^{fund}$, the share of TVPI from each investment simply reduces to the share of value from each investment.

$$S^n_{TVPI} = \frac{\text{Current Value}^n + \text{Cash Paid-Out}^n}{\sum_{n=0}^{N} (\text{Current Value}^n + \text{Cash Paid-Out}^n)} \tag{3.8}$$

HHI is then formed in the usual way.

$$HHI_{TVPI} = \sum_{n=0}^{N} S^n_{TVPI} \tag{3.9}$$

Figure 3.5 shows the pattern of HHI_{TVPI} over the course of the fund. The plot includes the median, 25th and 75th percentiles. The concentration of returns starts very high, as each fund only has a handful of investments. Over the first four years HHI_{TVPI} declines as the GP makes additional new investments. After the majority of investment have been made, the appears to be a slight increase in HHI_{TVPI} as some investment perform particularly well, and become a larger share of the value of the fund. Note that throughout the fund's life the interquartile range is large relative to the median HHI_{TVPI}, suggesting that there is significant heterogeneity among funds.

3.4.2.1 Existence of a Follow-on Fund and Concentration of Returns

This section mirrors the analysis from Table 3.3 linking the performance of the current fund to the ability to raise a follow-on fund. The dependent variable is an indicator variable which takes the value 1 if the GP raises a new fund. In Table 3.11, performance is measured using $TVPI$ and the HHI measure of the concentration of returns. If, all things equal, a portfolio which is dominated by a small number of very successful investments is less indicative of skill, we would expect HHI to have a negative effect on the ability of the GP to raise a new fund.

Model 1 is nearly identical to Model 1 in Table 3.3, but with $TVPI$ rather than $MIRR$ used to measure performance. The coefficient on $TVPI$ in Model 1 is 4.05, and is significant at the 1% level. This suggests that measuring performance using $TVPI$ is roughly equivalent to using $MIRR$.

Model 2 includes the additional HHI term. The coefficient on HHI is -8.87 and significant at the 5% level. The interaction term between HHI and $TVPI$ is not significant. Consistent with the intuition from the model, the marginal effect of HHI on the probability of raising a new fund is negative. This suggests that when returns are more concentrated among a small group of investments, the investors are less likely to perceive that the GP has sufficient skill to warrant a new fund.

3.4.2.2 Size of Follow-on Funds and Concentration of Returns

This section considers the relationship between the concentration of returns and the size of the next fund raised. Results are presented in Table 3.12. As in Table 3.4, the dependent variable is the relative size of the follow-on fund, calculated by dividing the size of the next fund by the size of the current fund. Models 1 and 2 include all funds, with GPs who did not raise a new fund assigned a size increase of 0. Model 3 considers only GPs who successfully raised a new fund.

Model 1 evaluates the effect of performance, measured by $TVPI$, on the size of the follow-on fund. The coefficient on $TVPI$ in Model 1 is 1.01, and is significant at the 1% level. Model 2 includes the additional HHI term. The coefficient on HHI is -5.52 and significant at the 1% level. The interaction term between HHI and $TVPI$ ia also negative and statistically significant. The resulting marginal effect of HHI on the size of the follow-on fund is negative. The sample in Model 3 is restricted only to GPs who successfully raised a follow-on fund. The coefficients on $TVPI$ and HHI are both insignificant. This suggests that conditional on raising a new fund, performance has little effect on the size of the new fund raised. This is consistent with the findings in Table 3.4 using $MIRR$ as a measure of performance. The results suggest that when returns are more concentrated among a small group of investments, GPs are likely raise a smaller fund, but as in the previous analysis with $MIRR$, this effect is largely driven at the extensive margin by the GPs who are unable to raise any new fund.

3.4.2.3 Time to Follow-on Fund and Concentration of Returns

This section estimates the relationship between the concentration of returns and the speed at which a GP raises a new fund. The model suggests that LPs are less likely to infer a GP has skill when their returns are largely driven by small number of very successful investments. In such a case the LP may wish to wait for more information from other GP investments before committing to a follow-on fund. This suggests that the concentration of returns should be negatively related to the speed at which GPs raise a new fund.

Table 3.13 presents a Cox proportional hazard model, similar to the model considered in Table V. The dependent variable is the time from the beginning of the current fund to the first closing of a follow-on fund. Each model is stratified by the vintage year of the current fund.

Model 1 presents results similar to those in Table 3.13, with $TVPI$ used at the measure of performance. Consistent with the earlier results, $TVPI$ has a positive and significant effect on the odds of raising a new fund in the next year. Model 2 add the HHI measure of the concentration of returns. The coefficient on HHI is -5.52, and significant at the 1% level. The interaction term between $TVPI$ and HHI is -1.53, and also significant at the 1% level. Together the marginal effect of concentrated returns on the odds or raising a new fund is strongly negative. For a fund in the third year with the median level of $TVPI$ prior to fund raising (1.2), a one standard deviation change in HHI (0.11) decreases the probability of raising a new fund by 59%. This suggests that LPs are uncertain about GPs whose returns are very concentrated among a small number of successful investments, and often require more evidence of skill before committing to invest capital in a follow-on fund.

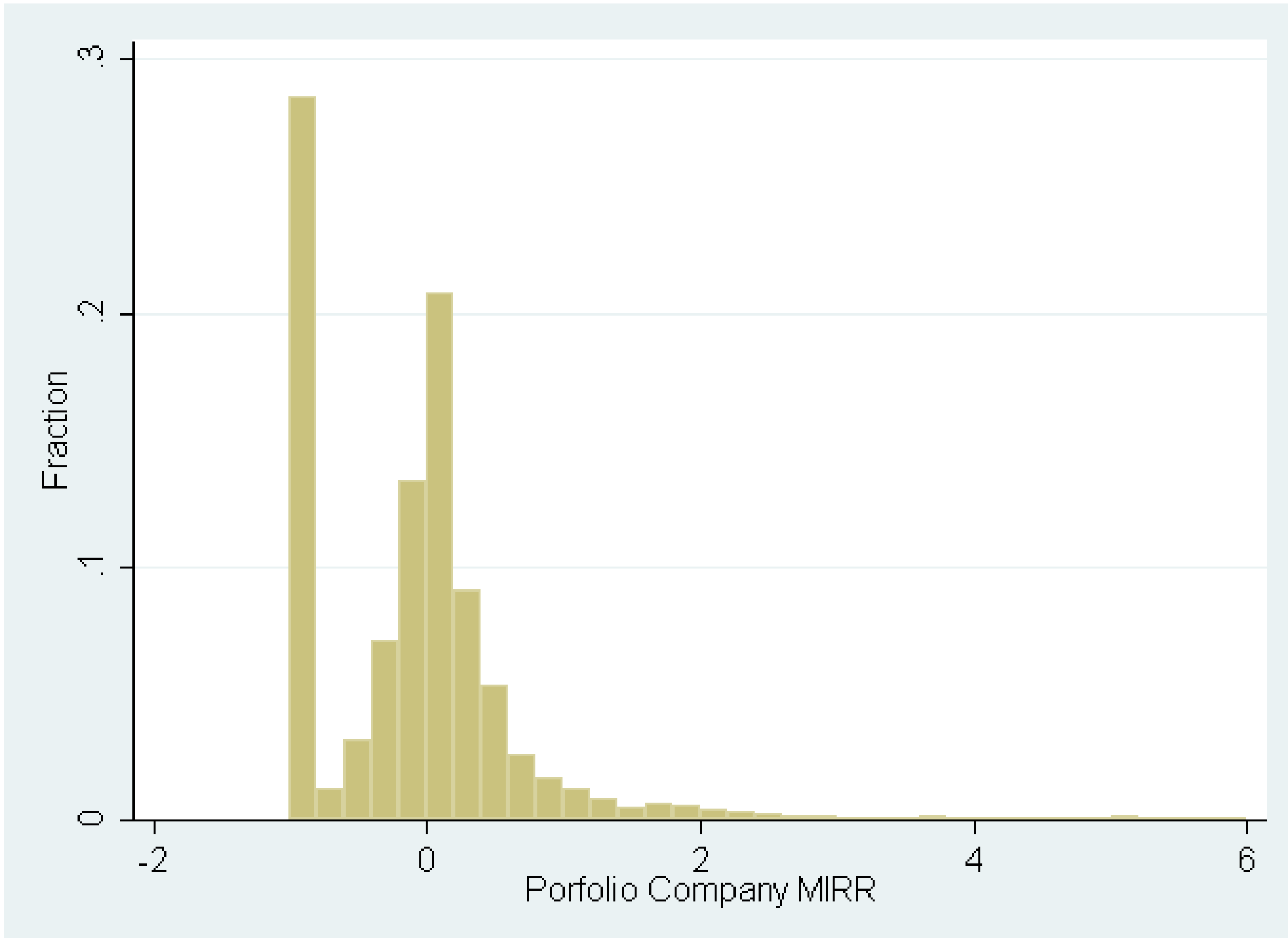

Figure 3.1: Distribution of Portfolio Company Returns

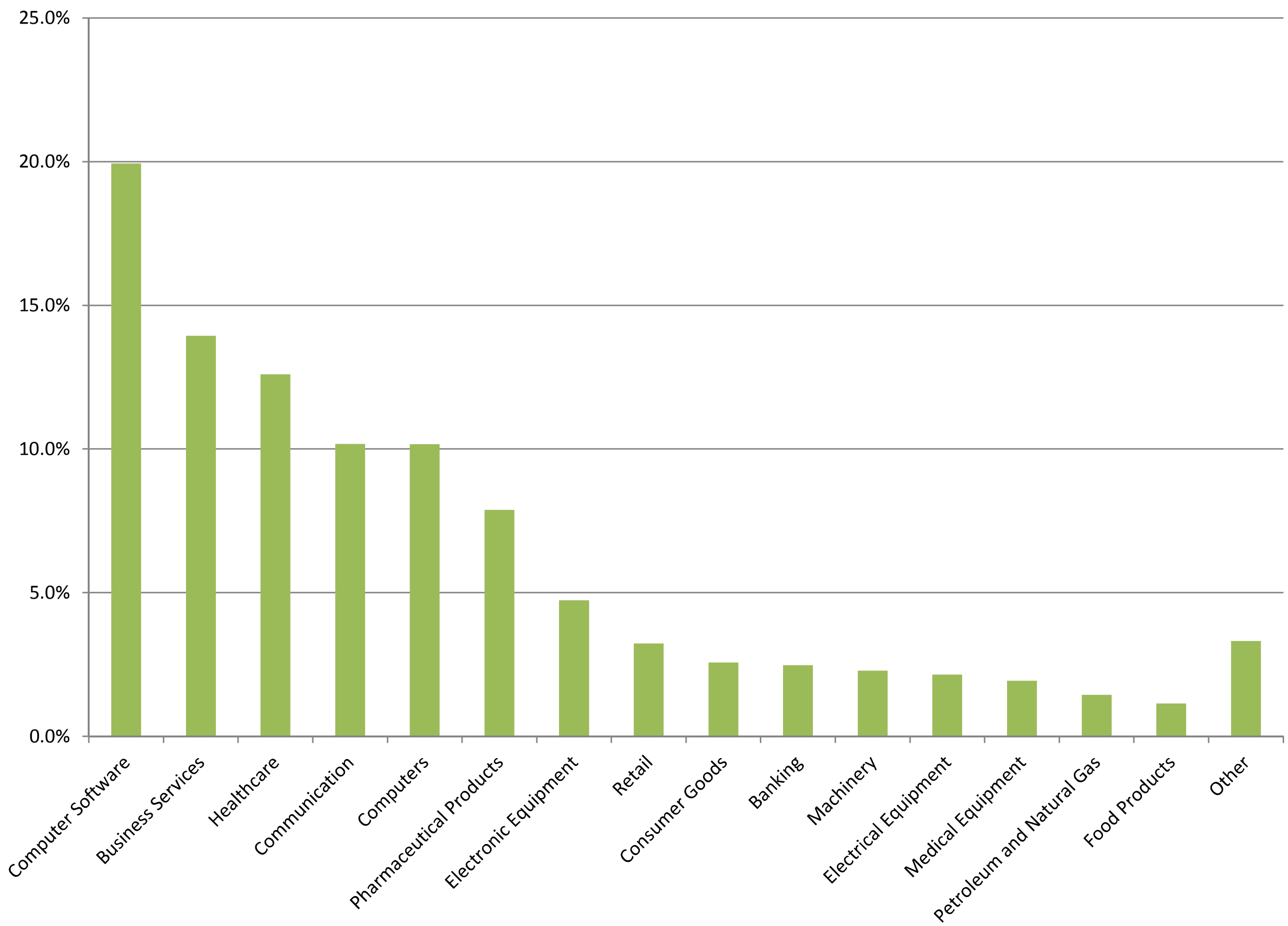

Figure 3.2: Portfolio Company Industry Distribution

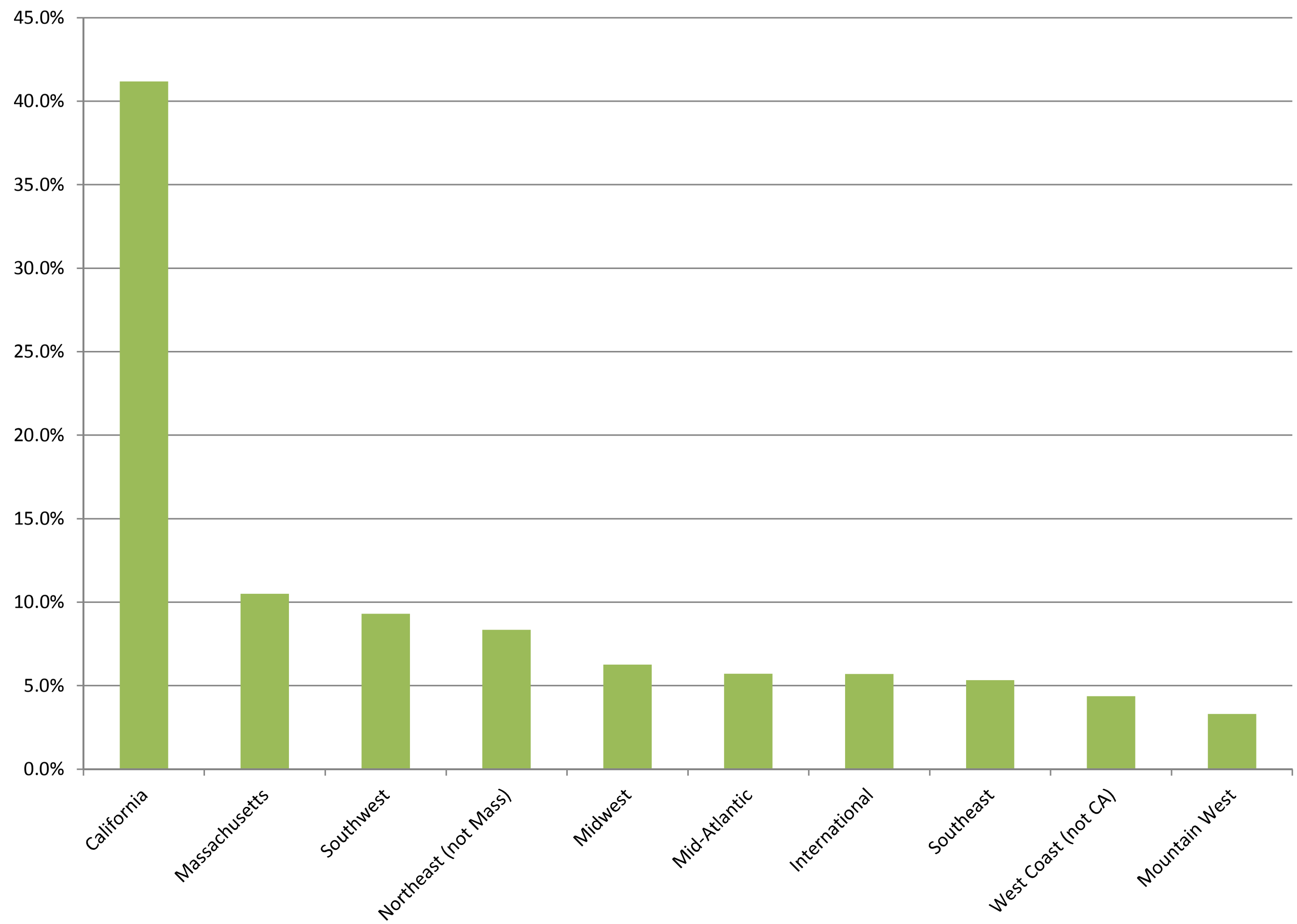

Figure 3.3: Portfolio Company Region Distribution

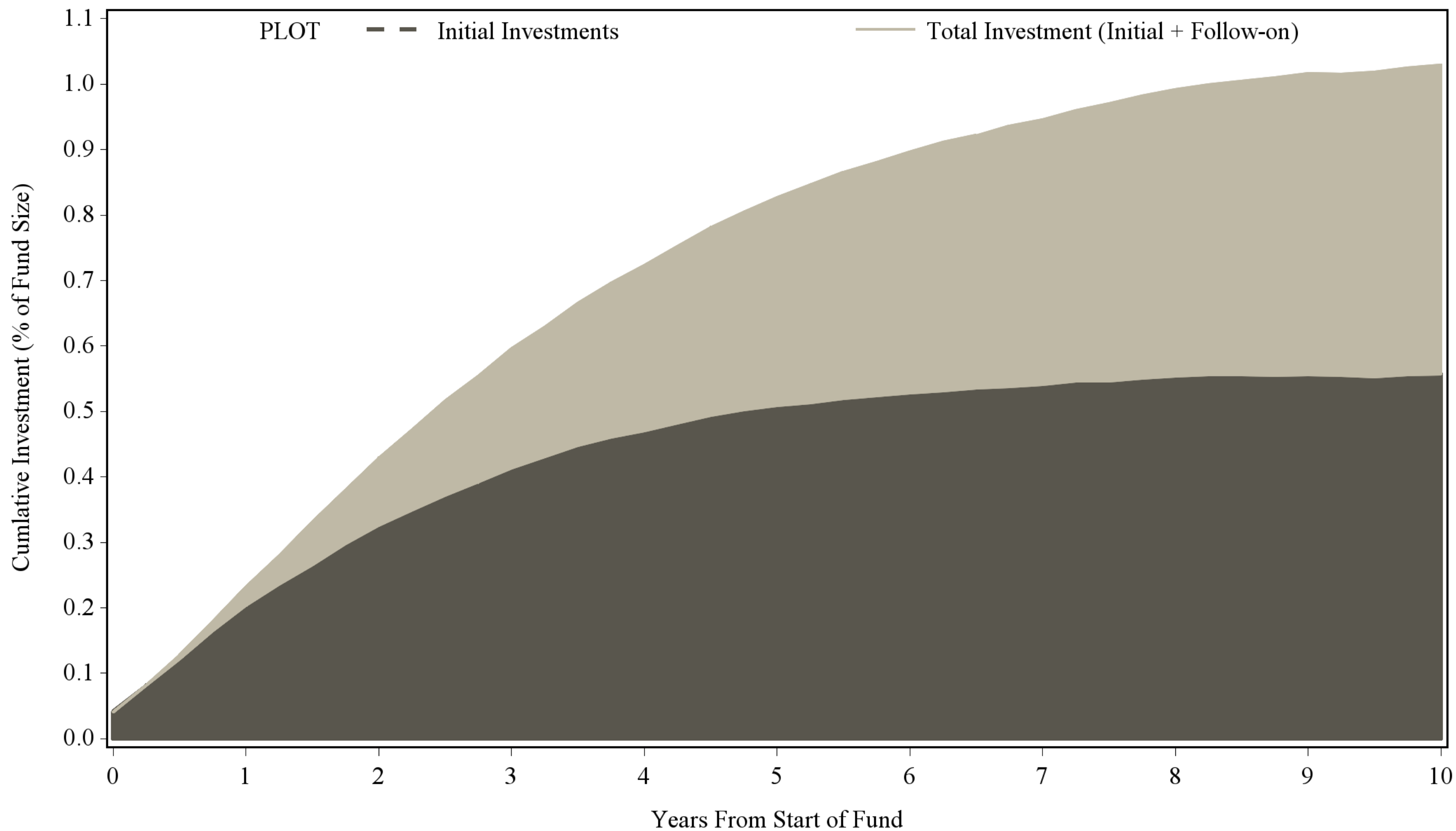

Figure 3.4: Cumulative Investment

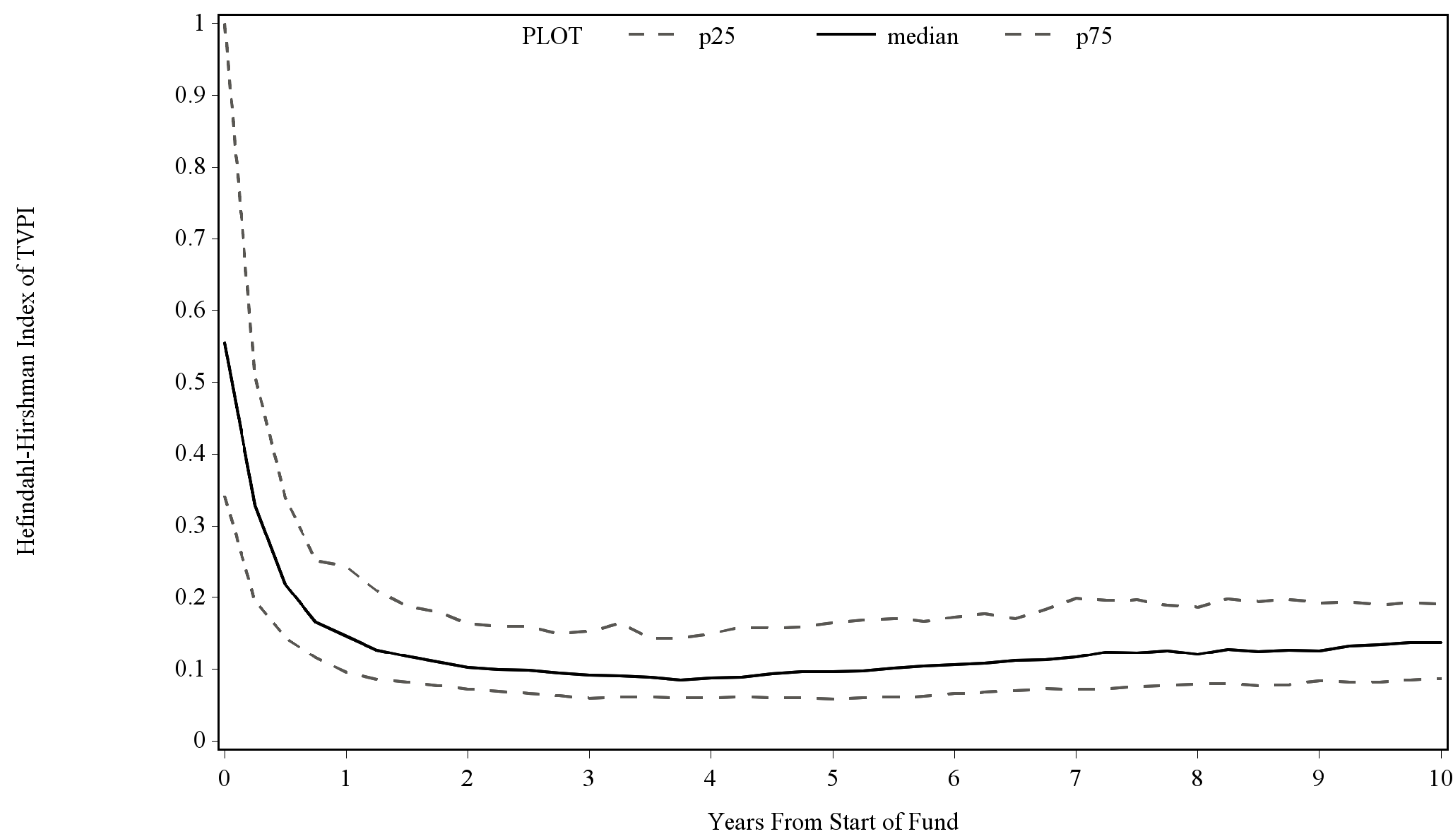

Figure 3.5: Concentration of Returns Over VC Fund Life

Table 3.1: Summary Statistics

Descriptive statistics for the sample of 181 venture capital funds between 1981 and 2003. Panel A presents statistics at the fund level. Previous Funds represents the number of venture capital funds operated by a GP prior to the current fund. Fund Size represents the capital committed to the fund and is listed in millions of dollars. Num of Investments is the number of portfolio company investments made by the fund. Final MIRR is the aggregate modified IRR of the fund gross of fees, calculated as described in Section 3, measured as of June 30, 2011. Final TVPI is the Total Value to Paid-In multiple, formed by dividing the sum of the cash flows out of the fund and the value of any unrealized fund assets as of June 30, 2011, by the cash flows from the firm to the portfolio company. Percentage With Follow-on presents the percentage of funds which successfully raised a follow-on fund. Panel B presents statistics for 144 funds who successfully raised a follow-on fund. This excludes 8 funds for which I can identify that a follow-on fund exists, but cannot obtain information on the size of the follow-on fund or date it first closed. Year Follow-on Fund is Raised gives the time in years between the first observed close of the current fund and the closing of the Follow-on Fund. Size Increase is the ratio of capital committed to the follow-on fund divided by the committed capital of the current fund. MIRR_{t-1} at Follow-on Close represents the MIRR of the current fund in the end of the quarter prior to the close of the follow-on fund. $\text{TVPI}_t - 1$ at Follow-on Close is the TVPI of the current fund in the quarter prior to the close of the follow-on fund. Panel C presents the summary statistics of the individual portfolio company investments. Initial Investment Size represents the amount of capital invested in the portfolio company over the first 3 quarters after the initial relationship is reported in the data. Size Increase is the additional capital invested by the firm in subsequent rounds of funding, expressed as a ratio to the size of the initial investment. Fund Age is the number of years following the first observed close of the fund when the portfolio company investment is made. Holding Period is the amount of time between the initial investment in a portfolio company and the fund's exit, expressed in years. Holding period is calculated using only realized investments. MIRR and TVPI in Panel C are the modified IRR and TVPI calculated at the portfolio company level.

Panel A: Fund Level Observations						
	Mean	Median	Std	Min	Max	N
Previous Funds	3.7	3.0	3.9	-	26.0	181
Fund Size ($million)	249.2	117.9	364.5	6.0	2,322.9	181
Num of Investments	36.9	32.0	20.6	5.0	125.0	181
Final MIRR	22.9%	13.9%	43.1%	-19.3%	432.8%	181
Final TVPI	2.9	1.9	3.6	0.1	27.7	181
Percentage With Follow-on	84%					181
Panel B: Follow-on Fund Observations						
	Mean	Median	Std	Min	Max	N
Year Follow-on fund is Raised	3.4	3.4	1.6	0.5	9.5	144
Size Increase	1.6	1.5	0.8	0.2	6.2	144
MIRR_{t-1} at Follow-on Close	37.5%	11.7%	87.9%	-57.0%	836.5%	144
TVPI_{t-1} at Follow-on Close	1.7	1.2	2.6	0.5	31.8	144
Panel C: Portfolio Company Level Observations						
	Mean	Median	Std	Min	Max	N
Initial Investment Size	4.0	2.0	5.5	0.0	33.8	6670
Size Increase	1.5	0.2	4.4	0.0	34.7	6670
Fund Age	2.1	1.8	1.9	0.0	16.0	6670
Holding Period (Years)	5.1	4.6	3.0	0.2	13.9	6318
MIRR	-2.6%	-3.5%	105.3%	-100.0%	598.8%	6670
TVPI	2.5	0.8	5.7	0.0	40.9	6670

Table 3.2: Sample Fund Characteristics by Vintage Year

Descriptive statistics for fund-level characteristics sorted by the year in which the fund closed its first round of funding. Data is taken from the 181 funds from 1981 through 2003 that made 5 or more portfolio company investments. For comparison, descriptive statistics are given for the sample of funds contained in VentureXpert that are identified as venture capital funds, administered by private equity firms or bank-affiliated private equity funds, and made 5 or more portfolio company investments. Num. of Funds represents the number of funds in the sample which closed their first observed round of funding in a given calendar year. Mean values are calculated by averaging over funds which closed in a given year. Mean Committed Capital is measured in millions of dollars and is the total capital committed to the partnership by both LPs and GPs. Mean MIRR is the average modified IRR, calculated as discussed in Section 3 of the text. Mean TVPI is calculated by averaging the undiscounted sum of the positive cash flows and terminal value for each fund, divided by the sum of the negative cash flows of the fund. Sample vs. VentureXpert Ratio of Committed Capital measures the total amount of capital committed to funds in the sample as a percentage of capital committed to funds listed in VentureXpert.

	Fund-of-Funds Sample				VentureXpert		
Year	Num. of Funds	Mean Committed Capital ($mil)	Mean MIRR	Mean TVPI	Num. of Funds	Mean Committed Capital ($mil)	Sample vs. VentureXpert Ratio of Committed Capital
1981/82	2	44.0	7.44%	1.50	166	17.7	3%
1983	9	58.9	10.50%	2.04	77	26.5	26%
1984	14	62.7	9.91%	1.78	70	24.3	52%
1985	3	31.3	6.14%	2.36	55	21.8	8%
1986	3	98.5	14.04%	2.33	40	20.8	36%
1987	11	57.3	17.53%	3.01	43	42.9	34%
1988	10	93.7	28.64%	3.61	25	49.3	76%
1989	10	52.2	18.02%	2.63	29	36.7	49%
1990	12	83.9	22.82%	2.91	24	80.4	52%
1991	6	120.7	22.89%	2.36	13	79.2	70%
1992	5	99.4	26.39%	2.72	22	42.1	54%
1993	8	141.7	56.50%	8.38	23	49.7	99%
1994	8	107.0	31.14%	4.54	33	57.5	45%
1995	6	230.2	76.23%	7.58	29	57.4	83%
1996	3	244.4	73.09%	4.44	46	81.6	20%
1997	3	135.5	73.92%	4.14	68	71.8	8%
1998	21	257.3	41.71%	2.98	70	119.0	65%
1999	18	427.1	1.45%	1.20	124	145.5	43%
2000	22	820.7	4.58%	1.35	188	174.6	55%
2001	5	543.7	8.50%	1.66	82	154.9	21%
2002/03	2	262.0	-6.73%	0.84	81	93.0	7%
Totals	181	249.2	22.9%	2.86	1,308	83.7	41%

Table 3.3: Existence of Follow-on Fund and Current Fund Performance

Coefficient estimates from probit analysis, relating the existence of a follow-on fund raised by a GP to the performance of the current fund and experience level of the GP. The dependent variable is an indicator variable which takes the value 1 when the GP successfully raises a follow-on fund. $MIRR_{t=3}$ years is the modified IRR of the current fund calculated three years into its existence. Ln(Previous Funds) is the natural logarithm of one plus the number of previous funds raised by the GP. The sample consists of 181 venture capital funds listed in Table I, excluding 8 funds for which the size or date of their follow-on fund could not be determined. Model 1 excludes an additional 28 observations in which vintage year dummies perfectly predict the existence of a follow-on fund. The robust standard errors reported beneath each coefficient are calculated using the method of White (1980). The lower portion of the table reports the marginal effect of $MIRR_{t=3}$ years on the probability that a follow-on fund exists for a fund GP with $MIRR_{t=3}$ years at its sample mean and experience of zero and three previous funds.

	Model 1	Model 2
$MIRR_{t=3\text{ years}}$	4.75**	3.92**
	(2.09)	(1.85)
Ln(Previous Funds)	0.13	0.21
	(0.20)	(0.16)
Ln(Previous Funds) * $MIRR_{t=3\text{ years}}$	-1.70*	-1.60*
	(1.01)	(0.92)
Constant	4.85***	0.65***
	(0.22)	(0.22)
Observations	145	173
Pseudo-R^2	0.148	0.088
Includes Vintage Year Dummies	Yes	No
Marginal Effect of MIRR (∂Pr. New Fund/$\partial MIRR_{t=3}$ years)		
Previous Funds = 0	1.30	1.15
p-value	0.030	0.040
Previous Funds = 3	0.60	0.41
p-value	0.018	0.028

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3.4: Change in Follow-on Fund Size and Current Fund Performance

Coefficient estimates from OLS regression and Tobit analysis relating the size of the follow-on fund raised by the GP to the performance and characteristics of the current fund. The dependent variable is the Size Increase of the follow-on fund measured as the ratio of the committed capital to the follow-on fund divided by the committed capital of the current fund. MIRR_{t-1} is the modified IRR of the current fund calculated at the end of the quarter before a new fund is raised. Ln(Previous Funds) is the natural logarithm of one plus the number of previous funds raised by the GP. Ln(Current Fund Committed Capital) is the natural logarithm of the size of capital committed by LPs to the GP's current fund measured in millions of dollars. All models contain unreported dummy variables for the vintage year of the current fund. The sample consists of 181 venture capital funds listed in Table I, excluding 8 funds for which the size or date of their follow-on fund could not be determined and 4 observations which are not identified due to the inclusion of vintage year dummy variables. The standard errors reported beneath each coefficient have been corrected for heteroskedasticity in the manner of White (1980). The lower portion of the table reports the marginal effect of MIRR_{t-1} on the increase in fund size for a fund GP with MIRR_{t-1} at sample mean, experience of zero, and three previous funds.

	Model 1 (OLS)	Model 2 (Tobit)	Model 3 (OLS)
MIRR_{t-1}	0.57*	0.76**	0.057
	(0.34)	(0.36)	(0.37)
MIRR^2_{t-1}	-0.032*	-0.039*	0.0023
	(0.019)	(0.021)	(0.018)
Ln(Previous Funds)	0.088	0.081	0.18
	(0.14)	(0.16)	(0.14)
Ln(Previous Funds) * $MIRR_{t-1}$	-0.15	-0.22	-0.029
	-0.18	(0.20)	(0.18)
Ln(Current Fund Commited Capital)	0.11	0.24**	-0.24*
	(0.096)	(0.11)	(0.12)
Constant	-0.90	-1.50	5.37**
	(1.73)	(2.10)	(2.24)
Observations	169	169	140
R^2 / Pseudo-R^2	0.362	0.143	0.426
Includes GPs With No Follow-On Fund	Yes	Yes	No
Marginal Effect of MIRR (∂Pr. New Fund/$\partial MIRR_{t-1}$ years)			
Previous Funds = 0	0.56	0.75	0.06
p-value	0.097	0.039	0.874
Previous Funds = 3	0.54	0.72	0.05
p-value	0.086	0.034	0.875

*** p<0.01, ** p<0.05, * p<0.1

Table 3.5: Early Fund Performance and Time to Follow-on fund

Coefficient estimates from a Cox regression with time-varying covariates. The dependent variable is the duration from the first closing of the current fund to the first closing of the GP's follow-on fund. $\text{MIRR}_{t-1}$is the modified IRR of each venture capital fund calculated at the end of the previous quarter. Ln(Previous Funds) is the natural logarithm of one plus the number of previous funds raised by the GP. Fund Age is the time the current fund has been operating measured in years. VentureXpert Funds $\text{Raised}_{t-1,t-5}$ is the number of venture capital funds raised over the previous year as reported in VentureXpert. The table displays the coefficients of the proportional hazard model, with the robust standard errors listed below, calculated in the manner of Lin and Wei (1989). The hazard model is stratified by vintage year. The lower section of the table lists the marginal effect of a 10% increase in MIRR_{t-1} on the hazard rate of a new fund being raised.

	Model 1	Model 2
MIRR_{t-1}	0.14***	0.31*
	(0.031)	(0.17)
Ln(Previous Funds)	0.15	0.16
	(0.10)	(0.10)
MIRR_{t-1}* Ln(Previous Funds)		-0.11
		(0.10)
VentureXpert Funds $\text{Raised}_{t-1,t-5}$	0.0077***	0.0077***
	(0.0018)	(0.0019)
Fund-Quarters	3197	3197
Partnerships	169	169
Model p-value	<0.001	<0.001
Proportional Change Hazard Ratio - 10% Increase in MIRR		
Fund Age = 3 Years , Previous Funds = 0	1.01	1.03
p-value	<0.001	0.061
Fund Age = 3 Years , Previous Funds = 3	1.01	1.02
p-value	<0.001	<0.001
p-value for difference		0.299

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3.6: Fund Performance and Portfolio Company

This table presents the maximum likelihood estimates of the expected mean and variance of venture capital portfolio company investments. The observed dependent variable is the return to each individual portfolio company investment made after the fund has been operating for two years. Variance is a latent variable imputed by the estimation procedure. A derivation of empirical model and log likelihood function appears in Appendix B. $MIRR_{t-1}$ is modified IRR at the end of the quarter before the portfolio company investment is made. $MIRR_{t-1}$ is set to zero for the first quarter in which investments are made by each fund. Fund Age represents the number of years since the closing of the fund at the time each portfolio company investment is made. NASDAQ Return represent the cumulative return of an equal-weighted portfolio of the smallest size decile of NASDAQ firms in CRSP during the holding period of each portfolio company. NASDAQ Variance represents the variance across cumulative returns to the individual NASDAQ firms in this portfolio. Ln(Previous Funds) represents the natural logarithm of the number of previous funds raised by general partner of the fund. Variance, the latent variable, is also included as an explanatory variable in the mean equation. The standard errors reported beneath each coefficient are clustered at the fund level. The lower portion of the table reports the marginal effect of $MIRR_{t-1}$ on the expected variance of a portfolio company selected by a GP running a fund in its third year. Panel A presents results with investment year and GP dummy variables included in specification of the mean equation. Panel B includes additional GP dummy variables in the specification of the variance equation.

Panel A: GP Dummy Variables Included in Mean Equation

	Model 1		Model 2	
	Mean	Variance	Mean	Variance
$MIRR_{t-1}$		1.28***		1.08***
		(0.094)		(0.34)
Fund Age		0.13***		0.13***
		(0.017)		(0.017)
Ln(Previous Funds)		0.022		0.012
		(0.042)		(0.045)
$MIRR_{t-1}$* Ln(Previous Funds)				0.12
				(0.19)
NASDAQ Variance		0.013***		0.013***
		(0.0023)		(0.0023)
NASDAQ Return	0.44***		0.44***	
	(0.099)		(0.099)	
Constant	-0.89*	-0.35***	-0.89*	-0.34***
	(0.53)	(0.099)	(0.53)	(0.10)
Observations	3,448		3,448	
AIC	7,670		7,672	
Investment Year Dummies	Mean Equation		Mean Equation	
GP Dummies	Mean Equation		Mean Equation	
Marginal Effect of MIRR ($\partial\sigma^2/\partial MIRR_{t-1}$)				
Fund Age = 3 Years , Previous Funds = 0		1.56		1.65
p-value		<0.001		<0.001
Fund Age = 3 Years , Previous Funds = 3		1.56		1.88
p-value		<0.001		<0.001
p-value for difference				0.534

Panel B: GP Dummy Variables Included in Mean and Variance Equation				
	Model 3		Model 4	
	Mean	Variance	Mean	Variance
$MIRR_{t-1}$		1.57***		2.05***
		(0.13)		(0.47)
Fund Age		0.092***		0.091***
		(0.020)		(0.020)
Ln(Previous Funds)		-0.029		-0.010
		(0.071)		(0.073)
$MIRR_{t-1}$* Ln(Previous Funds)				-0.31
				(0.28)
NASDAQ Variance		0.015***		0.015***
		(0.0023)		(0.0023)
NASDAQ Return	0.46***		0.47***	
	(0.095)		(0.095)	
Constant	-0.81*	-1.19***	-0.82*	-1.24***
	(0.42)	(0.34)	(0.43)	(0.35)
Observations	3,448		3,448	
AIC	7,358		7,359	
Investment Year Dummies	Mean Equation		Mean Equation	
GP Dummies	Mean & Var Eq.		Mean & Var Eq.	
Marginal Effect of MIRR ($\delta\sigma^2/\delta MIRR_{t-1}$)				
Fund Age = 3 Years , Previous Funds = 0		1.52		1.97
p-value		<0.001		<0.001
Fund Age = 3 Years , Previous Funds = 3		1.52		0.98
p-value		<0.001		<0.001
p-value for difference				0.275

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3.7: Portfolio Company Investment Size and Fund Performance

This table describes the relationship between fund performance, and the size of subsequent portfolio company investments made after the fund has been operating for two years. The dependent variable is the size of each initial portfolio company investment as a percentage of the committed capital of the fund. $MIRR_{t-1}$ is modified IRR at the end of the quarter before the portfolio company investment is made. Fund Age represents the number of year since the closing of the fund at the time each portfolio company investment is made. Ln(Previous Funds) represents the natural logarithm of the number of previous funds raised by general partner of the fund. The standard errors reported beneath each coefficient are clustered at the partnership level.

	Model 1	Model 2	Model 3
$MIRR_{t-1}$	0.66***	1.14**	0.94*
	(0.18)	(0.44)	(0.54)
Fund Age	-0.027	-0.027	-0.044
	(0.027)	(0.027)	(0.047)
Ln(Previous Funds)	-0.27	-0.25	-0.038
	(0.19)	(0.19)	(0.34)
$MIRR_{t-1}$* Ln(Previous Funds)		-0.30	-0.54**
		(0.24)	(0.27)
Constant	1.92***	1.88***	1.60*
	(0.30)	(0.31)	(0.87)
Observations	3,122	3,122	3,122
Model R^2	0.022	0.023	0.052
Year Dummies	No	No	Yes
GP Dummies	Yes	Yes	Yes

*** p<0.01, ** p<0.05, * p<0.1

Table 3.8: Diversifying Investments and Fund Performance

This table describes the relationship between fund performance, and the regional and industry diversification effect of subsequent portfolio company investments made after the fund has been operating for two years. The results presented are from a probit analysis whose dependent variable is an indicator for whether each portfolio company investment diversifies the committed capital of the fund across industries or regions. Models 1 and 2 present the results for diversification across industry which is classified using the Fama-French 49 industries. Models 3 and 4 report results of diversification across the 10 geographic regions depicted in Figure 4.1. $MIRR_{t-1}$ is modified IRR at the end of the quarter before the portfolio company investment is made. Fund Age represents the number of year since the closing of the fund at the time each portfolio company investment is made. Ln(Previous Funds) represents the natural logarithm of the number of previous funds raised by general partner of the fund. Ln(Fund Size) represents the natural logarithm of the committed capital of the fund. The lower portion of the table reports the marginal effect of $MIRR_{t-1}$ for a fund in its third year with GP experience of zero and three previous funds.

	Industry		Region	
	Model 1	Model 2	Model 3	Model 4
$MIRR^{Fund}_{t-1}$	-0.035	-0.18	-0.096	0.036
	(0.074)	(0.22)	(0.073)	(0.22)
Fund Age	-0.025**	-0.025**	-0.0075	-0.0076
	(0.013)	(0.013)	(0.013)	(0.013)
Ln(Previous Funds)	0.056	0.046	-0.088**	-0.079*
	(0.041)	(0.043)	(0.040)	(0.043)
$MIRR^{Fund}_{t-1}$* Ln(Previous Funds)		0.090		-0.084
		(0.13)		(0.13)
Ln(Fund Size)	-0.12***	-0.11***	0.061**	0.059**
	(0.026)	(0.026)	(0.026)	(0.026)
Constant	2.51***	2.50***	-0.91**	-0.89**
	(0.46)	(0.46)	(0.45)	(0.45)
Observations	3355	3355	3355	3355
Model Pseudo-R^2	0.007	0.007	0.002	0.002
Marginal Effect of MIRR (∂ Pr Increase in HHI / $\partial MIRR^{Fund}_{t-1}$)				
Fund Age = 3 Years , Previous Funds = 0	-0.01	-0.07	-0.04	0.01
p-value	0.635	0.417	0.186	0.871
Fund Age = 3 Years , Previous Funds = 3		-0.07		0.01
p-value		0.417		0.881
p-value for difference		0.497		0.526

*** p<0.01, ** p<0.05, * p<0.1

Table 3.9: Bivariate Comparison of Fund Ranking and Future Investment Performance

Descriptive statistics for the performance of venture capital fund portfolios sorted by the performance of previous investments. The sample is divided in to cohorts covering two year periods (e.g. 1981-82). Funds with less then 20% of their committed capital remaining, or who make less then three subsequent investments are excluded. The funds are then sorted by cohort into high ranking and low ranking funds by MIRR of the fund at a given fund age. Panel A presents results sorted at 2 years, Panel B present results sorted at 4 years. The first column list the number of observations in each group. Adjusted MIRR at Sort is the average difference between the MIRR of each fund at the sorting age and the cohort median value. The Post-Sort Portfolio presents the mean and standard deviation of the MIRR calculated using fund portfolios comprised of investments made after the sort and adjusted by the cohort median (i.e. one observation is the aggregate MIRR of one fund's entire ex-post investment portfolio minus the cohort median ex-post portfolio MIRR). The Pre-Sort Portfolio presents the final realized performance of the portfolio of investments made prior to the sort, adjusted by the cohort median portfolio performance. The bottom of each column lists the differences across each variable as well as the p-values of tests for differences across the groups. The first set of p-values is calculated using the assumption that the two samples are normally distributed. The second p-value is given for Levene(1960)'s robust test for equality of variances.

Panel A: Cohorts Sorted at 2 Years

		Adjusted	Post-Sort Portfolio		Pre-Sort Portfolio	
	Obs	MIRR at Sort	Mean	σ	Mean	σ
High MIRR	78	20%	51%	398%	8%	22%
Low MIRR	78	-13%	-6%	33%	0%	30%
H-L		33%	56%	365%	8%	-8%
P-Value (Normal Dist.)		<0.001	0.216	<0.001	0.068	0.001
P-Value (Levene)				0.071		0.606

Panel B: Cohorts Sorted at 4 Years

		Adjusted	Post-Sort Portfolio		Pre-Sort Portfolio	
	Obs	MIRR at Sort	Mean	σ	Mean	σ
High MIRR	50	8%	15%	65%	4%	9%
Low MIRR	50	-8%	-3%	30%	-9%	16%
H-L		16%	18%	35%	12%	-7%
P-Value (Normal Dist.)		<0.001	0.084	<0.001	<0.001	<0.001
P-Value (Levene)				0.140		0.028

Table 3.10: Early Fund Performance and Rate of Spending

Coefficient estimates from a stratified Cox regression with time-varying covariates. The dependent variable is the duration from the first closing of the fund until a given percentage of the fund's capital is spent. The columns across the top indicate the % of capital spent being used as the dependent variable (e.g. Model 1 and 2, use 70% of capital spent as the end of the spell duration) $MIRR^{Fund}_{t-1}$ is the modified IRR of each venture capital fund calculated at the end of the previous quarter. Ln(Previous Funds) is the natural logarithm of one plus the number of previous funds raised by the GP. Fund Age is the time the current fund has been operating measured in years. The table displays the coefficients of the proportional hazard model, with the robust standard errors listed below, calculated in the manner of Lin and Wei (1989). The hazard model is stratified by vintage year the fund is raised. The lower section of the table lists the marginal effect of a 10% increase in $MIRR^{Fund}_{t-1}$ on the hazard rate of a new fund being raised. The marginal effects are evaluated at the median year when the % of capital is reached for with GPs with zero previous experience and GPs with three previous funds.

	70% of Capital		80% of Capital		90% of Capital	
	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
$MIRR^{Fund}_{t-1}$	0.52***	-0.81	0.54***	-0.71	0.55***	-0.61
	(0.083)	(0.79)	(0.094)	(0.74)	(0.12)	(0.87)
Ln(Previous Funds)	0.17*	0.11	0.11	0.042	0.14	0.072
	(0.099)	(0.10)	(0.11)	(0.11)	(0.12)	(0.13)
$MIRR^{Fund}_{t-1}$* Ln(Previous Funds)		0.83*		0.77*		0.72
		(0.49)		(0.45)		(0.53)
Fund-Quarters	1982	1982	2689	2689	3899	3899
Partnerships	181	181	181	181	181	181
Model Pseudo-R^2	0.016	0.018	0.014	0.016	0.013	0.014
Proportional Change Hazard Ratio - 10% Increase in $MIRR^{Fund}_{t-1}$						
Med. Time to % of Capital (Yr)	4.25	4.25	5.25	5.25	6.5	6.5
Previous Funds = 0	1.05	0.92	1.05	0.93	1.06	0.94
p-value	<0.001	0.305	<0.001		¡0.001	0.483
Previous Funds = 3	1.05	1.04	1.05	1.04	1.06	1.04
p-value	<0.001	0.009	<0.001	0.008	<0.001	0.019
p-value for difference		0.090				

*** p<0.01, ** p<0.05, * p<0.1

Table 3.11: Existence of Follow-on Fund and Concentration of Returns

Coefficient estimates from probit analysis, relating the existence of a follow-on fund raised by a GP to the concentration of the current fund's performance among a small group of the investments. The dependent variable is an indicator variable which takes the value 1 when the GP successfully raises a follow-on fund. $TVPI^{Fund}_{t=3years}$ (Total Value / Put In) is measured in the third year of the fund by taking the sum of the net asset value of the fund plus the cash which has been paid out by the fund, divided by the amount of invested capital. $HHI_{TVPI,t=3years}$ is a Herfindahl-Hirshman index formed by using the relative share of each investment in the total TVPI of the fund. Section 3.4.2 describes the calculation and interpretation of $TVPI^{Fund}_{t=3years}$ in detail. Ln(Previous Funds) is the natural logarithm of one plus the number of previous funds raised by the GP. Each specification contains dummy variables for the vintage year of the current fund. The sample consists of 181 venture capital funds listed in Table I, excluding 8 funds for which the size or date of their follow-on fund is unknown and 28 funds for which vintage year dummies perfectly predict the existence of a follow-on fund. The robust standard errors reported beneath each coefficient are calculated using the method of White (1980).

	Model 1	Model 2
$TVPI^{Fund}_{t=3years}$	4.05***	3.59***
	(1.11)	(1.25)
$HHI_{TVPI,t=3years}$		-8.87**
		(4.37)
$TVPI^{Fund}_{t=3years}$ * $HHI_{TVPI,t=3years}$		1.86
		(3.01)
Ln(Previous Funds)	1.54***	1.18**
	(0.54)	(0.54)
$TVPI^{Fund}_{t=3years}$* Ln(Previous Funds)	-1.52***	-1.42***
	(0.52)	(0.48)
Constant	1.62**	1.68
	(0.73)	(1.27)
Observations	145	145
Pseudo-R^2	0.19	0.26

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3.12: Change in Follow-on Fund Size and Concentration of Returns

Coefficient estimates from OLS regression relating the size of the follow-on fund raised by the GP to the concentration of the current fund's performance among a small group of the investments. The dependent variable is the Size Increase of the follow-on fund measured as the ratio of the committed capital to the follow-on fund divided by the committed capital of the current fund. $TVPI^{Fund}_{t-1}$ (Total Value / Put In) is measured in the quarter before a new fund is raised by taking the sum of the net asset value of the fund plus the cash which has been paid out by the fund, divided by the amount of invested capital. $HHI_{TVPI,t-1}$ is a Herfindahl-Hirshman index formed by using the relative share of each investment in the total TVPI of the fund. Section 3.4.2 describes the calculation and interpretation of $HHI_{TVPI,t-1}$ in detail. Ln(Previous Funds) is the natural logarithm of one plus the number of previous funds raised by the GP. Ln(Current Fund Committed Capital) is the natural logarithm of the size of capital committed by LPs to the GP's current fund measured in millions of dollars. All models contain unreported dummy variables for the vintage year of the current fund. The sample consists of 181 venture capital funds listed in Table I, excluding 8 funds for which the size or date of their follow-on fund could not be determined and 4 observations which are not identified due to the inclusion of vintage year dummy variables. The standard errors reported beneath each coefficient have been corrected for heteroskedasticity in the manner of White (1980).

	Model 1	Model 2	Model 3
$TVPI^{Fund}_{t-1}$	0.42*	0.53**	-0.12
	(0.24)	(0.27)	(0.21)
$HHI_{TVPI,t-1}$		-0.90	0.32
		(1.14)	(1.03)
$TVPI^{Fund}_{t-1}$* $HHI_{TVPI,t-1}$		-0.47*	0.029
		(0.24)	(0.18)
Ln(Previous Funds)	0.36	0.12	0.10
	(0.23)	(0.28)	(0.25)
$TVPI^{Fund}_{t-1}$ * Ln(Previous Funds)	-0.24	-0.076	0.060
	(0.15)	(0.19)	(0.14)
Ln(Current Fund Commited Capital)	0.099	0.018	-0.23*
	(0.098)	(0.13)	(0.14)
Constant	-1.15	0.25	5.38**
	(1.75)	(2.36)	(2.51)
Observations	169	169	140
R^2	0.359	0.376	0.424

*** p<0.01, ** p<0.05, * p<0.1

Table 3.13: Time to Follow-on fund and Concentration of Returns

Coefficient estimates from a Cox regression with time-varying covariates. The dependent variable is the duration from the first closing of the current fund to the first closing of the GP's follow-on fund. $TVPI^{Fund}_{t-1}$ (Total Value / Put In) is measured in the quarter before a new fund is raised by taking the sum of the net asset value of the fund plus the cash which has been paid out by the fund, divided by the amount of invested capital. $HHI_{TVPI,t-1}$ is a Herfindahl-Hirshman index formed by using the relative share of each investment in the total TVPI of the fund. Section 3.4.2 describes the calculation and interpretation of $HHI_{TVPI,t-1}$ in detail. Ln(Previous Funds) is the natural logarithm of one plus the number of previous funds raised by the GP. VentureXpert Funds Raised$_{t-1,t-5}$ is the number of venture capital funds raised over the previous year as reported in VentureXpert. Each analysis is stratified by vintage year of the current fund. The sample consists of 181 venture capital funds listed in Table I, excluding 8 funds for which the size or date of their follow-on fund could not be determined and 4 observations which are not identified due to the inclusion of vintage year stratification. The table displays the coefficients of the proportional hazard model, with the robust standard errors listed below, calculated in the manner of Lin and Wei (1989).

	Model 1	Model 2
$TVPI^{Fund}_{t-1}$	1.10***	2.04***
	(0.31)	(0.36)
$HHI_{TVPI,t-1}$		-5.52***
		(1.65)
$TVPI^{Fund}_{t-1} * HHI_{TVPI,t-1}$		-1.53***
		(0.37)
Ln(Previous Funds)	0.96***	0.47
	(0.26)	(0.29)
$TVPI^{Fund}_{t-1}$* Ln(Previous Funds)	-0.64***	-0.51**
	(0.19)	(0.21)
VentureXpert Funds Raised$_{t-1,t-5}$	0.0045	-0.00093
	(0.0050)	(0.0050)
Fund-Quarters	3,145	3,145
Partnerships	169	169
Model p-value	<0.001	<0.001

*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Chapter 4

Conclusion

As better data becomes available, the venture capital and private equity literature is increasingly focused on understanding the economic incentives facing fund managers, and the resulting effects on their portfolios. This paper uses a unique data set to document several new stylized facts about these relationships. First, I confirm the finding in Kaplan and Schoar (2005) that the size of the next fund raised by the GP is concave in the performance of the current fund, and I demonstrate that this relationship is largely driven by the effect of successfully raising a new fund, rather than an increase in fund size conditional on raising a new fund. Second, I show that the speed at which venture capital GPs raise a new fund is positively related to the performance of their current fund. Finally, I show that, following good performance early in the fund, venture capital GPs pursue more risky portfolios by making larger investments in more volatile ventures.

As discussed in the introduction, these findings stand in contrast to the relationship between early performance, and subsequent investment choices, documented for mutual fund managers. This is a particularly interesting comparison because mutual fund managers and venture capital GPs perform a similar economic function. This suggests that the differences in behavior are linked to the institutional details surrounding these two forms of delegated portfolio management. The model I develop suggests that the difference in behavior is largely a result of the different response of career incentives to performance.

This paper also makes a contribution to the literature on which types of firms receive venture capital funding. This literature typically focuses on demand-side effects related to the characteristics of the firms. This paper is novel in that I suggest that the firms which receive funding may in part be determined by the implicit career incentives of the GPs. An interesting extension of this work would be to consider whether the effect documented in this paper might have an aggregate effect on the type of ventures which receive funding. Rhodes-Kropf and Nanda (2012a) document that during private equity booms, when recent returns have been high and available capital is plentiful, venture capital funds tend to invest in more volatile and more innovative firms. In a separate paper, Rhodes-Kropf and Nanda (2012b), propose that this relationship stems from the GP's uncertainty about the ability of the venture to receive follow-on financing from a third-party. This provides a potential alternative channel by which the performance of GPs might affect the aggregate level of innovation in the economy.

Appendices

Appendix A

Model Solution

The model solution is a Nash equilibrium consisting of investment choices by the GP in each investment period, and LP decisions in period 2 and 3 to invest in the GP's follow-on fund given each possible investment outcome. In equilibrium the LP must update his or her expectation of GP skill based on portfolio performance and a correct inference about the GP's unobservable investment choices. Solving the model through backward induction is somewhat tedious because the model is discrete and the type of investment chosen at $t = 1$ affects beliefs about the GP's skill, which is an important state variable in the $t = 2$ investment decision. Fortunately, the distribution of returns in the model, which are motivated by the relatively infrequent success of venture capital investing, allow a shortcut to immediately give Result 1 which states the optimal first period investment decision.

A.1 Result 1

Result 1 shows that when the GP performs sufficiently well in the first period, he is guaranteed a second fund; thus, there is no conflict between maximizing the value of the current fund and the value of the GP's career.

Proof. First, note that in the first period the outcomes $C_1 = X, 2X$ will be sufficient to raise a new fund after one period regardless of which investment is chosen in period 1. All of the investment choices can be written in the form:

$$Pr\left[c_1 = C_1\right] = \begin{cases} \alpha t_i + a & C_1 = 2X \\ (1-\alpha)\, t_i + b & C_1 = X \\ 1 - t_i - (a+b) & C_1 = 0 \end{cases} \tag{A.1}$$

By Bayes rule:

$$\Pr\left[t_i = t + \Delta t_g \mid c_1\right] = \frac{\Pr\left[c_1 \mid t_i = t + \Delta t_g\right] \cdot \Pr\left[t_i = t + \Delta t_g\right]}{\Pr\left[c_1\right]} \tag{A.2}$$

For:

$$\Pr\left[t_i = t + \Delta t_g \mid c_1 = 2X\right] = \frac{\alpha\left(t + \Delta t_g\right) + a}{\alpha\left(2t + \Delta t_g\right) + 2a} \geq \frac{1}{2} \tag{A.3}$$

$$\Pr\left[t_i = t + \Delta t_g \mid c_1 = X\right] = \frac{(1-\alpha)\left(t + \Delta t_g\right) + b}{(1-\alpha)\left(2t + \Delta t_g\right) + 2b} \geq \frac{1}{2} \tag{A.4}$$

$$\Pr\left[t_i = t + \Delta t_g \mid c_1 = 0\right] = \frac{1 - t - \Delta t_g - a - b}{2 - 2t - \Delta t_g - 2\left(a+b\right)} < \frac{1}{2} \tag{A.5}$$

The threshold for the GP to be able to raise a new fund is $\Pr\left[t_i = t + \Delta t_g\right] \geq 1/2$. For any value of α the GP will be able to raise a new fund following $c_1 \geq X$, because even when a particular outcome is entirely dependent on luck (e.g. outcome $c_1 = X$ when $\alpha = 1$), the GP will still be at least as good as another random draw from the population. The following table gives the

Deviation	$\Delta\Pr(c_1 = X)$	$\Delta\Pr(c_1 = 2X)$	$\Delta\Pr(c_1 \in \{X, 2X\})$
Safe	$2\gamma - (1-\alpha)\epsilon$	$-\gamma - \alpha\epsilon$	$\gamma - \epsilon$
Risky	$-2\gamma - (1-\alpha)\epsilon$	$\gamma - \alpha\epsilon$	$-\gamma - \epsilon$

change in the probability of each outcome by selecting the one of the alternative investments, relative to the standard investment.

Its clear that selecting the safe investment in period 1 results in the highest probability of raising a new fund. In the second period, given that they have raised a new fund, the GP has no incentive to deviate from the highest NPV project, and thus will pick the standard investment.

□

A.2 Result 2

In this section I characterize the possible equilibrium strategies, following $c_1 = 0$. The equilibrium requires that the investors hold correct beliefs about the investment choice of the GP, and given those beliefs, the GP's investment choice provides the highest expected value. First I consider pure strategies.

A.2.1 Pure Strategy Selecting Standard Investment

When under some outcome of c_2 the GP will be able to raise a new fund and ϵ is sufficiently low, a pure strategy equilibria of taking the standard investment does not exist, which is equivalent to the first statement in Result

2. The first requirement states that one failure in the first period ($c_1 = 0$) is not a sufficiently poor signal about the GP's skill to prevent him from raising a new fund regardless of the outcome of the second investment. The second requirement is a bound on how much NPV the GP would be willing to give up to pursue one of the alternative projects.

Proof. Suppose that there exists a pure strategy equilibrium where the GP selects the standard investment following $c_1 = 0$, and following either $c_2 = X$ or $c_2 = 2X$ (or both), the beliefs about the GP's skill would be sufficient to allow them to raise a new fund. It must be the case that deviating to select a different investment would not result in a higher expected value for the GP. Given that the value to a follow-on career is constant, the change in expected value for each alternative investment can be characterized by the change in probability across each outcome.

Deviation	$\Delta \Pr(c_2 = X)$	$\Delta \Pr(c_2 = 2X)$	$\Delta \Pr(c_2 \in \{X, 2X\})$
Safe	$2\gamma - (1-\alpha)\epsilon$	$-\gamma - \alpha\epsilon$	$\gamma - \epsilon$
Risky	$-2\gamma - (1-\alpha)\epsilon$	$\gamma - \alpha\epsilon$	$-\gamma - \epsilon$

The table above demonstrates that as $\epsilon \to 0$, for every combination of outcomes which would result in a new fund, there is an alternative investment which would provide a higher expected value than the standard investment. Consider the case when $c_2 = 2X$ will garner the GP a new fund, but $c_2 = X$ will not. The probability of earning a fund after selecting the risky investment as $\epsilon \to 0$ is higher by γ. Thus, selecting the risky investment would be a beneficial deviation. In the case where only the outcome $c_2 = X$ or when both $c_2 = X$ and $c_2 = 2X$ would result in new funds, as $\epsilon \to 0$, deviating to select the safe investment would increase the probability of raising a new fund by 2γ and γ respectively. Thus, the safe investment would be strictly preferred over the standard investment. Continuity ensures that this result holds up to some $\epsilon > 0$, where the reduced effect of skill in the alternative investments outweighs the potential benefit from adding or subtracting 2γ from the probability of a moderate outcome.

$\square$

A.2.2 Pure Strategy Selecting Risky Investment

First I calculate the change in probability for each outcome that would result from choosing an investment other than the risky investment.

Deviation	$\Delta \Pr(c_2 = X)$	$\Delta \Pr(c_2 = 2X)$	$\Delta \Pr(c_2 \in \{X, 2X\})$
Standard	$2\gamma + (1-\alpha)\epsilon$	$-\gamma\alpha\epsilon$	$\gamma + \epsilon$
Safe	4γ	-2γ	2γ

The table shows that the only situation in which the GP would not find it beneficial to deviate from the risky investment pure strategy is when $c_2 = 2X$, but not $c_2 = X$, will result in new fund. Given the safe investment selected in period 1 was a failure $c_1 = 0$, for $c_2 = 2X$ to raise a new fund Bayes rule gives the following:

$$\frac{\left[\alpha\left(t+\Delta t_g-\epsilon\right)+\frac{p}{2}-\gamma\right]\left(1-t-\Delta t_g-p-\gamma\right)}{\left[\alpha\left(t+\Delta t_g-\epsilon\right)+\frac{p}{2}-\gamma\right]\left(1-t-\Delta t_g-p-\gamma\right)+\left[\alpha\left(t-\epsilon\right)+\frac{p}{2}-\gamma\right]\left(1-t-p-\gamma\right)}\geq\frac{1}{2} \tag{A.6}$$

which simplifies to

$$t-\frac{\Delta t_g}{2}\leq\frac{1+2\epsilon}{2}-\frac{\left(\alpha+\frac{1}{2}\right)}{2\alpha}p-\frac{\left(\alpha+1\right)}{2\alpha}\gamma \tag{A.7}$$

Similarly it can be shown that for $c_2 = X$ to not result in a new fund the following inequality must hold:

$$t-\frac{\Delta t_g}{2}>\frac{1+2\epsilon}{2}-\frac{\frac{3}{2}-\alpha}{2\left(1-\alpha\right)}p+\frac{1+\alpha}{2\left(1-\alpha\right)}\gamma \tag{A.8}$$

Both inequalities are more likely to be satisfied when α is large; thus, this equilibrium is likely to be supported when $c_2 = 2X$ is more informative about the GP's type than $c_2 = X$. The other parameters of interest, p and $t - \frac{\Delta t_g}{2}$ have opposite effects on each inequality. If p is too high, then the outcome $c_2 = 2X$ will be largely attributed to luck, and the GP will not be able to raise a new fund following $c_2 = 2X$; thus, selecting the risky investment will do them no good. Similarly, when p is too low, $c_2 = X$ will be sufficient to raise a new fund; thus, the GP would be better off by selecting the safe investment which has a higher probability mass over $c_2 \geq X$. A similar intuition follows for $t - \frac{\Delta t_g}{2}$. When this value is high, the average GP stands a fairly good change of being successful such that the result $c_2 = 2X$ is not sufficiently informative about the GP's type to result in a new fund. When $t - \frac{\Delta t_g}{2}$ is low, any outcome $c_2 \geq X$ is sufficient to raise a new fund and the safe option provides more probability mass, which will result in a new fund.

A.2.3 Pure Strategy Selecting Safe Investment

The following table gives the change in in probability for each outcome that would results from choosing an investment other than the safe investment.

Deviation	$\Delta \Pr(c_2 = X)$	$\Delta \Pr(c_2 = 2X)$	$\Delta \Pr(c_2 \in \{X, 2X\})$
Standard	$-2\gamma + (1-\alpha)\epsilon$	$\gamma + \alpha\epsilon$	$-\gamma + \epsilon$
Risky	-4γ	2γ	-2γ

The table demonstrates that any time in which $c_2 = X$ results in a new fund, the GP will not benefit from deviating from the safe investment. The intuition is that the safe investment provides the most probability mass above $c_2 \geq X$, so that any deviation would decrease the odds of raising a new fund. As before, Bayes rule can be used to compute the inequality which ensures that the GP will raise a new fund following $c_2 = X$, given that investors believe he will select theR safe investment.

$$t - \frac{\Delta t_g}{2} \leq \frac{1+\epsilon}{2} - \frac{p + 2\gamma}{2(1-\alpha)} \tag{A.9}$$

Because there is only one inequality, the effects of each parameter are less ambiguous. The inequality is more likely to hold when α, p are small.

This coincides with the intuition that when $c_2 = X$ is very informative about the GP's type, the GP will select the safe investments which puts relatively more weight on $c_2 = X$.

A.2.4 Mixed Strategies

In the regions where pure strategies equilibria are infeasible because of incentive constraints, there may exist a mixed strategy equilibrium in which the GP randomly draws between a standard investment and one of the alternative investments. To remain incentive-compatible, a mixed strategy requires that the agent be indifferent between the two pure strategies involved. This will require that for $c_2 = X$ investors will be exactly indifferent between the GP and a new GP drawn from the population and the general partner will be granted a new fund with some positive probability less than one. This is demonstrated by setting equal the expected value of Eq. 2.5 under two pure strategies and simplifying. The following relationship must hold for mixed strategy consisting of the safe and standard investment.

$$\Pr\left[\text{New Fund} \mid c_1 = 0, c_2 = X\right] = \frac{(\gamma + \alpha\epsilon)}{(2\gamma - (1-\alpha)\,\epsilon)} \Pr\left[\text{New Fund} \mid c_1 = 0, c_2 = 2X\right] \tag{A.10}$$

Note that Eq. A.10 can be satisfied under two conditions. The first is that neither $c_2 = X$ nor $c_2 = 2X$ result in a new fund, so the GP is entirely indifferent to his investment choice. The second is that both $c_2 = X$ and $c_2 = 2X$ will result in a new fund with some positive probability, with the probability of a new fund being raised following $c_2 = X$ being strictly less than one. For the probability of raising a new fund to be less than one requires that investors be indifferent between financing the current GP, and drawing a new one from the population. The pdf for a mixed strategy consisting of selecting the safe investment with probability m and selecting the standard investment with probability $1-m$ is given by:

$$Pr\left[c_{mixsafe}=C_{mixsafe}\right]=\begin{cases}\alpha\left(t_i-m\epsilon\right)+\frac{p}{2}-m\gamma & C_{mixsafe}=2X\\ \left(1-\alpha\right)\left(t_i-m\epsilon\right)+\frac{p}{2}+2m\gamma & C_{mixsafe}=X\\ 1-\left(t_i-m\epsilon\right)-p-m\gamma & C_{mixsafe}=0\end{cases} \tag{A.11}$$

When the GP's first investment failed, $c_1=0$; ensuring that the GP can raise a new fund following $c_2=2X$ requires:

$$t+\frac{\Delta t_g}{2}\leq\frac{1+\left(1+m\right)\epsilon}{2}-\frac{\left(\alpha+\frac{1}{2}\right)}{2\alpha}p-\frac{\left(\alpha-m\right)}{2\alpha}\gamma \tag{A.12}$$

Ensuring that following $c_2=X$ investors are indifferent between investing in the current GP, and a new GP drawn from the population, requires that the following hold:

$$t+\frac{\Delta t_g}{2}=\frac{1+\left(1+m\right)\epsilon}{2}-\frac{\left(\frac{3}{2}-\alpha\right)}{2\left(1-\alpha\right)}p-\frac{\left(2m+1-\alpha\right)}{2\left(1-\alpha\right)}\gamma \tag{A.13}$$

So long as ϵ is rather small, Eq. A.13 is decreasing in m, so that for a given α the region where a safe/standard mixed strategy is feasible lies from the result of Eq. A.13 at $m=1$, to an upper boundary where $m=0$, or Eq. A.12

binds. To when Eq. A.12 binds we set the right hand side of Eq. A.12 and Eq. A.13 equal, yielding a minimum threshold for m of:

$$\underline{m}^{\text{safe/std}} = \max\left(0, \frac{p\left(\frac{1}{2}-\alpha\right)}{\gamma\left(1+\alpha\right)}\right) \tag{A.14}$$

This results in the following region where a mixed strategy consisting of the safe and standard investment is feasible:

$$\frac{1+\epsilon}{2} - \frac{p+2\gamma}{2\left(1-\alpha\right)} \leq t + \frac{\Delta t_g}{2} \leq \frac{1+\underline{m}^{\text{safe/std}}\epsilon}{2} - \frac{p+2\underline{m}^{\text{safe/std}}\gamma}{2\left(1-\alpha\right)} \tag{A.15}$$

Following the same arguments it can be shown that the feasible region for a mixed strategy consisting of the risky and standard investment is given by:

$$\overline{m}^{\text{risk/std}} = \min\left(1, \frac{p\left(\alpha-\frac{1}{2}\right)}{\gamma\left(1+\alpha\right)}\right) \tag{A.16}$$

$$\frac{1+\epsilon}{2} - \frac{\frac{3}{2}-\alpha}{2\left(1-\alpha\right)}p - \frac{\gamma}{2} \leq t + \frac{\Delta t_g}{2} \leq \frac{1+\overline{m}^{\text{risk/std}}\epsilon}{2} - \frac{\frac{3}{2}-\alpha}{2\left(1-\alpha\right)}p - \frac{1-\alpha-2\overline{m}^{\text{risk/std}}}{2\left(1-\alpha\right)}\gamma \tag{A.17}$$

The feasible regions for mixed strategies, as well as those for pure strategies, are plotted on Figure 2.3.

Appendix B

Extended Model Solution

The model solution is a Nash equilibrium which includes an explicit compensation function in addition to the GP's investment choices and LP's follow-on funding decisions considered in the base model. Results from the extended model focus on the GP's compensation function when agents use explicit contracts to return to the first-best equilibrium in which the standard investment is chosen at each period.

B.1 Claim 1

Claim 1, given in the text, suggests the explicit compensation function can be written without loss of generality in terms of a flat management fee, $A \geq 0$, and a performance sensitive portion.

$$\text{GP Explicit Compensation} = A + W_{gp}\left[C_1 + C_2\right] \tag{B.1}$$

This follows trivially from the limited liability and monotonicity constraint. Suppose the total compensation of the GP is given by a function

$Comp\,[C_1 + C_2]$. Define:

$$A = Comp[0] \tag{B.2}$$

$$W_{gp}\,[C_1 + C_2] = Comp\,[C_1 + C_2] - Comp[0] \tag{B.3}$$

$A \geq 0$ by the limited liability constraint on $Comp\,[C_1 + C_2]$, and the monotonicity constraint is preserved in $W_{gp}\,[C_1 + C_2]$.

B.2 Result 3

Proof. For the compensation function to result in the efficient equilibrium, at each node the expected payoff to the GP for selecting the standard investment, must be superior to the payoff from both the risky investment and the safe investment. The following list gives the inventive compatibility constraints at each node. The first constraint in each pair ensures that the standard investment is preferred to the safe investment. The second constraint in each pair ensures that the standard investment is preferred to the risky investment.

Incentive Compatibility Constraints

Following $C_1 = 2X$:

$$(\gamma + \alpha\epsilon)\,W_{gp}\,[4X] + (-2\gamma + (1-\alpha)\,\epsilon)\,W_{gp}\,[3X] + (\gamma - \epsilon)\,W_{gp}\,[2X] \geq 0 \tag{B.4}$$

$$(-\gamma + \alpha\epsilon)\,W_{gp}\,[4X] + (2\gamma + (1-\alpha)\,\epsilon)\,W_{gp}\,[3X] + (-\gamma - \epsilon)\,W_{gp}\,[2X] \geq 0 \tag{B.5}$$

Following $C_1 = X$:

$$(\gamma + \alpha\epsilon)\,W_{gp}\,[3X] + (-2\gamma + (1-\alpha)\,\epsilon)\,W_{gp}\,[2X] + (\gamma - \epsilon)\,W_{gp}\,[X] \geq 0 \tag{B.6}$$

$$(-\gamma+\alpha\epsilon)\,W_{gp}\,[3X]+(2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[2X]+(-\gamma-\epsilon)\,W_{gp}\,[X]\geq 0 \quad \text{(B.7)}$$

Following $C_1 = 0$:

$$(\gamma+\alpha\epsilon)\,W_{gp}\,[2X]+(-2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[X]+(-\gamma+\epsilon)\,F\geq 0 \quad \text{(B.8)}$$

$$(-\gamma+\alpha\epsilon)\,W_{gp}\,[2X]+(2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[X]+(\gamma+\epsilon)\,F\geq 0 \quad \text{(B.9)}$$

In Period 1:

$$\begin{aligned}&\left[\alpha\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\{(\gamma+\alpha\epsilon)\,W_{gp}\,[4X]+(-2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[3X]+(\gamma-\epsilon)\,W_{gp}\,[2X]\}\\&+\left[(1-\alpha)\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\{(\gamma+\alpha\epsilon)\,W_{gp}\,[3X]+(-2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[2X]+(\gamma-\epsilon)\,W_{gp}\,[X]\}\\&+\left[1-t-\frac{\Delta t_g}{2}-p\right]\{(\gamma+\alpha\epsilon)\,W_{gp}\,[2X]+(-2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[X]+(-\gamma+\epsilon)\,F\}\\&\geq 0 \quad \text{(B.10)}\end{aligned}$$

$$\begin{aligned}&\left[\alpha\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\{(-\gamma+\alpha\epsilon)\,W_{gp}\,[4X]+(2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[3X]+(-\gamma-\epsilon)\,W_{gp}\,[2X]\}\\&+\left[(1-\alpha)\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\{(-\gamma+\alpha\epsilon)\,W_{gp}\,[3X]+(2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[2X]+(-\gamma-\epsilon)\,W_{gp}\,[X]\}\\&+\left[1-t-\frac{\Delta t_g}{2}-p\right]\{(-\gamma+\alpha\epsilon)\,W_{gp}\,[2X]+(2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}\,[X]+(\gamma+\epsilon)\,F\}\\&\geq 0 \quad \text{(B.11)}\end{aligned}$$

Note that the first period constraints, B.10 and B.13 are redundant, as they are just a linear combination of the second period constraints.

The solution is also constrained by the typical investor rationality constraint, requiring LP's to receive expected cash flows which are greater or equal to their investment of $2I$:

$$
\begin{aligned}
&\left\{\left(\frac{1}{2}\right)\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]^2+\left(\frac{1}{2}\right)\left[\alpha t+\frac{p}{2}\right]^2\right\}\left\{4X-W_{gp}\left[4X\right]\right\}\\
&+\left\{\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]+\left[\alpha\left(t\right)+\frac{p}{2}\right]\left[\left(1-\alpha\right)\left(t\right)+\frac{p}{2}\right]\right\}\left\{3X-W_{gp}\left[3X\right]\right\}\\
&+\Bigg(\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[1-t-\Delta t_g-p\right]+\left(\frac{1}{2}\right)\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]^2+\\
&+\left[\alpha\left(t\right)+\frac{p}{2}\right]\left[1-t-p\right]+\left(\frac{1}{2}\right)\left[\left(1-\alpha\right)\left(t\right)+\frac{p}{2}\right]^2\Bigg)\left\{2X-W_{gp}\left[2X\right]\right\}\\
&\left\{\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[1-t-\Delta t_g-p\right]+\left[\left(1-\alpha\right)t+\frac{p}{2}\right]\left[1-t-p\right]\right\}\left\{X-W_{gp}\left[X\right]\right\}\\
&\geq 2I+A
\end{aligned}
\tag{B.12}
$$

$$
\begin{aligned}
&\left\{\left(\frac{1}{2}\right)\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]^2+\left(\frac{1}{2}\right)\left[\alpha t+\frac{p}{2}\right]^2\right\}\left\{4X-W_{gp}\left[4X\right]\right\}\\
&+\left\{\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]+\left[\alpha\left(t\right)+\frac{p}{2}\right]\left[\left(1-\alpha\right)\left(t\right)+\frac{p}{2}\right]\right\}\left\{3X-W_{gp}\left[3X\right]\right\}\\
&+\Bigg(\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[1-t-\Delta t_g-p\right]+\left(\frac{1}{2}\right)\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]^2\\
&+\left[\alpha\left(t\right)+\frac{p}{2}\right]\left[1-t-p\right]+\left(\frac{1}{2}\right)\left[\left(1-\alpha\right)\left(t\right)+\frac{p}{2}\right]^2\Bigg)\left\{2X-W_{gp}\left[2X\right]\right\}\\
&+\left\{\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[1-t-\Delta t_g-p\right]+\left[\left(1-\alpha\right)t+\frac{p}{2}\right]\left[1-t-p\right]\right\}\left\{X-W_{gp}\left[X\right]\right\}\\
&\geq 2I+A
\end{aligned}
\tag{B.13}
$$

Result 3.A - Convexity of $W_{gp}\left[C_1+C_2\right]$

Constraint B.13 can be re-written as:

$$W_{gp}\left[2X\right]\geq\left[2-\frac{1+\alpha}{\gamma-\alpha\epsilon}\epsilon\right]W_{gp}\left[X\right]+\left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right)F \tag{B.14}$$

Taking $\lim_{\epsilon\to 0}$ yields:

$$W_{gp}\left[2X\right]\geq 2W_{gp}\left[X\right]+\left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right)F \tag{B.15}$$

w.l.o.g. $W_{gp}[0] = 0$, so that the above expression yields:

$$\frac{1}{2}W_{gp}[2X] + \frac{1}{2}W_{gp}[0] \geq W_{gp}[X] + \left(\frac{\gamma - \epsilon}{\gamma + \alpha\epsilon}\right)\frac{F}{2} \tag{B.16}$$

By continuity there must exist $\bar{\epsilon}$ such that $W_{gp}[C_1 + C_2]$ must be convex in the region $C_1 + C_2 \in [0,\, 2X]$ for $\epsilon \leq \bar{\epsilon}$. The following result will show that if the efficient equilibrium is implementable there exists a solution with $W_{gp}[X] = 0$, such that $W_{gp}[C_1 + C_2]$ is convex in the region $C_1 + C_2 \in [0,\, 2X]$.

Result 3.B - General Form of $W_{gp}[C_1 + C_2]$

First, I show that if there exists an equilibrium which implements the standard investment in each period, then there must exist and wage function which implements the efficient equilibrium and all the investment comparability constrains which require the standard investment to be preferred to the safe investment hold with equality (Constrains B.4, B.6, B.8).

w.l.o.g. following $C_1 = 2X$, Standard $\geq$ Safe constrain binds

First consider the case where exists a wage function A, $W_{gp}[C_1 + C_2]$ in which results in the GP selecting the standard investment in each period and where Contraint B.4 doesn't bind:

$$(\gamma + \alpha\epsilon)\, W_{gp}[4X] + (-2\gamma + (1-\alpha)\,\epsilon)\, W_{gp}[3X] + (\gamma - \epsilon)\, W_{gp}[2X] = S \geq 0 \tag{B.17}$$

Now consider an alternative compensation function:

$$W'_{gp}[C_1 + C_2] = \begin{cases} W_{gp}[C_1 + C_2] & C_1 + C_2 \leq 3X \\ W_{gp}[4X] - \frac{1}{\gamma + \alpha\epsilon}S & C_1 + C_2 = 4X \end{cases} \tag{B.18}$$

$$A' = A + \left\{ \left(\frac{1}{2}\right) \left[\alpha \left(t + \Delta t_g\right) + \frac{p}{2}\right]^2 + \left(\frac{1}{2}\right) \left[\alpha t + \frac{p}{2}\right]^2 \right\} \left\{ \frac{1}{\gamma + \alpha\epsilon} S \right\} \tag{B.19}$$

The alternative compensation function clearly relaxes Constrain B.5, such that it must now be slack. By construction Contraint B.4 must bind, and the investor rationality constrain is unchanged. All other constrains are unnafacted by the change in $W_{gp}[4X]$, this A', $W'_{gp}[C_1 + C_2]$ must also implement the efficient equilibrium.

w.l.o.g. following $C_1 = X$, Standard $\geq$ Safe constrain binds

Now consider the case where there exists a wage function which implements the equilibrium wage function,A, $W_{gp}[C_1 + C_2]$ in which Constraint B.6 does not bind, such that

$$(\gamma + \alpha\epsilon) W_{gp}[3X] + (-2\gamma + (1-\alpha)\epsilon) W_{gp}[2X] + (\gamma - \epsilon) W_{gp}[X] = S \geq 0 \tag{B.20}$$

Now consider an alternative compensation function:

$$W'_{gp}[C_1 + C_2] = \begin{cases} W_{gp}[C_1 + C_2] & C_1 + C_2 \leq 2X \\ W_{gp}[3X] - \left(\frac{S}{\gamma+\alpha\epsilon}\right) & C_1 + C_2 = 3X \\ W_{gp}[4X] - \left(\frac{2\gamma+(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)\left(\frac{S}{\gamma+\alpha\epsilon}\right) & C_1 + C_2 = 4X \end{cases} \tag{B.21}$$

$$\begin{aligned} A' =& A + \left\{ \left(\frac{1}{2}\right) \left[\alpha \left(t + \Delta t_g\right) + \frac{p}{2}\right]^2 + \left(\frac{1}{2}\right) \left[\alpha t + \frac{p}{2}\right]^2 \right\} \left(\frac{2\gamma + (1-\alpha)\epsilon}{\gamma + \alpha\epsilon}\right) \left(\frac{S}{\gamma + \alpha\epsilon}\right) \\ &+ \left\{ \left[\alpha \left(t + \Delta t_g\right) + \frac{p}{2}\right] \left[(1-\alpha)\left(t + \Delta t_g\right) + \frac{p}{2}\right] + \left[\alpha (t) + \frac{p}{2}\right] \left[(1-\alpha)(t) + \frac{p}{2}\right] \right\} \left(\frac{S}{\gamma + \alpha\epsilon}\right) \end{aligned} \tag{B.22}$$

The alternative compensation function clearly relaxes Constrain B.7, such that it must now be slack. By construction Constraint B.6 must bind, and the investor rationality constrain is unchanged. Also by construction Constraint B.4 and Constraint B.5 remain unchanged. All other constrains are unnaffacted by the change in $W_{gp}[4X]$ and $W_{gp}[3X]$, thus A', $W'_{gp}[C_1+C_2]$ must also also implement the efficient equilibrium.

w.l.o.g. following $C_1 = 0$, Standard $\geq$ Safe constrain binds

Now consider the case where there exists a wage function which implements the equilibrium wage function,A, $W_{gp}[C_1+C_2]$ in which ConstraintB.8 does not bind, such that

$$(\gamma+\alpha\epsilon)\,W_{gp}[2X]+(-2\gamma+(1-\alpha)\,\epsilon)\,W_{gp}[X]+(-\gamma+\epsilon)\,F=S\geq 0 \quad \text{(B.23)}$$

Now consider an alternative compensation function:

$$W'_{gp}[C_1+C_2]=\begin{cases} W_{gp}[C_1+C_2] & C_1+C_2\leq X\\ W_{gp}[2X]-\left(\frac{S}{\gamma+\alpha\epsilon}\right) & C_1+C_2=2X\\ W_{gp}[3X]-\left(\frac{2\gamma+(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)\left(\frac{S}{\gamma+\alpha\epsilon}\right) & C_1+C_2=3X\\ W_{gp}[4X]-\left[\frac{(2\gamma+(1-\alpha)\epsilon)^2}{\gamma+\alpha\epsilon}-(\gamma-\epsilon)\right]\left(\frac{S}{(\gamma+\alpha\epsilon)^2}\right) & C_1+C_2=4X \end{cases} \quad \text{(B.24)}$$

$$\begin{aligned} A' =&A+\left\{\left(\frac{1}{2}\right)\left[\alpha\,(t+\Delta t_g)+\frac{p}{2}\right]^2+\left(\frac{1}{2}\right)\left[\alpha t+\frac{p}{2}\right]^2\right\}\left[\frac{(2\gamma+(1-\alpha)\,\epsilon)^2}{\gamma+\alpha\epsilon}-(\gamma-\epsilon)\right]\left(\frac{S}{(\gamma+\alpha\epsilon)^2}\right)\\ &+\Bigg(\left[\alpha\,(t+\Delta t_g)+\frac{p}{2}\right]\left[(1-\alpha)\,(t+\Delta t_g)+\frac{p}{2}\right]\\ &+\left[\alpha\,(t)+\frac{p}{2}\right]\left[(1-\alpha)\,(t)+\frac{p}{2}\right]\Bigg)\left(\frac{2\gamma+(1-\alpha)\,\epsilon}{\gamma+\alpha\epsilon}\right)\left(\frac{S}{\gamma+\alpha\epsilon}\right)\\ &+\Bigg(\left[\alpha\,(t+\Delta t_g)+\frac{p}{2}\right][1-t-\Delta t_g-p]+\left(\frac{1}{2}\right)\left[(1-\alpha)\,(t+\Delta t_g)+\frac{p}{2}\right]^2\\ &+\left[\alpha\,(t)+\frac{p}{2}\right][1-t-p]+\left(\frac{1}{2}\right)\left[(1-\alpha)\,(t)+\frac{p}{2}\right]^2\Bigg)\left(\frac{S}{\gamma+\alpha\epsilon}\right) \end{aligned} \quad \text{(B.25)}$$

The alternative compensation function clearly relaxes Constrain B.9, such that it must now be slack. By construction Constraint B.8 must bind, and the investor rationality constrain is unchanged. Also by construction Constraint B.4, Constraint B.5, Constraint B.6 and Constraint B.7 remain unchanged. Thus A', $W'_{gp}[C_1 + C_2]$ must also also implement the efficient equilibrium.

Using the result above, the following shows that if there exists an compensation function which implements the efficient equilibrium, then there exists an alternative compensation function in the form given in Result 3 B which also implements the efficient equilibrium.

First, I show that $W_{gp}[X] = 0$ w.l.o.g. Consider the case where there exists a wage function which implements the equilibrium wage function,A, $W_{gp}[C_1 + C_2]$ in which $W_{gp}[X] > 0$. Note that the results above demonstrate that we can assume without loss of generality that the constraints which ensure the GP prefers the standard investment all bind (B.4, B.6 and B.8).

Now consider an alternative compensation function:

$$W'_{gp}[C_1 + C_2] = \begin{cases} 0 & C_1 + C_2 \leq X \\ W_{gp}[2X] - \left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right) W_{gp}[X] & C_1 + C_2 = 2X \\ W_{gp}[3X] - \left[\frac{(2\gamma+(1-\alpha)\epsilon)^2}{\gamma+\alpha\epsilon} - (\gamma-\epsilon)\right]\left(\frac{W_{gp}[X]}{(\gamma+\alpha\epsilon)}\right) & C_1 + C_2 = 3X \\ W_{gp}[4X] - \left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)^3 W_{gp}[X] & C_1 + C_2 = 4X \end{cases} \tag{B.26}$$

$$\begin{aligned} A' =& A + \left\{\left(\frac{1}{2}\right)\left[\alpha(t+\Delta t_g) + \frac{p}{2}\right]^2 + \left(\frac{1}{2}\right)\left[\alpha t + \frac{p}{2}\right]^2\right\}\left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)^3 W_{gp}[X] \\ &+ \Bigg(\left[\alpha(t+\Delta t_g) + \frac{p}{2}\right]\left[(1-\alpha)(t+\Delta t_g) + \frac{p}{2}\right] \\ &+ \left[\alpha(t) + \frac{p}{2}\right]\left[(1-\alpha)(t) + \frac{p}{2}\right]\Bigg)\left(\frac{2\gamma+(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)\left[\frac{(2\gamma+(1-\alpha)\epsilon)^2}{\gamma+\alpha\epsilon} - (\gamma-\epsilon)\right]\left(\frac{W_{gp}[X]}{(\gamma+\alpha\epsilon)}\right) \\ &+ \Bigg(\left[\alpha(t+\Delta t_g) + \frac{p}{2}\right][1-t-\Delta t_g - p] + \left(\frac{1}{2}\right)\left[(1-\alpha)(t+\Delta t_g) + \frac{p}{2}\right]^2 \\ &+ \left[\alpha(t) + \frac{p}{2}\right][1-t-p] + \left(\frac{1}{2}\right)\left[(1-\alpha)(t) + \frac{p}{2}\right]^2\Bigg)\left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right) W_{gp}[X] \\ &+ \left\{\left[(1-\alpha)(t+\Delta t_g) + \frac{p}{2}\right][1-t-\Delta t_g - p] + \left[(1-\alpha)t + \frac{p}{2}\right][1-t-p]\right\} W_{gp}[X] \end{aligned} \tag{B.27}$$

The alternative compensation function is bound by the GPs limited liability constrains which requires $W_{gp}[X] \geq 0$.

Combing the two results, if $W_{gp}[X] = 0$, and , it follows that:

$$W_{GP}[2X] = \left(\frac{\gamma - \epsilon}{\gamma + \alpha\epsilon}\right) F \tag{B.28}$$

As constraints B.6 and B.4 also hold with equality yields the entire functional form:

$$W_{GP}[C_1 + C_2] = \begin{cases} 0 & \text{if } C_1 + C_2 \leq X \\ \left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right) F & \text{if } C_1 + C_2 = 2X \\ \left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)\left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right) F & \text{if } C_1 + C_2 = 3X \\ \left[\left(\frac{2\gamma-(1-\alpha)\epsilon}{\gamma+\alpha\epsilon}\right)^2 - \left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right)\right]\left(\frac{\gamma-\epsilon}{\gamma+\alpha\epsilon}\right) F & \text{if } C_1 + C_2 = 4X \end{cases} \tag{B.29}$$

Convexity Result

Note that the resulting function is convex over $C_1 + C_2 \in \{0, 2X\}$

$$\left(\frac{1}{2}\right) W_{gp}[2X] + \left(\frac{1}{2}\right) W_{gp}[0] = \left(\frac{1}{2}\right)\left(\frac{\gamma - \epsilon}{\gamma + \alpha\epsilon}\right) F \geq W_{gp}[X] = 0 \tag{B.30}$$

Thus if the efficient equilibrium is implementable, there exists a compensation function which is convex over $C_1 + C_2 \in \{0, 2X\}$, which will implement the efficient equilibrium.

□

B.3 Result 4

Proof. As with the previous result, the achieving a first-best equilibrium requires a pair of incentive computability constraints at each node. The constraints are identical to the previous case following $C_1 = 2X$, $C_1 = X$, but following $C_1 = 0$ the GP will only raise a new fund if he achieves $C_2 = 2X$:

Incentive Compatibility Constraints

Following $C_1 = 2X$:

$$(\gamma + \alpha\epsilon) W_{gp}[4X] + (-2\gamma + (1-\alpha)\epsilon) W_{gp}[3X] + (\gamma - \epsilon) W_{gp}[2X] \geq 0 \quad \text{(B.31)}$$

$$(-\gamma + \alpha\epsilon) W_{gp}[4X] + (2\gamma + (1-\alpha)\epsilon) W_{gp}[3X] + (-\gamma - \epsilon) W_{gp}[2X] \geq 0 \quad \text{(B.32)}$$

Following $C_1 = X$:

$$(\gamma + \alpha\epsilon) W_{gp}[3X] + (-2\gamma + (1-\alpha)\epsilon) W_{gp}[2X] + (\gamma - \epsilon) W_{gp}[X] \geq 0 \quad \text{(B.33)}$$

$$(-\gamma + \alpha\epsilon) W_{gp}[3X] + (2\gamma + (1-\alpha)\epsilon) W_{gp}[2X] + (-\gamma - \epsilon) W_{gp}[X] \geq 0 \quad \text{(B.34)}$$

Following $C_1 = 0$:

$$(\gamma + \alpha\epsilon) W_{gp}[2X] + (-2\gamma + (1-\alpha)\epsilon) W_{gp}[X] - (\gamma - \epsilon) F \geq 0 \quad \text{(B.35)}$$

$$(-\gamma + \alpha\epsilon) W_{gp}[2X] + (2\gamma + (1-\alpha)\epsilon) W_{gp}[X] - (\gamma - \epsilon) F \geq 0 \quad \text{(B.36)}$$

In Period 1:

$$
\begin{aligned}
&\left[\alpha\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\left\{\left(\gamma+\alpha\epsilon\right)W_{gp}\left[4X\right]+\left(-2\gamma+\left(1-\alpha\right)\epsilon\right)W_{gp}\left[3X\right]+\left(\gamma-\epsilon\right)W_{gp}\left[2X\right]\right\}\\
&+\left[\left(1-\alpha\right)\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\left\{\left(\gamma+\alpha\epsilon\right)W_{gp}\left[3X\right]+\left(-2\gamma+\left(1-\alpha\right)\epsilon\right)W_{gp}\left[2X\right]+\left(\gamma-\epsilon\right)W_{gp}\left[X\right]\right\}\\
&+\left[1-t-\frac{\Delta t_g}{2}-p\right]\left\{\left(\gamma+\alpha\epsilon\right)W_{gp}\left[2X\right]+\left(-2\gamma+\left(1-\alpha\right)\epsilon\right)W_{gp}\left[X\right]+\left(-\gamma+\epsilon\right)F\right\}\\
&+\left[\left(1-\alpha\right)\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\left(\gamma+\epsilon\right)F \qquad \geq 0
\end{aligned}
\tag{B.37}
$$

$$
\begin{aligned}
&\left[\alpha\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\left\{\left(-\gamma+\alpha\epsilon\right)W_{gp}\left[4X\right]+\left(2\gamma+\left(1-\alpha\right)\epsilon\right)W_{gp}\left[3X\right]+\left(-\gamma-\epsilon\right)W_{gp}\left[2X\right]\right\}\\
&+\left[\left(1-\alpha\right)\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\left\{\left(-\gamma+\alpha\epsilon\right)W_{gp}\left[3X\right]+\left(2\gamma+\left(1-\alpha\right)\epsilon\right)W_{gp}\left[2X\right]+\left(-\gamma-\epsilon\right)W_{gp}\left[X\right]\right\}\\
&+\left[1-t-\frac{\Delta t_g}{2}-p\right]\left\{\left(-\gamma+\alpha\epsilon\right)W_{gp}\left[2X\right]+\left(2\gamma+\left(1-\alpha\right)\epsilon\right)W_{gp}\left[X\right]+\left(\gamma+\epsilon\right)F\right\}\\
&-\left[\left(1-\alpha\right)\left(t+\frac{\Delta t_g}{2}\right)+\frac{p}{2}\right]\left(\gamma+\epsilon\right)F \qquad \geq 0
\end{aligned}
\tag{B.38}
$$

Note that the first period constraints, B.37 and B.38 are *not* redundant, as they were in the previous case. The solution is also constrained by the typical investor rationality constraint, requiring LP's to receive expected cash flows which are greater or equal to their investment of $2I$:

$$\left\{\left(\frac{1}{2}\right)\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]^2+\left(\frac{1}{2}\right)\left[\alpha t+\frac{p}{2}\right]^2\right\}\left\{4X-W_{gp}\left[4X\right]\right\}$$
$$+\left\{\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]+\left[\alpha\left(t\right)+\frac{p}{2}\right]\left[\left(1-\alpha\right)\left(t\right)+\frac{p}{2}\right]\right\}\left\{3X-W_{gp}\left[3X\right]\right\}$$
$$+\Bigg(\left[\alpha\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[1-t-\Delta t_g-p\right]+\left(\frac{1}{2}\right)\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]^2+$$
$$+\left[\alpha\left(t\right)+\frac{p}{2}\right]\left[1-t-p\right]+\left(\frac{1}{2}\right)\left[\left(1-\alpha\right)\left(t\right)+\frac{p}{2}\right]^2\Bigg)\left\{2X-W_{gp}\left[2X\right]\right\}$$
$$\left\{\left[\left(1-\alpha\right)\left(t+\Delta t_g\right)+\frac{p}{2}\right]\left[1-t-\Delta t_g-p\right]+\left[\left(1-\alpha\right)t+\frac{p}{2}\right]\left[1-t-p\right]\right\}\left\{X-W_{gp}\left[X\right]\right\}$$
$$\geq 2I+A \tag{B.39}$$

Result 4.A - Concavity of $W_{gp}\left[C_1+C_2\right]$

Constraint B.43 can be re-arranged in the following form:

$$W_{gp}\left[2X\right]\leq\left[2-\frac{1+\alpha}{\gamma-\alpha\epsilon}\epsilon\right]W_{gp}\left[X\right]-F \tag{B.40}$$

Taking $\lim_{\epsilon\to+0}$ yields:

$$W_{gp}\left[2X\right]\leq 2W_{gp}\left[X\right]-F \tag{B.41}$$

$W_{gp}\left[0\right]=0$, so that the above expression yields:

$$\frac{1}{2}W_{gp}\left[2X\right]+\frac{1}{2}W_{gp}\left[0\right]\leq W_{gp}\left[X\right]-\frac{F}{2} \tag{B.42}$$

By continuity $W_{gp}\left[C_1+C_2\right]$ must be concave in the region $C_1+C_2\in\left[0,\,2X\right]$ for $\epsilon\leq\bar{\epsilon}$.

Result 4.B - Minimum value of $\boldsymbol{W_{gp}[X]}$

Re-arranging Constraint B.43, and applying the monotonicity constraint that $W_{gp}[2X] \geq W_{gp}[X]$ leads to :

$$(2\gamma + (1-\alpha)\epsilon) W_{gp}[X] \geq (\gamma - \alpha\epsilon) W_{gp}[2X] + (\gamma - \epsilon) F \tag{B.43}$$

$$\geq (\gamma - \alpha\epsilon) W_{gp}[X] + (\gamma - \epsilon) F \tag{B.44}$$

$$W_{gp}[X] \geq \frac{\gamma - \alpha\epsilon}{\gamma + \epsilon} F \tag{B.45}$$

□

Appendix C

Maximum Likelihood Estimation

This appendix describes the likelihood equations used in Section 3.3.1 to estimate parametric equations using the information from each individual portfolio company investment. Each observations is the outcome of a single portfolio company investment governed by the following model:

$$MIRR_{i,j} = \max\left[-100\% \ , \ \beta_0 + \beta_1 \cdot IRR_{NASDAQ} + \nu_t + \alpha_i^{mean} + \epsilon_{i,j}\right] \quad \text{(C.1)}$$

$$\epsilon_{i,j} \sim \mathcal{N}(0, \sigma_{i,j}^2) \quad \text{(C.2)}$$

$$\sigma_{i,j}^2 = e^{\phi_0 + \phi_1 \cdot \sigma_{NASDAQ}^2 + \delta X_{i,j} + \alpha_i^{var}} \quad \text{(C.3)}$$

Eq. C.1 describes the observed return as being a truncated at -100%, and normally distributed around a mean which is exponentially related to a linear combination of GP and market characteristics at the time the investment is made. The variance of the error term, $\sigma_{i,j}^2$, is treated as a latent variable which is determined by Eq. C.3. Taking logs of the normal distribution, the resulting log likelihood for each observation is given by:

$$\ln \ell\left(\beta, \gamma, \nu_t, \alpha_i, \phi, \delta \mid MIRR_{i,j}\right) =$$

$$\begin{cases} -\frac{1}{2} ln 2\pi - \frac{\sigma_{i,j}^2}{2} - \frac{\left(MIRR_{i,j} - \beta_0 + \beta_1 \cdot IRR_{NASDAQ} + \gamma \cdot \sigma_{i,j}^2 + \nu_t + \alpha_i^{mean}\right)^2}{2} e^{-\sigma_{i,j}^2}, & \text{if } MIRR_{i,j} > -100\% \\ ln\Phi\left[\frac{-100\% - \left(\beta_0 + \beta_1 \cdot IRR_{NASDAQ} + \gamma \cdot \sigma_{i,j}^2 + \nu_t + \alpha_i^{mean}\right)}{e^{\frac{\left(\sigma_{i,j}^2\right)}{2}}}\right], & \text{if } MIRR_{i,j} = -100\% \end{cases} \tag{C.4}$$

After substituting Eq. C.3 for $\sigma_{i,j}^2$, parameter estimate are determined by maximizing the following sum of Eq. C.4 over all portfolio company observations:

$$\ln L\left(\beta, \gamma, \nu, \alpha, \phi, \delta \mid ...\right) = \sum_{i,j} \ln \ell\left(\beta, \gamma, \nu_t, \alpha_i, \phi, \delta \mid MIRR_{i,j}\right) \tag{C.5}$$

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