When Silicon Valley Meets Wall Street: An Economic Model of Financial Engineering

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Abstract

We study a model à la Kyle (1985) in which a trading firm hires a financial engineer to develop proprietary technology for an informational edge. The model features self-fulfilling multiple equilibria in technology adoption. In one equilibrium, excessive and inefficient innovation arises due to technological opacity and misaligned incentives between the firm and the engineer. The model links financial market outcomes to the labor market for financial engineers, demonstrating distinct comparative statics across equilibria. It offers a novel empirical strategy to detect inefficiencies in financial technology investment and reconciles mixed evidence on the impact of labor market interventions through the lens of financial market reactions.

JEL classification: G11, G12, G14, G23

Key words: informed trading, engineer, financial technology, opacity, labor market

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1 Introduction

Financial markets have long been shaped by technological investment, from early computer-based trading in the 1960s to the recent AI-powered trading technology (Allen and Gale, 1994; Tufano, 2003). Each wave of innovation has not only driven competition among trading firms but also fueled demand for engineers, making tech talent a critical input in financial innovation.[1] Despite this, existing research largely focuses on traders' information and speed acquisition as a proxy for technology investments, overlooking the distinct role of engineers, potential incentive misalignment between engineers and trading firms, and the frictions in their labor market. This gap raises key questions: How do constraints in hiring and retaining tech talent in the labor market affect financial market quality? When and for what types of technology does financial technology investment become excessive?[2]

We address these issues by embedding a labor market model for financial engineers into the static Kyle (1985) framework. In the trading stage, a single informed trader (trading firm) trades a risky asset with market makers after observing an imperfect signal about the asset's fundamentals. Instead of directly acquiring the signal, the firm hires an engineer who develops technology that generates such a signal, with higher-quality technology yielding more accurate information. The engineer improves technology through costly investments, and his compensation is determined through Nash bargaining with the trading firm (Acemoglu and Pischke, 1999). The engineer's wage endogenously includes a performance-based fee, which encourages her to enhance technology quality to boost trading profits, and a fixed component (e.g., a signing bonus). We assume that the firm and the engineer incur different marginal costs: while the firm's maintenance cost is shared with the engineer through the wage transfer, the engineer alone incurs the technology development cost.

[1] According to *Business Insider*, for example, financial institutions, including banks, hedge funds, and private equity firms, are poaching talent from AI companies amid AI transformations ("AI fever is triggering a new hunt for tech talent on Wall Street," April 2024).

[2] Michael Lewis's *Flash Boys* has highlighted concerns about excessive investments in the context of high-frequency trading (HFT).

This cost differential creates a misalignment of incentives. When severe, the engineer exerts just enough effort to avoid termination, deliberately limiting technology quality to keep the firm at a break-even point.

We distinguish between two types of financial technology: *transparent* technology, where market makers can observe its quality, and *opaque* technology, where quality remains hidden.[3] Transparency leads to a unique equilibrium: while higher-quality technology increases adverse selection and the price impact, it directly enhances the trading firm's informational advantage, resulting in a positive net impact on the trading profit. Weighing against the exogenous cost of technology development, the equilibrium level of technology investment is uniquely determined. In contrast, opacity gives rise to multiple equilibria: one of these resembles the benchmark transparent equilibrium, while another features a far more massive technology investment, referred to as the "high-tech" equilibrium. In the high-tech equilibrium, the trading firm adopts more aggressive trading strategies and improves the price efficiency. However, the market becomes illiquid (i.e., the price impact is high), and the price is highly volatile. Moreover, we show that all market participants are worse off in the high-tech equilibrium compared to the benchmark, making it Pareto inefficient.

The key mechanism is the strategic complementarity between the engineer's incentive to improve technology quality and market makers' belief about it. Since technology quality is unobservable, market makers form a belief about it and adjust the price accordingly. If they believe that sophisticated technology has been developed and deployed, they set a high price impact. It reduces the trading profit and discourages the firm from hiring the engineer. To meet the hiring requirement, in turn, the engineer indeed makes massive technology investments and boosts trading profits up to the firm's break-even level, thereby reinforcing the high-tech equilibrium. The symmetric logic applies when mar-

[3]For example, infrastructure investments in HFT technology, such as building microwave towers or co-location systems, and open-source AI trading strategies (e.g., Liu, Yang, Gao, and Wang, 2021) are often observable from the outside. In contrast, as illustrated by *Wired* ("Algorithms Take Control of Wall Street," December 2018), most investments in proprietary trading algorithms are harder to observe externally.

ket makers believe that technology quality is at the benchmark level, supporting the coexistence of the benchmark "low-tech equilibrium" along with the high-tech one.

We interpret the self-fulfilling nature of multiple equilibria as *fragility* in technology investment.[4] Once the economy enters into the parameter regions of multiple equilibria, a mere shift in the market's belief about unobservable technology quality can trigger disproportionately large financial technology investments, leading to a highly volatile price and market illiquidity. Therefore, even small policy interventions intended to improve worker welfare, such as a modest increase in minimum wages, can backfire and unintentionally lead to the Pareto-inefficient high-tech equilibrium.

Our model shows that the engineer's relative advantages in the labor market induce equilibrium multiplicity. For instance, it occurs when labor mobility is high and the firm must incur substantial costs to retain the engineer, or when the engineer has structurally higher bargaining power. In such situations, wage transfers to the engineer tend to be large, and the firm's share decreases. It tightens the hiring requirement, and the strategic complementarity between the market's belief and the engineer's investment is more likely to kick in. Moreover, the engineer's income becomes increasingly dependent on the performance-based salary. As a result, her innovation decision becomes more sensitive to the asset price (i.e., the price impact) and thus to market makers' belief, further reinforcing the strategic complementarity.

A key feature of our model is that comparative statics differ sharply between the high-tech and low-tech equilibria. When the firm's surplus changes due to an exogenous shock, the engineer adjusts technology quality to restore the firm's break-even condition. In the high-tech equilibrium, where investment is already excessive, the firm's marginal utility is negative, and further quality improvements reduce the firm's surplus. In contrast, in the low-tech equilibrium, such improvements remain beneficial. This asymmetry causes the

[4]As in Greenwood and Thesmar (2011), fragility refers to an economic state which is vulnerable to non-fundamental shifts in model parameters, such as those caused by changes in market beliefs.

engineer's innovation to respond differently across the two equilibria, generating two key implications.

First, since the engineer's technology choice affects the asset's price and financial market quality, our model provides a testable prediction. Namely, observing how these market indicators respond to well-identified exogenous shocks can help distinguish whether financial technology investments are the consequence of the inefficient high-tech equilibrium. While prior literature, particularly in the context of high-frequency trading (e.g., Budish, Cramton, and Shim, 2015), has raised concerns about socially wasteful innovation, our model provides a framework to empirically separate efficient from inefficient investments. Second, the presence of multiple equilibria offers a theoretical rationale for the mixed empirical evidence surrounding the effects of labor market interventions on innovations (e.g., Werner, 2023; Lee, 2024). In our framework, seemingly similar interventions can have opposing effects on innovations and financial markets depending on the type of equilibrium.

Finally, we endogenize the transparency of financial technology by allowing the trading firm to choose between transparent and opaque technology. This extension aims to capture the real-world investment, where trading firms often obscure their technology innovations.[5] The trading firm faces a tradeoff. On one hand, opacity encourages the engineer to develop higher-quality technology. This is because the price impact is set following market makers' belief and is inelastic to the actual technology quality. The firm is better off by this improvement, as the engineer's choice of quality in the low-tech equilibrium tends to be insufficient from the firm's perspective, i.e., opaque technology helps mitigate the incentive misalignment. On the other hand, the opacity gives birth to multiple equilibria, one of which involves inefficiently large-scale innovation and lower firm utility. Due to the multiplicity of equilibria, the firm can enjoy the aforementioned benefit of opacity only if the low-tech equilibrium

[5] Legal disputes over proprietary trading algorithms highlight such an incentive, as reported by *The Wall Street Journal* ("Legal Suit Sheds Light on Secret Trading Technology," June 2015). Also, many high-frequency trading firms try to hide their technology purchases from rivals, suggesting the opacity of their technology investments (*The Wall Street Journal*: "Trading Tech Accelerates Toward Speed of Light," August 2016).

is realized. Consequently, the firm prefers opacity when the underlying labor-market conditions involve severe incentive misalignment, so that the benefit from resolving it dominates the risk of falling into the inefficient high-tech equilibrium.

Our study is closely related to the literature on information and speed acquisition in financial markets. Traditional models, such as Grossman and Stiglitz (1980) on information acquisition, and more recent works, such as Foucault, Kadan, and Kandel (2013), Foucault, Kozhan, and Tham (2017), and Huang and Yueshen (2021) on speed acquisition, focus on traders' incentives while abstracting away from the role of entities creating these advantages.[6] Within this framework, the issue of overinvestment in financial technology has been understood as a result of a prisoner's dilemma among trading firms, featuring strategic substitution (Biais, Foucault, and Moinas, 2015; Budish, Cramton, and Shim, 2015).[7] Our model shifts the focus to the strategic complementarity between engineers and the market, providing a novel framework to explain massive technology investments while relating the labor market conditions to financial technology development.

Clarifying the trade-off involved in opaque technology investment is another contribution of our paper. Existing theoretical works, such as Banerjee and Breon-Drish (2020), Xiong and Yang (2023), and Aoyagi (forthcoming), emphasize the so-called pricing effect, whereby the inelastic price response due to opacity induces more aggressive information acquisition. In Kyle-type models with a monopolistic informed trader, this effect is the sole channel that makes opacity globally optimal. To generate an endogenous cost of opacity and obtain transparent investment in equilibrium, other structures, such as

[6]The literature following Admati and Pfleiderer (1986, 1988, 1990) introduces an information seller but typically assumes a monopolistic seller who is endowed with information and offering take-it-or-leave-it contracts to traders. In contrast, our model explicitly incorporates their incentive misalignment, bargaining, and labor market frictions.

[7]An exception is the theoretical study by Veldkamp (2006), which models a frenzy of information acquisition driven by decreasing average costs of information production. Her result relies on the non-rival nature of information (the near-zero marginal cost of producing additional signals), a feature that does not extend to financial technologies that generate such signals.

competition among multiple informed traders, must be introduced. By contrast, our model shows that opacity can give rise to a new, belief-driven cost: it generates multiple self-fulfilling equilibria, allowing inefficient high-tech outcomes to emerge. This mechanism enables a shift between transparent and opaque technology within a unified framework, depending on the underlying parameter values.

A further contribution of this paper is to formally connect financial market structure with the labor market for financial engineers, allowing labor market shocks to have observable consequences in financial markets. While prior studies, such as Philippon (2010) and Philippon and Reshef (2012), have examined major shifts in the employment landscape of the financial sector and the allocation of human capital between finance and non-finance industries in the context of economic growth, to our knowledge, no existing work systematically links information frictions in market microstructure, innovation in financial technology, and the labor market for engineers in a unified theoretical framework. Our model fills this gap by endogenizing these interactions.

The rest of the paper proceeds as follows. Section 2 presents a baseline model with transparent technology and its equilibrium, and Section 3 introduces opaque technology. Section 4 endogenizes the transparency regime of the technology and discusses policy implications. The Appendix contains all proofs for the theoretical results.

2 Model

This section presents a baseline model with transparent technology. The model consists of two building blocks: a technology-development stage in $t = 0$ and a trading stage in $t = 1$. All players introduced below are risk-neutral, and all random variables are assumed to be independent of each other.

The trading stage is based on Kyle (1985), where a single trading firm trades a risky asset with competitive market makers and noise traders. The asset's payoff, δ, follows a normal distribution $\delta \sim N(\bar{\delta}, \sigma_\delta^2)$ and is realized in the end of $t = 1$. The firm would trade as an informed trader by participating in the labor market and hiring a financial engineer who develops information technology in $t = 0$. The technology delivers a noisy signal about δ at the beginning of $t = 1$, which is specified by

$$s = \delta + \epsilon, \tag{2.1}$$

where $\epsilon \sim N(0, \sigma_\epsilon^2)$ represents noise. We define the *quality* of the signal and the technology by the following variable:

$$\phi \equiv \frac{Var(\delta) - Var(\delta|s)}{Var(\delta)} = \frac{\sigma_\delta^2}{\sigma_\delta^2 + \sigma_\epsilon^2}. \tag{2.2}$$

ϕ measures how much uncertainty in δ is resolved by observing the signal and is directly related to the signal precision, σ_ϵ^{-2}, which is a control variable for the engineer as specified below.

Financial market. The trading stage is standard. The trading firm places a market order for x units of the asset to maximize its expected profit conditional on the signal value:

$$\pi(s) = \max_x \mathrm{E}[(\delta - p)x|s]. \tag{2.3}$$

p denotes the price of the asset and is set by market makers upon observing the order flow:

$$y = x + u, \tag{2.4}$$

where $u \sim N(0, \sigma_u^2)$ represents the market order from noise traders. As in the standard Kyle (1985) model, the order flow conveys information about δ to market makers, and competition among them leads to the semi-strong efficient price:

$$p = \mathrm{E}[\delta|y]. \tag{2.5}$$

Moreover, the firm incurs the maintenance cost of the technology, $c_F\phi$ with $c_F > 0$, in the process of receiving and trading on the signal. It could arise from the costs of applying the technology to practical market situations and the expenses of maintaining or updating the equipment. The cost is increasing in ϕ, reflecting the fact that more sophisticated technologies require a higher maintenance cost.[8] Incorporating the maintenance cost, the firm's unconditional net expected profit from trading on the technology is given by

$$R(\phi) = \mathrm{E}[\pi(s)] - c_F \phi. \tag{2.6}$$

This profit is allocated between the firm and the engineer through the labor market specified below.

Labor market. At the beginning of $t = 0$, the engineer develops the technology by controlling its quality ϕ.[9] We assume that the engineer incurs a non-pecuniary development cost $c_E \phi$ with $c_E > 0$, which can be thought of as the required input of effort or the cost to establish skill to become a qualified financial engineer. Throughout the model, ϕ is observable to the trading firm regardless of the transparency of technology, which is justified by direct communications between the engineer and the firm.

Upon observing ϕ, the firm and the engineer engage in negotiation to pin down the wage transfer, w.[10] To describe this process, we divide the first period into infinite sub-periods ($n = 0, 1, \cdots$), where each sub-period involves Nash bargaining with the following procedures.[11]

1. At the beginning of sub-period n, the information about asset's payoff δ

[8]The cost is assumed to be linear in ϕ to solve the model analytically. Numerical results support our main results as long as the cost is increasing in ϕ. The same argument applies to the development cost of technology introduced below.

[9]We assume that the engineer sets the quality of technology, and the firm uses it without modification. Alternatively, the engineer may determine the maximum achievable quality (ϕ_{max}), and the firm may adjust its utilization rate ($\phi \leq \phi_{max}$). With this setting, the equilibrium outcome remains unchanged, as the firm fully utilizes the technology at its maximum quality ($\phi = \phi_{max}$).

[10]This timing assumption is consistent with the labor economics literature (e.g., Acemoglu and Pischke, 1999) that characterizes a non-binding wage contract. It is supported by the fact that the quality of the technology is hard to verify from an outsider's perspective (e.g., a court) and is consistent with our model's agenda, which aims to analyze the implications of opacity in financial technology.

[11]The discussion below shows that the two parties reach an agreement in the first round of bargaining on the equilibrium path. Any subsequent bargaining and the firm's wait-and-see strategy do not occur and remain off-equilibrium paths.

remains unobservable with probability $\rho \in (0, 1)$, while it becomes public with the complementary probability, $1 - \rho$. If δ is revealed, the negotiation does not happen, and both parties earn zero profits. Otherwise, they move on to the next step.

2. The trading firm may set up a bargaining table by paying the hiring cost, ξ. It could arise from administrative and screening costs and represent hiring frictions. The firm may also "wait and see" by not paying ξ and forgoing the current negotiation opportunity. In the latter case, they proceed to period $n + 1$ and start over from step 1.

3. In the Nash bargaining stage, the engineer has bargaining power $\gamma \in (0, 1)$ so that wage w_n is determined by solving

$$w_n = \arg\max_w (R - w - z_{F,n})^{1-\gamma}(w - z_{E,n})^{\gamma}, \tag{2.7}$$

where $z_{F,n}$ and $z_{E,n}$ represent the outside options of the firm and the engineer, respectively. $z_{F,n}$ and $z_{E,n}$ are endogenously determined by assuming that they move on to step 1 of the next sub-period $(n + 1)$ if the negotiation fails.

A few comments are in order. Firstly, although we introduce parameter ρ to specify the arrival probability of news about δ, it can also be thought of as the *persistency* of technology: technology characterized by a high ρ decays slowly relative to the lifetime of information, meaning that it stays useful for longer periods. This interpretation is useful when we explore the impact of technology's durability on equilibrium outcomes.

Furthermore, we can consider a setting where multiple homogeneous firms operate in the labor market. In this case, if the negotiation in a given sub-period fails, the firm can retain the engineer by paying ξ; otherwise, it forgoes the employment opportunity and earns zero profit (due to the lack of the informational advantage). The engineer then randomly matches with a new firm and faces the same bargaining problem. Even under this setting, the conclusion remains unchanged because only the firm that ultimately hires the engineer gains exclusive access to the technology, acquires information, and acts as a monopolistic trader, earning R in the trading stage. Other firms, lacking informational advantage over market makers, do not trade in equilibrium (Kyle, 1985), leaving the trading stage unchanged.

2.1 Equilibrium in Financial Market

The model is solved by taking steps backward. We focus on the linear equilibrium in the trading stage, where the trading firm's market order takes the form of

$$x = \beta(s - \bar{\delta}). \tag{2.8}$$

Namely, the trading quantity is determined by the trading intensity, β, multiplied by the firm's informational advantage over market makers, $s - \bar{\delta}$.

Given the trading strategy (2.8), the semi-strong efficient price in (2.5) is computed by following the Gaussian filtering rule:

$$p = \bar{\delta} + \lambda y, \tag{2.9}$$

where

$$\lambda = \frac{\beta \sigma_\delta^2}{\beta^2 \frac{\sigma_\delta^2}{\phi} + \sigma_u^2}. \tag{2.10}$$

Coefficient λ represents the price impact of order flow and is determined by the (observed) technology quality, ϕ, and the trading intensity of the firm, β. The more aggressive the informed trading, the stronger the price impact the market makers charge to counteract the adverse selection cost. As a high λ induces a large adverse price reaction to changes in order flow, it represents an illiquid financial market.

Incorporating market makers' pricing strategy in (2.9), the trading firm maximizes its expected trading profits.

$$\max_x \mathrm{E}[(\delta - p)x|s] = \max_x \left(\mathrm{E}[\delta|s] - \bar{\delta} - \lambda x\right) x, \tag{2.11}$$

where the conditional expected payoff is $\mathrm{E}[\delta|s] = \bar{\delta} + \phi(s - \bar{\delta})$. The FOC of (2.11) yields the optimal market order,

$$x = \frac{\phi}{2\lambda}(s - \bar{\delta}), \tag{2.12}$$

suggesting that the expression in (2.8) is consistent with (2.12) when

$$\beta = \frac{\phi}{2\lambda}. \tag{2.13}$$

Equation (2.13) implies that the trading firm trades more aggressively when it has more sophisticated financial technology, while a high price impact discourages aggressive trading.

Lemma 2.1. *The trading-stage equilibrium with transparent technology is characterized by*

$$\beta = \frac{\sigma_u}{\sigma_\delta}\sqrt{\phi}, \tag{2.14}$$

$$\lambda = \frac{\sigma_\delta}{2\sigma_u}\sqrt{\phi}. \tag{2.15}$$

Proof. Solving equations (2.10) and (2.14) yields the result. □

Lemma 2.1 suggests that a higher quality technology provides a larger informational advantage to the firm and leads to more intensive trading. It exacerbates the adverse selection problem for market makers and results in a higher price impact.

The firm's ex-ante expected profit after the maintenance cost is computed by using Lemma 2.1:

$$R(\phi) = \frac{\sigma_\delta \sigma_u}{2}\sqrt{\phi} - c_F \phi. \tag{2.16}$$

The first term represents the gross trading profit and is monotonically increasing in ϕ: although a heightened λ erodes the firm's trading profit, it is more than offset by the positive effect of large informational advantages. Due to the maintenance cost of the technology, R draws a single-peaked curve regarding ϕ, with the profit-maximizing level being $\phi_F \equiv \left(\frac{\sigma_u \sigma_\delta}{4c_F}\right)^2$. Although ϕ_F maximizes the firm's net profit, the following analysis shows that the engineer does not choose this level due to incentive misalignment.

2.2 Equilibrium in Labor Market

Given the net trading profit, R, the firm and the engineer engage in negotiation to pin down the wage transfer. The n-th bargaining round solves the problem in (2.7) and yields

$$w_n = \gamma(R - z_{F,n}) + (1-\gamma)z_{E,n}. \tag{2.17}$$

The outside options are determined by the subsequent bargaining opportunities. Appendix A shows that, on the equilibrium path, both the firm and the engineer anticipate that the subsequent negotiation succeeds when computing the current outside options, as failing the future negotiations becomes increasingly costly due to the possible revelation of δ. Thus, the outside options are characterized by

$$z_{F,n} = \rho(R - w_{n+1} - \xi), \tag{2.18}$$

$$z_{E,n} = \rho w_{n+1}. \tag{2.19}$$

Namely, conditional on δ remaining non-public, the firm pays ξ to start the next bargaining, anticipating return R and payment w_{n+1}. Solving (2.17)-(2.19) derives the following recursive equation for $\{w_n\}_{n=0}^{\infty}$:

$$w_n = \gamma[(1-\rho)R + \rho\xi] + \rho w_{n+1}.$$

Imposing the transversality condition, $\lim_{n=\infty} \rho^n w_n = 0$, it pins down the equilibrium wage.

Lemma 2.2. *In the labor market equilibrium, the firm and the engineer agree on the following w at the first bargaining round.*

$$w \equiv w_0 = \gamma\left(\xi\frac{\rho}{1-\rho} + R\right). \tag{2.20}$$

The wage transfer to the engineer consists of the constant payment in the first term, $\gamma\xi\frac{\rho}{1-\rho}$, and the portion of the trading profit in the second term, γR. The constant term can be seen as the signing bonus and arises from the hiring cost of the trading firm, ξ, which exogenously lowers its outside option. An increase in ξ favors the engineer, as it becomes more costly for the firm to retain the engineer for subsequent bargaining. The fixed payment also increases when the engineer gains stronger bargaining power (γ), and the technology becomes more persistent (ρ), as both factors strengthen the bargaining advantages of the engineer. γ also determines the split of the trading profits R between the two parties, making the allocation to the engineer proportional to γ.

2.3 Equilibrium Technology Investment

Hiring condition. Anticipating the equilibrium wage in (2.20), the trading firm at the beginning of $t = 0$ expects to obtain the following utility by engaging in the hiring process:

$$\begin{aligned} U_F &= R(\phi) - w - \xi \\ &= (1-\gamma)R(\phi) - \left(1 + \frac{\rho\gamma}{1-\rho}\right)\xi. \end{aligned} \tag{2.21}$$

The firm is willing to participate in the labor market if $U_F \geq 0$, which is referred to as the *hiring condition.* Otherwise, it fires the engineer and stays inactive in the trading stage. By substituting R in (2.16) and denoting $\kappa \equiv \frac{1-\rho+\rho\gamma}{(1-\rho)(1-\gamma)}$, the hiring condition is summarized by

$$\phi_L \leq \phi \leq \phi_H, \tag{2.22}$$

where $\{\phi_L, \phi_H\}$ are the solutions to $U_F = 0$ and given by

$$\phi_j = \begin{cases} \frac{\sigma_u^2\sigma_\delta^2}{16}\left(1 - \sqrt{1 - \frac{16c_F\kappa\xi}{\sigma_u^2\sigma_\delta^2}}\right)^2 & \text{for } j = L, \\ \frac{\sigma_u^2\sigma_\delta^2}{16}\left(1 + \sqrt{1 - \frac{16c_F\kappa\xi}{\sigma_u^2\sigma_\delta^2}}\right)^2 & \text{for } j = H. \end{cases} \tag{2.23}$$

Note that they exist if and only if

$$\xi \leq \bar{\xi} \equiv \frac{(1-\gamma)\sigma_u^2\sigma_\delta^2}{16c_F\kappa}. \tag{2.24}$$

In what follows, we focus on the parameters that satisfy (2.24), while the ultimate equilibrium characterization considers the entire set of parameters.[12]

Technology development. The engineer's optimization problem is described by

$$\max_{\phi\in[\phi_L,\phi_H]} U_E \equiv \gamma\left(R+\frac{\rho}{1-\rho}\xi\right)-c_E\phi, \tag{2.25}$$

where the first term represents the equilibrium wage in (2.20), and the hiring condition is summarized by $\phi \in [\phi_L, \phi_H]$. She never violates the hiring condition, as she loses her wage income and always experiences negative utility due to the development cost. Incorporating R in equation (2.16), the engineer's objective function is rewritten as a single-peaked curve with respect to ϕ:

$$U_E \equiv \left[\gamma\left(\frac{\sigma_\delta\sigma_u}{2\sqrt{\phi}}-c_F\right)-c_E\right]\phi+\gamma\frac{\rho}{1-\rho}\xi. \tag{2.26}$$

Proposition 2.1. *(i) If $\xi > \bar{\xi}$, there is no equilibrium. Otherwise, a unique equilibrium exists with*

$$\phi^* = \begin{cases} \phi_E \equiv \left(\frac{\gamma\sigma_u\sigma_\delta}{4(c_E+\gamma c_F)}\right)^2 & \text{if } \xi \leq \xi_0, \\ \phi_L \equiv \left(\frac{\sigma_u\sigma_\delta}{4}\right)^2\left(1-\sqrt{1-\frac{16c_F\kappa\xi}{\sigma_u^2\sigma_\delta^2}}\right) & \text{if } \xi > \xi_0, \end{cases} \tag{2.27}$$

where

$$\xi_0 \equiv \frac{\sigma_u^2\sigma_\delta^2\gamma}{16\kappa}\frac{\gamma c_F+2c_E}{(\gamma c_F+c_E)^2}. \tag{2.28}$$

(ii) The equilibrium existence threshold, $\bar{\xi}$, is monotonically decreasing in γ and ρ.

(iii) The threshold, ξ_0, that separates the ϕ_E and ϕ_L equilibria draws a single-

[12] When (2.24) is violated, $U_F < 0$ for all $\phi \in [0,1]$, and equilibrium does not exist.

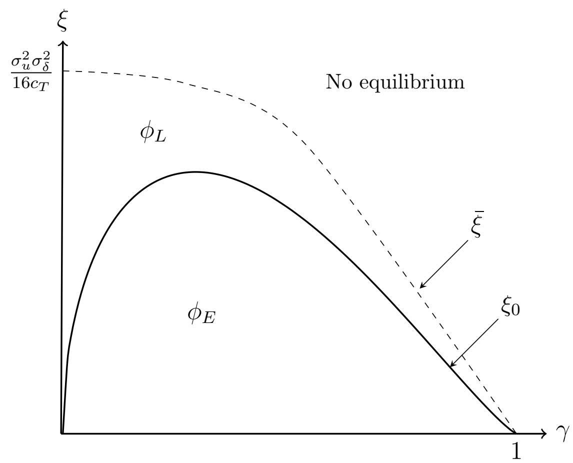


Figure 1: Equilibrium Technology Investment (Transparent)

Note: The figure characterizes the equilibrium technology investment in Proposition 2.1 by using ξ and γ, where the boundaries represent (2.24) and (2.28).

peaked curve against γ and is monotonically decreasing in ρ.

The cost differential is one of the factors that contribute to the incentive misalignment between the firm and the engineer: the maintenance cost, $c_F\phi$, is shared between the firm and the engineer through the wage transfer, whereas the engineer alone incurs the additional development cost, $c_E\phi$. Consequently, the engineer's (unconstrained) utility is maximized by ϕ_E in (2.27), but it falls short of the firm's profit-maximizing level ($\phi_E < \phi_F$).

Moreover, depending on the parameter values of the labor market, the engineer may choose ϕ_L, i.e., she withholds technology investment and lowers ϕ just to meet the hiring requirement.[13] Figure 1 illustrates the result by using the hiring cost (ξ) and the bargaining power of the engineer (γ). Firstly, no equilibrium exists when the hiring cost is too high ($\xi > \bar{\xi}$), as the firm would not hire the engineer, knowing it cannot recover its costs through trading. At intermediate hiring costs ($\xi_0 \leq \xi \leq \bar{\xi}$), the firm is willing to hire, but a strong incentive misalignment emerges: the firm, facing high ξ, enforces a strict hiring

[13] ϕ_H (the upper threshold of the hiring condition) does not constrain the engineer's choice, as the quality level at ϕ_H is too high from both players' perspectives, i.e., $\phi_E < \phi_H$ always holds.

condition, pushing the minimum requirement ϕ_L upward, while the engineer, relying more on a fixed salary than performance-based pay, has strong incentives to withhold costly investments. As a result, the engineer selects the lowest quality level that satisfies the hiring requirement, i.e., $\phi^* = \phi_L$. When the hiring cost becomes even lower ($\xi < \xi_0$), the share of the performance-based salary increases, and the incentive misalignment is mitigated. Consequently, the engineer's unconstrained optimality satisfies the hiring condition, leading to $\phi^* = \phi_E$. The impact of the persistency of technology (ρ) is analogous to that of ξ, as both parameters influence the equilibrium by changing the fixed component of the wage transfer (see equation [2.20]).

Finally, the engineer's bargaining power has ambiguous effects on ϕ^*, as represented by the non-monotonic reaction of ξ_0 to γ. On the one hand, a high γ increases the wage level (see [2.20]) and reduces the firm's share. It discourages the firm from hiring, and the minimum requirement (ϕ_L) increases. On the other hand, a large w diminishes the impact of the engineer-specific development cost, $c_E\phi$, in her optimization (see [2.25]), making her incentive more aligned with that of the firm. When γ is very small, the firm's profit share is sufficiently large, and the first channel is not significant compared to the second one. Consequently, an increase in γ (with ξ being fixed) tends to cause a switch from ϕ_L to ϕ_E. As γ becomes high, the first channel grows dominant, and a further increase in γ pushes the equilibrium back to ϕ_L, shaping ξ_0 into a hump-shaped curve.

2.4 Comparative Statics

Technology quality. The labor market conditions influence the equilibrium technology quality (ϕ^*) differently depending on whether the hiring condition is binding.

Corollary 2.1. *(i) ϕ^* is increasing in the engineer's bargaining power (γ).*

(ii) ϕ^* is increasing in the hiring cost (ξ) and the technology persistency (ρ) when the hiring condition is binding ($\phi^* = \phi_L$), while it is independent of these factors when the condition is slack ($\phi^* = \phi_E$).

If the hiring condition is binding, higher-quality innovations emerge when the engineer gains more leverage in the labor market. This is because of a reduction in the firm's share. As the engineer obtains a larger allocation, it becomes difficult for the firm to break even, and it requires a higher minimum quality level when hiring the engineer (i.e., $\phi^* = \phi_L$ increases). Even when the hiring condition is slack, stronger engineer bargaining power (γ) has a positive impact on ϕ^*, as it resolves the incentive misalignment by increasing w and making $c_E\phi$ less salient in the engineer's optimization. Conversely, the hiring cost (ξ) and the technology persistency (ρ) have no influence when the hiring condition is slack, as they affect only the fixed signing bonus and, conditional on being hired, the engineer ignores this term when choosing ϕ.

Financial market quality. To explore the equilibrium in the financial market, we rely on the standard measures of the financial market quality: (i) the price impact, λ, representing the inverse market liquidity, (ii) the price informativeness, defined as the residual uncertainty in the asset's payoff upon observing the price, $\frac{\mathrm{Var}[\delta]}{\mathrm{Var}[\delta|p]} = \frac{2}{2-\phi}$, and (iii) the price volatility, $\mathrm{Var}[p] = \frac{\sigma_\delta^2\phi}{2}$. As all market quality measures are represented as a monotone function of the technology quality, the comparative statics of these measures reflect Corollary 2.1.

Proposition 2.2. *(i) When the hiring condition is binding, the price impact, the price informativeness, and the price volatility increase with γ, ξ, and ρ.*

(ii) When the hiring condition is slack, these quality measures increase with γ, while they are independent of ξ and ρ.

Proposition 2.2 suggests testable implications on how the labor market for the technology engineer influences investment in financial technology and, in turn, shapes the overall quality of the financial market. It essentially offers a practical avenue to estimate unobservable labor market forces using observable financial data. However, these results all rely on a somewhat unrealistic assumption that the nature and quality of financial technology are observable to outsiders. In the next section, we relax this assumption by introducing opacity in technology and demonstrate how it alters the properties of the equilibrium.

3 Opaque Technology

This section shows that the opacity in technology quality leads to multiple equilibria, one of which involves inefficiently large-scale innovations. To distinguish them from the transparent case in Section 2, we refer to the equilibrium in this section as *opaque equilibrium*, and that in Section 2 as *the transparent equilibrium*.

When technology is opaque, its quality ϕ is not observable to market makers.[14] They form a *belief* about technology quality, denoted as $\tilde{\phi}$, and set the price according to it (Xiong and Yang, 2023). While the belief on the equilibrium path must be consistent with the actual quality, $\tilde{\phi} = \phi$, it could take any values off the path. As the labor market and the bargaining result remain unchanged, we leverage the result of Lemma 2.2, and first derive the implications for the trading-stage equilibrium.

3.1 Equilibrium in Financial Market

Consider the equilibrium in the trading stage. If the price follows the linear strategy $p = \bar{\delta} + \lambda y$, the firm's optimal reaction is given by $\beta = \frac{\phi}{2\lambda}$, as equation (2.13) attests. With opaque technology, however, market makers believe that the trading firm responds to the price impact λ by adopting $\tilde{\beta} \equiv \frac{\tilde{\phi}}{2\lambda}$. Given this strategy, the price is determined by the standard filtering rule under $\tilde{\phi}$:

$$p = \tilde{\mathrm{E}}[\delta|y] = \bar{\delta} + \lambda y,$$

[14]We implicitly assume that the trading firm and the engineer cannot convey signals about ϕ to market makers in a credible manner. Hence, they cannot influence market makers' beliefs and take them as given in deciding on their strategies.

where $\tilde{\mathrm{E}}$ indicates the expectation under $\tilde{\phi}$ and

$$\lambda = \frac{\tilde{\beta}\sigma_\delta^2}{\tilde{\beta}^2\frac{\sigma_\delta^2}{\tilde{\phi}} + \sigma_u^2}. \tag{3.1}$$

Applying market makers' belief about the trading strategy, $\tilde{\beta}$, to equation (3.1), we pin down the price impact. Conversely, given λ, the trading firm follows the strategy $\beta = \frac{\phi}{2\lambda}$ derived in equation (2.13), as it knows the true ϕ.

Lemma 3.1. *(i) The equilibrium in the trading stage is characterized by*

$$\beta = \frac{\sigma_u}{\sigma_\delta}\frac{\phi}{\sqrt{\tilde{\phi}}}, \tag{3.2}$$

$$\lambda = \frac{\sigma_\delta}{2\sigma_u}\sqrt{\tilde{\phi}}. \tag{3.3}$$

(ii) The net expected trading surplus is given by

$$R(\phi, \tilde{\phi}) = \frac{\sigma_\delta\sigma_u}{2\sqrt{\tilde{\phi}}}\phi - c_F\phi. \tag{3.4}$$

The first term of $R(\phi, \tilde{\phi})$ represents the expected gross trading profit and is characterized by both ϕ and $\tilde{\phi}$. Firstly, the trading profit, conditional on the signal realization, is computed by (3.2) and (3.3):

$$\mathrm{E}[(\delta - p)x|s] = \frac{\sigma_u}{\sigma_\delta}\frac{\phi^2}{2\sqrt{\tilde{\phi}}}(s - \bar{\delta})^2. \tag{3.5}$$

ϕ in the numerator represents the trading intensity, β, computed on the true technology quality, while $\tilde{\phi}$ appears in the denominator because market makers set the price impact, λ, according to this belief. Taking the unconditional expectation of (3.5) following the true ϕ leads to the first term in equation (3.4). Unlike the profit derived from transparent technology in (2.6), opaque technology forms $R(\phi, \tilde{\phi})$ into a *linear* function of ϕ, as it separates the price impact from the actual technology quality, ϕ.

3.2 Equilibrium Technology Investment

Optimal technology for engineer. The trading profit in (3.4) is allocated to the firm and the engineer following the bargaining result in Lemma 2.2. Hence, the firm's utility and the hiring condition in (2.22) are modified as

$$U_F = (1-\gamma)\left(R(\phi,\tilde{\phi}) - \kappa\xi\right) \geq 0. \tag{3.6}$$

As in Section 2, the hiring condition in (3.6) imposes the minimum requirement on the technology quality to make the firm willing to hire the engineer:

$$\phi \geq \Gamma(\tilde{\phi}) \equiv \frac{2\kappa\xi\sqrt{\tilde{\phi}}}{\sigma_u\sigma_\delta - 2c_F\sqrt{\tilde{\phi}}}. \tag{3.7}$$

Unlike the transparent equilibrium, however, the lower bound, $\Gamma(\tilde{\phi})$, is an increasing function of $\tilde{\phi}$, suggesting that the firm requires a higher quality level when market makers believe that it has acquired more sophisticated technology. This is because they anticipate severe adverse selection and set a high price impact, which in turn reduces the trading profit of the firm.[15]

The engineer's objective function (2.26) is also modified as follows:

$$U_E = w - c_E\phi = \gamma\left[\left(\frac{\sigma_u\sigma_\delta}{2\sqrt{\tilde{\phi}}} - c_F\right)\phi + \frac{\rho}{1-\rho}\xi\right] - c_E\phi. \tag{3.8}$$

When the technology is opaque, the engineer cannot influence market makers' belief ($\tilde{\phi}$) by controlling the technology investment (ϕ). Therefore, she cannot internalize the negative effect of a heightened price impact, and only the marginal benefit of increasing the informational advantage, after the marginal maintenance and development costs, matters when she improves ϕ. Consequently, U_E becomes a *linear* function of ϕ rather than a single-peaked curve

[15] If condition (3.7) binds and the market's belief is consistent ($\tilde{\phi} = \phi$), it reduces to $U_F = 0$ in (2.21) with transparent technology, generating the same cutoffs, $\{\phi_L, \phi_H\}$, as those in equation (2.23). In the opaque equilibrium, we do not impose $\tilde{\phi} = \phi$ at this stage, representing the fact that the firm and the engineer cannot influence $\tilde{\phi}$.

as analyzed in Section 2. Here, $\tilde{\phi}$ negatively affects the marginal benefit of improving ϕ and leads to the three distinct cases as follows.

Firstly, when market makers believe that the technology quality is relatively low and set a low price impact, the marginal utility of improving ϕ tends to be positive and, therefore, the engineer is willing to increase it. This situation arises if

$$\tilde{\phi} \leq \phi_M \equiv \left(\frac{1}{2}\frac{\gamma\sigma_u\sigma_\delta}{\gamma c_F + c_E}\right)^2, \tag{3.9}$$

where subscript "M" indicates that the marginal utility of improving ϕ becomes zero at $\tilde{\phi} = \phi_M$.

Secondly, if $\tilde{\phi}$ exceeds ϕ_M, market makers set a high price impact, and the marginal cost of developing higher-quality technology dominates the marginal benefit of trading on it. In this case, the engineer seeks to reduce the quality down to the point that secures her employment status, i.e., $\phi \geq \Gamma(\tilde{\phi})$ in (3.7).

Finally, when $\tilde{\phi}$ increases even higher, developing the technology becomes unprofitable for all $\phi \in [0, 1]$, and the engineer leaves the labor market. Hence, solving the engineer's optimization, the rationality (participation) condition kicks in to ensure non-negative utility. This situation arises when $\tilde{\phi}$ exceeds the following cutoff.

$$\tilde{\phi} \geq \phi_N \equiv \left(\frac{1}{2}\frac{\gamma\sigma_u\sigma_\delta}{(1-\rho+\gamma\rho)c_E + \gamma c_F}\right)^2, \tag{3.10}$$

where subscript "N" indicates that ϕ_N sets the threshold for non-participation by the engineer. Summarizing conditions (3.7), (3.9), and (3.10), we obtain the engineer's best-response function to market makers' belief, $\tilde{\phi}$.

Lemma 3.2. *The optimal technology quality for the engineer is given by*

$$\phi = B(\tilde{\phi}) \equiv \begin{cases} 1 & \text{if } \tilde{\phi} < \phi_M, \\ \in [0, \Gamma(\tilde{\phi})] & \text{if } \tilde{\phi} = \phi_M, \\ \Gamma(\tilde{\phi}) & \text{if } \phi_M < \tilde{\phi} < \phi_N, \\ 0 & \text{if } \phi_N \leq \tilde{\phi}, \end{cases} \tag{3.11}$$

where the second line suggests that the engineer is indifferent between all $\phi \in [0, \Gamma(\tilde{\phi})]$.

As in Section 2, incentive misalignment emerges due to the engineer-specific development cost ($c_E\phi$) that cannot be shared with the firm, and the labor market conditions influence the severity of this issue by affecting the structure of the wage transfer. On top of that, opaque technology introduces market makers' belief $\tilde{\phi}$ as a critical factor that determines the magnitude of the incentive misalignment by influencing the engineer's marginal utility of improving ϕ.

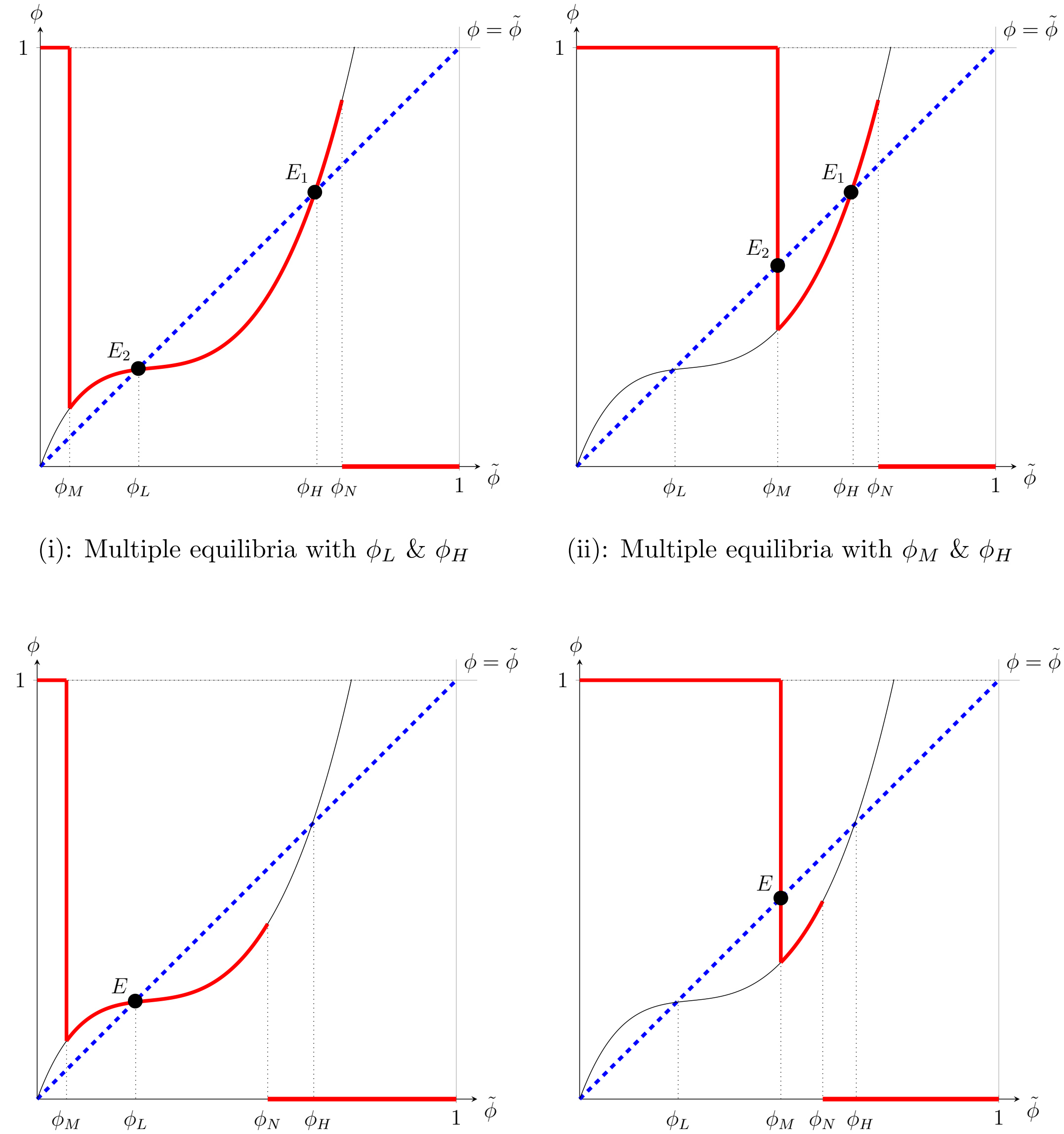
Equilibrium technology quality. In the equilibrium, market makers' belief about the technology quality must be consistent with the actual quality, imposing $\tilde{\phi} = \phi$. Therefore, given the best-response investment by the engineer in Lemma 3.2, the equilibrium ϕ^* is determined as the solutions to the fixed point problem:

$$\phi = B(\phi). \tag{3.12}$$

Figure 2 visualizes this problem: the red curve depicts $B(\tilde{\phi})$, and the blue dashed (45-degree) line suggests the belief-consistency condition in the equilibrium, $\tilde{\phi} = \phi$. It shows the possibility of different equilibria depending on the cutoffs and parameter values.

Proposition 3.1. *When the technology is opaque, there are five equilibrium cases depending on the relative positions of* ϕ_L, ϕ_H, ϕ_M, *and* ϕ_N.

- *(i) If* $\phi_M < \phi_L < \phi_H < \phi_N$, *there are multiple equilibria with self-fulfilling beliefs, one with* $\phi^* = \phi_L$ *and the other with* $\phi^* = \phi_H$.
- *(ii) If* $\phi_L < \phi_M < \phi_H < \phi_N$, *there are multiple equilibria with self-fulfilling beliefs, one with* $\phi^* = \phi_M$ *and the other with* $\phi^* = \phi_H$.
- *(iii) If* $\phi_M < \phi_L < \phi_N < \phi_H$, *there is a unique equilibrium with* $\phi^* = \phi_L$.
- *(iv) If* $\phi_L < \phi_M < \phi_N < \phi_H$, *there is a unique equilibrium with* $\phi^* = \phi_M$.
- *(v) If* $\phi_H < \phi_M$, *there is no equilibrium.*



(i): Multiple equilibria with ϕ_L & ϕ_H

(ii): Multiple equilibria with ϕ_M & ϕ_H

(iii): Unique equilibrium with ϕ_L

(iv): Unique equilibrium with ϕ_M

Figure 2: Equilibrium Technology Quality

Note: The red lines represent the best-response technology investment by the engineer given by $\phi = B(\tilde{\phi})$ in equation (3.11). The belief-consistency condition, $\phi = \tilde{\phi}$, is depicted by the blue dashed lines. The black dots represent equilibria. The numbers of panels correspond to the cases in Proposition 3.1.

Panels (i)–(iv) in Figure 2 correspond to the cases in Proposition 3.1 that focus on parameter values such that equilibrium exists.

The key feature of the engineer's best-response quality, $\phi = B(\tilde{\phi})$, is the upward-sloping curve arising from the binding hiring condition, i.e., $B(\tilde{\phi}) = \Gamma(\tilde{\phi})$ with $\frac{d\Gamma(\tilde{\phi})}{d\tilde{\phi}} > 0$. This represents the strategic complementarity between the engineer's technology development and market makers' belief about technology quality. Intuitively, when $\tilde{\phi}$ is high, market makers anticipate that order flow is highly informative and set a high price impact to offset adverse selection, thereby reducing the firm's trading profit. To meet the hiring condition, the engineer must provide the firm with a large informational advantage and indeed develops high-quality technology in response.

One interesting result that emerges from opacity is the possibility of multiple equilibria, as cases (i) and (ii) illustrate. Due to the strategic complementarity described above, if market makers, for whatever reason, believe that the technology is very high (at ϕ_H), it becomes optimal for the engineer to actually choose the high quality level, supporting $\phi^* = \phi_H$ as an equilibrium. Even though her marginal utility is negative at ϕ_H, she obtains a strictly positive surplus upon being hired. Hence, she is willing to deliver a substantially high-quality technology by incurring a large development cost just to conform to the market's belief and to secure her employment position at the firm. As the same logic supports an equilibrium with a relatively low quality technology at ϕ_L or ϕ_M, multiple self-fulfilling outcomes arise. We refer to the equilibrium with ϕ_H as the "high-tech equilibrium," while that with ϕ_L or ϕ_M is the "low-tech equilibrium." Note that the technology quality in the transparent benchmark corresponds to the low-tech equilibrium, as confirmed by the fact that ϕ_M converges to ϕ_E when the engineer internalizes the price impact due to transparent technology.

Labor market and financial technology. Before exploring the implications of equilibrium, we formalize the impact of labor market conditions. Figure 3 visualizes the results of Proposition 3.1 on the γ-ξ plane, making it comparable with Figure 1 for the transparent equilibrium.

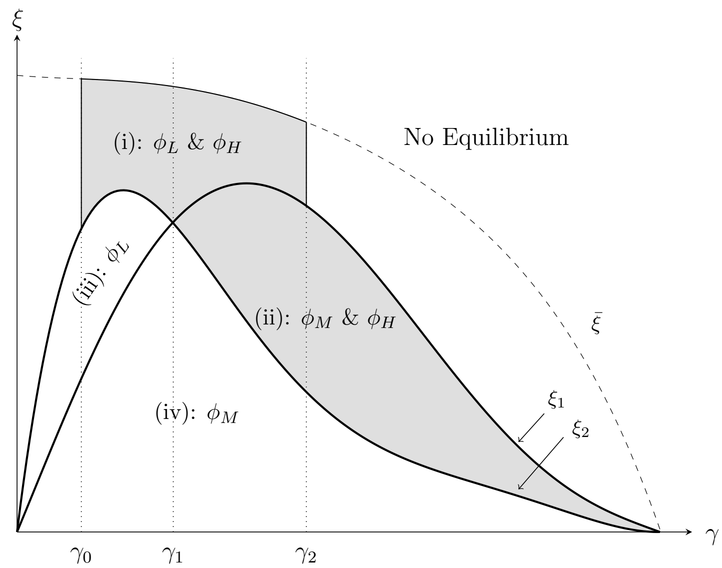


Figure 3: Equilibrium Types and Labor Market Conditions

Note: this figure plots thresholds, $\bar{\xi}, \xi_1, \xi_2$ and $\gamma_0, \gamma_1, \gamma_2$, that characterize equilibrium types in Proposition 3.1. The number of each region corresponds to that in the proposition, and the gray area admits multiple equilibria.

Proposition 3.2. *The opaque equilibrium is characterized by parameter cutoffs, $\{\xi_1, \xi_2, \gamma_0, \gamma_1, \gamma_2\}$, all provided in Appendix D, such that;*

(i) If $\gamma_0 < \gamma < \gamma_2$ and $\max\{\xi_1, \xi_2\} < \xi < \bar{\xi}$, then case (i) is realized, and multiple equilibria involving $\phi^* = \phi_L$ and ϕ_H emerge.

(ii) If $\gamma_1 < \gamma$ and $\xi_2 < \xi < \xi_1$, then case (ii) is realized, and multiple equilibria involving $\phi^* = \phi_M$ and ϕ_H emerge.

(iii) If $\gamma < \gamma_1$ and $\xi_1 < \xi < \xi_2$, then case (iii) is realized and the unique equilibrium with $\phi^* = \phi_L$ arises.

(iv) If $\xi < \min\{\xi_1, \xi_2\}$, case (iv) is realized and the unique equilibrium with $\phi^* = \phi_M$ arises.

(v) Otherwise, there is no equilibrium.

As in the transparent case, no equilibrium exists when the hiring cost (ξ) and the engineer's bargaining power (γ) are too high, because they lead to a large transfer from the firm to the engineer upon hiring, and the firm does not have an incentive to participate regardless of the technology quality. Similarly, equilibrium disappears when γ is very low, as it leads to a small compensation that is not sufficient to cover the engineer's development cost.[16] Furthermore, the intuition behind the emergence of regions (iii) and (iv) that support a unique equilibrium is analogous to the transparent equilibrium in Section 2 and Figure 1.

Unlike the transparent equilibrium, multiple equilibria with the possibility of excessive technology investment arise when both ξ and γ are moderately high, as illustrated by cases (i) and (ii). Remember that the high-tech equilibrium emanates from the binding hiring condition (3.7) that leads to the strategic complementarity between the engineer's choice of ϕ and the market's belief $\tilde{\phi}$. When the hiring cost of the firm is high or the bargaining power of the engineer is strong, the firm finds itself in a weak position in the labor market with a diminished hiring incentive. Consequently, the hiring condition is more likely to bind, triggering the strategic complementarity and the multiplicity of equilibrium.

Regarding the impact of technology persistence ρ, a similar figure to Figure 3 can be drawn by taking ρ as the x-axis, though the analysis becomes more complex, and we leave a detailed analysis for Appendix XXX. It shows that multiple equilibria are more likely to arise when ρ is moderately high. The intuition is analogous to the role of ξ, as both parameters influence the equilibrium selection through changes in the fixed signing bonus, $\left(1 + \frac{\rho\gamma}{1-\rho}\right)\xi$.

3.3 Inefficiency

The high-tech equilibrium is a distinctive feature of our model, driven by the complementarity between the engineer's quality choice and the market's belief.

[16] When the technology is transparent, the model admits an equilibrium even when γ is very small. This is because the price impact in equation (2.15) diminishes and converges to zero when ϕ approaches zero. As a small price impact amplifies the marginal benefit of increasing ϕ (the first term of equation [2.21]), the engineer is willing to participate whenever $\gamma > 0$. The opacity of the technology eliminates this effect, as the engineer does not incorporate the influence of ϕ on the price impact.

Building on the discussions surrounding HFT, a natural question arises: Is the level of investment in the high-tech equilibrium inefficient or excessive from a welfare perspective?

As market makers break even, the trading profit and costs arising from the technology development are split between the trading firm, the engineer, and noise traders. The trading firm's ex-ante expected utility is computed based on (2.21):

$$U_F(\phi^*) = \begin{cases} 0 & \text{if } \phi^* = \phi_L \text{ and } \phi_H. \\ \kappa(\xi_1 - \xi) & \text{if } \phi^* = \phi_M. \end{cases} \tag{3.13}$$

When $\phi^* = \phi_L$ and ϕ_H, the hiring condition is binding, and the engineer seeks to lower the quality level just to meet the hiring requirement, making the trading firm break even after the maintenance cost of technology and the wage payment. At $\phi^* = \phi_M$, in contrast, the engineer is indifferent between lowering and improving ϕ. Hence, the trading firm, which does not incur the development cost, earns positive profits. This is captured by the second line, where $\phi^* = \phi_M$ arises only if $\xi_1 > \xi$. Therefore, the trading firm is weakly better off if the economy switches from the high-tech equilibrium to the low-tech one when multiple equilibria exist.

Similarly, the engineer's expected utility is given by

$$U_E(\phi^*) = \begin{cases} \frac{\gamma}{(1-\rho)(1-\gamma)}\xi - c_E\phi^* & \text{if } \phi^* = \phi_L \text{ and } \phi_H, \\ \gamma\frac{\rho}{1-\rho}\xi & \text{if } \phi^* = \phi_M, \end{cases} \tag{3.14}$$

where the following inequalities hold:

$$U_E(\phi_H) < U_E(\phi_M) < U_E(\phi_L). \tag{3.15}$$

For the engineer, ϕ_H is too high and induces a negative marginal utility. However, she must secure her employment status by achieving it and conforming to the market's belief, supporting it as her worst-case scenario.

Noise traders' utility is defined as the expected trading surplus from executing market order $u \sim N(0, \sigma_u^2)$:

$$U_N(\phi^*) = \mathrm{E}[(\delta - p)u] = -\frac{\sigma_u \sigma_\delta}{2}\sqrt{\phi^*}. \tag{3.16}$$

Due to the zero-sum nature of the trading stage, U_N represents the direct transfer of the adverse selection cost imposed on market makers. As the high-tech equilibrium exhibits the worst adverse selection cost, the price impact becomes very high, and U_N deteriorates.

Overall, when the parameters admit multiple equilibria, the engineer and noise traders are strictly better off if the economy moves from the high-tech equilibrium (ϕ_H) to the other one (either ϕ_M or ϕ_L). As the trading firm's utility either stays unaffected or strictly increases, while market makers are unaffected, we obtain the following result.

Proposition 3.3. *The high-tech equilibrium is Pareto inefficient.*

This result corroborates the idea in both theoretical and policy-oriented literature that excessive investment into financial technology can be socially inefficient. For example, Budish, Cramton, and Shim (2015) argue that the arms race in HFT leads to socially wasteful competition. Similarly, Biais, Foucault, and Moinas (2015) highlight that faster technology can generate negative externalities by reducing overall market liquidity and harming slower participants. Notably, the arms race in the literature arises due to competition among traders that essentially features the prisoners' dilemma with strategic substitution. By contrast, our model identifies a different mechanism rooted in strategic complementarity between the engineer and the market, deriving the inefficient outcome as one of multiple equilibria.

Our theory proposes important implications. Firstly, the self-fulfilling nature of the inefficient high-tech equilibrium suggests that even in the absence of fundamental changes, such as those in the payoff distribution of financial assets or the costs of technological development, a shift in belief alone can trigger an inefficient boom in financial innovation. This also highlights a form of fragility in financial technology investment: even minor changes in belief or small perturbations in a parameter can lead to large swings in technology investment and financial market quality. As we show below in Section 4, policy interventions in the financial labor market, such as a minimum-wage law, can push the economy into such regions, unintentionally causing the inefficient outcome. Secondly, the fact that multiple equilibria exist and, as shown below, differ in terms of comparative statics has empirical value.

3.4 Comparative Statics

The high-tech equilibrium in our model appears consistent with real-world phenomena—such as the substantial investment in HFT technologies and, more recently, the increasing interest in applying AI to financial markets. One of the model's contributions is to provide a formal criterion for assessing whether such investment booms are indeed inefficient.

Comparative statics of the low-tech equilibrium (ϕ_L, ϕ_M) are the same as those in the transparent equilibrium presented in Corollary 2.1 and Proposition 2.2. On the other hand, the high-tech equilibrium responds differently to changes in the labor market.

Proposition 3.4. *In the high-tech equilibrium, the technology quality and all financial market quality measures, including the price impact, the price informativeness, and the price volatility, decrease with ξ, γ, and ρ.*

When the labor market conditions become more favorable for the engineer—as she obtains strong bargaining power (γ), the hiring cost for the firm is high (ξ), and the technology becomes durable (ρ)—the firm's profit function shifts downward, discouraging its hiring of the engineer. To counteract and keep the firm's profit, the engineer needs to adjust the technology quality. At the low-tech equilibrium (ϕ_L or ϕ_M), the firm's profit curve is increasing in ϕ due to a relatively low price impact. At the high-tech equilibrium, however, ϕ_H is an excessive investment, and its marginal impact on the firm's utility is negative. Thus, to maintain the firm's utility and the employment status, the engineer brings the quality down, leading to the opposite reaction of ϕ_H to that of ϕ_L and ϕ_M. As analyzed in Section 2, the measures of financial market quality exhibit a one-to-one relationship to the technology quality in our model, leading to Proposition 3.4.

Although the quality of technology itself may not be directly observable to econometricians, financial market prices are observable. Therefore, Proposition 3.4 offers a distinctive testable prediction linking labor market frictions with financial market outcomes. In particular, the reactions of the financial market differ across equilibria and can serve as an indicator of whether investment in financial technology is excessive in the sense of Pareto efficiency. This stands in contrast to existing literature, which typically focuses on models with a unique equilibrium. This result also provides a novel policy implication, as discussed in Subsection 4.3 below.

4 Endogenous Opacity

This section analyzes endogenous opacity by allowing the trading firm to choose the transparency type of the technology. It also considers policy implications, such as minimum wage interventions in the labor market.

4.1 Setup

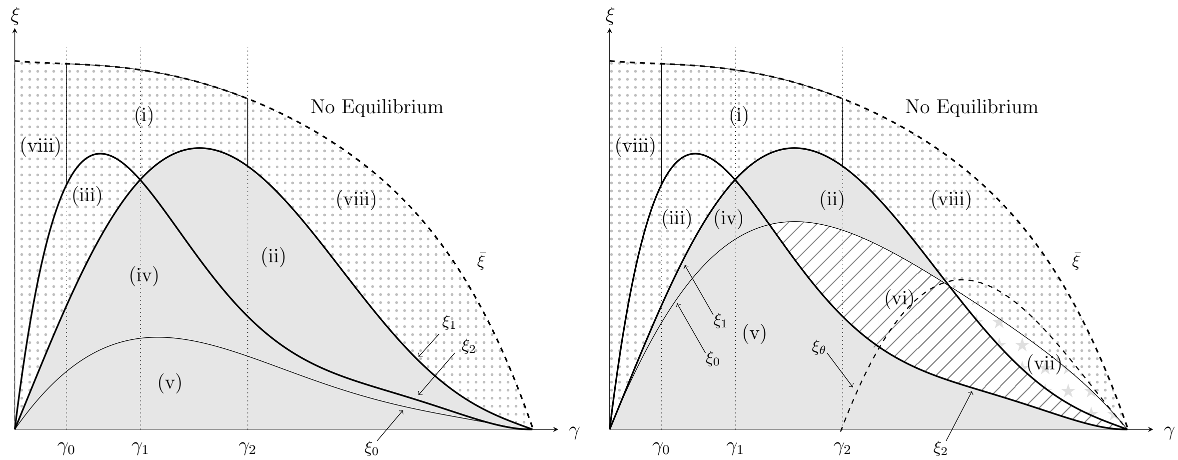
Before the engineer develops the technology, the trading firm decides on the transparency type of the technology, $\chi \in \{0, 1\}$, which is either transparent ($\chi = 0$) or opaque ($\chi = 1$). Transparent technology, such as an open-source AI trading algorithm, reveals its quality to the market, while opaque technology, such as a proprietary in-house trading strategy, is not observable to market makers. The choice over the transparency of a technology naturally belongs to the firm, as it determines how the resulting technology and information will be positioned and protected in operation. Since the technology is acquired for strategic use in trading, the firm optimally decides whether to pursue observable or hidden innovation before hiring the engineer.

To explore the strategic choice by the firm that anticipates multiple equilibria in the technology-development stage, we introduce an equilibrium-selection device. In particular, if the parameter values admit multiple equilibria, all players in the model coordinate their beliefs according to a realization of a sunspot shock $z \in \{0, 1\}$ (e.g., Diamond and Dybvig, 1983; Cooper and Ross, 1998). Namely, with $\theta \equiv \Pr(z = 1)$, a spot appears on the sun, and the high-tech equilibrium is realized, while if it does not show up with the complementary probability, the low-tech equilibrium (either ϕ_M or ϕ_L) is realized.

4.2 Equilibrium Opacity

As Sections 2 and 3 demonstrate, there are three levels of technology quality in evaluating the firm's expected utility. The first case involves the break-even technology qualities, ϕ_L and ϕ_H, that lead to zero expected profits for the firm. They tend to arise when the incentives of the firm and the engineer are misaligned: the engineer withholds technology investment as long as ϕ meets the hiring requirement. The second case is characterized by ϕ_M, where the engineer is indifferent between improving ϕ and not, i.e., the engineer faces zero marginal utility of increasing ϕ. This case arises only if the technology is opaque, and the engineer cannot internalize the negative effect of a heightened price impact, shaping her utility, U_E, into a linear function of ϕ. The third case involves ϕ_E that maximizes unconstrained U_E when the technology is transparent. Both ϕ_M and ϕ_E provide the trading firm with strictly positive utility, $U_F > 0$, as the incentives of the firm and the engineer are relatively well aligned, thereby preventing the investment withholding by the engineer. However, the firm could be better off by improving ϕ further: the engineer's choice of ϕ incorporates the engineer-specific development cost and is insufficient from the firm's perspective.

Figure 4 overlays Figures 1 (the transparent equilibrium) and 3 (the opaque equilibrium). The equilibrium classification depends on the relative marginal cost ($c_E \lesseqgtr 0.5c_F$), as it determines the degree of the incentive misalignment, and Figure 4 separates possible cases into panels (a) and (b). Accordingly, Table 1 summarizes the technology quality and the expected utility of the firm under transparent and opaque technology in each region specified in Figure 4.



(i): Case with $c_E > 0.5c_F$ (ii): Case with $c_E < 0.5c_F$

Figure 4: Equilibrium Technology Quality

Note: The figure overlays Figures 1 and 3. The dotted areas represent the parameter regions where the firm is indifferent between $\chi = 0$ and 1, the gray areas suggest that $\chi = 1$ is optimal, the areas with diagonal lines indicate the optimal χ depends on the value of θ, as represented by another threshold ξ_θ, and the areas with starts suggest that $\chi = 0$ is optimal.

Proposition 4.1. *The equilibrium transparency type of the technology is characterized as follows.*

(i) If $c_E > 0.5c_I$, then developing the opaque technology ($\chi = 1$) is a dominant strategy for the firm.

(ii) If $c_E \leq 0.5c_F$, there is a cutoff, ξ_θ, such that;

(ii-a) The firm chooses transparent technology ($\chi = 0$) when $\xi_2 < \xi < \min\{\xi_\theta, \xi_0\}$.

(ii-b) Otherwise, opaque technology ($\chi = 1$) is dominant.

The key insight is that the opacity generally strengthens the engineer's incentive to improve technology quality by making the price impact insensitive to the actual technology quality ϕ. When the hiring condition is slack, and thus the equilibrium ϕ is insufficient from the firm's perspective, switching from transparent to opaque technology boosts the firm's utility through this

	Technology quality		Firm's utility	
Region/Regime	Transparent	Opaque	Transparent	Opaque
(i)	ϕ_L	ϕ_L or ϕ_H	0	0
(ii)	ϕ_L	ϕ_M or ϕ_H	0	$(1-\theta)\kappa(\xi_1-\xi)$
(iii)	ϕ_L	ϕ_L	0	0
(iv)	ϕ_L	ϕ_M	0	$\kappa(\xi_1-\xi)$
(v)	ϕ_E	ϕ_L	$\kappa(\xi_0-\xi)$	$\kappa(\xi_1-\xi)$
(vi)	ϕ_E	ϕ_M or ϕ_H	$\kappa(\xi_0-\xi)$	$(1-\theta)\kappa(\xi_0-\xi)$
(vii)	ϕ_E	NE	$\kappa(\xi_0-\xi)$	0
(viii)	ϕ_L	NE	0	0

Table 1: The firm's expected utility

Note: The table tabulates the equilibrium technology quality and the firm's expected utility when it chooses transparent ($\chi = 0$) and opaque ($\chi = 1$) technology in each region shown in Figure 4. Regions (vi) and (vii) appear only if $c_E < 0.5c_F$. In the last two columns, the transparency regime that generates higher firm utility is highlighted in blue, while both regimes yield the same utility level if both columns are highlighted. "NE" suggests that no equilibrium exists.

channel. However, opacity may lead to the self-fulfilling high-tech equilibrium, driving the firm's utility to zero, imposing a cost of choosing $\chi = 1$.

When the firm's hiring cost is high and the engineer has weak bargaining power, as represented by regions (i), (iii), and (viii) in Figure 4, even the opaque regime results in either the engineer holding back from improving technology so that the hiring condition is binding or no equilibrium exists. These factors increase the share of the fixed signing bonus and reduce the performance-based component that would otherwise align incentives of the engineer and the firm. Since the opaque equilibrium already features the engineer withholding and the binding hiring condition (or non-participation by the firm), the same applies under transparency. The firm always breaks even, regardless of technology's transparency type, and is indifferent between $\chi = 0$ and 1.

As the hiring cost decreases and the engineer's bargaining power improves, her incentive to withhold gradually weakens. In an intermediate region, represented by (ii) and (iv), the engineer withholds under transparent technology but not under opacity. In this case, the firm earns strictly positive expected utility by choosing the opaque regime, while the transparent regime yields zero profit. Hence, the firm strictly prefers opacity ($\chi = 1$).

If the hiring cost falls further or the engineer's bargaining power becomes sufficiently strong, as in region (v), she no longer withholds under either regime. However, opacity still leads to higher technology quality, and the firm benefits from this improvement as its marginal utility is positive. Therefore, it prefers the opaque regime ($\chi = 1$).

Transparent technology becomes optimal under three conditions, as represented by regions (vi) and (vii): a low hiring cost with strong engineer bargaining power, a low c_E relative to c_F, and a high probability of a sunspot when multiple equilibria exist. It highlights the tradeoff of choosing opaque technology. On the one hand, opacity encourages the engineer's technology investment and mitigates the incentive misalignment between the firm and the engineer. This increase in ϕ benefits the firm, as it faces positive marginal utility of improving ϕ when the hiring condition is slack. This channel is rooted in the inelastic price impact and, similar to the literature, such as Xiong and Yang (2023) and Aoyagi (forthcoming), encourages the firm to choose opaque technology. On the other hand, the opacity leads to belief-driven multiple equilibria, and the firm can enjoy the benefit of opacity only if the low-tech equilibrium is realized. Otherwise, the market believes ϕ_H, and the engineer makes excessive investments to secure her employment, driving the firm's profit to zero. As Proposition 4.1 attests, this tradeoff is represented by the cutoff, ξ_θ: opaque technology is optimal only when the underlying incentive misalignment is sufficiently severe ($\xi > \xi_\theta$) so that the benefit of resolving it dominates the utility cost of opacity.

Notably, the mechanism behind the emergence of the transparent equilibrium is unique to our model. The literature suggests that models with a monopolistic insider (e.g., Xiong and Yang, 2023) admit only the positive effect of opacity on technology acquisition through an inelastic price impact, making the opaque regime optimal for all parameter values. To address the possibility of transparent information acquisition, the models need additional forces, such as competition among informed traders. In contrast, our model highlights the trader's utility cost of choosing opaque technology. It arises from the possibility of belief-driven multiple equilibria that may involve inefficiently excessive technology investments.

4.3 Policy Implications

The analysis so far has shown that the incentive misalignment between the firm and the engineer plays a central role in shaping the equilibrium technology investment. This raises a natural question: how would government intervention in the labor market affect these outcomes? We explore the implications of widely adopted and controversial labor market policies through the lens of our model, such as minimum wage and non-compete agreements.

Minimum wage. As a leading example, we first consider minimum wage—one of the most widely implemented labor market policies around the world. In relation to technology investments, much of the literature in labor economics focuses on labor-saving innovation in response to rising wages (e.g., through automation, robotics, or AI adoption), grounded in the basic trade-off between capital and labor (Zeira, 1998; Acemoglu and Restrepo, 2018; Hémous and Olsen, 2022). Our model provides a workplace to analyze the impact of minimum wage on profit-enhancing innovations in the finance industry, beyond labor-saving technology.

Minimum wage is described in the model as a lower bound imposed on the fixed component of the engineer's wage:

$$m \leq \frac{\rho}{1-\rho}\gamma\xi, \tag{4.1}$$

where m represents the minimum wage enforced by the law, and the right-hand side is the fixed component of w in equation (2.20). It is rewritten in terms of the hiring cost:

$$\xi_m \equiv (1-\rho)\frac{m}{\rho\gamma} \leq \xi. \tag{4.2}$$

The minimum wage law imposes a lower bound on the hiring cost, restricting the parameter space that admits equilibrium. ξ_m draws a monotonically decreasing curve on the γ-ξ plane in Figure 3, and a high m can put the economy into the regions with multiple equilibria and opaque technology.

Intuitively, an increase in the fixed payment due to the minimum wage law tightens the hiring condition, as it enlarges the transfer from the firm to the engineer, discouraging the firm from hiring. It also distorts the engineer's incentive by making her performance-based salary less important. Therefore, it triggers the strategic complementarity between the engineer and market makers, giving birth to the high-tech equilibrium.

This result suggests that minimum wage may have unintended consequences: while it aims to improve the engineer's fixed salary and indeed enhances innovation, it can result in excessive investments in technology due to the self-fulfilling nature of the high-tech equilibrium. As shown in Proposition 3.3, this high-tech equilibrium is Pareto inefficient, and the engineer incurs utility costs, contrary to the intended purpose of the minimum-wage policy.

Non-compete agreement. The role of non-compete agreements (NCAs) in shaping firm behavior and innovation outcomes has been controversial in recent years, not only within the financial sector but across a wide range of industries.[17] The literature has yet to reach consensus on the net effect of the tradeoff created by NCAs: while they may strengthen firms' incentives to invest in worker training by reducing the risk of talent poaching (Jeffers, 2024),

[17] The enforceability of NCAs in the U.S. has traditionally been governed by state law, resulting in substantial cross-state variation. The U.S. Federal Trade Commission's 2024 ruling to ban most NCAs and the subsequent legislative pushback in states such as Texas have prompted intensive debates.

they can also hinder knowledge spillovers (Saxenian, 1996).

As shown by Johnson, Lavetti, and Lipsitz (2023), one direct implication of enforceable NCAs is the increased ability of firms to retain workers, particularly those engaged in innovative activities. Building on this insight, our model can examine how a reduction in worker retention costs, induced by NCAs, alters equilibrium innovations in financial technology.

When the economy admits multiple equilibria, the effect of a reduction in hiring or retention costs, ξ, differs across the high-tech and the low-tech equilibria, as shown in Corollary 2.1 and Proposition 3.4. In general, however, a decline in ξ shifts the economy toward regions where the unique low-tech equilibrium prevails. This shift occurs because NCAs improve the firm's bargaining position, reducing the fixed component of the engineer's wage and thereby alleviating incentive misalignment.

Consistent with the existing literature, NCAs lead to more aggressive hiring and a slack hiring condition. However, our model yields a distinctive prediction: stricter enforcement of NCAs can eliminate the high-tech equilibrium (Proposition 3.2; Figure 3), thereby suppressing inefficiently large-scale innovation investments. Even in the low-tech equilibrium, Corollary 2.1 shows that technology quality weakly declines as NCAs become more stringent, as the improved position of the firm in the labor market reduces the minimum required technology quality for hiring. Accordingly, restricting NCAs (e.g., the 2024 proposal by the U.S. Federal Trade Commission) may restore equilibrium multiplicity: while this could stimulate innovation, it may also reintroduce inefficient overinvestment.

Bargaining power. Furthermore, our model provides a theoretical background to interpret recent labor market trends, particularly those affecting bargaining power. A growing literature highlights the role of monopsony (labor market concentration) that strengthens firms' bargaining power and suppresses wages (e.g., Azar, Marinescu, and Steinbaum, 2022). While less studied in finance, evidence reported by Aquilina, Budish, and O'neill (2022) on HFT activities suggests a concentration toward a limited number of large financial institutions, implying a similar landscape in the market for engineers. Other institutional shifts, such as wage transparency, may also affect relative bargaining power, though empirical findings remain mixed (e.g., Werner, 2023).

In our framework, when engineers' bargaining power (γ) is low, equilibrium is unique, and innovations and the financial market exhibit monotone reactions (Corollary 2.1; Proposition 2.2). However, above a certain threshold suggested by Proposition 3.4, multiple equilibria emerge, and responses of equilibrium variables diverge across high- and low-tech equilibria. This multiplicity helps reconcile conflicting empirical results and applies more broadly: shocks such as H-1B visa restrictions or changes in unionization may generate different outcomes depending on the economy's equilibrium state. This result is unique to our framework, which features multiple equilibria driven by strategic complementarities and explicitly links the financial and labor markets.

5 Conclusion

This paper studies a model à la Kyle (1985) where a trading firm hires an engineer to develop financial technology to gain an informational advantage. The hiring process and technology development involve the labor market and incentive misalignment. We show that opaque technology, where market makers cannot observe the technology quality of the trading firm, generates strategic complementarity between the engineer's innovation incentive and market makers' beliefs about technology quality. Consequently, the model features multiple self-fulfilling equilibria, one of which involves excessive and Pareto-inefficient technology investments. In this "high-tech" equilibrium, the trader adopts more aggressive trading strategies, and the price becomes more informative, while it also leads to an illiquid market with a highly volatile price. We show the distinctive comparative statics results across our benchmark and the high-tech equilibrium, providing an empirical tool to identify inefficiency in financial technology investments. It also provides a theoretical rationale for the mixed empirical evidence for the impact of labor market interventions, such as minimum wage and non-compete agreements.

As a direction for future research, it would be interesting to extend our theory of technology investment to a broader growth framework. This could shed light on whether the inefficiencies arising from strategic complementarities and multiple equilibria are unique to the financial sector or also relevant to technology investment in other industries, with potential macroeconomic implications.

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Appendix

A Proof of Lemma 2.2

Consider the n-th bargaining round. Given the wage level in (2.20), the firm and the engineer earn the following utility if they agree on the wage:

$$U_{F,n} - z_{F,n} = (1-\gamma)(R - z_{F,n} - z_{E,n}),$$

$$U_{E,n} - z_{E,n} = \gamma(R - z_{F,n} - z_{E,n}).$$

Therefore, if $R \geq Z_n \equiv z_{F,n} + z_{E,n}$, then they reach the agreement in the n-th round. Otherwise, negotiation fails. At the n-th bargaining round, both players' outside option depends on the next-round's outcome. If they anticipate an agreement in the next round,

$$z_{F,n} = \rho(R - w_{n+1} - \xi),$$
$$z_{E,n} = \rho w_{n+1},$$

so that the total outside option is $Z_n = (1-\rho)(R-\xi)$. Conversely, if they anticipate that the next round also fails, it becomes $Z_n = \rho Z_{n+1}$. Therefore, if they anticipate an agreement at a certain bargaining round, say the n'-th round, then it holds that $Z_{n'} = (1-\rho)(R-\xi) < R$. Hence, they reach an agreement for all n, in particular, meaning that the bargaining concludes at the first round. Suppose that such n' does not exist, i.e., they anticipate that all bargaining rounds fail. This implies that $R < Z_n$ for all n. However, it also holds that $Z_n = \rho Z_{n+1}$ for all n, leading to $Z_n = 0$, a contradiction to $R < Z_n$. Therefore, there is at least one n' such that the firm and the engineer anticipate an agreement at the n'-th round, which in turn implies that they agree at the first round, anticipating an agreement in the next round in case that they fail the first round. The above argument leads to the recursive equation in (2.2), and solving it with the transversality condition yields the wage level in (2.20).

B Proof of Lemma 2.1

U_E in equation (2.26) satisfies the SOC, and the FOC implies that it is maximized at ϕ_E in equation (2.27) when ignoring the hiring condition. The thresholds for the hiring condition, ϕ_L and ϕ_H, are the solutions to the following quadratic equation with respect to $\sqrt{\phi}$:

$$H(\phi) = 2c_F\phi - \sigma_u\sigma_\delta\sqrt{\phi} + 2\kappa\xi = 0. \tag{B.1}$$

It can be directly confirmed that $\phi_E < \phi_H$ holds for all parameter values. Also, $\phi_E \geq \phi_L$ if and only if $H(\phi_E) \leq 0$, which is equivalent to $\xi \leq \xi_0 = \frac{\sigma_u^2\sigma_\delta^2\gamma}{16\kappa}\frac{\gamma c_F+2c_E}{(\gamma c_F+c_E)^2}$. Since $\kappa = \frac{1-(1-\rho)\gamma}{(1-\rho)(1-\gamma)}$, it holds that $\frac{d\xi_0}{d\rho} < 0$. As for the reaction of ξ_0 to changes in γ, we obtain

$$\frac{d\xi_0}{d\gamma} = \frac{\sigma_u^2\sigma_\delta^2}{16\kappa^2}\frac{\kappa(2\gamma c_F + 2c_E)(\gamma c_F + c_E) - \gamma(\gamma c_F + 2c_E)\left(\frac{\gamma c_F+c_E}{(1-\gamma)^2(1-k)} + 2c_F\kappa\right)}{(\gamma c_F + c_E)^3}. \tag{B.2}$$

At the limit of $\gamma = 0$ and $\gamma = 1$, the derivative becomes $\frac{d\xi_0}{d\gamma}|_{\gamma=0} = \frac{\sigma_u^2\sigma_\delta^2}{8c_E} > 0$, and $\frac{d\xi_0}{d\gamma}|_{\gamma=1} = -\frac{\sigma_u^2\sigma_\delta^2(1-\rho)}{16}\frac{c_F+2c_E}{(c_F+c_E)^2} < 0$, while $\xi_0 = 0$ at both $\gamma = 0$ and 1. Hence, ξ_0 is globally hump-shaped with respect to γ. Letting $C = c_E/c_F$, the numerator of (B.2) is proportional to the following:

$$L(\gamma) \equiv -\gamma^3 - C\gamma^2\,(3 + 4\rho) - 2C^2\,(1-\rho)\,\gamma + 2C^2(1-\rho).$$

Since L is monotonically decreasing in γ, and from the fact that $L(0) > 0 > L(1)$, there is a unique solution to $L(\gamma) = 0$, implying that ξ_0 takes a hump-shaped curve against γ.

C Proof of Corollary 2.1, Propositions 2.2, and 3.4

Taking the first-order derivative of ϕ_L, ϕ_H, ϕ_M, and ϕ_N with respect to parameters ξ, γ, ρ and applying them to the market quality measures directly leads to the results.

D Proof of Propositions 3.1 and 3.2

n this proof, we rewrite the conditions regarding the positions of $(\phi_L, \phi_H, \phi_M, \phi_N)$ into parameters of the labor market (ξ, γ, ρ). Firstly, it holds that $\phi_M < \phi_N$ for all parameter values. Given that ϕ_L and ϕ_H are the solution to $H(\phi) = 0$ in equation (B.1) and its tipping point is $\sqrt{\phi} = \frac{\sigma_u \sigma_\delta}{4c_F}$, $\phi_M \in [\phi_L, \phi_H]$ if and only if

$$\xi \leq \xi_1 \equiv \frac{\gamma}{4\kappa} c_E \left(\frac{\sigma_u \sigma_\delta}{\gamma c_F + c_E} \right)^2. \tag{D.1}$$

Otherwise, $\phi_M < \phi_L$ holds when $\gamma < \gamma_2 \equiv \frac{c_E}{c_F}$, while $\phi_M > \phi_H$ when $\gamma > \gamma_1$. Similarly, $\phi_N \in [\phi_L, \phi_H]$ if and only if

$$\xi \leq \xi_2 \equiv \frac{\gamma(1-\gamma)(1-\rho)}{4} c_E \left(\frac{\sigma_u \sigma_\delta}{\gamma c_F + (1-(1-\rho)\gamma) c_E} \right)^2. \tag{D.2}$$

Otherwise, $\phi_N < \phi_L$ holds when $\gamma < \gamma_0 \equiv (1-(1-\rho)\gamma)\frac{c_E}{c_F}$, while $\phi_N > \phi_H$ when $\gamma > \gamma_0$.

Configuration of thresholds. Comparing the thresholds of the hiring cost, it is straightforward to check $\max\{\xi_1, \xi_2\} < \bar{\xi}$ for all parameter values. Moreover, from (D.1), $\xi_1 = 0$ at $\gamma = 0$ and $\gamma = 1$. Also,

$$\frac{d\xi_1}{d\gamma} \sim [1 - (1-\gamma)^2\rho - 2\gamma] c_E - \gamma c_F \left(1 - (1-\gamma)^2 \rho\right).$$

Hence, ξ_1 is increasing in γ if and only if

$$A_1(\gamma) \equiv \max \left\{ \frac{\gamma}{1 - 2\frac{\gamma}{1-(1-\gamma)^2\rho}}, 0 \right\} < \frac{c_E}{c_F} = \gamma_2,$$

where $A_1(\gamma) > 0$ if and only if $\gamma < g_1 \equiv \frac{\sqrt{1-\rho}(1-\sqrt{1-\rho})}{\rho}$. For $\gamma < g_1$, $A_1(\gamma)$ is monotonically increasing in γ. Since $A_1(0) = 0$ and $\lim_{\gamma \to g_1} A_1(\gamma) = \infty$, there is a unique γ such that $A_1(\gamma) = \gamma_2$, meaning that ξ_1 takes a single-peaked curve against γ.

Similarly, from (D.2), $\xi_2 = 0$ holds at $\gamma = 0$ and $\gamma = 1$. Also,

$$\frac{d\xi_2}{d\gamma} \sim \frac{-\gamma c_F + (1 - 2\gamma - \rho(1-\gamma))c_E}{(\gamma c_F + (1-(1-\gamma)\rho)c_E)^3},$$

suggesting that ξ_2 is increasing in γ if and only if

$$A_2(\gamma) \equiv \max\left\{\frac{\gamma}{1 - 2\gamma - \rho(1-\gamma)}, 0\right\} < \gamma_2.$$

$A_2(\gamma) > 0$ if $\gamma < g_2 \equiv \frac{1-\rho}{2-\rho}$, and A_2 is monotonically increasing in γ when $\gamma < g_2$ with $A_2(0) = 0$ and $\lim_{\gamma \to g_2} A_2(\gamma) = \infty$. Therefore, there is a unique γ such that $A_2(\gamma) = \gamma_2$, meaning that ξ_2 takes a single-peaked curve against γ.

Comparing ξ_1 and ξ_2, it holds that

$$\xi_1 - \xi_2 = \xi_1 \rho (1-\gamma) \frac{\gamma^2 c_F^2 - (1-(1-\gamma)\rho)c_E^2}{(\gamma c_F + (1-(1-\gamma)\rho)c_E)^2}. \tag{D.3}$$

Therefore, ξ_1 and ξ_2 have three intersections. The first and the second ones are at $\gamma = 0$ and $\gamma = 1$, where $\xi_1 = \xi_2 = 0$. The third one is at $\gamma = \gamma_1$, where the following condition holds:

$$A_I(\gamma) = \frac{\gamma}{\sqrt{1-(1-\gamma)\rho}} = \gamma_2. \tag{D.4}$$

Note that A_I is monotonically increasing in γ with $A_I(0) = 0$ and $A_I(1) = 1 > \gamma_2$. Therefore, condition (D.4) has a unique solution at

$$\gamma_1 \equiv \frac{\rho\gamma_2 - \sqrt{\rho^2\gamma_2^2 + 4(1-\rho)}}{2}\gamma_2 < \gamma_2.$$

Therefore, $A_1 > A_2$ if and only if $\gamma > \gamma_1$. The above analyses support Figure 3.

Finally, summarizing the possible equilibrium types, we confirm the following: (i) $\phi_M < \phi_L$ and $\phi_H < \phi_N$ hold if and only if $\xi > \max\{\xi_1, \xi_2\}$ and $\gamma \in (\gamma_0, \gamma_2)$, (ii) $\phi_L < \phi_M$ and $\phi_H < \phi_N$ hold if and only if $\xi_2 < \xi < \xi_1$, (iii)

$\phi_M < \phi_L < \phi_N < \phi_H$ hold if and only if $\xi_1 < \xi < \xi_2$, and (iv) $\phi_L < \phi_M$ and $\phi_N < \phi_H$ hold if and only if $\xi < \min\{\xi_1, \xi_2\}$. (v) Otherwise, there is no equilibrium.

E Proof of Proposition 4.1

Comparing ξ_0 and ξ_1, it holds that

$$\xi_1 - \xi_0 = \frac{\sigma_u^2 \sigma_\delta^2 \gamma}{16\kappa} \frac{2c_E - \gamma c_F}{(\gamma c_F + c_E)^2}. \tag{E.1}$$

Therefore, these thresholds have a unique intersection in $\gamma \in (0, 1)$ characterized by $\hat{\gamma} = \min\{2\frac{c_E}{c_F}, 1\}$. Note that $\hat{\gamma} = 1$ and thus $\xi_0 < \xi_1$ for all $\gamma \in (0, 1)$ when $c_E < 0.5c_F$. Similarly, comparing ξ_2 and ξ_0,

$$\xi_2 - \xi_0 = \frac{\sigma_u^2 \sigma_\delta^2 \gamma}{16\kappa c_F} K(\gamma), \tag{E.2}$$

where

$$K(\gamma) = 4\frac{(\gamma\rho + 1 - \rho)\gamma_2}{(\gamma(\rho + \gamma_2) + (1 - \rho)\gamma_2)^2} - \frac{\gamma + 2\gamma_2}{(\gamma + \gamma_2)^2} \tag{E.3}$$

with $\gamma_2 = \frac{c_E}{c_F}$. Consider the slope of $\xi_2 - \xi_0$ at $\gamma = 0$:

$$\begin{aligned} \frac{d(\xi_2 - \xi_0)}{d\gamma}|_{\gamma=0} &= K(0)\frac{\sigma_u^2 \sigma_\delta^2}{16c_F}\frac{d\frac{\gamma}{\kappa}}{d\gamma}|_{\gamma=0} + \frac{\sigma_u^2 \sigma_\delta^2 \gamma}{16\kappa c_F}|_{\gamma=0}\frac{dK(0)}{d\gamma} \\ &= K(0)\frac{\sigma_u^2 \sigma_\delta^2}{16c_F} \\ &> 0 \end{aligned}$$

where the second equality holds due to $\kappa \to \infty$ and $\frac{d}{d\gamma}\frac{\gamma}{\kappa} \to 1$ as $\gamma \to 0$, and the last inequality obtains from $K(0) = \frac{2}{\gamma_2}\frac{1+\rho}{1-\rho} > 0$. By continuity and the fact that $\xi_0 = \xi_2 = 0$ at $\gamma = 0$, $\xi_0 < \xi_2$ holds for small and positive values of γ. By continuity and the fact that $\xi_0 = \xi_2 = 0$ at $\gamma = 0$, $\xi_0 < \xi_2$ holds for small and positive values of γ.

Also, at the limit of $\gamma \to 1$, $\lim_{\gamma \to 1} K(\gamma) = \frac{2c_E - c_F}{(c_F + c_E)^2}$. Since $\xi_2 = \xi_0$ at $\gamma = 1$,

ξ_2 converges to ξ_0 from above if, and only if, $c_E > 0.5c_F$. In other words, if $c_E < 0.5c_F$, there must be at least one γ such that $K(\gamma) = 0$. Suppose that such γ exists and denote it as $\bar{\gamma} \in (0,1)$. Re-arranging (E.3) confirms that K is proportional to $k(\gamma) \equiv \sum_{l=0}^{3} \alpha_l \gamma^l$ with

$$\alpha_3 = -(\rho - \gamma_2)^2,$$

$$\alpha_2 = 2\gamma_2 \left[2(1-\rho)[1 - \gamma_2(\rho + \gamma_2)] - (\rho - \gamma_2)^2\right],$$

$$\alpha_1 = \gamma_2^2 \left[4\rho\gamma_2 + (1-\rho)\left(7 + \rho - 4(\rho + \gamma_2)\right)\right],$$

$$\alpha_0 = 2(1-\rho)\gamma_2^3(1+\rho).$$

Given that $\bar{\gamma}$ satisfies $k(\bar{\gamma}) = 0$, the slope of $k(\gamma)$ at $\gamma = \bar{\gamma}$ must be negative as

$$\frac{dk(\bar{\gamma})}{d\gamma} = \frac{\alpha_3\bar{\gamma}^3 - 2\alpha_0 - \alpha_1\bar{\gamma}}{\bar{\gamma}} < 0,$$

where the inequality comes from $\alpha_3 < 0$, $\alpha_1 > 0$, and $\alpha_0 > 0$. By the mean-value theorem, the above inequality implies that $\bar{\gamma}$ (if it exists) is unique. Hence, ξ_0 and ξ_2 have either one intersection or not. By putting above arguments together with the behavior of K at the limit of $\gamma = 1$, $K(\gamma) = 0$ has a unique solution, $\bar{\gamma} \in (0,1)$, such that $\xi_0 < \xi_2 \Leftrightarrow \gamma < \bar{\gamma}$, if $c_E < 0.5c_F$. Otherwise, $K(\gamma) > 0$ and $\xi_0 < \xi_2$ for all $\gamma \in (0,1)$. Moreover, $K(2\gamma_2) < 0$ and thus $\bar{\gamma} < 2\gamma_2$. Hence, if $c_E < 0.5c_F$, and ξ_0 has an intersection each with ξ_1 as $\hat{\gamma}$ and ξ_2 at $\bar{\gamma}$, it holds that $\bar{\gamma} < \hat{\gamma}$.

Finally, we derive ξ_θ. As Table 1 summarizes, there is no clear dominance relationship between $\chi \in \{0,1\}$ only in region (iv). In this region, $\chi = 0$ becomes optimal if, and only if,

$$\kappa(\xi_0 - \xi) > (1-\theta)\kappa(\xi_1 - \xi).$$

This inequality can be rewritten as the following:

$$\xi < \xi_\theta \equiv \frac{\xi_0 - \theta\xi_1}{1-\theta} = \frac{\sigma_u^2\sigma_\delta^2\gamma}{16\kappa(1-\theta)} \frac{\gamma c_F - 2(2\theta - 1)c_E}{(\gamma c_F + c_E)^2}.$$

Since $\xi_1 - \xi_\theta = \frac{\xi_1 - \xi_0}{1-\theta}$ and $\xi_0 - \xi_\theta = \theta\frac{\xi_1 - \xi_0}{1-\theta}$, ξ_θ draws the curve that goes through regions (v), (vi), and XXX with $\hat{\gamma}$ being the intersection with ξ_1 and ξ_0. It also converges to $\xi_\theta = 0$ at $\gamma = 1$. Note also that $\xi_\theta = 0$ at $\gamma = 0$. Hence, if $\theta < \frac{1}{2}$, then $\xi_\theta > 0$ for all γ, while $\theta \geq \frac{1}{2}$ leads to $\gamma_\theta \equiv 2(2\theta - 1)\gamma_2$, such that, $\xi_\theta < 0 \Leftrightarrow \gamma < \gamma_\theta$. Figure 4 illustrates the case with $\theta > \frac{1}{2}$, while these cases provide the same results.