When Silicon Valley Meets Wall Street: A Theory of Financial Overengineering*

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October 25, 2025

Abstract

We study a model of financial markets with asymmetric information, in which a trading firm hires a financial engineer to develop proprietary technology to obtain an informational edge. The signal produced through this hiring is firm-specific and non-contractible, leading to a bilateral monopoly in wage determination. The model admits multiple self-fulfilling equilibria in technology innovation. In one equilibrium, excessive and inefficient innovation arises due to technological opacity and misaligned incentives between the firm and the engineer. The model connects financial market outcomes to contractual frictions in the finance industry and yields novel empirical implications for identifying inefficiencies in financial technology investment.

JEL classification: G11, G12, G14, G23

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

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*For helpful comments and discussions, we thank Daisuke Adachi, Takanori Adachi, Kosuke Aoki, Utpal Bhattacharya, Briana Chang, Zhi Da, Masao Fukui, Goutham Gopalakrishna, Kiichi Kitajima, Albert (Pete) Kyle, Dan Li, Don Noh, Yoshio Nozawa, Kazuhiko Ohashi, Maureen O'Hara, Yusuke Osaki, Jian Sun, Yasuhiko Tanigawa, Yusuke Tsujimoto, Jiro Yoshida, Kathy Yuan, and seminar participants at the University of Tokyo, Waseda University, the Tokyo Metropolitan University, Waseda Summer Workshop in Finance, and HKUST. All errors and omissions are our own.

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1 Introduction

Financial markets have long been shaped by technological investment, from early computer-based trading in the 1960s (Allen and Gale, 1994; Tufano, 2003) to the recent AI-powered trading technology (IMF, 2024). Each wave of innovation has not only driven competition among trading firms but also fueled demand for engineers and skilled workers, making tech talent a critical input in financial innovation.[1] Despite this, existing research largely focuses on traders' direct and observable information or speed acquisition as a proxy for technology investments, overlooking the distinct role of engineers and potential incentive misalignment between engineers and trading firms. This gap raises key questions: How do employment contracts between trading firms and engineers mutually interact with financial variables such as market liquidity and asset prices? What factors drive "financial overengineering," defined as excessive investment in financial technology that ultimately harms social welfare?[2] More specifically, how do different forms of technological development, such as internal vs. external, and the visibility of the technology, meaning transparent vs. opaque innovations, affect overengineering?

We address these issues by formulating a model, which embeds an incentive problem in contracting between the firm and the engineer, followed by a trading game à la Kyle (1985). In the trading stage, a single informed trader (trading firm) trades a risky asset with a competitive market maker after observing an imperfect signal about the asset's fundamentals. Rather than acquiring this signal directly, the firm in the contracting stage hires a financial engineer to develop proprietary technology that generates the signal, with higher-level technology providing more accurate information. The engineer improves the technology through costly investment, and her compensation is determined via Nash bargaining with the firm. Following the classic

[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).

incomplete contracts literature (Hart and Moore, 1990; Acemoglu and Pischke, 1999), we assume that the technology development is non-contractible, and the engineer alone bears the cost of technology development. This cost asymmetry creates an incentive misalignment: when the problem is severe, the engineer's individually optimal technology level falls short of the firm's minimum hiring requirement. To avoid termination, the engineer is compelled to develop technology that just satisfies this minimum threshold, where the firm breaks even. In our benchmark case with *transparent* technology, where the market maker can observe technology level, such equilibrium is uniquely determined.

Departing from standard models, our key innovation is to allow for technological *opacity*, under which the engineer's technology development is hidden from the market maker.[3] This shift dramatically changes the nature of the incentive problem and gives rise to multiple equilibria: one of these resembles the benchmark transparent equilibrium, while another features a substantially larger 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 informativeness. However, the market becomes illiquid, and the price is highly volatile. Moreover, all market participants are worse off in the high-tech equilibrium compared to the benchmark "low-tech" equilibrium, making it Pareto inefficient. This inefficiency arises because a highly precise signal amplifies the firm's trading profit at the expense of a noise trader, while the cost of developing high-level technology ultimately outweighs the gains from trading, reducing the net payoffs of both the firm and the engineer.

The key mechanism is the strategic complementarity between the engineer's incentive to improve technology level and the market maker's *belief* about it. Since opaque technology is unobservable, the market maker forms a

[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.

belief about the technology level and adjusts the price accordingly. If she believes that sophisticated technology has been developed, she sets a high price impact to counteract the adverse selection problem (Kyle, 1985). It would reduce the trading profit and discourage the firm from hiring the engineer. To meet the hiring requirement, in turn, the engineer indeed makes massive technology investments and boosts trading profits to uphold the firm's incentive to continue employing the engineer, thereby reinforcing the high-tech equilibrium. The same logic applies when the market maker believes the technology to be unsophisticated at the benchmark level, supporting the coexistence of the low-tech and the high-tech equilibria. We interpret the self-fulfilling nature of multiple equilibria as *fragility* in technology investment.[4] Once the economy admits multiple equilibria, a mere shift in the market's belief about unobservable technology can trigger disproportionately large financial technology investments, leading to a highly volatile price and market illiquidity.

Our model shows that the engineer's relative advantages in the bargaining with the firm 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, the engineer's compensation tends to be high, while the firm's share decreases. It tightens the hiring requirement, and the abovementioned strategic complementarity 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's price and thus to the market maker's belief, further reinforcing the strategic complementarity.

Comparative statics differ markedly across the high-tech and low-tech equilibria in our model. When the firm's surplus changes due to an exogenous shock, the engineer adjusts technology development to restore the firm's hiring incentive. In the high-tech equilibrium, where investment is already excessive,

[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.

the firm's marginal utility is negative, and holding back on further overinvestment helps recover the firm's surplus, while the opposing mechanism applies to the low-tech equilibrium. This asymmetry causes the engineer's innovation to respond differently across the two equilibria, generating two key implications. First, since technology influences the asset's price and financial market quality, observing market responses to exogenous shocks can empirically distinguish an 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 inefficient investments. Second, the multiple equilibria offers a theoretical rationale for the mixed empirical evidence surrounding the effects of labor market interventions on innovations, such as non-compete clause (e.g., Werner, 2023; Lee, 2024). In our framework, seemingly similar interventions can have opposing effects on innovations and financial markets depending on whether the economy is in the high-tech or low-tech equilibrium.

As an extension, 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] Opaque technology induces the following tradeoff for the firm. On one hand, opacity renders the market maker's pricing strategy inelastic to the true technology level, thereby encouraging the engineer's technology development. This effect is demonstrated by the existing theoretical studies, such as Banerjee and Breon-Drish (2020), Xiong and Yang (2023), and Aoyagi (2025). In our model, the firm in the low-tech equilibrium is better off by this technology improvement, as opacity helps mitigate the incentive misalignment. On the other hand, the opacity gives birth to the high-tech equilibrium, involving inefficiently large-scale in-

[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 importance of opacity in their technology investments (*The Wall Street Journal*: "Trading Tech Accelerates Toward Speed of Light," August 2016).

novation and lower firm utility. This belief-driven cost of opacity is a unique feature of our model, which helps explain the optimality of transparent and opaque innovations within a unified framework.[6]

Finally, while our benchmark discussion focuses on an engineer developing proprietary trading technology, the core mechanism extends beyond this specific mode of trading-edge acquisition. More generally, our model captures the internal generation of firm-specific information through human capital. The model equally applies to a setting in which an information analyst generates signals through proprietary data analysis, provided that the resulting information is used exclusively within the firm. In contrast to third-party information or technology vendors, who operate as monopolists by serving multiple clients (as described in Admati and Pfleiderer, 1986 and subsequent studies), our structure features bilateral monopoly between the firm and the human capital, which in turn sows the seed for overinvestment in trading edges.

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. Within these frameworks, 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). Our model shifts the focus to the strategic complementarity between engineers and market makers, providing a novel framework to explain massive technology investments as a result of self-fulfilling multiple equilibria.

The literature following Admati and Pfleiderer (1986, 1988, 1990) introduces an information seller but typically assumes a monopolistic seller who is

[6] In the existing studies, an additional market structure must be introduced to generate costs of opacity and to support the transparent information acquisition. For example, Xiong and Yang (2023) demonstrate that opaque information acquisition is costly when a market involves competition among multiple informed traders.

endowed with information and offering take-it-or-leave-it contracts to traders. Veldkamp (2006) describes frenzies in a perfectly competitive information market driven by decreasing average costs of information production. These models, however, highlight the non-rival nature of informational services, a feature that does not extend to financial technologies or tech workers intended for exclusive use by a single trading firm. Our model explicitly incorporates incentive misalignment and explores overinvestment in such trading edges when the firm acquires it through firm-specific human capital.

A broader 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, 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 and demonstrates the possibility of Pareto inefficient overinvestments in technology.

The rest of the paper proceeds as follows. Section 2 presents a baseline model with transparent technology, and Section 3 explores its equilibrium. Section 4 introduces opaque technology, and Section 5 considers the firm's choice between transparent and opaque technology innovation. Section 6 provides dicussions. The Appendix contains all proofs for the theoretical results.

2 Model

This section presents a baseline model with four risk-neutral agents: a trading firm, an engineer, a market maker, and a noise trader.[7] In the financial market, a single risky asset is traded. The asset's payoff, δ, is realized in the end of

[7]Following the convention, we assume that competitive market makers exist, while only one of them actively executes incoming orders on the equilibrium path. It ensures the competitive price, as other market makers would undercut any non-competitive prices off the equilibrium path.

the game and follows a normal distribution with mean $\bar{\delta}$ and variance σ_δ^2. The trading firm, upon hiring the engineer, receives a noisy signal about the asset's payoff, $s = \delta + \epsilon$, where the noise term, ϵ, is normally distributed with mean 0 and variance σ_ϵ^2.

Technology. We model technology as the precision of the firm's noisy signal and define the level of technology by $\varphi \equiv \mathrm{SD}[\delta]/\mathrm{SD}[s] = \sqrt{\sigma_\delta^2/(\sigma_\delta^2 + \sigma_u^2)}$. It measures how much uncertainty in δ is resolved by observing the signal and is directly related to the signal precision, σ_ϵ^{-2}.[8] The engineer in the technology development stage controls $\varphi \in [0, 1]$ by incurring the *development cost* $C_e(\varphi) = c_e\varphi^2$ with $c_e > 0$.[9] It 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, we assume that φ is observable to the trading firm through its direct communications with the engineer. In this section, we consider the benchmark model where φ is transparent and is observable also to the market maker. Section 4, in contrast, analyzes *opaque* technology by assuming that φ is not observable to the market maker.

Bargaining. Upon observing φ, the firm decides whether to hire the engineer at wage w. The wage level is determined through the Nash bargaining between the engineer and the firm, where they have bargaining power $\gamma \in (0, 1)$ and $1-\gamma$, respectively.[10] We assume that the bargaining process involves two rounds.[11]

[8] The engineer actually controls σ_ϵ^2, while it corresponds one-to-one with determining φ. Hence, for notational simplicity, we henceforth assume that she controls φ.

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

[10] We assume that the negotiation happens after the engineer develops technology. 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 technology level 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] Alternatively, we may assume that the engineer and the firm engage in infinite repetetion of bargaining, where the asset's payoff is revealed to public in the end of each bargaining

If they fail to agree in the first round, the firm may incur a renegotiation cost, $\xi > 0$, and set up the second-round bargaining with the engineer. ξ captures the labor market frictions and can be interpreted as the cost to retain the engineer in the bargaining process. If the second round fails again, we assume that the third round would result in zero payoffs for both parties. This could be due to technology becomes obsolete, i.e., multiple rounds of negotiation take time, and the engineer's technology becomes no longer relevant by the end of the third round. If they reach an agreement, the firm pays w and receives the signal, s. Otherwise, the firm does not observe s and, due to the lack of informational advantages, stays inactive in the subsequent trading stage.

Financial market. In the process of extracting and trading on the signal, the firm incurs the *maintenance cost* of the technology, $C_f(\varphi) = c_f\varphi^2$ with $c_f > 0$. 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 the technology level, φ, reflecting the fact that more sophisticated technologies require a higher maintenance cost.[12] The trading stage is based on Kyle (1985), where the risky asset is traded among the firm, the market maker, and the noise trader. The trading firm places a market order for $x \in \mathbb{R}$ units of the asset to maximize its conditional expected profit:

$$\pi(s) = \max_x \mathrm{E}[(\delta - p)x|s]. \tag{2.1}$$

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

$$y = x + u, \tag{2.2}$$

where $u \sim N(0, \sigma_u^2)$ represents a random market order from the noise trader. As in the standard Kyle (1985) model, the order flow conveys information

period with some probability.

[12]Both the technology development and maintenance costs are assumed to be quadratic in φ for tractability, while the main results are robust to generalizaing cost functions, as long as they are weakly convex in φ and satisfy several regularity conditions.

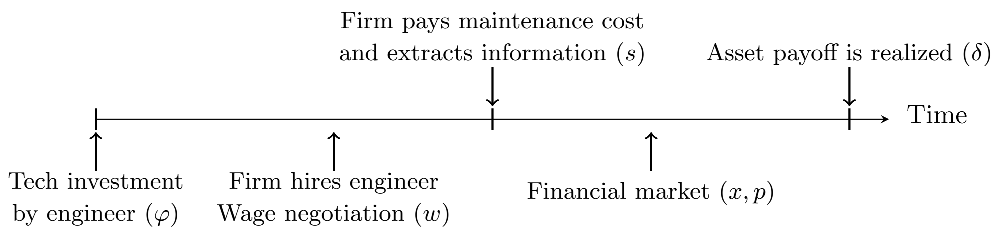


Figure 1: Timing of Events

about δ to the market maker, leading to the semi-strong efficient price:

$$p = \mathrm{E}[\delta|y]. \tag{2.3}$$

Incorporating the maintenance cost, the firm's unconditional net expected trading profit, $\mathrm{E}[\pi(s)] - c_f\varphi^2$, is split between the firm and the engineer through the wage transfer.

Timing and utility. The timing of the events is summarized in Figure 1, and the model unfolds as follows:

1. (Technology development.) The engineer chooses the technology level, $\varphi \in [0, 1]$, incurring the development cost, $c_e\varphi^2$.
2. (Hiring and bargaining.) The firm observes φ and decides whether to hire the engineer. If the firm hires the engineer, they negotiate over the wage, w, through Nash bargaining. If they agree on w, the firm pays the wage and moves on to the trading stage.
3. (Trading.) The firm pays the maintenance cost, $c_f\varphi^2$, extracts the private signal, s, and engages in the asset trading. In the end of the trading stage, the asset's payoff, δ, is realized.

In the end of the game, the trading firm obtains its utility from the trading profit, net of the maintenance cost and the wage payment, defined as $U_f = \pi(s) - c_f\varphi^2 - w$. Conversely, the engineer derives her utility from the wage after incurring the development cost, $U_e = w - c_e\varphi^2$. Note that the market maker breaks even, and the noise trader's expected utility (defined in Section 4) mirrors the adverse selection cost imposed by the trading firm.

Equilibrium. The equilibrium of our model is defined as follows:

Definition 1. *The equilibrium consists of the technology level (φ), the firm's hiring decision, the wage level (w), the firm's trading strategy (x), and the asset's price (p), such that, (i) the engineer chooses φ to maximize her expected utility, $\mathrm{E}[U_e]$, (ii) the firm chooses whether to hire the engineer and selects the trading strategy to maximize its expected utility, $\mathrm{E}[U_f]$, (iii) the wage maximizes the Nash product of the firm's and the engineer's surplus at the bargaining stage; (iv) the market maker sets the price according to (2.3), and (v) every agent' belief about other agents' behavior is consistent.*

In what follows, we impose the following parameter restrictions:

Assumption 2.1. *(i) The renegotiation cost satisfies $\xi < \hat{\xi} \equiv \frac{(1-\gamma)\sigma_\delta^2\sigma_u^2}{16\gamma c_f}$.*
(ii) The firm's marginal maintenance cost satisfies $c_f > \max\{2c_e, \frac{\sigma_\delta\sigma_u}{2}\}$.

The renegotiation cost, ξ, exogenously reduces the outside option for the firm and puts the engineer in a stronger bargaining position. A substantially high ξ leads to a high wage and discourages the firm from hiring, resulting in no equilibrium. The first assumption restricts such high wages. Conditions on c_f are to avoid a corner solution ($\varphi = 1$) and to focus on interesting equilibrium scenarios.[13]

Remarks. Unlike the one-sided monopoly structure in Admati and Pfleiderer (1986) or the perfectly competitive information market in Veldkamp (2006), where information is treated as a non-rival tradable good, our setting involves firm-specific human capital and the proprietary technology it generates. Because such human capital cannot be easily redeployed or used across multiple firms (due to NDA or non-compete clause), the interaction between a firm

[13]The assumptions on c_f are innocuous, and relaxing them yields equilibrium patterns covered as sub-cases in the analyses below.

and a worker is described by a bilateral monopoly (e.g., Acemoglu and Pischke, 1999). Although our main discussion attributes the firm's trading edge to information technology, the implications of the non-binding contract and asymmetric bargaining power for equilibrium outcomes extend more broadly to trading-edge acquisition via hiring human capital, whether for information or for speed technology.

3 Transparent Technology

We first study the benchmark case with transparent technology. The level of technology developed by the engineer and observed by the firm is denoted by φ. In contrast, the market maker is rational and can compute the equilibrium technology level, denoted as φ^*. She knows that that φ^* is chosen in equilibrium, and it is assumed to be common knowledge among all market participants. When technology is transparent and observable to the market maker, $\varphi = \varphi^*$ always holds. Nonetheless, we distinguish φ^* from φ for the sake of analyses in Section 4, where technology opacity prevents the market maker from observing φ, and $\varphi^* = \varphi$ may not hold off the equilibrium path.

3.1 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

$$x = \beta\varphi^2(s - \bar{\delta}). \tag{3.1}$$

Namely, the firm's strategy is determined by the trading intensity, $\beta > 0$, multiplied by the firm's informational advantage over the market maker, $\varphi^2(s - \bar{\delta})$.[14]

[14] The linear filtering yields $\mathrm{E}[\delta|s] = \bar{\delta} + \varphi^2(s - \bar{\delta})$, suggesting that the difference between the firm's conditional expectation and the market maker's expectation about the asset's payoff is $\mathrm{E}[\delta|s] - \mathrm{E}[\delta] = \varphi^2(s - \bar{\delta})$.

Given the trading strategy (3.1), the semi-strong efficient price in (2.3) is computed by following the linear filtering rule:

$$p = \bar{\delta} + \lambda(\varphi^*)y, \tag{3.2}$$

where

$$\lambda(\varphi^*) = \frac{\beta\varphi^{*2}\sigma_\delta^2}{\beta^2\varphi^{*2}\sigma_\delta^2 + \sigma_u^2}. \tag{3.3}$$

Coefficient λ represents the price impact of order flow. It increases with the equilibrium technology level, φ^*, and the trading intensity of the firm, β, as both factors exacerbate adverse selection either through a large informational advantage of the firm or its aggressive trading. As a high λ causes a large price reaction to changes in order flow, it represents an illiquid financial market.

Incorporating the market maker's pricing strategy in (3.2), the trading firm maximizes its expected utility, which is equivalent to the expected trading profit, as the wage and the maintenance cost are sunk at the trading stage:

$$\max_x \mathrm{E}[(\delta - p)x|s] = \max_x \left(\mathrm{E}[\delta|s] - \bar{\delta} - \lambda x\right) x. \tag{3.4}$$

The conditional expected payoff is $\mathrm{E}[\delta|s] = \bar{\delta} + \varphi^2(s - \bar{\delta})$, and the first-order condition of (3.4) yields the optimal trading strategy as follows:

$$x = \frac{\varphi^2}{2\lambda(\varphi^*)}(s - \bar{\delta}). \tag{3.5}$$

The expression in (3.1) is consistent with (3.5) when

$$\beta = \frac{1}{2\lambda(\varphi^*)}. \tag{3.6}$$

Solving (3.3) and (3.6), x and p are characterized by

$$\beta = \frac{\sigma_u}{\sigma_\delta\varphi^*}, \tag{3.7}$$

and

$$\lambda = \frac{\sigma_\delta}{2\sigma_u}\varphi^*. \tag{3.8}$$

Moreover, the firm earns the following expected trading profit conditional on its private signal:

$$\pi(s) = \frac{\varphi^4 (s - \bar{\delta})^2}{4\lambda(\varphi^*)}. \tag{3.9}$$

The numerator represents the firm's (quadratic) informational advantage over the market maker, while the denominator implies that the firm holds back from trading aggressively when the price impact is high, lowring the expected profit. Similarly, the unconditional expected profits of the firm is given by

$$\bar{\pi} \equiv \mathrm{E}[\pi(s)] = \frac{\sigma_\delta \sigma_u}{2} \frac{\varphi^2}{\varphi^*}. \tag{3.10}$$

Therefore, the engineer's choice of technology (φ) directly contributes to the trading profits by expanding the firm's informational advantage, while the equilibrium technology level (φ^*) reduces the expected profit by increasing the price impact through the market maker's reaction.

3.2 Wage Negotiation

Given the net trading profit, $\bar{\pi}$, the firm and the engineer engage in negotiation to pin down the wage transfer. In the first round of negotiation, they solve the following Nash bargaining problem:

$$\max_w \, (w - z_e)^\gamma \left(\bar{\pi} - c_f \varphi^2 - w - z_f\right)^{1-\gamma}, \tag{3.11}$$

where z_e and z_f represent endogenous outside options that the engineer and the firm would obtain if the first-round bargaining fails. Note that the engineer's development cost, $c_e\varphi^2$, does not appear in (3.11), as it has been sunk at this stage.

The outside options, z_e and z_f, are endogenously derived from the second-round bargaining. The firm and the engineer in the second raount would negotiate over wage w' to solve the following problem, noting that their outside options are zero if they fail to agree:

$$\max_{w'} w'^{\gamma} \left(\bar{\pi} - c_f \varphi^2 - w'\right)^{1-\gamma}. \tag{3.12}$$

As the second-round bargaining would always succeed with $w' = \gamma(\bar{\pi} - c_f \varphi^2)$, the outside options for the firm and the engineer, after incorporating the renegotiation cost, become

$$\begin{aligned} z_f &= (\bar{\pi} - c_f \varphi^2) - w' - \xi \\ &= (1-\gamma)(\bar{\pi} - c_f \varphi^2) - \xi, \end{aligned} \tag{3.13}$$

and

$$z_e = w' = \gamma(\bar{\pi} - c_f \varphi^2). \tag{3.14}$$

respectively. Incorporating these options, the first-round bargaining in (3.11) pins down the following equilibrium wage:

Lemma 3.1. *In the bargaining process, the firm and the engineer agree on the following w at the first round.*

$$w = \gamma\left(\xi + \bar{\pi} - c_f \varphi^2\right). \tag{3.15}$$

The wage transfer to the engineer consists of the constant payment in the first term, $\gamma\xi$, and the portion of the trading profit, $\gamma(\bar{\pi} - c_f \varphi^2)$. The constant term arises from the renegotiation cost, ξ: it imposes a cost on the firm to retain the engineer and exogenously lowers the firm's outside option. The fixed payment also increases when the engineer gains stronger bargaining power (γ), while it also determines the split of the net trading profits between the two parties.

3.3 Expected Utility

Based on the result in the wage bargaining and the financial market, the *ex-ante* expected utility of the firm and the engineer is derived as follows:

$$\begin{aligned}\bar{U}_f &= \mathrm{E}\left[\pi(s) - w - c_f\varphi^2\right]\\ &= (1-\gamma)\left(\frac{\sigma_\delta\sigma_u}{2\varphi^*} - c_f\right)\varphi^2 - \gamma\xi, \end{aligned}\tag{3.16}$$

and

$$\begin{aligned}\bar{U}_e &= \mathrm{E}\left[w - c_e\varphi^2\right]\\ &= \gamma\xi + \left(\frac{\gamma\sigma_\delta\sigma_u}{2\varphi^*} - \gamma c_f - c_e\right)\varphi^2, \end{aligned}\tag{3.17}$$

where $\bar{U}_j$ denote the unconditional expected utility of the firm ($j = f$) and the engineer ($j = e$), i.e., $\bar{U}_j = \mathrm{E}[U_j]$. Note that the equilibrium technology level, φ^*, negatively influences the expected trading profits through a hightened price impact, lowering the utility of the firm and the engineer. However, in the case of transparent technology, technology development by the engineer is observable to the market maker, and $\varphi = \varphi^*$ always holds both on and off equilibrium paths. Hence, (3.16) and (3.17) reduce to

$$\bar{U}_f = (1-\gamma)\frac{\sigma_\delta\sigma_u}{2}\varphi - (1-\gamma)c_f\varphi^2 - \gamma\xi, \tag{3.18}$$

and

$$\bar{U}_e = \gamma\xi + \frac{\gamma\sigma_\delta\sigma_u}{2}\varphi - (\gamma c_f + c_e)\varphi^2, \tag{3.19}$$

suggesting that the benefit of obtaining a larger informational advantage outwighs the negative impact of a hightened price impact.

Under transparency, the individually optimal technology levels for the firm and the engineer are given by $\varphi_f \equiv \frac{\sigma_\delta\sigma_u}{4c_f}$ and $\varphi_e \equiv \frac{\gamma\sigma_\delta\sigma_u}{4(\gamma c_f + c_e)}$, respectively, while the joint surplus for the contracting parties is maximized at $\varphi_v \equiv \frac{\sigma_\delta\sigma_u}{4(c_f + c_e)}$. Therefore, the engineer's optimal technology level is lower than both φ_f and φ_v. This underinvestment arises from incentive misalignment, since the engineer alone bears the development cost (c_e). On top of that, the hold-up problem exacerbates the issue: knowing that the engineer captures only γ fraction of the net trading profit, she is discouraged to develop technology.

3.4 Hiring Decision

At the hiring decision, the trading firm anticipates to obtain $\bar{U}_f$ in equation (3.18) by hiring the engineer, while it receives zero utility if it does not hire. Therefore, the firm is willing to hire the engineer if $\bar{U}_f \geq 0$ holds. We refer to this condition as the *hiring condition.* From (3.18), it is equivalent to

$$\varphi_L \leq \varphi \leq \varphi_H, \tag{3.20}$$

where $\{\varphi_L, \varphi_H\}$ are the solutions to $\bar{U}_f = 0$ and given by[15]

$$\begin{aligned} \varphi_L &= \frac{\sigma_u \sigma_\delta}{4c_f}\left(1 - \sqrt{1 - \frac{16c_f \xi \gamma}{\sigma_u^2 \sigma_\delta^2 (1-\gamma)}}\right), \\ \varphi_H &= \frac{\sigma_u \sigma_\delta}{4c_f}\left(1 + \sqrt{1 - \frac{16c_f \xi \gamma}{\sigma_u^2 \sigma_\delta^2 (1-\gamma)}}\right). \end{aligned} \tag{3.21}$$

3.5 Technology Development

The engineer's optimization problem in the technology-development stage is described by

$$\max_{\varphi \in [\varphi_L, \varphi_H]} \bar{U}_e, \tag{3.22}$$

with $\bar{U}_e$ in (3.19), and the hiring condition is summarized by $\varphi \in [\varphi_L, \varphi_H]$. The engineer never selects technology levels that violate the hiring condition, as she loses her wage income and always experiences non-positive utility due to the development cost.[16]

Since the engineer's expected utility in (3.19) exhibits a single-peaked curve in relation to φ, the equilibrium technology level, φ^*, is determined either by

[15] Assumption 2.1 ensures that $0 < \varphi_L < \varphi_H < 1$.

[16] Assumption 2.1 ensures $\mathrm{E}[U_e] > 0$ and that the engineer's participation condition is always slack in the following equilibrium.

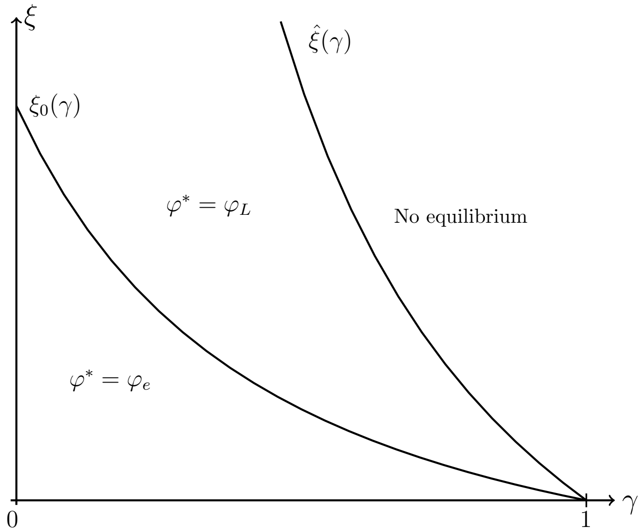


Figure 2: Equilibrium Technology Level (Transparent)

Note: The figure characterizes the equilibrium technology level in Proposition 3.1 by ξ and γ, where the boundaries represent $\hat{\xi}$ in Assumption 2.1 and ξ_0 in (3.24).

her unconstrained optimum level or by the binding hiring condition:

Proposition 3.1. *A unique equilibrium exists, where the technology level is*

$$\varphi = \varphi^* = \begin{cases} \varphi_e \equiv \frac{\gamma \sigma_u \sigma_\delta}{4(c_e + \gamma c_f)} & \textit{if } \xi \leq \xi_0, \\ \varphi_L & \textit{if } \xi > \xi_0, \end{cases} \tag{3.23}$$

with the threshold of the renegotiation cost being

$$\xi_0 \equiv \frac{\sigma_u^2 \sigma_\delta^2 (1-\gamma)(\gamma c_f + 2c_e)}{16(\gamma c_f + c_e)^2}. \tag{3.24}$$

Figure 2 illustrates the equilibrium characterization by the renegotiation cost, ξ, and the bargaining power of the engineer, γ. It suggests that the hiring condition is binding ($\varphi^* = \varphi_L$) when the renegotiation cost is relatively large, $\xi > \xi_0$.[17] Although ξ appears only as the fixed salary in the engineer's

[17]The upper threshold of the hiring condition, φ_H, does not constrain the engineer's

utility and does not influence the engineer's unconstrained optimal level, it lowers the firm's utility by making it costly to retain the engineer. Hence, it tightens the hiring condition, and the minimum level required for hiring (φ_L) increases. Consequently, the engineer deviates from her unconstrained optimal level (φ_e) and is forced to bring the technology level up to the required level for hiring. Also, the threshold value, ξ_0, is monotonically decreasing in γ, as strong engineer bargaining power pushes the firm's utility downward, thereby tightening the hiring condition with ξ being fixed.

Overall, the benchmark model admits two types of unique equilibrium, depending on the renegotiation cost and the engineer's bargaining power. These factors capture labor market conditions, such as demand for financial engineers and labor mobility, thereby linking the financial technology development to the labor market condition in the finance industry. The results indicate that favorable bargaining positions for engineers foster more intensive technology development, which in turn boosts the firm's trading profits but does not necessarily improve its net utility once technology and labor costs are incorporated.

4 Opaque Technology

This section demonstrates that opacity in technology levels lead to overengineering in the sense of Pareto efficiency. For clarity, the equilibrium in this section is referred as the *opaque* equilibrium, while that in Section 3 is referred to as the *transparent* equilibrium.

When technology is opaque, φ is not observable to the market maker. Nevertheless, she rationally computes and anticipates the equilibrium technology level, φ^*, as it is a deterministic and constant level the engineer would choose. Thus, we search for equilibrium in which, along the path toward that equilibrium, the engineer actually chooses $\varphi = \varphi^*$ as her optimal response to the market's common knowledge of φ^*, while no restrictions are imposed on

choice in the benchmark model, as the technology level at φ_H is too high from both players' perspectives, i.e., $\varphi_e < \varphi_H$ always holds.

the engineer's choice off the path, meaning that they may deviate from each other. Importantly, in the hiring decision and the technology development stage, technology opacity prevents the firm and the engineer from influencing the price impact through driving the market maker's belief.[18] Accordingly, the expected utility of the firm and the engineer in equations (3.16) and (3.17) makes a distinction between the equilibrium technology level (φ^*) that the market maker anticipates and the engineer's choice (φ).

4.1 Hiring Decision

Given the equilibrium technology level, the hiring condition restricts the engineer's choice of φ. Rearranging the condition $\bar{U}_f \geq 0$, we obtain

$$\varphi \geq H(\varphi^*) \equiv \sqrt{\frac{\gamma}{1-\gamma}\frac{2\xi\varphi^*}{\sigma_u\sigma_\delta - 2c_f\varphi^*}}. \tag{4.1}$$

As in Section 3, it imposes the minimum technology level required for hiring. Importantly, however, this lower bound, $H(\varphi^*)$, is an increasing function of φ^*, suggesting that the firm requires a higher technology level when the market maker rationally anticipates a high equilibrium technology level. Intuitively, such a belief induces the market maker to sets a high price impact to counteract severe adverse selection (see [3.8]). Given the engineer's choice, φ, this hightened price impact reduces the firm's expected trading profit and tightens the hiring condition, resulting in a higher technology level required for hiring.

[18]The firm and the engineer do not have a comitmment device and cannot convey signals about φ to the market maker in a credible manner. Even if the engineer deviates from the equilibrium technology level, which happens off the equilibrium path, it does not affect the market maker's computation of φ^* through the noisy order flow, $x+u$, as there always exists a realization of noise, u, that makes the order flow consistent with φ^*.

4.2 Technology Development

The engineer at the technology development stage maximizes her expected utility in (3.17) following the hiring condition:

$$\max_{\varphi} \bar{U}_e = \max_{\varphi} \gamma\xi + \left(\frac{\gamma\sigma_\delta\sigma_u}{2\varphi^*} - \gamma c_f - c_e\right)\varphi^2, \tag{4.2}$$
$$\text{s.t. } \varphi \geq H(\varphi^*).$$

When the technology is opaque, the engineer cannot lead the market maker's belief about the equilibrium technology level, nor can she internalize the adverse effect of a stronger price impact on the marginal utility of technology development. Consequently, the engineer's marginal utility does not diminish as φ increases.

Marginal utility. Based on (4.2), the engineer benefits from increasing the technology level if, and only if, the following condition holds:

$$\varphi^* \leq \varphi_M \equiv \frac{\gamma\sigma_\delta\sigma_u}{2(\gamma c_f + c_e)}, \tag{4.3}$$

where subscript "M" indicates that the engineer's marginal utility becomes zero at $\varphi^* = \varphi_M$. If the above inequality holds, the price impact stays weak so that a marginal increase in φ is beneficial to the engineer. Otherwise, the expected profit margin becomes too small to cover the marginal maintenance and development costs due to a hightened price impact, leading to the negative marginal utility of technology development.

Participation condition. When inequality (4.3) is violated, the engineer may suffer from a negative utility at high levels of φ^*, as the technology-related costs outweighs the small trading profits. Thus, under $\varphi^* > \varphi_M$, we incorporate the engineer's participation condition, $\bar{U}_e \geq 0$. It reduces to the following upper limit of the technology level:

$$\varphi \leq \Omega(\varphi^*) \equiv \sqrt{\frac{2\gamma\xi\varphi^*}{2(\gamma c_f + c_e)\varphi^* - \gamma\sigma_\delta\sigma_u}}. \tag{4.4}$$

Ω, is monotonically decreasing in φ^*, as it increases the price impact and makes it harder for the engineer to maintain positive utility through technology development.

On the one hand, when the equilibrium technology level is high, the hiring requirement (4.1) tightens, i.e., $H(\varphi^*)$ is monotonically increasing in φ^*. On the other hand, $\Omega(\varphi^*)$ is monotonically decreasing in φ^*, suggesting that deriving positive utility from such high-level technology becomes increasingly difficult for the engineer due to a hightened price impact. When φ^* is sufficiently high, $H(\varphi^*) > \Omega(\varphi^*)$ may hold, meaning that no technology level satisfies both the hiring and the participation conditions. In other words, the engineer develops technology in the equilibrium only if φ^* is relatively low to ensure $H(\varphi^*) < \Omega(\varphi^*)$, which reduces to the following cutoff:

$$\varphi^* < \varphi_N \equiv \frac{\sigma_\delta\sigma_u}{2(c_f + c_e)}. \tag{4.5}$$

Subscript "N" indicates that φ_N imposes the threshold such that the engineer chooses not to participate, resulting in no technology development ($\varphi = 0$).

Best-response technology level. Summarizing conditions (4.3)–(4.5), the engineer's optimal technology development is characterized by the following best-response function to the market maker's belief about the equilibrium technology level.

Lemma 4.1. *The optimal technology level for the engineer is given by*

$$\varphi = B(\varphi^*) \equiv \begin{cases} 1 & \text{if } \varphi^* < \varphi_M, \\ \in [0, H(\varphi^*)] & \text{if } \varphi^* = \varphi_M, \\ H(\varphi^*) & \text{if } \varphi_M < \varphi^* < \varphi_N, \\ 0 & \text{if } \varphi_N \le \varphi^*, \end{cases} \tag{4.6}$$

where the second line suggests that the engineer is indifferent between all $\varphi \in [0, H(\varphi^*)]$.

4.3 Equilibrium

In equilibrium, the engineer's choice of the technology level, characterized by (4.6), must be consistent with the market maker's belief about its equilibrium level, imposing $\varphi = \varphi^*$. Therefore, given the engineer's best-response function in Lemma 4.1, φ^* is determined by the solutions to the fixed point problem:

$$\varphi^* = B(\varphi^*). \tag{4.7}$$

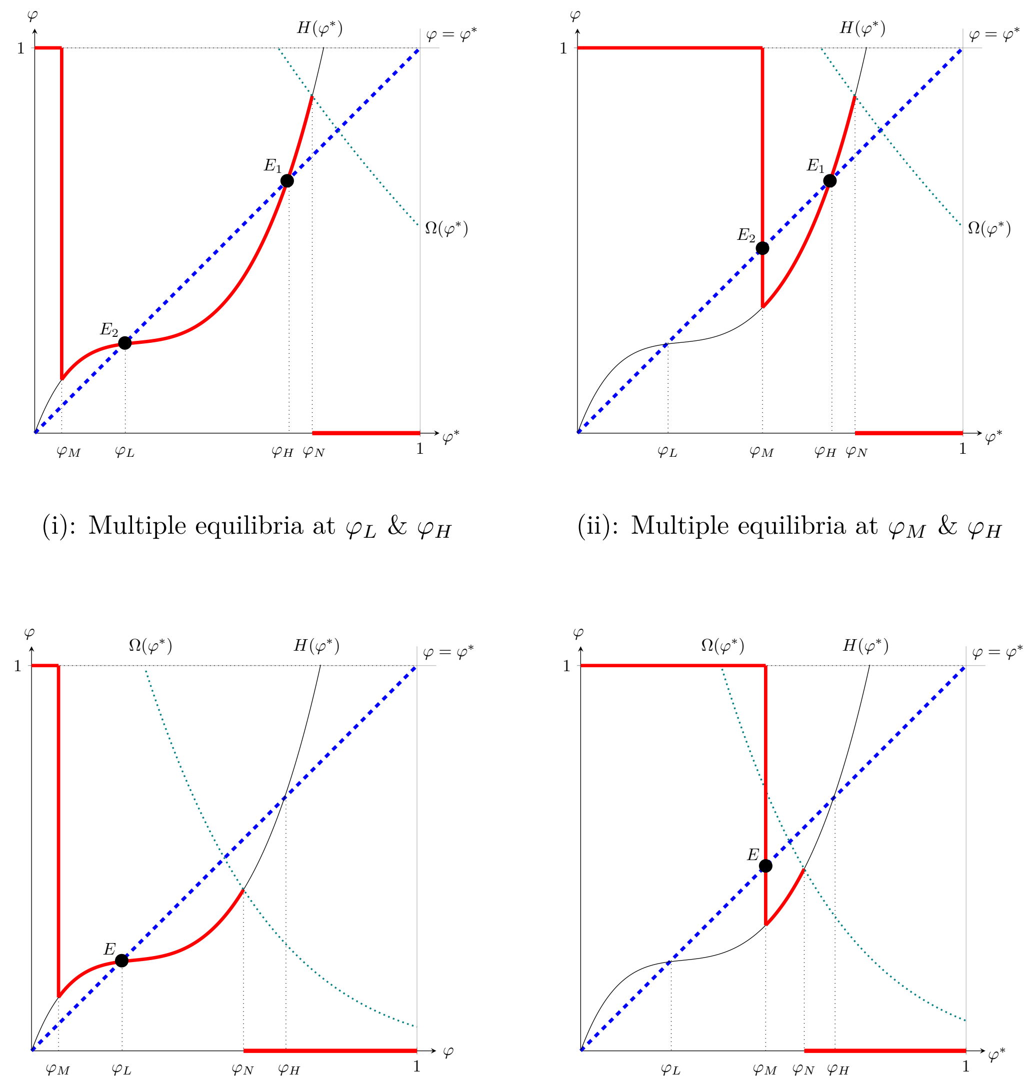
Figure 3 visualizes this problem: the red curve depicts $B(\varphi^*)$, and the blue dashed (45-degree) line suggests the belief-consistency condition in the equilibrium. It shows the possibility of different equilibria depending on the cutoffs and parameter values. Panels (i)–(iv) correspond to the cases in Proposition 4.1 below that guarantee the existence of equilibrium.

Proposition 4.1. *When technology is opaque, there are five equilibrium cases depending on the relative positions of $\varphi_L, \varphi_H, \varphi_M$, and φ_N.*

(i) If $\varphi_M < \varphi_L < \varphi_H < \varphi_N$, there are multiple equilibria with self-fulfilling beliefs, one with $\varphi^* = \varphi_L$ and the other with $\varphi^* = \varphi_H$.

(ii) If $\varphi_L < \varphi_M < \varphi_H < \varphi_N$, there are multiple equilibria with self-fulfilling beliefs, one with $\varphi^* = \varphi_M$ and the other with $\varphi^* = \varphi_H$.

(iii) If $\varphi_M < \varphi_L < \varphi_N < \varphi_H$, there is a unique equilibrium with $\varphi^* = \varphi_L$.



(i): Multiple equilibria at φ_L & φ_H

(ii): Multiple equilibria at φ_M & φ_H

(iii): Unique equilibrium at φ_L

(iv): Unique equilibrium at φ_M

Figure 3: Equilibrium Technology Level (Opaque)

Note: The red lines represent the best-response technology level by the engineer given by $\varphi = B(\varphi^*)$ in equation (4.6). The belief-consistency condition, $\varphi = \varphi^*$, is depicted by the blue dashed lines. Each black dot represents equilibrium. The numbers of panels correspond to the cases in Proposition 4.1.

(iv) If $\varphi_L < \varphi_M < \varphi_N < \varphi_H$, there is a unique equilibrium with $\varphi^* = \varphi_M$.

(v) If $\varphi_H < \varphi_M$, there is no equilibrium.

The key feature of the engineer's best-response technology development, $\varphi = B(\varphi^*)$, is the upward-sloping curve arising from the binding hiring condition, i.e., $B(\varphi^*) = H(\varphi^*)$ with $\frac{dH(\varphi^*)}{d\varphi^*} > 0$. This represents the strategic complementarity between the engineer's technology development and its equilibrium level anticipated by the market maker. Intuitively, when φ^* is high, the order flow is highly informative and thus incurs a strong price impact. Given the engineer's choise, φ, the firm faces a small expected trading profit and is discouraged to hire the eigneer, as captured by an increase in the minimum technology level required for hiring. To meet the hiring condition, the engineer responds to high φ^* by actually developing high-level technology. It provides the firm with a large informational advantage and restores its hiring incentive.

An 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 the market maker, for whatever reason, believes that $\varphi^* = \varphi_H$ is realized in the equilibrium, it becomes optimal for the engineer to actually choose this high technology level, supporting it as an equilibrium. As the same logic supports an equilibrium with a relatively low level 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 level in the transparent benchmark corresponds to the low-tech equilibrium, as confirmed by the convergence of φ_M to φ_E when the engineer internalizes the price impact.

By rewriting the conditions in Proposition 4.1, we formalize how contractual conditions between the firm and the engineer influence equilibrium types.

Corollary 4.1. *Define the following cutoffs.*

$$\xi_1(\gamma) \equiv \frac{(1-\gamma)c_e\sigma_\delta^2\sigma_u^2}{4\gamma(c_f+c_e)^2}, \tag{4.8}$$

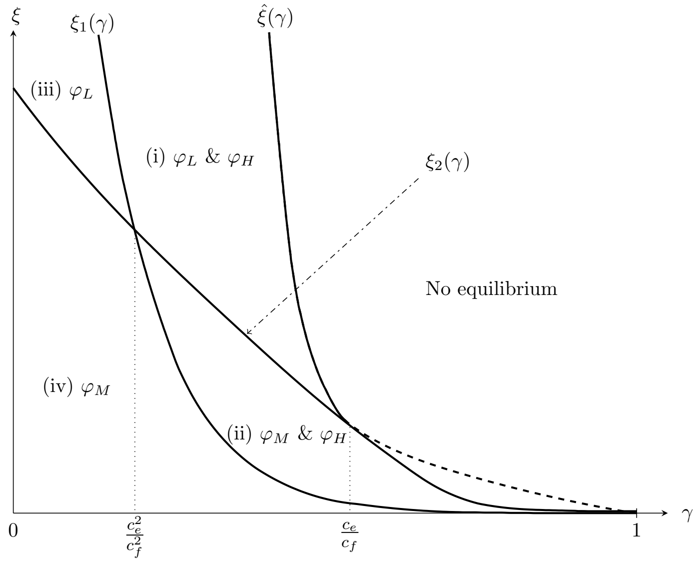


Figure 4: Equilibrium Types and Labor Market Conditions

Note: This figure plots thresholds, $\bar{\xi}, \xi_1, \xi_2$ and $\gamma_0, \gamma_1, \gamma_2$, that characterize equilibrium types in Proposition 4.1. The number of each region corresponds to that in the proposition, and the gray area admits multiple equilibria.

and

$$\xi_2(\gamma) \equiv \frac{(1-\gamma)c_e\sigma_\delta^2\sigma_u^2}{4(\gamma c_f + c_e)^2}. \tag{4.9}$$

The opaque equilibrium in Proposition 4.1 is characterized by γ and ξ as follows:

(i) If $\gamma \in \left[0, \frac{c_e}{c_f}\right]$ and $\max\{\xi_1, \xi_2\} < \xi < \bar{\xi}$, then case (i) of Proposition 4.1 is realized.

(ii) If $\gamma \in \left[\frac{c_e^2}{c_f^2}, 1\right]$ and $\xi \in [\xi_1, \xi_2]$, then case (ii) of Proposition 4.1 is realized.

(iii) If $\gamma \in \left[0, \frac{c_e^2}{c_f^2}\right]$ and $\xi \in [\xi_2, \xi_1]$, then case (iii) of Proposition 4.1 is realized.

(iv) If $\xi < \min\{\xi_1, \xi_1\}$, case (iv) of Proposition 4.1 is realized.

(v) Otherwise, there is no equilibrium.

As in the transparent case, no equilibrium exists when the renegotiation cost (ξ) and the engineer's bargaining power (γ) are very high. Similarly, the intuition behind the unique equilibrium in regions (iii) and (iv) is analogous to the transparent equilibrium in Section 2 and Figure 2.

By contrast, opacity in technology development leads to multiple equilibria with the possibility of excessive technology investment 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, $\varphi^* = H(\varphi^*)$, that leads to the strategic complementarity between the engineer's choice of φ and the market maker's belief, φ^*. When the renegotiation 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 wage negotiation. Consequently, the hiring condition is more likely to bind, triggering the strategic complementarity and the multiplicity of equilibrium. Although the engineer's marginal utility is negative at φ_H, a high ξ and γ guarantee a large fixed salary, and the engineer obtains a strictly positive surplus upon being hired. Therefore, she is willing to deliver a substantially high-level technology to avoid being dismissed by the firm, though it involves a large development cost.

4.4 Market Quality

To explore implications of multiple equilibria for the financial market, we rely on the standard measures of the financial market quality. Firstly, we use the price impact, $\lambda = \frac{\sigma_\delta}{2\sigma_u}\varphi^*$, to measure market illiquidity. Secondly, the price informativeness is defined as the residual uncertainty in the asset's payoff upon observing the price:

$$\frac{\mathrm{Var}[\delta]}{\mathrm{Var}[\delta|p]} = \frac{2}{2-\varphi^{*2}}. \tag{4.10}$$

Finally, as the measure of market variations, we compute the price volatility:

$$\mathrm{Var}[p] = \frac{\sigma_\delta^2\varphi^{*2}}{2}. \tag{4.11}$$

All market quality measures are represented as a monotonically increasing function of the equilibrium technology level φ^*, leading to the following result.

Proposition 4.2. *In the high-tech equilibrium, compared to the low-tech equilibrium, the market is less liquid, and the price is more informative but more volatile.*

The market impact of the high-tech equilibrium is intuitive, as the firm trades more intensively on higher quality information generated through a more sophiticated technology compared to the low-tech equilibrium. The order flow reflects highly precise information about the asset's payoff, and the market maker updates the price substantially, leading to a high price impact. Due to the same logic, the price becomes informative about the asset's payoff. However, the price is more volatile, because both the fundamental information and noise trading are amplified in the price due to the high price impact.

4.5 Inefficiency

Building on the discussions surrounding technology investments in real financial markets, a natural question arises: Is the level of investment in the high-tech equilibrium inefficient or excessive, either from a welfare or a firm's perspective? As the market maker breaks even, the trading profit and costs arising from the technology development are split between the trading firm, the engineer, and the noise trader. We examine how this surplus allocation differs between the high-tech and low-tech equilibria.

Firstly, the firm's ex-ante expected utility is derived from (3.16):

$$\bar{U}_f(\varphi^*) = \begin{cases} 0 & \text{if } \varphi^* = \varphi_L \text{ and } \varphi_H. \\ \gamma(\xi_2(\gamma) - \xi) & \text{if } \varphi^* = \varphi_M. \end{cases} \tag{4.12}$$

When $\varphi^* = \varphi_L$ and φ_H, the hiring condition is binding, and the trading firm breaks even after paying the maintenance cost and the wage. At $\varphi^* = \varphi_M$, in contrast, the engineer is indifferent between lowering and improving φ after incorporating the development cost, suggesting that the trading firm, without incurring the development cost, earns positive utility. This is captured by the second line of (4.12), where $\varphi^* = \varphi_M$ arises only if $\xi_2 > \xi$ (Corollary 4.1).

Although the trading firm earns a larger gross trading profit in the high-tech equilibrium (see [3.10]), it is weakly better off if the economy switches from the high-tech to the low-tech equilibrium when multiple equilibria exist.

Similarly, the engineer's expected utility in (3.17) is reduced to

$$\bar{U}_e(\varphi^*) = \begin{cases} \frac{\gamma}{1-\gamma}\xi - c_e\varphi^{*2} & \text{if } \varphi^* = \varphi_L \text{ and } \varphi_H, \\ \gamma\xi & \text{if } \varphi^* = \varphi_M, \end{cases} \tag{4.13}$$

where we observe $\bar{U}_e(\varphi_H) < \bar{U}_e(\varphi_M) < \bar{U}_e(\varphi_L)$. Note that φ_H is too high and induces a negative marginal utility for the engineer. However, if the market maker believes that this technology level is realized in equilibrium, the engineer actually conforms to this belief by incurring a large development cost, as doing otherwise would cost her the job. Hence, the engineer is also better off by switching to the low-tech equilibrium.

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

$$\bar{U}_n(\varphi^*) = \mathrm{E}[(\delta - p)u] = -\frac{\sigma_u\sigma_\delta}{2}\varphi^*. \tag{4.14}$$

Due to the zero-sum nature of the trading stage, $\bar{U}_n$ represents the direct transfer of the adverse selection cost imposed on the market maker, suggesting that the firm earns profits at the expense of the noise trader. As the high-tech equilibrium induces the largest adverse selection cost, the price impact becomes the highest among three equilibria, and the noise trader experiences the lowest expected utility.

Overall, when the parameters admit multiple equilibria, the engineer and the noise trader are strictly better off if the economy switches 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 due to this switch, while the market maker is unaffected, we obtain the following result.

Proposition 4.3. *The high-tech equilibrium is Pareto inferior to other equilibria.*

This result corroborates the idea in both theoretical and policy-oriented literature that excessive investments 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 novel mechanism rooted in technology opacity and strategic complementarity between the engineer and the market maker, deriving the inefficient outcome as one of multiple equilibria.

The overinvestment arising from our mechanism offers unique insights. Namely, the inefficient high-tech equilibrium emerges as a result of self-fulfilling beliefs. Even in the absence of fundamental changes, such as those in the payoff distribution of financial assets or the productivity of financial technologies, a shift in belief alone can trigger an inefficient boom in financial innovation. This result 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 discuss below in Section 5, policy interventions in the financial labor market, such as an enforcement law of non-compete clause, can push the economy into such regions, unintentionally causing the inefficient outcome.

Furthermore, our result underscores the importance of technological advancements *outside* the financial industry. Innovations in information technologies and AI often originate in non-financial sectors such as the broader tech industry, while these developments tend to trigger major waves of technological adoption and specific-purpose innovations in finance (Jiang, Rebucci, and Zhang, 2025). According to our model, such innovations outside the financial sector can shape the market's beliefs that the equilibrium technology level is φ_H rather than φ_L or φ_M, which in turn drive excessive technology investments within the financial industry ($\varphi^* = \varphi_H$).

4.6 Comparative Statics

4.6.1 Technology and financial market

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.

Proposition 4.4. *The equilibrium technology level exhibits the following reactions to changes in the contractual conditions:*

(i) φ_H *is monotonically decreasing in the engineer bargaining power* (γ)*, while* φ_L *and* φ_M *are monotonically increasing in* γ.

(ii) φ_H *is monotonically decreasing in the renegotiation cost* (ξ)*,* φ_L *is monotonically increasing in* ξ*, and* φ_M *is independent of* ξ.

(iii) The financial market quality measures (price impact, informativeness, and volatility) respond monotonically and in the same direction to changes in φ^* *within each equilibrium regime.*

When the bargaining conditions become more favorable for the engineer, as she obtains strong bargaining power (γ) or the renegotiation cost for the firm becomes high (ξ), the firm's profit function shifts downward, discouraging its hiring of the engineer. To maintain the firm's hiring motivation, the engineer needs to adjust the technology development. 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. Thus, the engineer improves the technology level to maintain the firm's utility, leading to increases in the price impact, its volatility, and informativeness. At the high-tech equilibrium, however, φ_H is an excessive investment, and the marginal impact of further technological improvements on the firm's utility is negative. The engineer optimally lowers the technology level, leading to the opposite reactions of φ_H and financial market quality measures compared to the low-tech equilibrium.[19]

[19]The hiring cost, ξ, becomes irrelevant to the equilibrium technology level when $\varphi^* =$

Although the quality of technology itself is rarely observable to econometricians in reality, financial market prices are observable. Therefore, Proposition 4.4 offers a distinctive testable prediction linking labor market or contractual frictions in the finance industry with financial market outcomes. In particular, the reactions of the financial market differ across equilibria and can serve as an indicator of excessive technology development in the sense of Pareto efficiency. This sharply contrasts with the existing literature, which typically explains financial arms races as a unique equilibrium and infers inefficiency through counterfactual benchmarks. By contrast, our model endogenizes inefficiency through belief-driven multiple equilibria, yielding observationally distinguishable implications.

4.6.2 Engineer compensation

Would the engineer's salary also increase when overinvestment occurs? The wage transfer in the equilibrium is computed based on (3.15):

$$w(\varphi^*) = \begin{cases} \frac{\gamma\xi}{1-\gamma} & \text{when } \varphi^* = \varphi_L \text{ and } \varphi_H, \\ \gamma\xi + c_e \frac{\gamma^2 \sigma_u^2 \sigma_\delta^2}{4(\gamma c_f + c_e)^2} & \text{when } \varphi^* = \varphi_M. \end{cases} \tag{4.15}$$

Regardless of the equilibrium type, the engineer compensation is monotonically increasing in her bargaining power (γ) and the firm's renegotiation cost (ξ). Also, comparing wages in (4.15) with parameter values being fixed, it holds that $w(\varphi_M) > w(\varphi_L) = w(\varphi_H)$.[20] These results help analyze two sources of wage variation for the engineer: differences across parameter regions and those across multiple equilibria conditional on parameter values.

Firstly, Proposition 4.1 indicates that the economy with a unique low-tech equilibrium leads to modest wages for the engineer, as the equilibrium is unique only when both ξ and γ are relatively low. In contrast, when these parameters increase, not only the engineer compensation grows, but also the

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φ_M, as it affects the engineer's utility only through the fixed base salary.

[20] Direct comparison implies $w(\varphi_M) - w(\varphi_H) = \frac{\gamma^2}{1-\gamma}(\xi_2(\gamma) - \xi) > 0$, where the inequality holds because multiple equilibria with φ_M and φ_H arise only if $\xi < \xi_2(\gamma)$.

economy falls in the regions for multiple equilibria. Therefore, our findings suggest that financial engineers earn higher average wages in equilibria with inefficiently large technology investments, compared to economies where only the modest level of investment arises as the unique equilibrium. This result aligns with observations in reality: technology investment booms, such as the current surge in AI-related investment, coincide with hightened compensation of technical talent (Philippon and Reshef, 2012).

Secondly, however, conditional on the economy being in regions for multiple equilibria, and assuming that model parameters are fixed, wages in the high-tech equilibrium are paradoxically lower than in the low-tech one. This counterintuitive result reflects a form of inefficiency: in the high-tech equilibrium, innovation efforts are inefficiently excessive and driven by the market's belief that φ_H will be selected rather than φ_L or φ_M, crowding out labor compensation. While this may seem at odds with the narrative of booming tech salaries during innovation surges, our results highlight that higher equilibrium wages are driven more by the structural labor market environment (i.e., being in regions for multiple equilibria) than by the specific equilibrium selected within that environment.

5 Strategic Opacity

This section analyzes the firm's choice between the transparent and opaque technology. It uncovers the strategic incentives behind opaque innovations and offers new insights, particularly regarding the costs of opacity.

5.1 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 ($\chi = 1$). The choice over χ 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 facing multiple equilibria, 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 sunspot shock $z \in \{0,1\}$ (e.g., Diamond and Dybvig, 1983; Cooper and Ross, 1998). Namely, with $\theta \equiv \Pr(z=0)$, a spot does not appear on the sun, and the low-tech equilibrium (either φ_M or φ_L) is realized, while if it shows up with the complementary probability, the high-tech equilibrium is realized. We assume that the sun-spot shock is realized after the firm chooses χ but prior to its hiring decision.

Equilibrium. The equilibrium in this extended model consists of the baseline equilibrium defined in Definition 1, augmented by the technology's transparency regime, such that the firm chooses $\chi \in \{0,1\}$ to maximize its *ex-ante* expected utility:

$$\chi^* = \arg\max_{\chi \in \{0,1\}} \bar{U}_f, \tag{5.1}$$

where $\bar{U}_f$ under the transparent ($\chi = 0$) and opaque ($\chi = 1$) regimes is given by (3.19) and (4.12), respectively, and the expectation also accounts for the realization of the sunspot shock, z, in the presence of multiple equilibria.

5.2 Equilibrium Opacity

To compare the firm's utility in the transparent and the opaque equilibria, Figure 5 overlays Figures 2 (the transparent equilibrium) and 4 (the opaque equilibrium). Also Table 1 summarizes the technology level and the expected firm utility in both equilibria in each region specified in Figure 5.

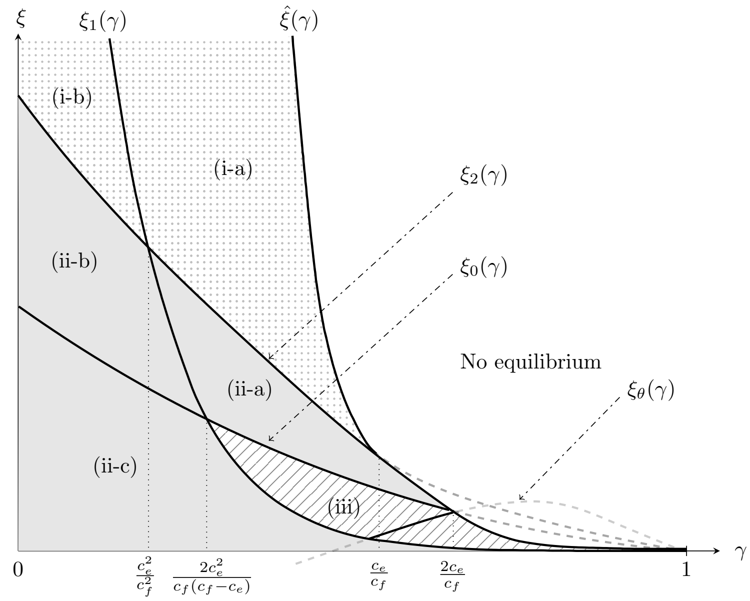

Figure 5: Endogenous Opacity

Note: The figure overlays Figures 2 and 4. 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 that the optimal χ depends on the value of θ, and the white areas suggest that no equilibrium exists in either regime. The roman numerals correspond to those in Proposition 5.1.

Proposition 5.1. *The optimal transparency regime for the firm is characterized as follows:*

(i) If $\xi \in [\xi_2, \hat{\xi}]$, then the firm is indifferent between transparent and opaque technology.

(ii) If $\xi \in [\xi_1, \xi_2]$ or $\xi \in [\max\{\xi_0, \xi_1\}, \xi_2]$, then the firm chooses opaque technology so that $\chi^* = 1$.

(iii) If $\xi \in [\xi_1, \min\{\xi_0, \hat{\xi}\}]$, there is a cutoff of the renegotiation cost, $\xi_\theta \equiv \frac{\xi_0 - \theta\xi_2}{1-\theta}$.[21] *If $\xi > \xi_\theta$, the firm chooses opaque technology, $\chi^* = 1$, and otherwise, it chooses transparent technology $\chi^* = 0$.*

[21] ξ_θ satisfies $\xi_\theta < \xi_0$ when $\gamma < \frac{2c_e}{c_f}$, while it converges to $\xi_\theta = \xi_0 = \xi_2$ at $\gamma = \frac{2c_e}{c_f}$.

Region/Regime	Technology quality		Firm's utility	
	Transparent	Opaque	Transparent	Opaque
(i-a)	φ_L	φ_L or φ_H	0	0
(i-b)	φ_L	φ_L	0	0
(ii-a)	φ_L	φ_M or φ_H	0	$\theta\gamma(\xi_2(\gamma) - \xi)$
(ii-b)	φ_L	φ_M	0	$\gamma(\xi_2(\gamma) - \xi)$
(ii-c)	φ_e	φ_M	$\gamma(\xi_0(\gamma) - \xi)$	$\gamma(\xi_2(\gamma) - \xi)$
(iii)	φ_e	φ_M or φ_H	$\gamma(\xi_0(\gamma) - \xi)$	$\theta\gamma(\xi_2(\gamma) - \xi)$

Table 1: Firm's Expected Utility

Note: This table tabulates the equilibrium technology level and the firm's expected utility when it chooses transparent ($\chi = 0$) and opaque ($\chi = 1$) technology in each region shown in Figure 5. In the last two columns, the transparency regime that generates higher or equivalent firm utility is highlighted in blue. The table focuses on the parameter values that guarantee the existence of equilibrium in both transparency regimes.

Opaque technology leads to the following tradeoff and shapes the equilibrium χ^*. On the one hand, as highlighted in the literature, such as Xiong and Yang (2023) and Aoyagi (2025), the opacity generally strengthens the engineer's incentive to improve the technology level by making the price impact insensitive to the engineer's choice. This effect manifests as $\varphi_M > \varphi_e$, i.e., the engineer's marginal utility becomes zero at a higher technology level. 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 mitigating the incentive problem. On the other hand, opacity may lead to the self-fulfilling high-tech equilibrium, in which the engineer's technology development becomes excessive and drives the firm's utility to zero. The emergence of the high-tech equilibrium can be seen as the endogenous cost of opaque technology and is unique to our model that features belief-driven multiple equilibria.

When the firm's renegotiation cost is high, as represented by region (i) in Figure 5, the hiring condition is binding in both opaque and transparent regimes ($\varphi_e < \varphi_M < \varphi_L$). The engineer is required to achieve φ_L under transparent technology, while she produces either φ_L or φ_H under opacity depending on the market maker's belief. In all cases, the firm breaks even and is indifferent between $\chi = 0$ and 1.

As the renegotiation cost diminishes, the minimum technology level for hiring also starts decreasing. When ξ is intermediate, as represented by regions (ii-a) and (ii-b), opaque technology encourages the engineer to produce a relatively high technology level so that the hiring condition stays slack if the low-tech equilibrium is realized ($\varphi_M > \varphi_L$). In contrast, the transparent technology level still falls short of the hiring condition ($\varphi_L > \varphi_e$) due to the elastic price impact. Although opacity may lead to the high-tech equilibrium, where the firm earns zero utility, the low-tech equilibrium brings about strictly positive utility under opacity. As the transparent regime always yields zero utility, the firm strictly prefers opaque technology ($\chi = 1$).

When ξ and φ_L decline even more, the hiring condition becomes slack even in the transparent regime (region [ii-c]), so that the engineer chooses her unconstrained optimal technology level, and the firm earns strictly positive utility. However, under opacity and when the equilibrium is unique, the firm always enjoys the benefit of opacity due to a hightened technology level ($\varphi_M > \varphi_e$), rendering $\chi = 1$ the optimal choice. In contrast, when multiple equilibria arise under opacity (region [iii]), the cost of opacity materializes due to the high-tech equilibrium. Transparent technology can be a dominant strategy only in this last case under strong engineer bargaining power and a small renegotiation cost ($\xi < \xi_\theta$). These factors mitigate the incentive misalignment between the firm and the engineer, and thus the benefit of opacity shrinks, making transparent technology the optimal choice for the firm. Note that the cutoff, ξ_θ, shifts upward when θ decreases, expanding the region for $\chi^* = 0$. As the high-tech equilibrium becomes more likely, the cost of opacity grows larger, so that transparent technology becomes more attractive for the firm.

Notably, the mechanism behind the emergence of the transparent equilibrium is unique to our model. The literature focuses on 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 existing models need additional forces, such as competition among informed traders (e.g., Xiong and Yang, 2023). In contrast, our model highlights the trader's utility cost of choosing opaque technology based on the belief-driven multiple equilibria and overengineering. It helps explain the possibility of both transparent and opaque innovations in a unified framework.

6 Discussion

6.1 Policy Implication

The analysis so far has shown that the incentive misalignment between the firm and the engineer plays a critical role in shaping the equilibrium technology investment. This raises a natural question: how would government interventions in the labor market affect the equilibrium outcomes?

Renegotiation costs. As the leading example of government interventions that influence the contractual condition, the non-compete agreements (NCAs) and their impact on technology innovation have been controversial in recent years, not only within the financial sector but across a wide range of industries.[22] 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. However, the literature has yet to reach consensus on its consequences: while it may strengthen firms' incentives to invest in worker training by reducing the risk of talent poaching (Jeffers, 2024), it can also hinder knowledge spillovers (Saxenian, 1996).

[22] 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.

In our model, such interventions can alter equilibrium innovations in financial technology through a reduction in worker retention costs, ξ. When the economy admits multiple equilibria, the reaction of the economy differs across the high-tech and the low-tech equilibria, as shown in Proposition 4.4. Namely, when the technology level is already excessive, the enforcement of NCAs would facilitate innovation even more, while the opposite is true in the low-tech equilibrium.

In general, a decline in ξ shifts the economy toward regions where the unique low-tech equilibrium prevails, as Figures 4 illustrates. Consistent with the existing literature, NCAs lead to more aggressive hiring and a slack hiring condition in our model. However, it also yields a distinctive prediction: stricter enforcement of NCAs can eliminate the high-tech equilibrium (Proposition 4.1; Figure 4), thereby suppressing inefficiently large-scale innovation investments. Even in the low-tech equilibrium, Proposition 4.4 shows that technology level weakly declines as NCAs become more stringent, as the improved position of the firm in the labor market reduces the minimum required technology level for hiring. Conversely, 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), and the impacts of other policy interventions, such as H-1B visa restrictions or changes in unionization, have been controversial. 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 weak, the low-tech equilibrium tends to be unique, as Proposition 4.1 demonstrates. In this equilibrium, increases in engineer bargaining power enhance technology innovations. As engineers gain even stronger bargaining power, however, multiple equilibria emerge, and responses of innovations and other equilibrium variables diverge across the high-tech and low-tech equilibria (Proposition 4.4). This result is unique to our framework, which features multiple equilibria, and helps reconcile conflicting empirical results,

Compensation structure. Several restrictions on compensation structure have been widely implemented in the labor market, including minimum wages or contractual floors (though these may not be binding in the finance industry) to protect workers (Zeira, 1998; Acemoglu and Restrepo, 2018; Hémous and Olsen, 2022).[23] Regarding the impact of restrictions on the compensation structures, much of the literature in labor economics focuses on labor-saving innovation (e.g., through automation, robotics, or AI adoption), grounded in the basic trade-off between capital and labor. Our model provides a workplace to analyze the reactions of profit-enhancing innovations in the finance industry, beyond labor-saving technology.

For example, minimum wages and contractual floors are described in the model as a lower bound imposed on the fixed component of the engineer's wage, such as $m \leq \gamma\xi$, where m represents the lower bound enforced by the law. It is re-written as $\xi_m \equiv \frac{m}{\gamma} < \xi$ and restricts parameter spaces for equilibrium by drawing a monotonically decreasing curve on the γ-ξ plane in Figure 4. The imposition or an increase in m can put the economy into the regions with multiple equilibria and opaque technology, as it tightens the hiring condition and distorts the engineer's incentive by making her performance-based salary less important. Therefore, while such interventions aim to improve the engineer's fixed salary and indeed enhance innovation, they can result in excessive investments in technology due to the self-fulfilling nature of the high-tech

[23] Another widely-adopted restriction is bonus caps intended to limit excessive risk-taking (Albuquerque et al., 2019; Freixas and Rochet, 2013), while most of the caps are applied to the executive salaries rather than workers' salaries.

equilibrium.

6.2 Acquiring Trading Edges

While our model emphasizes a trading firm's relationship with a financial engineer who develops proprietary trading technology, the mechanism we identify extends beyond this specific setting. In particular, our framework sheds light on a broader range of circumstances in which firms may inefficiently overinvest in acquiring a trading edge, such as superior information or speed advantages. The key ingredients that drive this inefficiency are (i) the presence of information frictions in financial markets (as in Kyle, 1985), (ii) contractual frictions between the firm and the provider of the trading edge, and (iii) opacity surrounding the trading edge from the market maker's perspective.

This insight extends beyond the case of in-house technology development. It applies more generally to how trading firms acquire various forms of informational or technological advantages, allowing us to predict when overinvestments may or may not arise. For instance, consider the acquisition of soft information. If information is treated as a non-rival good and obtained from a monopolistic seller (e.g., an external analyst as in Admati and Pfleiderer, 1986, 1988, 1990) or through a perfectly competitive market (as in Veldkamp, 2006), multiple equilibria in information acquisition do not arise. In these cases, information providers extract the entire trading surplus or the marginal cost of information production, and the optimal information acquisition is determined uniquely. By contrast, when a firm hires an in-house analyst who incurs the costs of information discovery and provides it exclusively to the firm, overinvestment becomes a concern depending on the severity of contractual frictions. A similar distinction applies to the acquisition of speed advantages: belief-driven multiple equilibria may arise when in-house speed technology is produced through hiring firm-specific tech workers, while they do not arise in relation to technology provided by a third-party vendor (e.g., Quincy Data providing high-speed information feeds for HFTs). In practice, the core technologies of financial firms are typically developed in-house by hiring firm-specific workers and kept proprietary, which makes overinvestment a particularly important concern.

Also, it is worth noting that opacity of information or speed acquisition is not independent of acquisition strategies. For example, a third-party vender often reveals its technology quality via advertised service menus, while a trading firm tries to hide what it acquires from competitors. Similarly, when speed and information advantages are developed in-house by engineers, hired exclusively for that purpose, the opacity is expected to be high (e.g., NDA prevents information leakage).

In summary, our framework underscores that overacquisition of trading edge emerges when it is embedded in firm-specific human capital and hidden from other market participants. This prediction has particular relevance for the recent trend of firms hiring AI talent to develop proprietary trading systems, where both opacity and contractual frictions are inherent.

7 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 an incentive misalignment due to contractual frictions. We show that opaque technology, where the market maker cannot observe the technology level of the trading firm, generates strategic complementarity between the engineer's innovation incentive and the market maker's belief about it. Consequently, the model features multiple self-fulfilling equilibria, one of which involves excessive and Pareto-inefficient technology investments. In this "high-tech" equilibrium, the trading firm adopts more aggressive trading strategies, and the price becomes more informative, while it also leads to an illiquid market with a highly volatile price. Our benchmark and the high-tech equilibria exhibit distinctive comparative statics, 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 strict enforcement of 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, generating potential macroeconomic implications.

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Appendix

A Proof of Lemma 3.1

The wage level, w, in equation (3.15) is obtained by directly solving the Nash bargaining problem in (3.11). By agreeing on this wage level, the firm obtains $(1-\gamma)(\bar{\pi} - c_f\varphi^2) - \gamma\xi > z_f$, and the engineer obtains $\gamma(\bar{\pi} - c_f\varphi^2) + \gamma\xi > z_e$. Since both players are better off by the wage transfer in the first round than forgoing it, they agree in the first bargaining round.

B Proof of Proposition 3.1

$\bar{U}_e$ in equation (3.19) satisfies the second-order condition. Thus, the first-order condition implies that it is maximized at φ_e in equation (3.23) 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 φ:

$$I(\varphi) = 2c_f\varphi^2 - \sigma_u\sigma_\delta\varphi + 2\frac{\gamma}{1-\gamma}\xi = 0. \tag{B.1}$$

Firstly, the determinant of $I = 0$ is positive if, and only if,

$$\xi < \hat{\xi} \equiv \frac{1-\gamma}{\gamma}\frac{\sigma_\delta^2\sigma_u^2}{16c_f}, \tag{B.2}$$

imposing the first condition in Assumption 2.1. Also,

$$I(1) < 0 \Leftrightarrow \xi > \frac{1-\gamma}{\gamma}\left(\frac{\sigma_\delta\sigma_u}{2} - c_f\right), \tag{B.3}$$

and

$$I'(1) < 0 \Leftrightarrow c_f > \frac{\sigma_\delta\sigma_u}{4}. \tag{B.4}$$

Hence, these conditions are satisfied if $c_f > \frac{\sigma_\delta\sigma_u}{2}$, and the second condition in Assumption 2.1 ensures $0 < \varphi_L < \varphi_H < 1$.

In comparison with φ_e, it can be directly confirmed that $\varphi_e < \varphi_H$ for all parameter values. Also, $\varphi_e \geq \varphi_L$ if and only if $I(\varphi_e) \leq 0$, which is equivalent to $\xi \leq \xi_0(\gamma) = \frac{\sigma_u^2\sigma_\delta^2(1-\gamma)}{16}\frac{\gamma c_f + 2c_e}{(\gamma c_f + c_e)^2}$, where ξ_0 is monotonically decreasing and convex in γ with $\xi_0(0) = \frac{\sigma_u^2\sigma_\delta^2}{4c_e}$ and $\xi_0(1) = 0$.

C Proof of Proposition 4.1 and Corollary 4.1

Firstly, it holds that $\varphi_M < \varphi_N$ for all parameter values. Given that φ_L and φ_H are the solution to $I(\varphi) = 0$ in equation (B.1) and its tipping point is $\varphi = \frac{\sigma_u\sigma_\delta}{4c_f}$, $\varphi_M \in [\varphi_L, \varphi_H]$ if, and only if, $I(\varphi_M) > 0$. This inequality is equivalent to

$$\xi \leq \xi_2(\gamma) \equiv \frac{1-\gamma}{4}\frac{c_e\sigma_u^2\sigma_\delta^2}{(\gamma c_f + c_e)^2}. \tag{C.1}$$

Otherwise, $\varphi_M < \varphi_L$ holds when $\gamma < \frac{c_e}{c_f}$, while $\varphi_M > \varphi_H$ holds if $\gamma > \frac{c_e}{c_f}$. Similarly, $\varphi_N \in [\varphi_L, \varphi_H]$ if, and only if, $I(\varphi_N) > 0$, which is equivalent to

$$\xi \leq \xi_1(\gamma) \equiv \frac{1-\gamma}{4\gamma}\frac{c_e\sigma_u^2\sigma_\delta^2}{(c_e + c_f)^2}. \tag{C.2}$$

Otherwise, due to $c_f > c_e$ by the second condition in Assumption 2.1, $\varphi_N > \varphi_H$ holds.

Both of the above thresholds, ξ_1 and ξ_2, are monotonically decreasing and convex in γ and converge to 0 at $\gamma = 1$. Also, $\lim_{\gamma=0}\xi_1(\gamma) = \infty$ and $\gamma_2(0) = \frac{\sigma_u^2\sigma_\delta^2}{4c_e}$. Comparing the thresholds of the renegotiation cost,

$$\xi_2(\gamma) > \xi_1(\gamma) \Leftrightarrow \gamma > \left(\frac{c_e}{c_f}\right)^2, \tag{C.3}$$

$$\hat{\xi}(\gamma) - \xi_1(\gamma) = \sigma_u^2\sigma_\delta^2\frac{1-\gamma}{4\gamma c_f}\frac{(c_f - c_e)^2}{(c_f + c_e)^2} > 0, \tag{C.4}$$

and

$$\hat{\xi}(\gamma) - \xi_2(\gamma) = \sigma_u^2\sigma_\delta^2\frac{1-\gamma}{4\gamma c_f}\frac{(\gamma c_f - c_e)^2}{(\gamma c_f + c_e)^2}. \tag{C.5}$$

Hence, $\hat{\xi}$ and ξ_2 are tangent to each other at $\gamma = \frac{c_e}{c_f}$, depicting the curves in Figure 3.

D Proof of Propositions 4.2 and 4.4

Taking the first-order derivative of $\varphi_L, \varphi_H, \varphi_M$, and φ_N with respect to parameters ξ and γ, and applying them to the market quality measures directly leads to the results.

E Proof of Proposition 5.1

Comparing ξ_0 and ξ_1, it holds that

$$\xi_1 - \xi_0 = \frac{-(1-\gamma)\sigma_u^2 \sigma_\delta^2 c_e^3}{16\gamma(c_f + c_e)^2(\gamma c_f + c_e)^2} \Delta\xi(\gamma), \tag{E.1}$$

where

$$\Delta\xi(\gamma; a) \equiv (1-a)^2 a\gamma^2 + 2(1-a)^2\gamma - 4, \tag{E.2}$$

with $a \equiv \frac{c_f}{c_e}$. Note that $\Delta\xi$ is monotonically increasing in γ. Also, $\Delta\xi(2/a; a) > 0$ when $c_f > 2c_e$ due to the second condition in Assumption 2.1. Hence, $\Delta\xi = 0$ has a unique solution, given by $\gamma = \frac{2c_e^2}{c_f(c_f - c_e)}$, such that $\xi_1 < \xi_0 \Leftrightarrow \gamma > \frac{2c_e^2}{c_f(c_f - c_e)}$. Comparing with ξ_2, it holds that

$$\xi_2 - \xi_0 = (1-\gamma)\sigma_u^2 \sigma_\delta^2 \frac{2c_f - \gamma c_e}{16(\gamma c_f + c_e)^2}, \tag{E.3}$$

suggesting that $\xi_2 > \xi_0 \Leftrightarrow \gamma < \frac{2c_e}{c_f}$.

Finally, ξ_θ is defined as the threshold for inequality $\gamma(\xi_0 - \xi) > \gamma\theta(\xi_2 - \xi)$, leading to $\xi_\theta = \frac{xi_0 - \theta\xi_2}{1-\theta}$. We obtain $\xi_\theta - \xi_0 = \frac{\theta}{1-\theta}(\xi_0 - \xi_2)$ and $\xi_\theta - \xi_2 = \frac{1}{1-\theta}(\xi_0 - \xi_2)$. Hence, if $\gamma < \frac{2c_e}{c_f}$, then $\xi_\theta < \xi_0 < \xi_2$, while $\gamma > \frac{2c_e}{c_f}$ leads to $\xi_\theta > \xi_0 > \xi_2$. At $\gamma = \frac{2c_e}{c_f}$, these three thresholds intersect with each other.