

# Information Technology and Bank Competition\*

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## **Abstract**

In a spatial model of bank competition, we study how information technology (IT) affects lending competition, stability, and welfare. The effects of an IT improvement depend on whether or not it weakens the influence of bank–borrower distance on monitoring costs. If so, then bank competition intensifies, which can reduce banks’ profitability and stability and have an ambiguous welfare effect. Otherwise, competition intensity does not vary, improving the profitability and stability of banks and welfare. Banks will acquire the best possible IT if it is cheap enough; otherwise, different types of IT investment co-move in response to shocks.

*JEL Classification:* G21, G23, I31

*Keywords:* bank stability, credit, monitoring/screening, FinTech, Big Data, price discrimination, deposit insurance, regulation

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# 1 Introduction

The banking industry is undergoing a digital revolution. Banks feel increasing pressure from the threat of financial technology (FinTech) companies and BigTech platforms that adopt innovative information and automation technology in traditional banking businesses. Prominent examples can be seen in China, where Alibaba and Tencent – the two largest BigTech companies – are active in a wide range of financial services that include payments, wealth management, and lending. In the United States, online FinTech lenders now account for some 8%–12% of new mortgage loan originations (Buchak et al., 2018; Fuster et al., 2019) and about a third of personal unsecured loans (Balyuk and Davydenko, 2019). The banking sector itself is transforming from reliance on physical branches to adopting information technology (IT) and Big Data in response to the increased supply of technology and to changes in consumer expectations of service, which are the two main drivers of digital disruption (FSB, 2019; Vives, 2019). The banking sector is investing increasingly in IT. Information technology allows financial intermediaries to offer personalized services and to price discriminate. The COVID-19 pandemic has accelerated this digitalization process and fosters remote loan operations; the result is stimulation of the development and diffusion of IT in the banking sector (Carletti et al., 2020).

How do the development and diffusion of information technology affect bank competition? How do banks choose their IT investment? Are banks more or rather less stable as IT develops? What are the welfare implications of information technology? To answer those questions, we build a model of spatial competition in which banks compete to provide entrepreneurs with loans. The key ingredients of our model are that price-discriminating banks are differentiated and offer personalized monitoring/screening services to entrepreneurs.

We model the lending market as a linear city à la Hotelling (1929) where two banks – which are located symmetrically at two extremes of the city – compete for entrepreneurs who are distributed along the city. Entrepreneurs can undertake risky investment projects, which may either succeed or fail, but have no initial capital; hence they require funding from banks. Banks have no direct access to investment projects, so their profits are derived from offering loans to entrepreneurs. Banks compete in a Bertrand fashion by simultaneously posting their discriminatory loan rate schedules. In addition to financing entrepreneurs, another critical bank function is monitoring entrepreneurs in order to increase the probability of their projects' success (see e.g. Martinez-Miera and Repullo, 2019). As an alternative, banks can screen entrepreneur projects and help identify the

good ones. Either the monitoring or the screening effort of a bank increases the success probability of a financed project. Monitoring/screening is more costly for a bank if there is more distance between its expertise and the entrepreneur’s project characteristics.<sup>1</sup> Information technology can generate two types of outcomes. The first is by lowering the costs of monitoring/screening an entrepreneur without affecting banks’ relative cost advantage in different locations – for example, by making improvements in the ability to analyze data and acquire information with better information management software (e.g. desktop applications). The second is by reducing the effect of bank–borrower distance on monitoring/screening costs; for example, IT can facilitate the transmission of information with better communication facilities (e.g. videoconferencing) or transforming soft information into hard information. Big Data and machine learning techniques as well as credit scoring systems may influence both types of outcomes.<sup>2</sup> In what follows, the term “monitoring” will refer both to monitoring proper and to screening.

Under the set-up just described, we study how information technology affects bank competition and obtain results consistent with the available empirical evidence. We find that by adopting more advanced IT, whatever its type, a bank can charge higher loan rates to entrepreneurs (and will become more stable). The reason is that a bank’s IT progress increases its competitive advantage.

When two competing banks each makes technological progress, that progress will not increase the overall competitive advantage of either bank. In this case, the different types of IT progress can yield different results. If IT progress involves only a reduction in the costs of monitoring an entrepreneur without altering banks’ relative cost advantage, then banks’ competition intensity will not be affected by such technology progress. In this case, the loan rates that banks charge to entrepreneurs will not vary, although banks will become more profitable and stable because monitoring is now cheaper. However, if IT progress involves a weakening in the influence of bank–borrower distance on monitoring costs, then banks’ competition intensity will increase. The result follows because this type of technological progress reduces banks’ differentiation. As a consequence, the loan rates offered to entrepreneurs will decline for both banks, which thereby can become less profitable and less stable.

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<sup>1</sup>There is also evidence that firm–bank *physical* distance also matters for bank lending. Degryse and Ongena (2005) document spatial discrimination in loan pricing; see also Petersen and Rajan (2002) and Brevoort and Wolken (2009).

<sup>2</sup>There are many companies (e.g., Zestfinance, Scienaptic systems, Datarobot, Underwrite.ai) that help the financial industry improve credit screening via Big Data and machine learning techniques, thus transforming soft data into hard data. See also Boot et al. (2020).

When banks endogenously determine their IT, the equilibrium results depend on the cost of IT. If IT is cheap enough, then both banks will acquire the best possible IT in their quest to compete for the market, which eliminates bank differentiation and hence induces extremely intense bank competition. If IT is not so cheap, then the two types of IT co-move in an interior symmetric equilibrium in response to cost shocks; that is, a decrease in the marginal cost of acquiring one type of IT will increase banks' investment in both types of IT.

Finally, we analyze the welfare effects of information technology progress. We find that more intense competition is not always welcome from the perspective of social welfare. When competition in the lending market is at a low level, increasing competition intensity improves welfare because more competition greatly increases entrepreneurs' utility. Yet too much competition can reduce social welfare because high competition intensity will decrease banks' incentive to monitor entrepreneurs, which in turn will render those projects less likely to succeed. So if IT progress weakens the influence of bank–borrower distance on monitoring costs, then that progress may or may not benefit social welfare owing to the consequent increased bank competition – which improves or reduces welfare according as whether there was a low or high level of competition to start. In fact, if information technology is cheap, banks would be trapped in a prisoner's dilemma and choose endogenously very low levels of differentiation, excessive from the social point of view. If IT progress simply means that the cost of monitoring an entrepreneur is lower (and that banks' relative cost advantage is unaffected), then there is no competition effect and social welfare will improve. This outcome arises also if, in equilibrium, banks do not compete with each other; in that case, the only effect of IT progress is to make monitoring cheaper.

Our baseline model assumes that depositors can observe the bank's monitoring effort (which determines its risk position). Our results hold also if depositors are protected by a fairly priced deposit insurance scheme and do *not* observe monitoring levels. The reason is that risk is priced fairly in both cases and so banks' payoff functions are the same.

**Related literature.** Our work builds on the spatial competition models of Hotelling (1929) and Thisse and Vives (1988); but our model focuses on bank competition. Similarly to our paper, Matutes and Vives (1996) and Cordella and Yeyati (2002) study bank competition within a spatial competition framework. Yet in their work, banks compete for deposits and can directly invest in risky assets. In contrast, the banks in our model compete to finance entrepreneurs' projects, monitor them, and are able to price discrim-

inate.<sup>3</sup> Almazan (2002) studies how bank capitalization, interest rates, and regulatory shocks can affect bank competition and monitoring efficiency in a spatial competition model where a bank’s monitoring expertise decreases linearly with bank–borrower distance. In Almazan’s model, the only difference between banks is the level of their capital; banks cannot strategically choose loan rates because loan contracts are offered by entrepreneurs, who have all bargaining power vis-a-vis banks. In our work, banks differ in their IT and the strategic pricing of banks is based on their competitive advantage – which is affected by information technology.

Our study indeed belongs to the literature that studies information technology and bank competition. Hauswald and Marquez (2003) find that improving an informed bank’s ability to process information strengthens the “winner’s curse” (adverse selection) faced by an uninformed bank, decreases the intensity of bank competition, and increases the loan rate that borrowers are expected to pay. However, if both informed and uninformed banks can easily access public information, then the information gap between them becomes smaller; this softens the winner’s curse, increases the intensity of bank competition, and reduces borrowers’ expected loan rate. Hauswald and Marquez (2006) extend that model by allowing (a) endogenous investment by banks in information processing technology and (b) bank–borrower distance to have a negative effect on the precision of banks’ information. Similarly to our work, these authors find that the equilibrium loan rates received by borrowers are decreasing in bank-borrower distance and in the intensity of bank competition (measured by the number of banks).<sup>4</sup> Our approach differs in a fundamental aspect: there is no winner’s curse in our framework since a rejected borrower leaves the market. In our model, bank screening benefits both banks and entrepreneurs because uninformed entrepreneurs can learn from banks’ screening results about the potential profitability of their projects; hence when deciding on which bank to borrow from, entrepreneurs will consider not only the competing banks’ loan rates but also their intensity

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<sup>3</sup>Villas-Boas and Schmidt-Mohr (1999) build a spatial lending competition model in which a bank offers a menu of contracts with different collateral levels to sort borrowers of different qualities. Their focus is how bank competition affects the collateral requirements of contracts; in contrast, our main topic is how banks’ information technology is endogenously determined and how it affects lending competition, bank stability and social welfare.

<sup>4</sup>Using a similar framework, He et al. (2020) introduce “open banking” – an information sharing mechanism that enables borrowers to share their customer data stored in a bank with a FinTech lender that has advanced information processing technology but no access to customer data. They find that open banking increases the FinTech lender’s screening ability and competitiveness but that the “screening ability gap” between the bank and the FinTech lender does not necessarily shrink. In particular, open banking can soften the lending competition and so hurt borrowers if the FinTech lender is “overempowered” by the data sharing mechanism.

of screening.

Our results differ from Hauswald and Marquez models where an improvement in the entire banking sector’s IT will soften bank competition; banks’ IT investment is decreasing in the intensity of bank competition; and social welfare is increasing in the intensity of bank competition if competition is already very intense. In contrast, we find that bank competition is either intensified or unaffected by the banking sector’s IT improvement, depending on the type of the improved IT; banks may have extremely strong incentive to invest in IT even if bank competition is highly intense, in which case banks are trapped in a prisoner’s dilemma; and social welfare may be decreasing in the intensity of bank competition. In addition, our work analyzes the interplay of different types of IT and the strategic relation between different banks’ IT investment.

Several papers have emphasized the importance of monitoring in banking.<sup>5</sup> Martinez-Miera and Repullo (2019) examine the effectiveness of monetary and macroprudential policies in addressing a financial system’s risks within a framework where bank monitoring can increase the probability that investing in an entrepreneur yields a positive return. This is similar to our set-up. However, our focus is on how information technology affects bank monitoring, which in turn affects bank competition, stability, and social welfare. Our work is also related to the extensive literature that explores the connection between bank competition and bank stability (for a survey, see Vives, 2016).<sup>6</sup>

Finally, we propose a theoretical framework relevant to the empirical literature on information technology adoption in the lending market, which has thrived owing to the rise of FinTech in recent years (Vives, 2019).<sup>7</sup> To start with, there is considerable evidence showing that IT makes non-traditional data – such as soft information (Iyer et al., 2016), friendships and social networks (Lin et al., 2013), applicants’ description text (Dorfleitner et al., 2016; Gao et al., 2018; Netzer et al., 2019), contract terms (Kawai et al., 2014; Hertzberg et al., 2016), mobile phone call records (Björkegren and Grissen, 2020), digital footprints (Berg et al., 2020), and cashless payment information (Ghosh et al., 2021) – useful for assessing the quality of borrowers.

Moreover, there is a wide stream of research that documents the increases in lending efficiency brought about by information technology. Frost et al. (2019) report that, in

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<sup>5</sup>See, e.g., Diamond (1984) and Holmstrom and Tirole (1997) for pioneering work.

<sup>6</sup>For example, Gehrig (1998) finds that under certain conditions the entry of a new bank into a formerly monopolistic banking market will reduce the incumbent’s screening efforts and so increase its bank risk.

<sup>7</sup>Philippon (2016) claims that the existing financial system’s inefficiency can explain the emergence of new entrants that bring novel technology to the sector.

Argentina, credit-scoring techniques based on Big Data (e.g., platform transactions and the reputation of sellers) and processed with machine learning and artificial intelligence techniques have outperformed credit bureau ratings in terms of predicting the loss rates of small businesses.<sup>8</sup> Kwan et al. (2021) find that banks with better IT originate more “paycheck protection program” loans – especially in areas with more severe COVID-19 outbreaks, higher levels of Internet use, and more intense bank competition; this is consistent with our finding that a higher intensity of bank competition increases the sensitivity of a bank’s loan volume to its IT progress. Pierri and Timmer (2021) study the implications of IT in banking for financial stability; these authors find that pre-crisis IT adoption that was higher by one standard deviation led to 10% fewer non-performing loans during the 2007–2008 financial crisis; we provide a consistent result that a bank will become more stable as its IT progresses. Ahnert et al. (2021) document that small business lending by banks with higher IT adoption is less affected by the distance between the bank headquarters and their borrower; our model is in line with the finding by showing that a bank’s geographic reach will be extended if the bank adopts better information technology.

The rest of our paper proceeds as follows. Section 2 presents the model set-up; in Section 3, we examine the lending market equilibrium with given information technology. Section 4 studies how banks endogenously determine their IT investment. In Section 5, we analyze how information technology affects bank stability, and Section 6 provides a welfare analysis of information technology progress. We conclude in Section 7 with a summary of our findings. Appendix A presents all the proofs, and the other appendices deal with extensions and robustness checks.

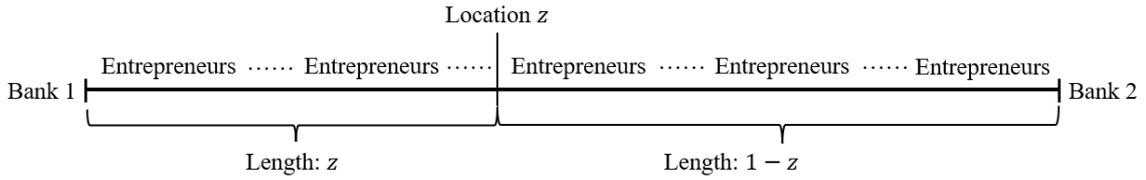
## 2 The model

**The economy and players.** The economy is represented by a linear “city”, of length 1, that is inhabited by entrepreneurs and banks. A point on the city represents the characteristics of an entrepreneur (type of project, technology, . . .) at this location, and two close points mean that the entrepreneurs in those locations are similar. Entrepreneurs’ types are uniformly distributed along the city.

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<sup>8</sup>Furthermore, Fuster et al. (2019) estimate that technology-based lenders process mortgage applications 20% faster than do traditional lenders yet without incurring greater default risk. Buchak et al. (2018) find that lenders with advanced technology can offer more convenient services to borrowers and hence charge higher loan rates in the US mortgage market than do traditional banks.

There are two banks, labeled by  $i = \{1, 2\}$ , located at the two extremes of the city. Hence banks are closer to some entrepreneurs than to others. This means, for example, that banks are specialized in different sectors of the economy. If the distance between an entrepreneur and bank 1 is  $z$ , we say that the entrepreneur is located at (location)  $z$ . As a result, the distance between an entrepreneur at  $z$  and bank 2 is  $1 - z$ . At each location (e.g. location  $z$ ) there is a potential mass  $M$  of entrepreneurs. Figure 1 gives an illustration of the economy.



**Figure 1:** The Economy.

**Entrepreneurs and monitoring intensity.** Each entrepreneur has no initial capital but is endowed with a risky investment project that requires a unit of funding; hence entrepreneurs require funding from banks to undertake projects. The investment project of an entrepreneur at  $z$  yields the following risky return:

$$\tilde{R}(z) = \begin{cases} R & \text{with probability } m(z), \\ 0 & \text{with probability } 1 - m(z). \end{cases}$$

In case of success (resp. failure), the entrepreneur's investment yields  $R$  (resp. 0). The probability of success is  $m(z) \in [0, 1]$ , which represents how intensely the entrepreneur is monitored by a bank. More specifically, the project of an entrepreneur (monitored with intensity  $m(z)$ ) succeeds if and only if

$$\theta \geq 1 - m(z),$$

where  $\theta$  is a random variable (or say, risk factor) that is uniformly distributed over the interval  $[0, 1]$ ; hence the event  $\theta \geq 1 - m(z)$  happens exactly with probability  $m(z)$ . The random variable  $\theta$  is the same across all entrepreneurs; in other words, it is a common risk factor that can be viewed as a measure of economic conditions. An entrepreneur at  $z$  who borrows from bank  $i$  with loan rate  $r_i(z)$  will receive a residual payoff of  $R - r_i(z)$  (resp. 0) from the investment when her project succeeds (resp. fails).

**Bank deposits.** For simplicity, we assume that banks have no initial capital and must therefore finance bank loans by attracting funds from risk-neutral depositors. Bank deposits are not insured, and the funding supply of depositors is perfectly elastic when the expected payoff of a unit of deposits is no less than the risk-free rate  $f$ . The deposit rate of bank  $i$  is denoted by  $d_i$ , which must be set so as to make depositors break even. We assume that, before  $d_i$  is determined, banks' monitoring intensities have already been observed by depositors. Hence  $d_i$  can be adjusted to reflect bank  $i$ 's risk, which ensures that the bank's expected payment to a unit of deposits is no less than  $f$  regardless of how intensely the bank chooses to monitor. This situation is equivalent to the case where depositors cannot observe the monitoring intensity of loans but are protected by a fairly priced deposit insurance scheme.

**Entrepreneurs' funding demand.** An entrepreneur at location  $z$  can borrow and invest at most 1 unit of funding. If an entrepreneur at  $z$  borrows at loan rate  $r(z)$  and is monitored with intensity  $m(z)$ , then her expected net return on the investment is

$$\pi^e(z) \equiv (R - r(z))m(z).$$

We assume that the entrepreneur derives utility  $\pi^e(z) - \underline{u}$  by implementing the risky project and seeks funding if and only if  $\pi^e(z) \geq \underline{u}$ . We interpret  $\underline{u}$  as the reservation utility of the entrepreneur's alternative activities. For each entrepreneur at  $z$ ,  $\underline{u}$  is independently and uniformly distributed on  $[0, M]$ . The total funding demand (which is also the measure of entrepreneurs who require funding) at location  $z$  is therefore

$$D(z) = M \int_0^M \frac{1}{M} 1_{\{\pi^e(z) \geq \underline{u}\}} d\underline{u} = \pi^e(z),$$

and total entrepreneurial utility at location  $z$  can be written as

$$M \int_0^M \frac{1}{M} (\pi^e(z) - \underline{u}) 1_{\{\pi^e(z) \geq \underline{u}\}} d\underline{u} = \frac{(\pi^e(z))^2}{2}.$$

**Monitoring and information technology.** The two banks can use monitoring to increase entrepreneurs' probability of success. More specifically, if an entrepreneur at  $z$  borrows from bank  $i$  and if the bank monitors the entrepreneur with intensity  $m_i(z)$ , then

the bank incurs the non-pecuniary quadratic monitoring cost

$$C_i(m_i(z), z) = \frac{c_i}{2(1 - q_i s_i)} (m_i(z))^2. \quad (1)$$

Here  $c_i \geq \underline{c} > R$ ,  $R \geq \sqrt{2c_i f}$ ,  $q_i \in [0, 1)$ , and  $s_i$  is the distance between bank  $i$  and entrepreneur  $z$ ; we have  $s_i = z$  (resp.,  $s_i = 1 - z$ ) if  $i = 1$  (resp.,  $i = 2$ ). The parameters  $c_i$  and  $q_i$  are inverse measures of the efficiency of bank  $i$ 's monitoring technology. Parameter  $c_i$  represents bank  $i$ 's general monitoring efficiency. Later we will show that  $c_i$  can be interpreted as “the cost of acquiring an efficiency unit of information”; that is,  $c_i$  inversely measures the bank's ability to acquire information and/or analyze data. Parameter  $q_i$  measures the influence of bank–borrower distance on monitoring costs.<sup>9</sup> (See the interpretation below.) The cost function (1) reflects the fact that a bank has a greater capacity to discipline nearby borrowers and must expend more effort to monitor entrepreneurs who are more distant from the bank's expertise or geographic location.

The constraint  $R \geq \sqrt{2c_i f}$  must hold to guarantee that bank  $i$  is willing to provide loans to at least some entrepreneurs in the market. The lower bound  $\underline{c}$  of  $c_i$  is assumed to be higher than  $R$  to ensure that bank  $i$ 's monitoring intensity - which is equal to the success probability of monitored entrepreneurs - is always smaller than 1.

**Remark:** The cost function (1) has two crucial properties when  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$ . First, the ratio of the two banks' monitoring costs at location  $z$  (i.e.,  $C_1(m_1, z)/C_2(m_2, z)$ ) is independent of  $c$  for any given  $m_1$  and  $m_2$ :

$$\frac{C_1(m_1, z)}{C_2(m_2, z)} = \frac{1 - q(1 - z)}{1 - qz} \left( \frac{m_1}{m_2} \right)^2.$$

This property implies that increasing  $c$  does not affect a bank's relative cost advantage (or disadvantage), although it makes monitoring more costly for both banks. The second property is

$$\frac{\partial^2 \left( \frac{C_1(m_1, z)}{C_2(m_2, z)} \right)}{\partial z \partial q} = \frac{2(1 - q(1 - z))}{(1 - qz)^3} \left( \frac{m_1}{m_2} \right)^2 > 0,$$

which means that the sensitivity of the relative cost advantage to  $z$  is increasing in  $q$ . Note that  $C_1(m_1, z)/C_2(m_2, z)$  increases with  $z$ . Therefore, increasing  $q$  not only makes monitoring more costly but also magnifies the importance of entrepreneurs' locations in determining the relative cost advantage (or disadvantage) of a bank.

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<sup>9</sup>A similar classification of technology can be found in Boot et al. (2020).

**Interpretation of monitoring.** Banks do not directly participate in firms' management but they can collect firm data and assess whether the firm is acting appropriately to return its loan, which disciplines firms' management.<sup>10</sup> This type of monitoring relies on collecting and processing information about the firm, so it is facilitated by any advancement in the lending bank's information technology. In our model, monitoring benefits both banks and entrepreneurs; hence we can view it as banks' advising, mentoring or/and information production that are valuable for entrepreneurs.

To give a more specific interpretation to parameters  $q_i$  and  $c_i$  of the monitoring cost function (1), we assume that bank  $i$ 's monitoring intensity at  $z$  (denoted by  $m_i(z)$ ) is determined by two factors: data analysis and distance friction, that is

$$m_i(z) \equiv \underbrace{\alpha_i I_i(z)}_{\text{data analysis}} \underbrace{\sqrt{1 - q_i s_i}}_{\text{distance friction}},$$

where  $\alpha_i$  measures bank  $i$ 's efficiency of analyzing data and  $I_i(z)$  is the amount of information (or data) acquired by the bank about the monitored entrepreneur at  $z$ . The data analysis factor,  $\alpha_i I_i(z)$ , reflects the idea that monitoring relies on collecting and processing information about the firm; monitoring is more effective if the bank has more information about the firm (i.e., if  $I_i(z)$  is higher) or if the bank has a better model of analyzing data (i.e., if  $\alpha_i$  is larger). However, bank  $i$ 's monitoring intensity is not solely determined by  $\alpha_i I_i(z)$  because entrepreneurs have different characteristics, which gives rise to the distance friction factor. We can understand distance friction in two ways. First, if we treat  $s_i$  as the physical distance between location  $z$  and the bank (branch/headquarters), then the distance friction represents the loss in soft information generated when the bank's branch at location  $z$  transmits entrepreneurs' data to the headquarter of the bank (see Liberti and Petersen, 2019). The second way is to view  $s_i$  as the "distance" between entrepreneurs' characteristics and the bank's expertise. The bank's data analyzing model works best when monitoring entrepreneurs of certain types (e.g., entrepreneurs from certain industries that the bank specializes in).

We further assume that acquiring information amount  $I_i(z)$  will cost bank  $i$

$$\frac{\gamma_i}{2} (I_i(z))^2,$$

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<sup>10</sup>Tirole (2010) distinguishes two forms of monitoring: active and speculative. An *active* monitor can directly intervene to prevent or correct a firm's policy, whereas a *speculative* monitor cannot. In reality, debt holders do not directly interfere in the management of a firm unless the firm defaults on its debts.

where  $\gamma_i$  measures the bank’s cost of information acquisition. If the bank chooses monitoring intensity  $m_i(z)$  for an entrepreneur at  $z$ , then the amount of information (i.e.,  $I_i(z)$ ) needed is equal to  $m_i(z)/(\alpha_i\sqrt{1-q_i s_i})$ , which will cost the bank

$$\frac{\gamma_i}{2\alpha_i^2(1-q_i s_i)}(m_i(z))^2.$$

If we let  $c_i \equiv \gamma_i/\alpha_i^2$ , then the cost of monitoring an entrepreneur at location  $z$  with intensity  $m_i(z)$  is exactly given by the cost function (1). Note that  $c_i$  equals bank  $i$ ’s information acquisition cost adjusted by data analyzing efficiency; hence we can interpret  $c_i$  as the “cost of acquiring an efficiency unit of information”.

Parameter  $c_i$  measures two abilities of bank  $i$ : information acquisition and data analysis. If the bank can collect data with lower costs (i.e., if  $\gamma_i$  is lower), or if the bank’s data analyzing model is more efficient (i.e., if  $\alpha_i$  is higher), then  $c_i$  will be lower. Adopting unconventional information, like digital footprints (see Berg et al., 2020), to assess borrowers is an example of reducing  $c_i$ . To make use of unconventional data, a lender must develop a more powerful credit assessment model, which corresponds to an increase in  $\alpha_i$ . Furthermore, data collection becomes easier if more kinds of information are useful, which means  $\gamma_i$  will decrease. Another example of decreasing  $c_i$  is to invest in information management software (e.g. desktop applications). Adopting better software can improve the efficiency of document assembly and information classification and processing, which facilitates both information acquisition and data analyzing (see e.g. He et al., 2021) and hence reduces  $c_i$ .

Parameter  $q_i$  measures the magnitude of information loss when soft information is transmitted, or the efficiency loss when the bank uses its data analyzing model to monitor entrepreneurs who are distant from the bank’s expertise. Decreasing  $q_i$  calls for improving the bank’s ability to transmit information or developing a data analyzing model that can be better applied to various entrepreneurs. This can be accomplished by improving bank  $i$ ’s communication facilities (e.g. video conferencing). Better communication technology can improve a bank’s ability to transmit soft information by facilitating the exchange of information and opinions among the bank branching network, or by enabling local borrowers to directly provide soft information to the distant bank headquarter. Another way to decrease  $q_i$  is with changes in organizational structure which increase the bank’s reliance on hard information, which is easier to transmit (see Degryse et al., 2009).

There also exist technology improvements that reduce both  $c_i$  and  $q_i$ . For example, machine learning, together with big data, and credit scoring systems decrease  $c_i$  by

improving bank  $i$ 's ability to collect and process data (as argued above) and they also increase the bank's capability to harden soft information and reduce the bank's reliance on officers' expertise and experience, lowering  $q_i$ . This transforms "relationship" lending into "transactions" lending.

**A screening interpretation.** We can reinterpret monitoring as "screening" with a model in which banks can increase the quality of their loans by screening entrepreneurs' projects.<sup>11</sup> In this screening-based model, we assume that entrepreneurs are of two types: good or bad. The project of a good (resp. bad) entrepreneur succeeds with a positive (resp. zero) probability. Banks and entrepreneurs have the same prior belief about the distribution of entrepreneurial types. By screening an entrepreneur, a bank receives a signal that is either "favorable" or "unfavorable" and thereby reveals (in part) the entrepreneur's type. Entrepreneurs must determine which bank to approach for loan *before* bank screening takes place; if an entrepreneur is rejected after bank screening, she exists the lending market, so no winner's curse will arise. Entrepreneurs do not know their own types, so there is no adverse selection between entrepreneurs and banks in our model; rather, there is *inverse* selection whereby banks – after screening – know more about projects than do the entrepreneurs themselves. Banks will lend only to entrepreneurs who exhibit favorable signals, so an entrepreneur can perfectly infer her signal, and therefore update her belief, based on whether or not she is able to secure bank funding. The bank screening result provides the entrepreneur with information about the potential profitability of her project. This is valuable because the entrepreneur must give up her reservation utility (the equivalent of  $\underline{u}$  in the monitoring model) if implementing her project. The project of an entrepreneur who receives bank financing will succeed with a higher probability if the bank's screening intensity (the equivalent of  $m_i(z)$  in the monitoring model) is higher, from which it follows that the entrepreneur's expected utility of implementing her project will increase with the lending bank's intensity of screening. Thus screening benefits banks and entrepreneurs both, which is a key feature of our model. The cost of increasing the signal's precision by raising the screening intensity is greater for an entrepreneur located farther away from the bank. The main results of the monitoring model are robust to the screening interpretation.

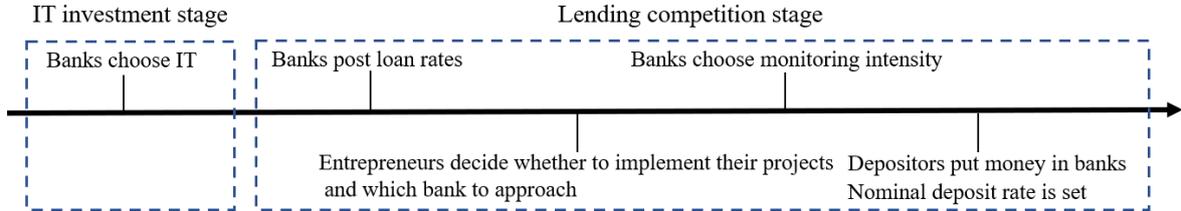
**Competition with discriminatory loan pricing.** In extending loans, banks compete in a localized Bertrand fashion. Bank  $i$  follows a discriminatory pricing policy in which the loan rate  $r_i(z)$  varies as a function of the entrepreneurial location  $z$ .<sup>12</sup>

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<sup>11</sup>The screening-based model is available upon request.

<sup>12</sup>Degryse and Ongena (2005) document spatial discrimination in loan pricing. See also Agarwal and

The timing of the two-stage duopoly banking game is shown in Figure 2 and consists of an IT investment stage and a lending competition stage. At the IT investment stage, banks simultaneously choose their information technology (i.e., bank  $i$  determines  $q_i$  and  $c_i$ ). Then at the lending competition stage, banks compete taking as given  $q_i$  and  $c_i$ .



**Figure 2:** Timeline.

Within the lending competition stage, the following events take place in sequence: First, banks post loan rate schedules simultaneously. Once the loan rate schedules are chosen and posted, entrepreneurs decide whether to implement their projects and which bank to approach for funding. Given entrepreneurs' decisions and the loan rates of each bank, bank  $i$  chooses its optimal monitoring intensity depending on the location of entrepreneurs (i.e.,  $m_i(z)$ ). Finally, depositors – after observing  $m_i(z)$  – put their money into banks and are promised a nominal deposit rate  $d_i$ .

### 3 Equilibrium at the lending competition stage

In this section we analyze the equilibrium at the lending competition stage and seek to establish how the development and diffusion of information technology can affect bank competition. Two types of equilibria may arise in our model. The first type is the equilibrium with direct bank competition, in which case all locations are served by the two banks. The second type is the local monopoly equilibrium, where the two banks do not compete with each other and some locations are not served by either bank. Throughout the section we focus only on the equilibrium with direct competition but we also characterize the local monopoly equilibrium in Appendix LM.

Since banks' loan rates can vary with entrepreneurial location, there is localized Bertrand competition between banks at each location. Without loss of generality, we concentrate on location  $z$  and analyze how banks set loan rates to compete for entrepreneurs at  $z$ . We solve the equilibrium by backward induction and so first examine how banks

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Hauswald (2010).

choose their monitoring intensity. Bank  $i$ 's loan rate and monitoring intensity for entrepreneurs at  $z$  are denoted by  $r_i(z)$  and  $m_i(z)$ , respectively.

**Optimal choice of monitoring intensity.** According to the timeline, an entrepreneur at  $z$  has already decided whether to implement her project and which bank to borrow from *before* banks choose their monitoring intensity. If an entrepreneur at  $z$  approaches bank 1, then bank 1's expected profit (or payoff function) from financing the entrepreneur can be written as

$$\pi_1(z) \equiv r_1(z)m_1(z) - f - \frac{c_1}{2(1 - q_1z)}(m_1(z))^2. \quad (2)$$

The first term of  $\pi_1(z)$  is the expected repayment of bank 1's loans from an entrepreneur at  $z$ , because the entrepreneur repays bank 1 the amount  $r_1(z)$  with probability  $m_1(z)$ . The second term measures bank 1's funding costs by borrowing from depositors. Note that what determines bank 1's funding costs is the risk-free rate  $f$ , not the bank's nominal deposit rate  $d_1$ . The reason is that  $d_1$  is determined after depositors have observed bank 1's monitoring intensity schedule and is adjusted to reflect the bank's ultimate risk. When a bank makes its decisions, it knows that its expected return to depositors will be  $f$ . Finally, the third term represents bank 1's non-pecuniary monitoring costs.

**Fairly priced deposit insurance and non-observable monitoring.** In this case, bank 1's payoff from financing an entrepreneur at  $z$  is the same as Equation (2) because risk is appropriately priced when it is observable by depositors and also when it is not observable yet there is fairly priced deposit insurance. It follows that all propositions based on Equation (2) are valid also in the case with fairly priced deposit insurance.<sup>13</sup>

Bank 1 chooses its optimal monitoring intensity  $m_1(z)$  to maximize its expected profit  $\pi_1(z)$ , while taking  $r_1(z)$  as given; the result is presented in Lemma 1.

**Lemma 1.** *Bank 1's optimal monitoring intensity for entrepreneurs at  $z$  is given by*

$$m_1(z) = \frac{r_1(z)(1 - q_1z)}{c_1}.$$

*A symmetric result holds for bank 2.*

Note that  $m_1(z)$  is decreasing in  $c_1$  since bank 1 has less incentive to monitor as monitoring becomes more costly. Second,  $m_1(z)$  is also decreasing in  $z$  because monitoring

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<sup>13</sup>The model with fair deposit insurance is available upon request.

an entrepreneur at  $z$  is more costly for bank 1 when the entrepreneur is located farther away. Finally,  $m_1(z)$  is increasing in  $r_1(z)$ . This statement follows because  $r_1(z)$  represents bank 1's marginal benefit of monitoring an entrepreneur at  $z$ . The higher is  $r_1(z)$ , the more bank 1 receives from the entrepreneur's loan repayment when her project succeeds and so the more incentive bank 1 has to increase its intensity of monitoring.<sup>14</sup>

**Best loan rate.** Which bank is able to attract an entrepreneur at  $z$  depends on which bank can provide a better loan rate (or “price”) to the entrepreneur.

**Definition 1.** *The best loan rate that bank  $i$  can offer to an entrepreneur at  $z$  is the loan rate that maximizes the entrepreneur's expected utility and ensures the bank a non-negative profit.*

In a competition of the Bertrand type, a bank that wants to win the contest for an entrepreneur at  $z$  must offer a loan rate that is more attractive to the entrepreneur than its rival bank's best loan rate. The best loan rate is characterized by our next lemma.

**Lemma 2.** *If  $R \geq \sqrt{8c_i f / (1 - q_i)}$ , then bank  $i$ 's best loan rate is  $R/2$  for any entrepreneur. Neither bank will offer a loan rate that is lower than  $R/2$ .*

We can best explain Lemma 2 by proving it here. Since the two banks are symmetric, we focus on bank 1. We know that the expected utility of an entrepreneur at  $z$  when she borrows from bank 1 is

$$U \equiv \pi^e(z) - \underline{u} = (R - r_1(z))m_1(z) - \underline{u};$$

here, by Lemma 1,  $m_1(z) = r_1(z)(1 - q_1 z)/c_1$ . The best loan rate that bank 1 could offer is the  $r_1(z)$  that maximizes  $U$ , and the result is exactly  $R/2$ .

Bank 1's expected profit from financing an entrepreneur at  $z$  (viz.  $\pi_1(z)$ ) is given in (2). By Lemma 1,  $\pi_1(z)$  is equal to  $(r_1(z))^2(1 - q_1 z)/(2c_1) - f$ , which is obviously positive when  $r_1(z) = R/2$  and  $R \geq \sqrt{8c_1 f / (1 - q_1)}$ . Therefore, the best loan rate is acceptable to bank 1. In a symmetric way, we can show the result for bank 2.

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<sup>14</sup>According to Lemma 1, bank 1's payment  $d_1$  to depositors does not affect  $m_1(z)$ . This result differs from the findings of Martinez-Miera and Repullo (2019), who assume that depositors cannot observe a bank's monitoring intensity and show that such intensity is determined by the bank's “intermediation margin”, which is the bank's loan income *minus* its payment to depositors. In this case, a higher deposit rate will reduce the marginal benefit of monitoring; hence banks choose lower monitoring intensities when the deposit rate is high. Yet in our paper,  $d_i$  is adjusted to bank  $i$ 's risk because its monitoring intensity is observable to depositors.

Lemma 2 conveys the information that (a) simply lowering the loan rate may not increase a bank's attractiveness and (b) the lower bound for a bank's loan rate should be  $R/2$ . These statements follow because a lower loan rate to an entrepreneur at  $z$  implies a lower monitoring intensity and hence a higher probability of her failure, although it leaves her a higher payoff in the event of success. When bank  $i$ 's loan rate is too low (as low as  $R/2$ ), the effect of the loan rate on monitoring intensity becomes dominant; in that case, bank  $i$  cannot attract entrepreneurs by further reducing its loan rate.

When  $R$  is not large enough (i.e., when  $R < \sqrt{8c_i f / (1 - q_i)}$ ), a loan rate as low as  $R/2$  cannot ensure banks a non-negative profit at some locations. In this case, a bank's best loan rate is not always  $R/2$ .<sup>15</sup> In order to convey our ideas in the simplest way, we maintain throughout the section the assumption that  $R \geq \sqrt{8c_i f / (1 - q_i)}$  so that banks' best loan rate is always  $R/2$  (the case where  $R$  is *not* large enough is relegated to Appendix B). In Appendix LM we show that this assumption eliminates the possibility of local monopoly equilibria.

**Monopoly loan rate.** The monopoly loan rate of bank  $i$  is the loan rate that bank  $i$  would choose if it faced no competition. While the best loan rate is the *lower* bound of a bank's loan rate, the monopoly loan rate is the *upper* bound. It is characterized as follows.

**Lemma 3.** *The monopoly loan rate  $r_1^m(z)$  of bank 1 for entrepreneurs at  $z$  is the largest solution of the following equation:*

$$\frac{(r_1^m(z))^2(3R - 4r_1^m(z))(1 - q_1 z)}{2c_1} + (2r_1^m(z) - R)f = 0$$

(a symmetric statement holds for bank 2). Both  $r_1^m(z)$  and  $r_2^m(z)$  are higher than the best loan rate  $R/2$ .

At location  $z$ , bank  $i$  would never offer a loan rate that is higher than its monopoly loan rate  $r_i^m(z)$ . It follows that bank  $i$ 's loan rate for entrepreneurs at  $z$  should be between  $r_i^m(z)$  and  $R/2$  in equilibrium.

**Equilibrium loan rate.** Given Lemmas 2 and 3, we can solve for the banks' equilibrium loan rates. The two banks are symmetric, so we look at how bank 1 chooses its loan rate for entrepreneurs at  $z$ .

If bank 1 wants to attract an entrepreneur  $z$  who is looking to undertake a project, it must offer the entrepreneur a loan rate that is more attractive than the best loan

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<sup>15</sup>A bank's best loan rate is higher than  $R/2$  at some or even all locations when  $R$  is not large enough.

rate  $R/2$  of bank 2. If bank 1 cannot do so, then the entrepreneur will instead be served by bank 2. However, if bank 1 can indeed offer a better loan rate, then its best strategy is to maximize its own profit – subject to the constraint that the entrepreneur’s expected utility is no less than what she would derive by accepting the best loan rate ( $R/2$ ) offered by bank 2. Reasoning in this way yields Proposition 1, which gives the equilibrium loan rates.

**Proposition 1.** *Assume that  $R \geq \max \left\{ \sqrt{\frac{8c_1 f}{1-q_1}}, \sqrt{\frac{8c_2 f}{1-q_2}} \right\}$ . Let*

$$\begin{aligned} r_1^{\text{comp}}(z) &\equiv \frac{R}{2} \left( 1 + \sqrt{1 - \frac{c_1}{c_2} \frac{1 - q_2(1-z)}{1 - q_1 z}} \right), \\ r_2^{\text{comp}}(z) &\equiv \frac{R}{2} \left( 1 + \sqrt{1 - \frac{c_2}{c_1} \frac{1 - q_1 z}{1 - q_2(1-z)}} \right), \\ \tilde{x} &\equiv \frac{1 - \frac{c_1}{c_2} + \frac{c_1}{c_2} q_2}{\frac{c_1}{c_2} q_2 + q_1}. \end{aligned}$$

*When  $0 < \tilde{x} < 1$ , there exists an equilibrium in which entrepreneurs located in  $[0, \tilde{x}]$  (resp.  $(\tilde{x}, 1]$ ) are served by bank 1 (resp. bank 2). The equilibrium loan rates of bank 1 and bank 2, respectively  $r_1^*(z)$  and  $r_2^*(z)$ , are as follows:*

$$\begin{aligned} r_1^*(z) &= \min\{r_1^{\text{comp}}(z), r_1^m(z)\}, \quad z \in [0, \tilde{x}]; \\ r_2^*(z) &= \min\{r_2^{\text{comp}}(z), r_2^m(z)\}, \quad z \in (\tilde{x}, 1]. \end{aligned}$$

Proposition 1 describes an equilibrium with direct bank competition. The restriction  $0 < \tilde{x} < 1$  guarantees that both banks can attract a positive number of entrepreneurs in equilibrium. If this restriction does not hold, then the result is an equilibrium in which one bank dominates the lending market; however, the banks’ pricing policy in Proposition 1 is robust for a more general  $\tilde{x}$ .<sup>16</sup>

One implication of Proposition 1 is that bank-borrower distance matters for bank lending. Specifically, bank 1 (resp. bank 2) can originate loans only in the region  $[0, \tilde{x}]$  (resp.  $(\tilde{x}, 0]$ ), and so must give up entrepreneurs who are sufficiently distant. Meanwhile,

<sup>16</sup>For example, if  $c_2$  is large enough then  $\tilde{x} \geq 1$ ; in this case, bank 1 serves all entrepreneurs. When  $c_2$  is large, bank 2’s intensity of monitoring entrepreneurs is low and the bank is unable to attract any entrepreneur even when it offers the best loan rate  $R/2$ . Bank  $i$ ’s equilibrium loan rate for entrepreneurs at  $z$  still equals  $r_i^*(z)$  even when bank  $i$  dominates the market, since rival bank  $j$ ’s competitive pressure still exists despite that it serves no entrepreneurs.

note that  $\tilde{x}$  is decreasing in  $q_1$  and  $c_1$ ; this means bank 1's lending can reach farther locations if its information technology develops (i.e., if  $q_1$  and/or  $c_1$  decrease). This result is in line with Ahnert et al. (2021) who document that small business lending by banks with higher IT adoption is less affected by the distance between the bank headquarters and their borrowers.

Since the two banks are symmetric, we simply look at bank 1's pricing strategy. Proposition 1 tells us that two cases may arise when bank 1 chooses its loan rate for entrepreneurs at  $z$ . In the first case, which occurs when  $c_1/c_2$  is small enough and/or  $q_2(1-z)$  is large enough, bank 2 cannot put enough competitive pressure on bank 1 and so the latter has enough market power to maintain its monopoly loan rate  $r_1^m(z)$  for entrepreneurs at  $z$ . In this case, there is actually no effective competition between the banks because the existence of bank 2 does not affect bank 1's monopoly loan rate. In the second case, which occurs when  $c_1/c_2$  is not too small and  $q_2(1-z)$  is not too large, bank 2 can exert sufficient competitive pressure and so bank 1 can no longer maintain its monopoly loan rate for entrepreneurs at  $z$ . In this case, bank 1's loan rate for entrepreneurs at  $z$  is  $r_1^{\text{comp}}(z)$ , which is lower than  $r_1^m(z)$ . (The superscript "comp" is used to indicate that the bank faces effective competition.)

Because our focus here is on bank competition, we are primarily interested in  $r_i^{\text{comp}}(z)$ . The following corollary gives a simple property of  $r_1^{\text{comp}}(z)$ ; a symmetric result holds for  $r_2^{\text{comp}}(z)$ .<sup>17</sup>

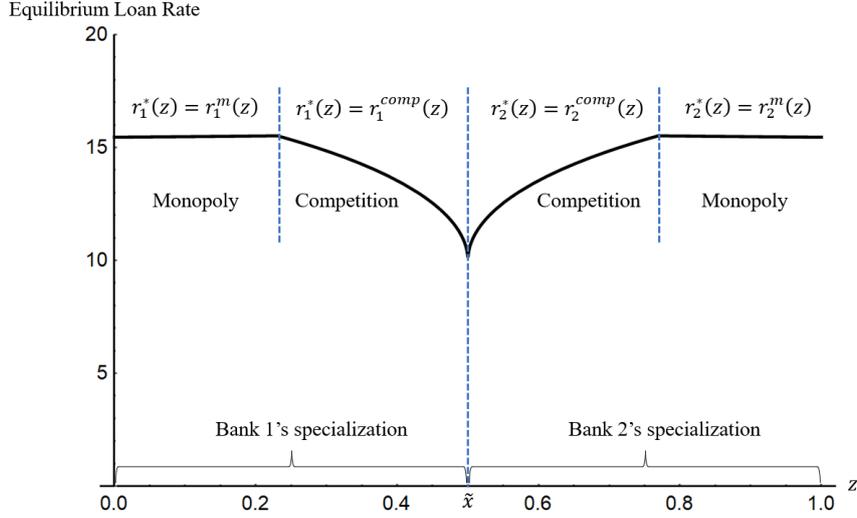
**Corollary 1.** *If  $0 < \tilde{x} < 1$ , then  $r_1^{\text{comp}}(z)$  is decreasing in  $z$  when  $z \in [0, \tilde{x}]$ . At the location  $z = \tilde{x}$ , we have  $r_1^{\text{comp}}(z) = R/2$ .*

The intuition underlying Corollary 1 is that, if entrepreneurs at  $z$  are quite close to bank 1 and therefore distant from bank 2, then bank 1 can easily find a loan rate that is more attractive to the entrepreneurs than the best loan rate offered by bank 2 – that is because a long distance makes it too costly for bank 2 to monitor them. As a consequence, bank 1 has more market power to increase its own profit by raising  $r_1^{\text{comp}}(z)$  when competing for entrepreneurs at  $z$ . The location  $z = \tilde{x}$  is special because, at that point, neither bank has a cost advantage when monitoring an entrepreneur and so the competition there between banks is greatest and the equilibrium loan rate is the best loan rate  $R/2$ . Figure 3 illustrates the banks' equilibrium loan rates.

The total funding demand of entrepreneurs at location  $z$  also varies with  $z$ , which is established in our next corollary.

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<sup>17</sup>See Appendix LM for more details.



**Figure 3: Equilibrium Loan Rates for Different Locations.** This figure plots the equilibrium loan rate against the entrepreneurial location in the equilibrium under direct bank competition. The parameter values are  $R = 20$ ,  $f = 1$ ,  $c_1 = 1.01R$ ,  $c_2 = 1.01R$ ,  $q_1 = 0.5$ , and  $q_2 = 0.5$ .

**Corollary 2.** *If  $0 < \tilde{x} < 1$  and if there is effective bank competition at  $z$  (i.e., if  $r_i^{\text{comp}}(z) < r_i^m(z)$ ), the total funding demand of entrepreneurs at  $z$  is increasing (resp., decreasing) in  $z$  when  $z \in [0, \tilde{x}]$  (resp.,  $z \in (\tilde{x}, 1]$ ).*

The intuition here is that banks must compete more intensely near the “indifference location”  $\tilde{x}$  and so entrepreneurs there receive more attractive loan rates and thus derive greater utility, which stimulates total funding demand in the area.

**Information technology and bank competition.** Next we study how bank competition is affected by a change in information technology and offer several corollaries. Since the two banks are symmetric, we can restrict our attention to bank 1.

**Corollary 3.** *When  $z \in (0, \tilde{x})$  and if there is effective bank competition at  $z$  (i.e., if  $r_1^{\text{comp}}(z) < r_1^m(z)$ ),  $r_1^{\text{comp}}(z)$  is increasing in the bank’s competitive advantage: due to better general monitoring technology (lower  $c_1/c_2$ ) or more expertise (lower  $\frac{1-q_2(1-z)}{1-q_1z}$ ).*

Bank 1’s equilibrium loan rate is decreasing in  $c_1$  and  $q_1$  and is increasing in  $c_2$  and  $q_2$ . As  $c_1$  or  $q_1$  increases, monitoring becomes more costly for bank 1; this outcome reduces bank 1’s competitive advantage and induces it to decrease its loan rate in an attempt to maintain market share. Yet as  $c_2$  or  $q_2$  increases, monitoring becomes more costly for bank 2 and therefore reduces bank 2’s competitive advantage. As a result, bank 1 will increase its loan rate in this case. Note that bank 1 will specialize in a smaller area

(i.e.,  $\tilde{x}$  will decrease) and meanwhile offer lower loan rates when bank 2's IT improves (by decreasing  $c_2$  or/and  $q_2$ ). This is in line with Blickle et al. (2021) who document that bank specialization is associated with more favorable loan rates, especially when the threat of rival lenders is high.

We have witnessed the development and diffusion of information technology throughout the entire banking sector, leading to the question how bank competition is affected by changes in the sector's information technology. To answer this question, we let  $c_1 = c_2 = c$  and  $q_1 = q_2 = q$  and then analyze how equilibrium loan rates vary with  $c$  and  $q$ , which can be viewed as two inverse measures of the banking sector's information technology.

**Corollary 4.** *Let  $c_1 = c_2 = c$  and  $q_1 = q_2 = q$ . If there is effective bank competition at  $z$  (i.e., if  $r_i^{\text{comp}}(z) < r_i^m(z)$ ), then bank  $i$ 's equilibrium loan rate  $r_i^{\text{comp}}(z)$  is increasing in  $q$  (except for  $z = 1/2$ ) but is not affected by  $c$ .*

Corollary 4 highlights a crucial difference between  $c$  and  $q$ . As  $q$  increases, monitoring costs become more sensitive to distance; this reduces banks' incentive to monitor far-away entrepreneurs. Then entrepreneurs are more willing to choose nearby banks because the monitoring intensity to which they are subject decreases more rapidly with distance as  $q$  increases. The result is that both banks can post higher loan rates for their respective entrepreneurs, so  $r_i^{\text{comp}}(z)$  is increasing in  $q$ . In sum: increasing  $q$  not only makes monitoring more costly but also increases banks' differentiation, and the latter effect renders bank competition less intense.<sup>18</sup> In contrast, if  $c$  increases then banks' monitoring costs increase but their differentiation is unaffected; hence equilibrium loan rates are not affected.

Corollary 4 tells us that, when studying how changes in information technology affect bank competition, we should first specify the *type* of IT change. Finally, observe that this corollary holds for a general cost function  $C_i(m_i, z) = g(c_i, q_i, s_i)m_i^2$  that satisfies

$$\frac{\partial \left( \frac{C_1(m_1, z)}{C_2(m_2, z)} \right)}{\partial c} = 0 \quad \text{and} \quad \frac{\partial^2 \left( \frac{C_1(m_1, z)}{C_2(m_2, z)} \right)}{\partial z \partial q} > 0$$

when  $c_1 = c_2 = c$ ,  $q_1 = q_2 = q$ , and  $g(c_i, q_i, s_i)$  is an increasing function of  $c_i$ ,  $q_i$  and  $s_i$ .

Next we look at the relation between the bank sector's IT and a bank's aggregate profit. At the lending competition stage, bank 1's aggregate profit from all locations is

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<sup>18</sup>If  $q = 0$  (and  $c_1 = c_2 = c$ ), then banks' differentiation will disappear and the intensity of bank competition will be maximal; in this case, both banks must offer their best loan rate for all locations. If  $q = 0$  and  $c_1 \neq c_2$ , then the bank with better IT will dominate the entire lending market and so drive out the other bank.

equal to  $\int_0^{\tilde{x}} D(z)\pi_1(z)dz$ ; here  $D(z)$  is the funding demand at location  $z$ , and  $\pi_1(z)$  is bank 1's profit from financing an entrepreneur at  $z$ . Symmetrically we can define bank 2's aggregate profit. When  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$  hold,  $\tilde{x}$  is equal to  $1/2$ . The following proposition shows how a bank's aggregate profit is affected by the banking sector's information technology.

**Proposition 2.** *Let  $c_1 = c_2 = c$  and  $q_1 = q_2 = q$ . Bank  $i$ 's aggregate profit from all locations is decreasing in  $c$  while it is increasing in  $q$  if  $q$  is sufficiently small.*

Decreasing  $c$  makes monitoring cheaper without making bank competition more intense. In contrast, the net effect of  $q$  is more complex. Decreasing  $q$  has two competing effects on bank  $i$ 's aggregate profit. First, there is a cost-saving effect: a smaller  $q$  makes monitoring less costly for bank  $i$  for a given  $m_i(z)$ , which should increase the bank's profit. Second, there is a differentiation effect: according to Corollary 4, a smaller  $q$  decreases bank differentiation and so increases the intensity of bank competition, which should reduce bank profit. Proposition 2 shows that the differentiation effect will dominate the cost-saving effect when  $q$  is small enough. The reason is that the intensity of bank competition will go to infinity as  $q$  approaches 0 (i.e., as bank differentiation disappears); in contrast, for a given monitoring intensity  $m_i(z)$ , a marginal decrease in  $q$  can reduce the costs of monitoring an entrepreneur at  $z$  by only

$$\frac{\partial C_i(m_i(z), z)}{\partial q} = \frac{2s_i c}{4(1 - qs_i)^2} (m_i(z))^2,$$

which is finite even if  $q$  approaches 0. As a consequence, the differentiation effect dominates the cost-saving effect if  $q$  is small enough.

Since parameter  $q$  inversely measures how intensely the two banks compete, we can study how a bank's aggregate loan volume is affected by the intensity of bank competition. Bank 1's (resp. bank 2's) aggregate loan volume is equal to  $L_1 \equiv \int_0^{\tilde{x}} D(z)dz$  (resp.  $L_2 \equiv \int_{\tilde{x}}^1 D(z)dz$ ). The following proposition shows how  $L_i$  is affected by  $q$  in the case  $q_1 = q_2 = q$ .

**Proposition 3.** *Let  $q_1 = q_2 = q$ . If there is effective bank competition at all locations (i.e., if  $r_i^{comp}(z) < r_i^m(z)$  holds for all  $z \in [0, 1]$ ), then the sum of the two banks' aggregate loan volume is decreasing in  $q$  (i.e.,  $\left. \frac{\partial(L_1+L_2)}{\partial q} \right|_{q_i=q} < 0$ ); and the sensitivity of bank  $i$ 's aggregate loan volume to  $c_i$  is decreasing in  $q$  (i.e.,  $\left. \frac{\partial^2 L_i}{\partial c_i \partial q} \right|_{q_i=q} > 0$ ).*

The first part of Proposition 3 (i.e.,  $\frac{\partial(L_1+L_2)}{\partial q}\Big|_{q_i=q} < 0$ ) states that the banking sector will originate more loans when bank competition is more intense (i.e., when  $q$  is smaller). The intuition is that banks must offer more attractive loan rates as competition intensifies; this improves entrepreneurs' utility and thus increases their funding demand. The second part (i.e.,  $\frac{\partial^2 L_i}{\partial c_i \partial q}\Big|_{q_i=q} > 0$ ) of the proposition states that IT progress of a bank (i.e. a lower  $c_i$ ) will bring more loan volume to the bank when the intensity of bank competition is larger (i.e., when  $q$  is smaller). Two reasons contribute to the result. First of all, a bank's marginal "geographic expansion" (which is caused by the bank's IT progress) will bring more loans to the bank if  $q$  is smaller because entrepreneurs demand more funding at each location when banks compete more intensely. Second, a bank's marginal IT progress will lead to a larger geographic expansion if  $q$  is smaller (i.e.,  $\frac{\partial^2 \bar{x}}{\partial c_1 \partial q}\Big|_{q_i=q} > 0$ ) because the IT progress can affect more (distant) entrepreneurs' decisions when bank differentiation is smaller. The second part of the proposition is consistent with Kwan et al. (2021) who find that banks with better IT originate more "paycheck protection program" loans especially in areas with more intense bank competition.

**What happens when  $R$  is not large enough?** In Appendix B we consider the case when  $R$  is not large enough and so bank  $i$  cannot make a non-negative profit by posting the loan rate  $R/2$ . In this case, the best loan rate bank that  $i$  can offer to entrepreneurs at  $z$  equals the loan rate that exactly brings bank  $i$  zero profit at that location. Appendix B shows that bank  $i$ 's best loan rate (which is also its lowest acceptable loan rate) is higher than  $R/2$  and is increasing in both  $q_i$  and  $c_i$  if  $R/2$  is too low to ensure bank  $i$  a non-negative profit at  $z$ .

The result of Corollary 3 is robust in this case because increasing  $c_i$  or  $q_i$  makes monitoring more costly for bank  $i$  and reduces its competitiveness – irrespective of whether or not bank  $i$ 's best loan rate is  $R/2$ . However, the result that  $r_i^{\text{comp}}(z)$  is unaffected by  $c$  (Corollary 4) does not hold when  $R/2$  is not bank  $i$ 's best loan rate. Appendix B reveals that  $r_i^{\text{comp}}(z)$  is increasing in  $c$  (provided that  $c_1 = c_2 = c$  and  $q_1 = q_2 = q$ ) if banks' best loan rates are determined by their zero-profit conditions. This follows because, when  $R/2$  is too low, bank  $i$ 's best loan rate is increasing in  $c$ ; in other words, the higher is  $c$ , the higher a loan rate bank  $i$  must charge in order to guarantee a non-negative profit. As  $c$  increases, the best loan rate that bank  $i$  can offer to entrepreneurs at  $z$  will also increase, which reduces the attractiveness of bank  $i$ 's best loan rate. As a result, if entrepreneurs at  $z$  are located relatively closer to bank  $j$  ( $j \neq i$ ) then bank  $j$  faces less competition pressure from bank  $i$  and is able to set a higher loan rate for entrepreneurs at  $z$  as bank  $i$ 's

best loan rate increases.

**Endogenous bank differentiation.** In our model banks are by assumption located at the two extremes of the linear city; that is, the differentiation of banks' expertise is maximal. We find from a numerical study that such maximal bank differentiation will arise endogenously in equilibrium if banks have similar IT (i.e., if  $q_1$  and  $c_1$  are respectively close to  $q_2$  and  $c_2$ ), because then it is a dominant strategy for either bank to stay as distant as possible from its rival. However, if a bank's IT is sufficiently better than that of the other bank (e.g., if  $q_1$  and/or  $c_1$  are sufficiently lower than  $q_2$  and/or  $c_2$ ), then the bank with better IT would prefer a small or even zero distance from its rival in order to obtain more market share or drive the other bank out of the market; in contrast, the bank with inferior IT would like to maximize its distance from the rival to protect its market share. In this case, there may be no pure equilibrium in locations.

## 4 Technology investment choice

In this section, we analyze how banks endogenously determine their information technology - represented by  $q_i$  and  $c_i$  - at the IT investment stage. Throughout this section we assume that the equilibrium at the lending competition stage is characterized by Section 3; that is,  $R$  is sufficiently large (i.e.,  $R \geq \max\{\sqrt{8c_1f/(1-q_1)}, \sqrt{8c_2f/(1-q_2)}\}$ ) so that banks' best loan rate is equal to  $R/2$ .

To develop an IT infrastructure that is characterized by  $q_i$  and  $c_i$ , bank  $i$  must pay a cost  $T(q_i, c_i) \geq 0$ . We assume that  $T$  is smooth with  $\partial T(q_i, c_i)/\partial q_i \leq 0$  and  $\partial T(q_i, c_i)/\partial c_i \leq 0$ , which means that adopting better information technology needs more investment and so is (weakly) more costly. Bank 1's ex ante profit at the IT investment stage is equal to

$$\Pi_1(q_1, q_2, c_1, c_2) \equiv \int_0^{\tilde{x}} D(z)\pi_1(z)dz - T(q_1, c_1),$$

where  $\int_0^{\tilde{x}} D(z)\pi_1(z)dz$  is bank 1's aggregate profit at the lending competition stage. Hereafter  $\Pi_1(q_1, q_2, c_1, c_2)$  is also written as  $\Pi_1$  for short. In a symmetric way we can define bank 2's first stage profit (i.e.,  $\Pi_2$ ).

## 4.1 Bank IT investments: substitutes or complements?

Are the two types of bank  $i$ 's own IT investment (i.e., affecting  $q_i$  and  $c_i$ ) substitutes or complements? What is the strategic relation between bank 1's IT investment and bank 2's IT investment?

**Bank's own IT investments: substitutes or complements?** Let us focus on bank 1. If  $q_1$  and  $c_1$  are complements (resp. substitutes), then bank 1 has higher (resp. lower) incentive to decrease  $q_1$  if  $c_1$  is smaller; that is,  $\partial^2\Pi_1/(\partial q_1\partial c_1) > 0$  (resp.  $\partial^2\Pi_1/(\partial q_1\partial c_1) < 0$ ). The complexity of the integral  $\int_0^{\tilde{x}} D(z)\pi_1(z)dz$  makes it very difficult to determine the sign of  $\partial^2\Pi_1/(\partial q_1\partial c_1)$  in an analytical way. However, we can obtain the following numerical result.

**Numerical Result 1.**<sup>19</sup> *Let bank competition be effective at all locations and let  $0 < \tilde{x} < 1$  hold. If  $T(q_1, c_1)$  is submodular (i.e., if  $\partial^2 T(q_1, c_1)/(\partial q_1\partial c_1) \leq 0$ ), then  $c_1$  and  $q_1$  are complements for bank 1:*

$$\frac{\partial^2\Pi_1}{\partial q_1\partial c_1} > 0.$$

Numerical Result 1 states that if investing in one type of IT does not increase the marginal cost of developing the other type then the two types of IT are complements for the bank. A smaller  $c_1$  (resp.  $q_1$ ) increases bank 1's marginal benefit of decreasing  $q_1$  (resp.  $c_1$ ) for three reasons. First, a bank 1's monitoring efficiency at location  $z$  is determined by  $\frac{1-q_1z}{c_1}$ , so a marginal decrease in  $q_1$  (resp.  $c_1$ ) has a larger effect on improving the bank's monitoring efficiency if  $c_1$  (resp.  $q_1$ ) is smaller. Second, it is easy to show that  $\frac{\partial^2\tilde{x}}{\partial q_1\partial c_1} > 0$ ; which means that a marginal decrease in  $q_1$  (resp.  $c_1$ ) will bring bank 1 a larger market share if  $c_1$  (resp.  $q_1$ ) is smaller. Finally, we can show that  $\frac{\partial(D(\tilde{x})\pi_1(\tilde{x}))}{\partial c_1} < 0$  and  $\frac{\partial(D(\tilde{x})\pi_1(\tilde{x}))}{\partial q_1} < 0$ ; this means a smaller  $c_1$  (resp.  $q_1$ ) will increase bank 1's expected lending profit at the indifference location  $z = \tilde{x}$ , which increases the marginal benefit of extending market share by reducing  $q_1$  (resp.  $c_1$ ).<sup>20</sup> As a consequence,  $q_1$  and  $c_1$  are complements if  $T(q_1, c_1)$  is submodular.

**Banks' IT investments: strategic substitutes or strategic complements?** We obtain the following.

<sup>19</sup>The grid of parameters is as follows:  $R$  ranges from 15 to 100;  $\underline{c} = 1.01R$ ;  $q_i$  ranges from 0 to 0.3;  $f$  ranges from 0.8 to 1.2;  $c_1$  ranges from  $\underline{c}$  to  $1.3R$ ;  $c_2$  ranges from  $\max\{c_1 - c_1q_2, \underline{c}\}$  to  $c_1/(1 - q_1)$ , which ensures that  $0 < \tilde{x} < 1$ .

<sup>20</sup>It can be shown that  $D(\tilde{x})\pi_1(\tilde{x}) = \frac{(1-q_2(1-\tilde{x})R^2)}{4c_2} \left( \frac{R^2}{8} \frac{1-q_2(1-\tilde{x})}{c_2} - f \right)$ , which is decreasing in  $q_1$  and  $c_1$  because  $\tilde{x}$  is decreasing in  $q_1$  and  $c_1$ .

**Numerical Result 2.** <sup>21</sup> *If bank competition is effective at all locations and if  $0 < \tilde{x} < 1$ , then  $q_1$  and  $c_2$  are strategic substitutes for bank 1:  $\partial^2\Pi_1/(\partial q_1\partial q_2) < 0$  while the signs of  $\partial^2\Pi_1/(\partial c_1\partial c_2)$ ,  $\partial^2\Pi_1/(\partial c_1\partial q_2)$  and  $\partial^2\Pi_1/(\partial q_1\partial c_2)$  are ambiguous.*

As bank 2 improves its IT by decreasing  $q_2$  or/and  $c_2$ , there are three competing effects on bank 1's marginal benefit of developing IT. First, there is a "share squeezing effect" that decreases bank 1's marginal benefit of reducing  $q_1$  or/and  $c_1$ . This effect means a decrease in  $q_2$  or/and  $c_2$  will reduce the market share (represented by  $\tilde{x}$ ) of bank 1. A smaller  $\tilde{x}$  means a smaller marginal benefit of serving the region  $[0, \tilde{x}]$  with better IT and this should decrease bank 1's incentive to develop IT and thus be strategically substitutive. Second, there is a "boundary profit effect" that increases bank 1's marginal benefit of developing IT. It means that bank 1's expected profit at the indifference location  $z = \tilde{x}$  will increase as  $q_2$  or/and  $c_2$  decreases, because bank 1 can specialize in a smaller area.<sup>22</sup> A higher profit at location  $z = \tilde{x}$  implies a larger marginal benefit of extending market share, so bank 1 should have greater incentive to reduce  $q_1$  or/and  $c_1$ ; from this perspective, the two banks' IT should be strategic complements. Finally, there is a "share sensitivity effect" that can be either strategically substitutive or complementary. The share sensitivity effect means  $\partial\tilde{x}/\partial q_1$  and  $\partial\tilde{x}/\partial c_1$  - both of which are negative - may increase or decrease as the IT of bank 2 improves; if  $\partial\tilde{x}/\partial q_1$  (resp.  $\partial\tilde{x}/\partial c_1$ ) decreases, then bank 1 has greater incentive to reduce  $q_1$  (resp.  $c_1$ ) because doing so can extend more its market share.

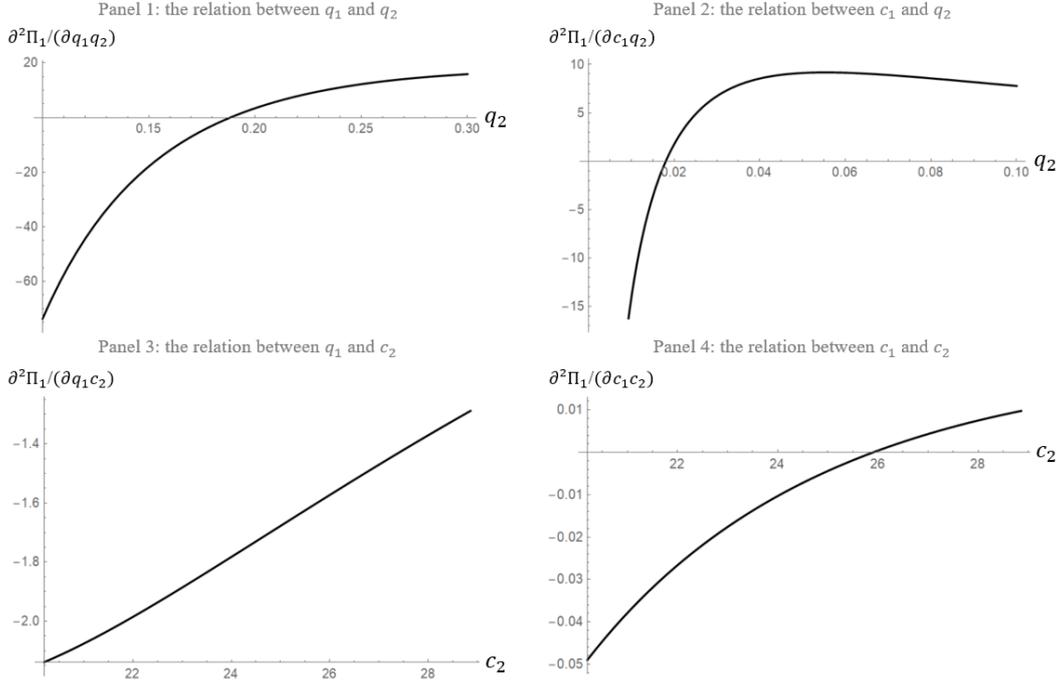
The strategic relation between the IT of bank 1 and that of bank 2 depends on which effect dominates. Numerical Result 2 shows that  $q_1$  and  $c_2$  are strategic substitutes, which means the share squeezing effect is dominant. However, for the IT pairs  $\{c_1, c_2\}$ ,  $\{c_1, q_2\}$  and  $\{q_1, q_2\}$ , the strategic relation is ambiguous. Figure 4 gives a graphic illustration of the numerical result.

## 4.2 Equilibrium technology investment

We restrict attention to subgame perfect equilibria (SPE) of the two stage game. The equilibrium at the IT investment stage relies on the properties of function  $T(q_i, c_i)$ . The

<sup>21</sup>The grid of parameters is as follows:  $R$  ranges from 15 to 100;  $\underline{c} = 1.01R$ ;  $q_i$  ranges from 0 to 0.3;  $f$  ranges from 0.8 to 1.2;  $c_1$  ranges from  $\underline{c}$  to  $1.3R$ ;  $c_2$  ranges from  $\max\{c_1 - c_1q_2, \underline{c}\}$  to  $c_1/(1 - q_1)$ , which ensures that  $0 < \tilde{x} < 1$ .

<sup>22</sup>It can be shown that  $D(\tilde{x})\pi_1(\tilde{x}) = \frac{(1-q_1\tilde{x})R^2}{4c_1} \left( \frac{R^2}{8} \frac{1-q_1\tilde{x}}{c_1} - f \right)$ , which is decreasing in  $q_2$  and  $c_2$  because  $\tilde{x}$  is increasing in  $q_2$  and  $c_2$ .



**Figure 4: The Effects of  $q_2$  and  $c_2$  on Bank 1's Marginal Benefit of IT investment.** This figure shows how the sign of  $\partial^2\Pi_1/(\partial IT_1\partial IT_2)$  varies with parameters when bank competition is effective at all locations and  $0 < \tilde{x} < 1$ , where  $IT_1 = q_1$  or  $c_1$  and  $IT_2 = q_2$  or  $c_2$ . In Panels 1 and 2, the parameter values are  $R = 20$ ,  $f = 1$ ,  $c_1 = 1.01R$ ,  $c_2 = 1.01R$  and  $q_1 = 0.1$ . In Panels 3 and 4, the parameter values are  $R = 20$ ,  $f = 1$ ,  $c_1 = 1.01R$ ,  $q_1 = 0.3$  and  $q_2 = 0.3$ .

following proposition characterizes banks' endogenous technology investment when IT is cheap to acquire.

**Proposition 4.** *If*

$$\Pi_i(0, 0, \underline{c}, \underline{c}) = \frac{R^2}{8\underline{c}} \left( \frac{R^2}{8\underline{c}} - f \right) - T(0, \underline{c}) > 0, \quad (3)$$

*then at the unique SPE we have that  $q_1 = q_2 = 0$  and  $c_1 = c_2 = \underline{c}$ .*

Condition (3) means banks can still make a positive profit when both banks acquire the best possible information technology. If Condition (3) is satisfied, we say IT is cheap to acquire. Proposition 4 states that both banks will endogenously choose the best possible IT if it is cheap. In this equilibrium, bank competition at the lending competition stage is extremely intense because there is no bank differentiation when  $q_1 = q_2 = 0$ ; bank 1 (resp. bank 2) serves entrepreneurs in  $[0, 1/2]$  (resp.  $(1/2, 1]$ ) and offers the best loan rate  $R/2$  (each bank's expected profit at the lending competition stage is equal to  $\frac{R^2}{8\underline{c}} \left( \frac{R^2}{8\underline{c}} - f \right)$ ).

Indeed,  $q_i = 0$  and  $c_i = \underline{c}$  is indeed an equilibrium. Given that  $q_2 = 0$  and  $c_2 = \underline{c}$ , bank 1 can make a positive expected profit by setting  $q_1 = 0$  and  $c_1 = \underline{c}$  according to Condition (3); if bank 1 deviates (from  $q_1 = 0$  and  $c_1 = \underline{c}$ ), it will lose all its market share and so make 0 ex ante profit. Hence bank 1 has no incentive to deviate. The same reasoning applies to bank 2. The uniqueness of the equilibrium is relegated to the Appendix A. Both banks would be better-off if  $q$  ( $= q_1 = q_2$ ) were moderately increased from 0 (see Proposition 2). However, bank  $i$  is not willing to increase  $q_i$  because the marginal cost of doing so is infinite. As a consequence, both banks are trapped in a *prisoner's dilemma* if IT is cheap. Under Condition (3) a bank will always have the ability to get the whole market and exclude the rival unless the rival chooses the best technology; but since they both have access to the same IT they end up investing in the best technology and sharing the market.<sup>23</sup>

Now we look at banks' IT investment when Condition (3) is not satisfied. We impose conditions on the IT cost function to ensure the existence of a symmetric interior equilibrium. We assume that  $\partial T(q_i, c_i)/\partial q_i$  and  $\partial T(q_i, c_i)/\partial c_i$  are continuous functions, and that there exist  $\bar{q} > 0$  and  $\bar{c} > \underline{c}$  such that  $\partial T(q_i, c_i)/\partial q_i = 0$  for  $q_i \geq \bar{q}$  and  $\partial T(q_i, c_i)/\partial c_i = 0$  for  $c_i \geq \bar{c}$ . This assumption implies that bank  $i$  need only consider information technology that satisfies  $q_i \times c_i \in [0, \bar{q}] \times [\underline{c}, \bar{c}]$ . Finally, we assume  $\bar{q}$  and  $\bar{c}$  are sufficiently small so that bank competition is effective for all locations at the lending competition stage. Then we have the following result.

**Proposition 5.** *If  $\lim_{q_i \rightarrow 0} -q_i \partial T(q_i, c_i)/\partial q_i$  (resp.  $-c_i \partial T(q_i, c_i)/\partial c_i|_{c_i=\underline{c}}$ ) is large enough for any  $c_i \in [\underline{c}, \bar{c}]$  (resp. for any  $q_i \in [0, \bar{q}]$ ) and if  $-q_i \frac{\partial^2 T(q_i, c_i)/\partial q_i^2}{\partial T(q_i, c_i)/\partial q_i}$  and  $-c_i \frac{\partial^2 T(q_i, c_i)/\partial c_i^2}{\partial T(q_i, c_i)/\partial c_i}$  are large enough for  $q_i \times c_i \in (0, \bar{q}) \times [\underline{c}, \bar{c}]$ , then there exists a unique symmetric interior equilibrium:  $q_i = q^* \in (0, \bar{q})$  and  $c_i = c^* \in (\underline{c}, \bar{c})$ .<sup>24</sup>*

<sup>23</sup>Bank  $i$  is not willing to deviate from  $q_i = 0$  and  $c_i = \underline{c}$  despite a potentially large marginal benefit of deviation because the extent of strategic complementarity between bank  $i$ 's IT and  $q_j$  ( $j \neq i$ ) is infinitely high in this boundary equilibrium (see Numerical Result 4 in Online Appendix C). In such an equilibrium without bank differentiation, a slight deviation at the IT investment stage will cause a discontinuous profit fall at the lending competition stage, so the marginal cost of deviation is infinite.

<sup>24</sup>The assumption that  $\lim_{q_i \rightarrow 0} -q_i \partial T(q_i, c_i)/\partial q_i$  and  $-c_i \partial T(q_i, c_i)/\partial c_i|_{c_i=\underline{c}}$  are large enough ensures that there exists an interior solution  $\{q^*, c^*\}$  that satisfies both banks' first order conditions. The assumption that  $\lim_{q_i \rightarrow 0} -q_i \partial T(q_i, c_i)/\partial q_i$  is large enough for any  $c_i \in [\underline{c}, \bar{c}]$  ensures that Condition (3) cannot hold. A large  $\lim_{q_i \rightarrow 0} -q_i \partial T(q_i, c_i)/\partial q_i$  means  $-\partial T(q_i, c_i)/\partial q_i$  and  $1/q_i$  have the same order as  $q_i$  approaches 0; this ensures:  $T(0, c_i) = -\int_0^{\bar{q}} \frac{\partial T(q_i, c_i)}{\partial q_i} dq_i = +\infty$ . Thus  $q_i = 0$  is never affordable for bank  $i$  since its expected profit at the lending competition stage is finite. The requirement about  $-q_i \frac{\partial^2 T(q_i, c_i)/\partial q_i^2}{\partial T(q_i, c_i)/\partial q_i}$  and  $-c_i \frac{\partial^2 T(q_i, c_i)/\partial c_i^2}{\partial T(q_i, c_i)/\partial c_i}$  guarantees that the interior solution is unique and indeed constitutes an equilibrium.

Next, we look at the interplay between the two types of information technology in the symmetric interior equilibrium. To do this, we further assume that

$$T(q_i, c_i) \equiv \beta_q Q(q_i) + \beta_c H(c_i), \quad (4)$$

where  $Q(\cdot) \geq 0$ ,  $H(\cdot) \geq 0$ , are smooth with  $Q'(\cdot) \leq 0$  and  $H'(\cdot) \leq 0$ . The cost function (4) implies that the costs of the two types of IT are independent, so  $T(q_i, c_i)$  cannot induce any interaction between the two types of information technology by itself. Parameter  $\beta_q > 0$  (resp.  $\beta_c > 0$ ) affects bank  $i$ 's total and marginal costs of reducing  $q_i$  (resp.  $c_i$ ). Introducing parameters  $\beta_q$  and  $\beta_c$  enables us to analyze how banks' equilibrium information technology will be affected by a shock on the cost of one type of IT. The following proposition provides the relevant result.

**Proposition 6.** *Under the assumptions of Proposition 5, at unique symmetric equilibrium we have:*

$$\frac{\partial q^*}{\partial \beta_q} > 0, \frac{\partial c^*}{\partial \beta_q} > 0, \frac{\partial q^*}{\partial \beta_c} > 0 \text{ and } \frac{\partial c^*}{\partial \beta_c} > 0.$$

Proposition 6 implies that the two types of IT (of the entire banking sector) co-move in the symmetric interior equilibrium but this results hides subtle interactions between banks' technological choices. Where does the co-movement come from? Numerical Result 3 provides the strategic relation between the two banks' IT in the symmetric case where  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold; the interior equilibrium displayed in Proposition 6 belongs to this case.

**Numerical Result 3.** <sup>25</sup> *If bank competition is effective at all locations and if  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold, then*

$$\frac{\partial^2 \Pi_1}{\partial c_1 \partial q_2} > 0, \frac{\partial^2 \Pi_1}{\partial q_1 \partial c_2} < 0, \frac{\partial^2 \Pi_1}{\partial q_1 \partial q_2} < 0 \text{ and } \frac{\partial^2 \Pi_1}{\partial c_1 \partial c_2} < 0.$$

When  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold,  $c_1$  and  $q_2$  are strategic complements for bank 1, while the strategic relation is substitutive for IT pairs  $\{q_1, c_2\}$ ,  $\{q_1, q_2\}$  and  $\{c_1, c_2\}$ . The results are explained by the interplay of effects displayed in Table 1. In Online Appendix C there is a more detailed explanation.

As  $\beta_q$  decreases, bank 1 reduces  $q_1$  because the direct effect of reducing  $\beta_q$  dominates the strategic substitutability effects of lower  $q_2$  and  $c_2$  (and is reinforced by the comple-

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<sup>25</sup>The grid of parameters is as follows:  $R$  ranges from 15 to 100;  $\underline{c} = 1.01R$ ;  $q_1 (= q_2)$  ranges from 0.01 to 0.3;  $f$  ranges from 0.8 to 1.2;  $c_1 (= c_2)$  ranges from  $\underline{c}$  to  $1.3R$ .

**Table 1: The Strategic Relation between Banks' IT in the Symmetric Case.**

	Share squeezing effect	Boundary profit effect	Share sensitivity effect	Net effect
$c_1$ and $q_2$	substitutive	complementary	complementary	complementary
$q_1$ and $c_2$	substitutive	complementary	substitutive	substitutive
$q_1$ and $q_2$	substitutive	complementary	complementary	substitutive
$c_1$ and $c_2$	substitutive	complementary	null	substitutive

mentary effect of the decrease in  $c_1$ ); and reduces  $c_1$  because the complementary effects of lower  $q_1$  and  $q_2$  dominate the strategic substitutability effect of a lower  $c_2$ .

As  $\beta_c$  decreases, bank 1 reduces  $c_1$  because the direct effect of reducing  $\beta_c$  dominates the strategic substitutability effect of a lower  $c_2$  (and is reinforced by the complementary effects of the decrease in  $q_1$  and  $q_2$ ); and reduces  $q_1$  because the complementary effect of a lower  $c_1$  dominates the strategic substitutability effects of lower  $q_2$  and  $c_2$ .

## 5 Bank stability

We study how the development and diffusion of information technology affects bank stability. To do so we use the probability of bank default as an inverse measure of bank stability. The probability of bank 1's default is denoted by  $\theta^*$ , which can be pinned down as described in Lemma 4.

**Lemma 4.** *Suppose the entrepreneurs located within  $[0, \tilde{x}]$  are served by bank 1. Let total funding demand at  $z \in [0, \tilde{x}]$  be  $D(z)$ , and let the loan rate of bank 1 be  $r_1(z)$  for entrepreneurs at  $z \in [0, \tilde{x}]$ . Then bank 1's default probability  $\theta^*$  is determined by the equality*

$$\int_0^{\theta^*} \int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta\right\}} dz d\theta + (1 - \theta^*) \int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta^*\right\}} dz - f \int_0^{\tilde{x}} D(z) dz = 0,$$

where  $1_{\{\cdot\}}$  is an indicator function that equals 1 if the condition in  $\{\cdot\}$  holds and equals 0 otherwise.

To see what is behind Lemma 4, we prove it here. Since the risk factor  $\theta$  is assumed to be uniformly distributed on  $[0, 1]$ , it follows that bank 1 would default when  $\theta < \theta^*$  if the bank's default probability is equal to  $\theta^*$ . So for a given  $\theta^*$ , the break-even condition

for depositors is

$$\int_0^{\theta^*} \int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta\right\}} dz d\theta + (1 - \theta^*) d_1 \int_0^{\tilde{x}} D(z) dz = f \int_0^{\tilde{x}} D(z) dz. \quad (5)$$

Equation (5) is interpreted to mean that bank 1's actual expected payment to depositors must equal their minimum expected payoff. To understand the equation, we start by looking at its right-hand side. Here  $\int_0^{\tilde{x}} D(z) dz$  is the aggregate funding amount that bank 1 borrows from its depositors and  $f$  is the minimum expected return required by those depositors. Thus  $f \int_0^{\tilde{x}} D(z) dz$  measures the minimum total expected payoff required by depositors. Next we look at the left-hand side, which represents bank 1's actual expected payment to depositors. When  $\theta$  is not lower than  $\theta^*$ , bank 1 stays solvent and is able to pay all of  $d_1 \int_0^{\tilde{x}} D(z) dz$  back to the depositors. However, if  $\theta < \theta^*$  then bank 1 cannot fully pay back depositors; instead, the bank repays the amount  $\int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta\right\}} dz$ , which is the aggregate loan repayment that the bank receives from entrepreneurs when  $\theta$  obtains. The indicator function  $1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta\right\}}$  appears in (5) because entrepreneurs at  $z$  have a positive loan repayment to bank 1 if and only if  $1 - m_1(z) \leq \theta$ . Integrating the bank's payoff to depositors from  $\theta = 0$  to  $\theta = 1$  yields the bank's expected payment to depositors, which is exactly the left-hand side of Equation (5).

Furthermore, bank 1 defaults if and only if  $\theta < \theta^*$  and so, when  $\theta = \theta^*$ , the aggregate loan repayment received by bank 1 should exactly equal the bank's promised payment to depositors. The implication is that

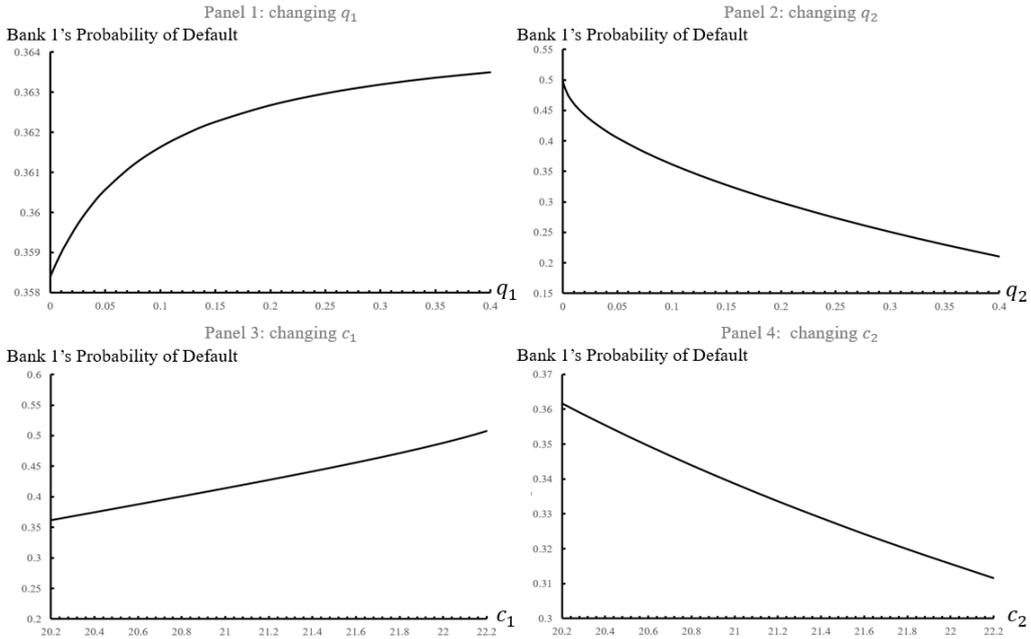
$$\int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta^*\right\}} dz = d_1 \int_0^{\tilde{x}} D(z) dz. \quad (6)$$

Equations (5) and (6) together determine  $d_1$  and  $\theta^*$ . Inserting (6) into (5) yields the equation displayed in Lemma 4.

**Bank stability when  $R$  is large.** Lemma 4 does not yield a closed-form solution for  $\theta^*$ , so we shall use numerical methods to analyze how IT change – as represented by changes in  $c_i$  or  $q_i$  – affects bank 1's default probability.

When  $R$  is large, bank 1 becomes less stable as  $q_1$  and/or  $c_1$  increases (see Panels 1 and 3 of Figure 5), which means that more advanced information technology is good for bank stability; as stated in Section 1, this result is consistent with the empirical findings of Pierri and Timmer (2021). An increase in  $q_1$  and/or  $c_1$  reduces bank 1's stability by

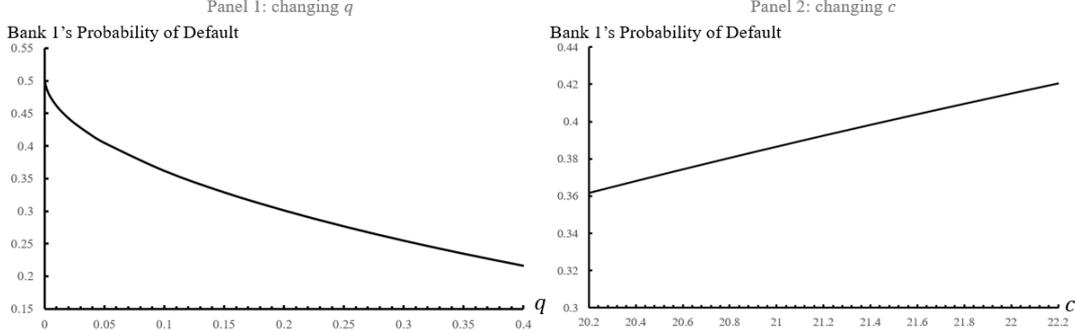
way of two channels. First, a higher  $q_1$  or  $c_1$  increases bank 1’s monitoring cost and so decreases bank 1’s incentive to monitor entrepreneurs; this factor reduces the investment projects’ likelihood of success. Second, Corollary 3 establishes that an increase in  $q_1$  and/or  $c_1$  decreases bank 1’s competitiveness (and market power) and thus forces the bank to set lower loan rates, which reduces not only bank 1’s monitoring intensity but also its “profit buffer” and therefore its stability. Yet we must point out that increasing  $q_1$  and/or  $c_1$  also has a pro-stability *market area effect*. Namely: as  $q_1$  and/or  $c_1$  increases, the region that bank 1 serves will shrink (i.e.,  $\tilde{x}_1$  will decrease); hence bank 1 can focus more on nearby entrepreneurs (who are easier to monitor), which promotes stability. However, this pro-stability market area effect is dominated by the two opposite effects mentioned previously.



**Figure 5: Bank 1’s Probability of Default (w.r.t.  $q_i$  and  $c_i$ ).** This figure plots bank 1’s probability of default against  $q_i$  and  $c_i$  in the equilibrium under direct bank competition. Except when used as a panel’s independent variable, the parameter values are  $R = 20$ ,  $f = 1$ ,  $c_1 = 1.01R$ ,  $c_2 = 1.01R$ ,  $q_1 = 0.1$ , and  $q_2 = 0.1$ .

As  $q_2$  and/or  $c_2$  increase, bank 1 becomes more stable (Panels 2 and 4 of Figure 5). This occurs because a higher  $q_2$  and/or  $c_2$  decreases bank 2’s competitive power (Corollary 3) and enables bank 1 to set a higher loan rate – which increases bank 1’s monitoring intensity and also its profit buffer, thereby improving its stability. However, increasing  $q_2$  and/or  $c_2$  has a negative market area effect on bank 1’s stability because the region

that bank 1 serves will expand (i.e.,  $\tilde{x}_1$  will increase) That being said, this market area effect is dominated by the first effect.



**Figure 6: Bank 1's Probability of Default (w.r.t.  $q$  and  $c$ ).** This figure plots bank 1's probability of default against  $q$  and  $c$  with the restriction that  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$  in the equilibrium under direct bank competition. Except when used as a panel's independent variable, the parameter values are  $R = 20$ ,  $f = 1$ ,  $c = 1.01R$ , and  $q = 0.1$ .

Letting  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$  allows us to analyze how the development and diffusion of information technology in the entire banking sector affect banks' stability. Although both  $q$  and  $c$  can be seen as inverse measures of IT in the banking sector, their effects on bank stability are different. Numerical results show that bank 1 becomes more stable as  $q$  increases but becomes less stable as  $c$  increases (see Figure 6). As  $q$  or  $c$  increases, the direct (cost) effect is that monitoring becomes more costly for banks; this effect reduces bank stability. Yet an increase in  $q$  increases banks' differentiation and so makes bank competition less intense (the differentiation effect). As a result, both banks can post higher loan rates (Corollary 4), which enhances the stability of both banks. Here the differentiation effect of  $q$  dominates.<sup>26</sup> In contrast, an increase in  $c$  does not have this kind of differentiation effect because  $c$  has no influence on banks' differentiation.

**Bank stability when  $R$  is not large.** If  $R \geq \max\{\sqrt{8c_1f/(1-q_1)}, \sqrt{8c_2f/(1-q_2)}\}$  is not satisfied (i.e., if  $R$  is not large), then the net effect of IT progress on bank stability is more complex. In Appendix LM, we show that a local monopoly equilibrium will arise if  $R$  is not large while  $q_i$  and/or  $c_i$  are sufficiently high (Proposition 12). However, as  $q$  or  $c$  decreases (with  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$ ), the local monopoly equilibrium may disappear and then banks begin to compete with each other. The effect of IT progress depends on whether or not banks enjoy local monopolies. Figure 7 graphically illustrates

<sup>26</sup>This result is in line with Jiang et al. (2017) who document that an intensification of bank competition materially boosts bank risk by reducing bank profits, charter values, and relationship lending.

how bank stability is affected by IT progress when  $R$  is not large.

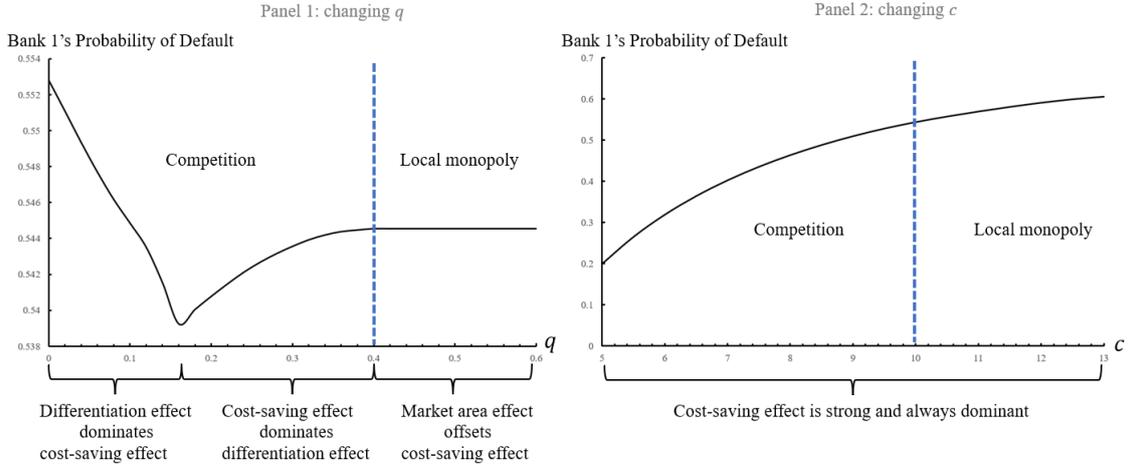
Our numerical study (see Panel 1 of Figure 7) indicates that, when banks are initially in a local monopoly equilibrium, bank 1's probability of default is constant at first; it then decreases and finally increases as  $q$  decreases. The intuition is as follows. At the beginning, a reduction in  $q$  does not change the equilibrium type; in this local monopoly equilibrium, bank stability does not vary with  $q$  because the cost-saving effect exactly offsets the "market area effect" (see Proposition 14 in Appendix LM for a detailed explanation). When  $q$  declines to a certain level, the equilibrium switches to the one with bank competition. In this new equilibrium, a further reduction in  $q$  would bring a (competition) differentiation effect, which would reduce bank stability. In this case, bank 1 will be more stable as  $q$  decreases unless  $q$  is small enough. This happens because if  $q$  is not small enough then bank 1 has monopoly power over a large part of its entrepreneurs; in this case effective bank competition occurs only for entrepreneurs who are located near the mid point  $z = 1/2$ . As a result, the (competition) differentiation effect of  $q$  is weak and the cost-saving effect dominates. However, when  $q$  is small enough, bank competition will be so intense that bank 1 has monopoly power over only a small (or vanishing) fraction of its entrepreneurs; then the (competition) differentiation effect of  $q$  will dominate the cost-saving effect. As a result, the net effect of a lower  $q$  on bank stability is reversed when  $q$  is small enough.<sup>27</sup>

The net effect of reducing  $c$  is simpler. Since a reduction in  $c$  significantly lowers the monitoring costs for all locations, it follows that the cost-saving effect of decreasing  $c$  is strong and always dominates other effects – that is, regardless of whether or not bank competition arises for a large group of entrepreneurs. Therefore, bank 1's probability of default is increasing in  $c$  (see Panel 2 of Figure 7).

**Deposit insurance.** If depositors are protected by a fairly priced deposit insurance scheme, then bank 1's probability of default is no longer as given in Lemma 4. The reason is that, when deposits are insured, the nominal deposit rate required by depositors is  $f$  rather than  $d_1$ . However, a numerical study shows that such deposit insurance only slightly reduces the probability of bank default and does not affect our results concerning the influence of information technology on bank stability.

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<sup>27</sup>Comparing Panel 1 of Figure 6 and Panel 1 of Figure 7, we find that the "decrease then increase" pattern of bank 1's probability of default (as illustrated in Panel 1 of Figure 7) does not arise when  $R$  is large, because a large  $R$  ensures effective bank competition for a significant range of (or even for all) locations.



**Figure 7: Bank 1's Probability of Default (w.r.t.  $q$  and  $c$ ) when  $R$  is not large.** This figure plots bank 1's probability of default against  $q$  and  $c$  with the restriction that  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$ . Except when used as a panel's independent variable, the parameter values are  $R = 5$ ,  $f = 1$ ,  $c = 10$ , and  $q = 0.4$ .

## 6 Welfare analysis

First we look at the relation between banks' equilibrium loan rates and socially optimal ones. We then analyze how the development and diffusion of the banking sector's information technology affect social welfare in the direct competition equilibrium described in Section 3 (where  $R$  is large). In Appendix LM, the welfare effect of IT progress in the local monopoly equilibrium is analyzed. Throughout the section we let  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$ , and hence use changes in  $q$  and  $c$  to measure the banking sector's IT change.

### 6.1 Socially optimal loan rates

If entrepreneurs at location  $z$  are financed by bank  $i$  and if  $\Omega \subseteq [0, 1]$  is the set of locations that are served, then social welfare is given by

$$\underbrace{\int_{\Omega} D(z) R m_i(z) dz}_{\text{Social benefits}} - \underbrace{\left( \int_{\Omega} D(z) f dz + \int_{\Omega} \frac{D(z)c}{2(1-qs_i)} (m_i(z))^2 dz + \int_{\Omega} \int_0^{D(z)} u du dz + (\theta_1^* + \theta_2^*) K \right)}_{\text{Social costs}}. \quad (7)$$

Here  $r_i(z)$  (resp.,  $m_i(z)$ ) is bank  $i$ 's loan rate (resp., monitoring intensity) for entrepreneurs at  $z$ ,  $D(z)$  is the total funding demand at  $z$ ,  $s_i$  is the distance between bank  $i$  and location  $z$ ,  $\theta_i^*$  is the probability that bank  $i$  goes bankrupt, and  $K$  is the deadweight loss

(i.e., bankruptcy costs) associated with a bank's failure. In our bank competition context, the social benefits of banks' lending behavior are measured by the expected value of all projects implemented; social costs consist of funding costs, monitoring costs, entrepreneurs' reservation utility, and bankruptcy costs. Entrepreneurs' reservation utility must be included in social costs because it measures the opportunity costs of giving up alternative activities. Bankruptcy costs can be interpreted as the costs of systemic banking sector failure given that both banks stay solvent or go bankrupt together when  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$  hold.

Recall  $\int_0^{D(z)} u \, du = (D(z))^2/2$  and  $D(z) = (R - r_i(z))m_i(z)$ . Then we can reorganize (7) as follows:

$$\begin{aligned}
W = & \underbrace{\int_{\Omega} \frac{((R - r_i(z))m_i(z))^2}{2} \, dz}_{\text{Entrepreneurs' aggregate expected utility}} \\
& + \underbrace{\int_{\Omega} D(z) \left( r_i(z)m_i(z) - f - \frac{c(m_i(z))^2}{2(1 - qs_i)} \right) \, dz}_{\text{Banks' expected profits}} - \underbrace{(\theta_1^* + \theta_2^*)K}_{\text{Deadweight loss of bankruptcy}}. \quad (8)
\end{aligned}$$

This expression divides social welfare into three components: entrepreneurs' aggregate utility, banks' profits, and the expected deadweight loss due to banks' failure. Using Equation (8), we can analyze the relation between equilibrium loan rates and socially optimal ones.

**Second best rates.** The second-best socially optimal loan rate schedule of bank  $i$ , denoted by  $\{r_i^{\text{SB}}(z)\}$ , maximizes social welfare (8) under the constraint that bank  $i$ 's monitoring intensity at  $z$  (viz.  $m_i(z)$ ) is equal to  $r_i^{\text{SB}}(z)(1 - qs_i)/c$ . In this case a benevolent social planner can choose loan rates for banks but cannot control banks' monitoring intensities; hence the latter must be as described in Lemma 1. Our next proposition gives the basic properties of  $r_i^{\text{SB}}(z)$ .

**Proposition 7.** *If  $K = 0$  and if location  $z$  is served by bank  $i$ , then the second-best socially optimal loan rate at location  $z$  (viz.,  $r_i^{\text{SB}}(z)$ ) is given by*

$$r_i^{\text{SB}}(z) = \frac{(2R^2(1 - qs_i) + 4cf) + \sqrt{(2R^2(1 - qs_i) + 4cf)^2 - 24cfR^2(1 - qs_i)}}{6R(1 - qs_i)},$$

which satisfies  $R/2 < r_i^{\text{SB}}(z) \leq r_i^m(z)$ . (Note that the equality  $r_i^{\text{SB}}(z) = r_i^m(z)$  holds only when bank  $i$ 's best loan rate at  $z$  is  $R$ .)

From the social planner's perspective, a higher  $r_i^{\text{SB}}(z)$  gives bank  $i$  more incentive to monitor, which increases the expected value of projects financed by bank  $i$ . Yet as  $r_i^{\text{SB}}(z)$  increases, entrepreneurs' utility will decrease (when  $r_i^{\text{SB}}(z) \geq R/2$ ). Hence a social planner must balance the social benefits and costs of increasing  $r_i^{\text{SB}}(z)$  – here  $R/2$  is one extreme loan rate, which maximizes entrepreneurs' utility; the monopoly loan rate  $r_i^m(z)$  is the other extreme, which maximizes banks' profits and also incentivizes them to choose high monitoring intensities – leading to the relation  $R/2 < r_i^{\text{SB}}(z) \leq r_i^m(z)$ .

Next we consider the relation between  $r_i^{\text{SB}}(z)$  and the equilibrium loan rate under effective bank competition (viz.,  $r_i^{\text{comp}}(z)$ ).

**Proposition 8.** *Let  $K = 0$ . If  $R > \sqrt{2cf}$  and if location  $z$  is served by bank  $i$ , then the inequality  $r_i^{\text{comp}}(z) < r_i^{\text{SB}}(z)$  holds for all locations when  $q$  is small enough.<sup>28</sup>*

The intensity of bank competition is too high when  $q$  (the differentiation between banks) is sufficiently low. From the perspective of social welfare, the benefits and costs of bank competition must be balanced. Entrepreneurs are better-off as the intensity of bank competition increases; but banks are then worse-off and monitoring intensities will decline, which reduces the expected value of investment projects.<sup>29</sup> Figure 8 offers a graphic presentation of this result.

**First-best rates.** Now we consider the first-best socially optimal case, where the social planner can choose not only the banks' loan rates but also their monitoring intensities. Thus banks' monitoring intensities are no longer constrained by Lemma 1. The following proposition characterizes the first-best socially optimal loan rates and monitoring intensities.

**Proposition 9.** *If  $K = 0$  and if location  $z$  is served by bank  $i$  then, at location  $z$ , the first-best socially optimal loan rate  $r_i^{\text{FB}}(z)$  and monitoring intensity  $m_i^{\text{FB}}(z)$  are given by*

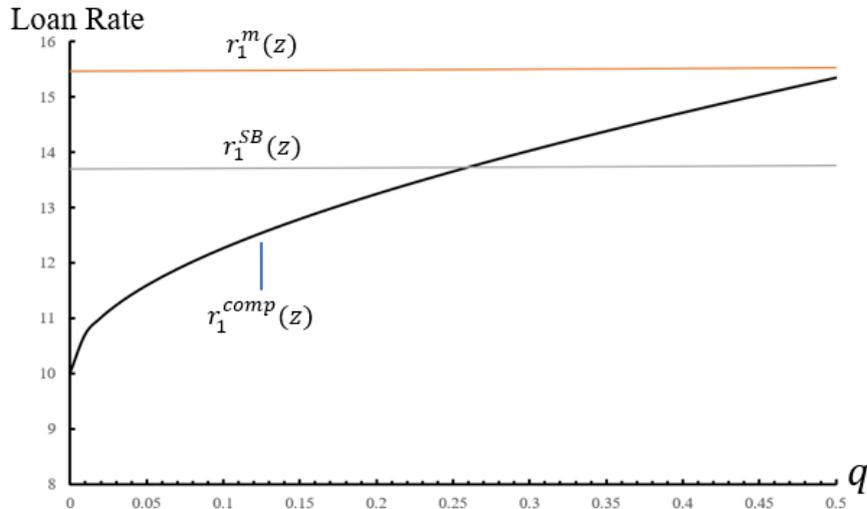
$$r_i^{\text{FB}}(z) = \frac{R}{2} + \frac{cf}{(1 - qs_i)R} \quad \text{and} \quad m_i^{\text{FB}}(z) = \frac{(1 - qs_i)R}{c};$$

here  $r_i^{\text{FB}}(z) \leq r_i^{\text{SB}}(z)$ . (Note that  $r_i^{\text{FB}}(z) = r_i^{\text{SB}}(z)$  only when bank  $i$ 's best loan rate at  $z$  is  $R$ .)

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<sup>28</sup>If  $R > \sqrt{2cf}$ , then there is always effective competition at  $z$  when  $q$  is small enough (recall that, throughout the paper, we must have  $R \geq \sqrt{2c_i f}$ ; otherwise, bank  $i$  is unwilling to serve any entrepreneur). In the boundary case  $R = \sqrt{2cf}$ , bank  $i$  must set its loan rate to  $R$  – even when  $q = 0$  – in order to ensure itself a non-negative profit; then we always have  $r_i^{\text{comp}}(z) = r_i^{\text{SB}}(z) = r_i^m(z) = R$  at locations served by bank  $i$ .

<sup>29</sup>Gehrig (1998) also finds that under certain conditions competition will decrease banks' screening efforts, and so reduce the quality of the overall loan portfolio.



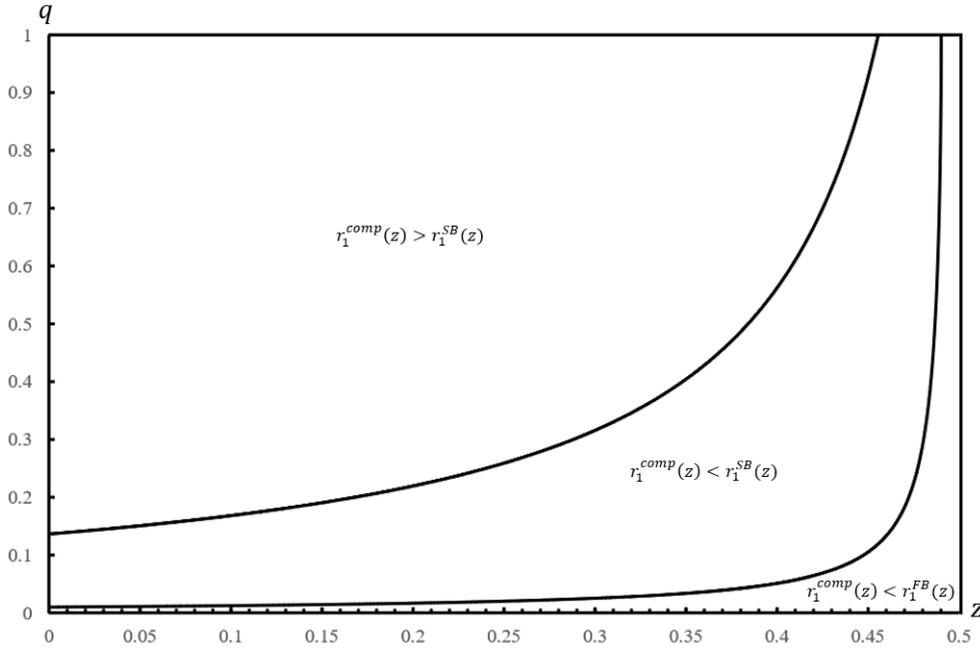
**Figure 8: Comparing  $r_1^{\text{comp}}(z)$ ,  $r_1^m(z)$ , and  $r_1^{\text{SB}}(z)$ .** This figure plots  $r_1^{\text{comp}}(z)$ ,  $r_1^m(z)$ , and  $r_1^{\text{SB}}(z)$  against  $q$ . The parameter values are  $R = 20$ ,  $f = 1$ ,  $c = 1.01R$ , and  $z = 0.25$ .

In the first-best case, a social planner can directly choose monitoring intensities and so need not rely on loan rates to incentivize banks' monitoring; the implication is that  $r_i^{\text{FB}}(z) \leq r_i^{\text{SB}}(z)$ . Meanwhile, the planner maximizes the expected value of investment projects (net of monitoring costs) by setting the first-best monitoring intensity at  $z$  to the same monitoring intensity that bank  $i$  would choose in equilibrium if and only if its loan rate were equal to the upper bound  $R$ .

The relation between the equilibrium loan rate under effective bank competition (viz.,  $r_i^{\text{comp}}(z)$ ) and the first-best socially optimal loan rate (viz.,  $r_i^{\text{FB}}(z)$ ) is given by Proposition 10.

**Proposition 10.** *Let  $K = 0$ . If  $R > \sqrt{2cf}$  and if location  $z$  is served by bank  $i$ , then  $r_i^{\text{comp}}(z) < r_i^{\text{FB}}(z)$  holds for all locations when  $q$  is small enough.*

In the first-best case, the monitoring intensity  $m_i^{\text{FB}}(z)$  is higher than what bank  $i$  would choose in equilibrium (unless the bank's equilibrium loan rate is  $R$ ). Since a higher monitoring intensity benefits entrepreneurs, the social planner must control  $r_i^{\text{FB}}(z)$  in order to avoid (inefficiently) excessive funding demand at location  $z$  – which means that  $r_i^{\text{FB}}(z)$  cannot be too low. So when bank competition is intense enough (i.e., when  $q$  is small enough), the equilibrium loan rate  $r_i^{\text{comp}}(z)$  will be lower than  $r_i^{\text{FB}}(z)$ . Figure 9 illustrates the relations involving  $r_1^{\text{comp}}(z)$ ,  $r_1^{\text{SB}}(z)$ , and  $r_1^{\text{FB}}(z)$  in  $z \times q$  space.



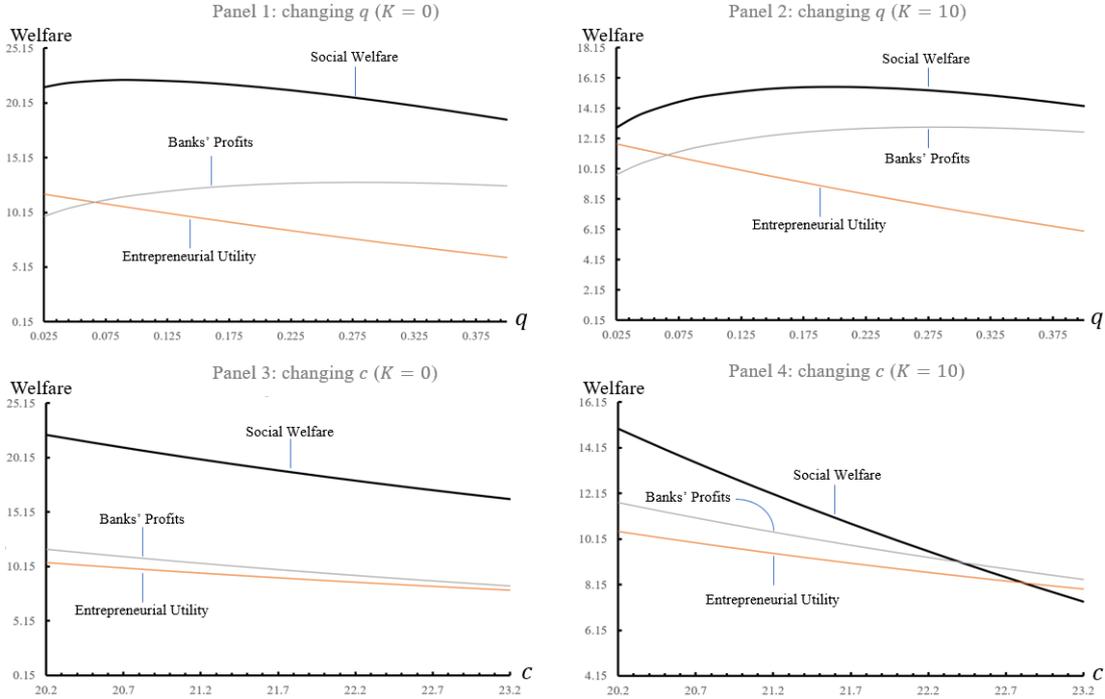
**Figure 9: Relations among  $r_1^{comp}(z)$ ,  $r_1^{SB}(z)$ , and  $r_1^{FB}(z)$  in  $z \times q$  space.** This figure compares  $r_1^{comp}(z)$  with  $r_1^{SB}(z)$  and  $r_1^{FB}(z)$  in  $z \times q$  space. The parameter values are  $R = 20$ ,  $c = 1.01R$ , and  $f = 1$ .

## 6.2 Welfare properties of the symmetric equilibrium

Here we examine the equilibrium described in Section 3 and analyze the welfare effects of information technology progress (i.e., of changes in  $q$  and  $c$ ). Figure 10 shows how entrepreneurs' utility, banks' profits, and social welfare vary with  $q$  and  $c$ .

A decrease in  $q$  will increase the intensity of banking competition because banks' differentiation will be diminished (by Corollary 4). From the perspective of entrepreneurs, greater bank competition translates into banks offering better loan rates, which always boosts entrepreneurs' utility. So as can be seen in Panels 1 and 2 of Figure 10, entrepreneurial utility increases if  $q$  decreases. From the bank's perspective, reducing  $q$  has two opposing effects. The first is a positive cost-saving effect: monitoring is cheaper when  $q$  is lower. Yet there is also a competition effect that banks dislike: a lower  $q$  implies more intense competition. The net effect – of decreasing  $q$  – on banks' profits is ambiguous. When  $q$  is not small, the cost-saving effect dominates and so decreasing  $q$  will increase banks' profits. When  $q$  is small enough, however, the competition effect will dominate and hence reducing  $q$  will decrease banks' profits (see Proposition 2). Perhaps more surprising is the following proposition, which shows that decreasing  $q$  reduces social welfare, even if there is no cost of bank failure (i.e., if  $K = 0$ ; see Panel 1 of Figure 10), for  $q$  small

enough.



**Figure 10: Social Welfare and Banking Sector's Information Technology under Competition.** This figure plots social welfare, entrepreneurial utility, and banks' profits against  $c$  and  $q$  in the equilibrium under bank competition. The parameter values are:  $R = 20$  and  $f = 1$  in all panels;  $c = 1.01R$  in Panels 1 and 2;  $q = 0.1$  in Panels 3 and 4;  $K = 0$  in Panels 1 and 3; and  $K = 10$  in Panels 2 and 4.

**Proposition 11.** *Let  $K = 0$ . Social welfare is increasing in  $q$  if  $q$  is sufficiently small while it is decreasing in  $c$ .*

The reason for the first result in Proposition 11 is that banks' equilibrium loan rates will be excessively low (as compared with socially optimal rates) when competition is too intense (i.e., when  $q$  is small enough; Proposition 8), which can dominate the cost-saving effect of decreasing  $q$  and thereby reduce social welfare. Competition determines not only the distribution of benefits between banks and entrepreneurs but also each bank's incentive to monitor entrepreneurs. As competition intensity increases, equilibrium loan rates will decline and so banks will prefer a lower monitoring intensity; this dynamic reduces the expected value of the entrepreneurs' projects and hence is detrimental to social welfare.

Panel 1 of Figure 10 gives a graphic illustration on how  $q$  affects social welfare when  $K = 0$ . When  $q$  is high, decreasing  $q$  and thus increasing competition intensity will

promote social welfare because now there is insufficient competition in the lending market to start with and entrepreneurs' aggregate utility is too low. Yet when  $q$  is low enough, decreasing  $q$  diminishes social welfare because competition intensity will be excessively high. Whether a reduction in  $q$  (and the resultant increased competition intensity) is welfare-improving depends on whether we start with a low or high level of competition. Recall that  $K$  is an exogenous cost associated with banks' failure. Since a higher intensity of bank competition will increase banks' probability of default, it follows that the socially optimal level of  $q$  will be higher when  $K$  is positive than when  $K = 0$  (see Panel 2 of Figure 10).

The second part of Proposition 11 shows that decreasing  $c$  simply improves social welfare when  $K = 0$  (see Panel 3 of Figure 10); the reason is that changing  $c$  has no effect on (competition) differentiation (Corollary 4). If  $K > 0$ , the welfare-improving effect of decreasing  $c$  will be strengthened (see Panel 4 of Figure 10), because decreasing  $c$  enhances bank stability and can therefore reduce the expected deadweight loss caused by banking failures.

In short: although reducing  $q$  and reducing  $c$  can each be viewed as progress in information technology, their welfare effects are quite different. So when discussing IT progress, one must stipulate the type of information technology change involved.

**Endogenous IT.** In Proposition 4, we have shown that  $q_1 = q_2 = 0$  (and  $c_1 = c_2 = \underline{c}$ ) will arise endogenously if Condition (3) holds; this implies that if IT is cheap to acquire, then banks would choose very low levels of differentiation, excessive from the social point of view. The cheap-IT scenario can arise for example if information technology is highly advanced in non-financial sectors and it spills over the banking sector.

**Local monopoly equilibrium.** In this equilibrium, banks do not compete with each other, so a decrease in  $q$  or  $c$  will bring only a cost-saving effect. As a consequence, social welfare is decreasing in  $q$  or  $c$  with local monopolies (see Appendix LM).

**Deposit insurance:** The formula for social welfare  $W$ , Equation (8), applies also to the case with a fairly priced deposit insurance scheme. The claim follows because (a) the deposit insurance fund always earns zero expected profit and (b) banks' payoff functions are not affected by such insurance. However, this does not mean that deposit insurance has no effect on social welfare. Because bank stability is no longer determined by Lemma 4 when deposits are insured, fairly priced deposit insurance will increase social welfare by reducing banks' probability of default ( $\theta_i^*$ ) when there is a positive deadweight loss associated with bank failure (i.e., when  $K > 0$ ). Yet this section's results – on how

IT progress affects social welfare – are robust in the case of fairly priced deposit insurance and a positive deadweight loss of bank failure.

## 7 Conclusion

Our study shows that whether (or not) the development and diffusion of information technology increases bank competition depends on whether it diminishes or increases differentiation among banks. In particular: if IT progress reduces the costs of monitoring/screening an entrepreneur without altering banks' relative cost advantage (i.e., lower  $c$ ), neither differentiation nor competition among banks is affected; hence banks will be more profitable and more stable. Yet if IT progress weakens the influence of bank–entrepreneur distance on monitoring/screening costs (i.e., lower  $q$ ) then differentiation among banks will decrease; bank competition will become more intense, so banks can be less profitable and less stable. We must therefore be careful to identify the kind of information technology change being considered before gauging its impact. In any case, and consistently with received empirical evidence, we find that a technologically more advanced bank – regardless of how changes in IT affect differentiation – commands greater market power and is more stable.

How banks endogenously choose their IT investment depends on the acquisition cost of IT. If it is cheap enough, then banks will acquire the best possible IT (i.e.,  $q_1 = q_2 = 0$  and  $c_1 = c_2 = \underline{c}$ ) in an attempt to obtain all the market, resulting in an equilibrium in which there is no bank differentiation and hence competition is extremely intense. If IT is not so cheap, then the two types of IT will co-move in response to a cost shock when a unique interior symmetric equilibrium exists.

We find that the welfare effect of information technology progress is ambiguous when it weakens the influence of bank–entrepreneur distance on monitoring/screening costs (lower  $q$ ). On the one hand, increasing competition intensity always favors entrepreneurs; on the other hand, more competition reduces banks' profits (and increases expected bankruptcy costs). Whether or not increased competition intensity benefits social welfare depends on whether the lending market has not enough or too much competition at the outset. When  $q$  is low, there is always excessive competition and insufficient monitoring. This is always the case when information technology is cheap because then banks choose endogenously a very low  $q$ . However, if banks enjoy local monopolies in equilibrium, then IT progress has no (competition) differentiation effect; it is always welfare-improving because such progress simply makes monitoring or screening less expensive.

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## Appendix A: Proofs

**Proof of Lemma 1.** Taking  $r_1(z)$  as given, maximizing  $\pi_1(z) \equiv r_1(z)m_1(z) - \frac{c_1}{2(1-q_1z)}(m_1(z))^2 - f$  by choosing  $m_1(z)$  directly yields the following first order condition:

$$r_1(z) - \frac{c_1}{(1-q_1z)}m_1(z) = 0 \implies m_1(z) = \frac{(1-q_1z)r_1(z)}{c_1}.$$

Symmetrically, we can derive  $m_2(z)$ .

**Proof of Lemma 3.** If bank 1 faces no competition, then it will choose  $r_1(z)$  to maximize its expected profit from location  $z$ ; such profit is equal to

$$\pi_1^{total}(z) \equiv D(z) \left( r_1(z)m_1(z) - \frac{c_1}{2(1-q_1z)}(m_1(z))^2 - f \right).$$

Recall that  $D(z) = (R - r_1(z))m_1(z)$  and  $m_1(z) = \frac{r_1(z)(1-q_1z)}{c_1}$ . After inserting  $D(z)$  and  $m_1(z)$  into  $\pi_1^{total}(z)$ , the objective function bank 1 finally needs to maximize is

$$\frac{(R - r_1(z))(r_1(z))^3(1 - q_1z)^2}{2c_1^2} - \frac{(R - r_1(z))r_1(z)(1 - q_1z)}{c_1}f.$$

The monopolistic loan rate, denoted by  $r_1^m(z)$ , that maximizes the objective function is determined by the following first order condition:

$$f(r_1(z)) \equiv \frac{(r_1(z))^2(3R - 4r_1(z))(1 - q_1z)}{2c_1} + (2r_1(z) - R)f = 0.$$

It is clear that  $f(-\infty) \rightarrow +\infty$ ,  $f(0) = -Rf < 0$  and  $f\left(\frac{R}{2}\right) = \frac{\left(\frac{R}{2}\right)^2 R(1-q_1z)}{2c_1} > 0$ . Therefore, within  $(-\infty, 0)$  and  $(0, \frac{R}{2})$ , there exist two roots for  $f(r_1(z)) = 0$ . However, those two roots cannot be the profit maximizing loan rate of bank 1 because we have shown that no bank would offer a loan rate that is lower than  $\frac{R}{2}$ .

We can further show that  $f(+\infty) \rightarrow -\infty$ . So there must exist a third root, denoted by  $r^{3rd}$ , within  $(\frac{R}{2}, +\infty)$ . If bank 1 finds it profitable to finance entrepreneurs at  $z$ , then  $r^{3rd}$  must be no larger than  $R$ , because total finding demand and bank 1's profit will be negative at location  $z$  if the bank offers a loan rate that is higher than  $R$ , which is never optimal for the bank. As a consequence,  $r^{3rd}$ , which must be within  $(\frac{R}{2}, R]$ , is the solution that maximizes bank 1's profit, and we denote it by  $r_1^m(z)$  in the main text. The schedule  $r_2^m(z)$  can be pinned down in the same way.

**Proof of Proposition 1.** First we determine the cut-off (indifference) location where an entrepreneur is indifferent about which bank to approach. Because the two banks compete in a localized Bertrand fashion, both banks will offer their best loan rates at the indifference location; meanwhile an entrepreneur at the location feels indifferent. So we have the following equation for the indifference location  $\tilde{x}$ :

$$\left(R - \frac{R}{2}\right) \frac{\frac{R}{2}(1 - q_1\tilde{x})}{c_1} - \underline{u} = \left(R - \frac{R}{2}\right) \frac{\frac{R}{2}(1 - q_2(1 - \tilde{x}))}{c_2} - \underline{u},$$

and the result is  $\tilde{x} = \frac{1 - \frac{c_1}{c_2} + \frac{c_1}{c_2}q_2}{\frac{c_1}{c_2}q_2 + q_1}$ . At the point  $\tilde{x}$  neither bank has a competitive advantage. On the left (resp. right) side of  $\tilde{x}$ , bank 1 (resp. bank 2) will have advantage in the competition with its rival. So if  $0 < \tilde{x} < 1$ , entrepreneurs in  $[0, \tilde{x}]$  are served by bank 1, while the other locations are served by bank 2.

At location  $z \in [0, \tilde{x}]$ , bank 1 must offer a loan rate  $r_1(z)$  to maximize its own profit from this location, subject to the constraint that an entrepreneur at  $z$ 's utility is no less than what she would derive from the best loan rate ( $\frac{R}{2}$ ) of bank 2. If bank 1 has no monopoly power on the entrepreneur, then bank 1's optimal choice is to set  $r_1(z)$  as high as possible; this implies the following equation:

$$(R - r_1(z)) \frac{r_1(z)(1 - q_1z)}{c_1} - \underline{u} = \left(R - \frac{R}{2}\right) \frac{\frac{R}{2}(1 - q_2(1 - z))}{c_2} - \underline{u}.$$

The equation yields  $r_1(z) = r_1^{\text{comp}}(z)$ . However, if  $r_1^{\text{comp}}(z)$  is higher than bank 1's monopoly loan rate  $r_1^m(z)$ , then bank 1 actually has monopoly power on entrepreneurs at  $z$ . In this case, bank 1 will simply choose  $r_1^m(z)$  as its loan rate. Therefore, bank 1's pricing strategy is  $r_1^*(z) = \min\{r_1^{\text{comp}}(z), r_1^m(z)\}$  for entrepreneurs located in  $[0, \tilde{x}]$ . Similarly, we can derive bank 2's equilibrium loan rate  $r_2^*(z)$ .

**Proof of Corollary 2.** If  $0 < \tilde{x} < 1$  and if there is effective competition between banks at  $z$ , the loan volume provided by bank 1 to entrepreneurs at  $z \in [0, \tilde{x}]$  is  $D(z) = (R - r_1^{\text{comp}}(z))m_1(z)$ . We can show that  $D(z) = \frac{(1 - q_2(1 - z))R^2}{4c_2}$ , which is increasing in  $z$  when  $z \in [0, \tilde{x}]$ . In the same way, we can show that the loan volume provided by bank 2 to entrepreneurs at  $z \in (\tilde{x}, 1]$  is decreasing in  $z$ .

**Proof of Proposition 2.** We need only look at bank 1's aggregate profit because the two banks are symmetric. If bank 1 has monopoly power in the region  $[0, x^m] \subset [0, 1/2]$ ,

then its aggregate profit (denoted by  $AP_1$ ) is given by

$$AP_1 \equiv \int_0^{x^m} D(z) \left( \frac{(r_1^m(z))^2(1-qz)}{2c} - f \right) dz + \int_{x^m}^{1/2} D(z) \left( \frac{(r_1^{comp}(z))^2(1-qz)}{2c} - f \right) dz.$$

We can show that

$$\frac{\partial AP_1}{\partial c} = \left( \begin{aligned} & \int_0^{x^m} \frac{\partial \left( D(z) \left( \frac{(r_1^m(z))^2(1-qz)}{2c} - f \right) \right)}{\partial c} dz + \int_{x^m}^{1/2} \frac{\partial \left( D(z) \left( \frac{(r_1^{comp}(z))^2(1-qz)}{2c} - f \right) \right)}{\partial c} dz \\ & + \left( D(x^m) \left( \frac{(r_1^m(x^m))^2(1-qx^m)}{2c} - f \right) - D(x^m) \left( \frac{(r_1^{comp}(x^m))^2(1-qx^m)}{2c} - f \right) \right) \frac{\partial x^m}{\partial c} \end{aligned} \right).$$

The third term of  $\partial AP_1 / \partial c$  is equal to 0 because at location  $z = x^m$ ,  $r_1^m(x^m)$  is equal to  $r_1^{comp}(x^m)$ . Therefore, the sign of  $\partial AP_1 / \partial c$  depends on the signs of its first two terms. Obviously we have  $\partial \left( D(z) \left( \frac{(r_1^m(z))^2(1-qz)}{2c} - f \right) \right) / \partial c < 0$  because bank 1's monopoly profit at  $z$  must be lower when monitoring is more costly. Meanwhile, we can also show that  $\partial \left( D(z) \left( \frac{(r_1^{comp}(z))^2(1-qz)}{2c} - f \right) \right) / \partial c < 0$  because  $D(z) = \frac{(1-q(1-z))R^2}{4c}$  is decreasing in  $c$  (see the proof of Corollary 2) while  $r_1^{comp}(z)$  is independent of  $c$  when  $z \in (x^m, 1/2]$ . Therefore, we have  $\partial AP_1 / \partial c < 0$ ; this means bank 1's aggregate profit is decreasing in  $c$ .

Next we look at the effect of  $q$ . If  $q$  is small enough, bank competition is effective at all locations (i.e.,  $x^m = 0$ ). In this case, we can show that

$$\frac{\partial AP_1}{\partial q} = \int_0^{1/2} \left( \frac{R^4 \sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} + \mu_b(q, c, z) \right) dz,$$

where  $\mu_b(q, c, z)$  is a term that is finite for  $q \rightarrow 0$ . For  $z < 1/2$ , it is easy to show  $\lim_{q \rightarrow 0} \frac{R^4 \sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} \rightarrow +\infty$ . If  $z = 1/2$ , we have  $\frac{R^4 \sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} = 0$ . Therefore, we must have  $\lim_{q \rightarrow 0} \frac{\partial AP_1}{\partial q} \rightarrow +\infty$ . As a result, bank 1's aggregate profit is increasing in  $q$  if  $q$  is sufficiently small.

**Proof of Proposition 3.** First we calculate  $\left. \frac{\partial(L_1+L_2)}{\partial q} \right|_{q_i=q}$ . If there is effective bank competition at all locations, we have

$$(L_1 + L_2)|_{q_i=q} = \int_0^{\tilde{x}} \frac{(1-q(1-z))R^2}{4c_2} dz + \int_{\tilde{x}}^1 \frac{(1-qz)R^2}{4c_1} dz,$$

because loan volume at  $z$  is equal to  $\frac{(1-q(1-z))R^2}{4c_2}$  (resp.  $\frac{(1-qz)R^2}{4c_1}$ ) if  $z \in [0, \tilde{x}]$  (resp.

$z \in (\tilde{x}, 1]$ ) according to the proof of Corollary 2. Therefore, it can be shown that

$$\begin{aligned} \frac{\partial(L_1 + L_2)}{\partial q} \Big|_{q_i=q} &= \int_0^{\tilde{x}} \frac{-(1-z)R^2}{4c_2} dz + \int_{\tilde{x}}^1 \frac{-zR^2}{4c_1} dz \\ &\quad + \left( \frac{(1-q(1-\tilde{x}))R^2}{4c_2} - \frac{(1-q\tilde{x})R^2}{4c_1} \right) \frac{\partial\tilde{x}}{\partial q}. \end{aligned}$$

Obviously the first two terms of  $\frac{\partial(L_1+L_2)}{\partial q} \Big|_{q_i=q}$  are negative. The third term of  $\frac{\partial(L_1+L_2)}{\partial q} \Big|_{q_i=q}$  is zero because  $\frac{(1-q(1-\tilde{x}))R^2}{4c_2} = \frac{(1-q\tilde{x})R^2}{4c_1}$  must hold at the indifference location  $\tilde{x}$ . As a consequence, we have  $\frac{\partial(L_1+L_2)}{\partial q} \Big|_{q_i=q} < 0$ .

Next we look at  $\frac{\partial^2 L_i}{\partial c_i \partial q} \Big|_{q_i=q}$ . We need only look at  $L_1$  since the two banks are symmetric. It can be shown that

$$\frac{\partial L_1}{\partial c_1} \Big|_{q_i=q} = \frac{(1-q(1-\tilde{x}))R^2}{4c_2} \frac{\partial\tilde{x}}{\partial c_1} = -\frac{R^2}{4c_2^2 \left(\frac{c_1}{c_2} + 1\right)^3} \frac{(2-q)^2}{q} < 0.$$

Obviously,  $\frac{\partial^2 L_i}{\partial c_i \partial q} \Big|_{q_i=q} > 0$  because  $\partial \left( \frac{(2-q)^2}{q} \right) / \partial q < 0$ .

**Proof of Proposition 4.** In the main text we have already shown that  $q_1 = q_2 = 0$  and  $c_1 = c_2 = \underline{c}$  indeed constitute an equilibrium. Here we show that the equilibrium is unique.

First, we show that  $\{q_2 = 0, c_2 = \underline{c}\}$  and  $\{q_1 > 0 \text{ or } c_1 > \underline{c}\}$  cannot be an equilibrium. If bank 2 chooses  $\{q_2 = 0, c_2 = \underline{c}\}$ , then bank 1's best response must be  $\{q_1 = 0, c_1 = \underline{c}\}$ , in which case bank 1's ex ante profit is  $\Pi_1(0, 0, \underline{c}, \underline{c}) > 0$ . In contrast, if bank 1's IT choice is not  $\{q_1 = 0, c_1 = \underline{c}\}$ , then bank 1's market share must be 0, which means

$$\Pi_1(q_1, 0, c_1, \underline{c}) \Big|_{q_1 > 0 \text{ or } c_1 > \underline{c}} = -T(q_1, c_1) \leq 0.$$

Therefore,  $\{q_1 > 0 \text{ or } c_1 > \underline{c}\}$  cannot be bank 1's best choice. Overall,  $\{q_2 = 0, c_2 = \underline{c}\}$  and  $\{q_1 > 0 \text{ or } c_1 > \underline{c}\}$  cannot be an equilibrium.

Reasoning symmetrically,  $\{q_1 = 0, c_1 = \underline{c}\}$  and  $\{q_2 > 0 \text{ or } c_2 > \underline{c}\}$  cannot be an equilibrium either.

Next, we show that  $\{q_1 > 0 \text{ or } c_1 > \underline{c}\}$  and  $\{q_2 > 0 \text{ or } c_2 > \underline{c}\}$  cannot be an equilibrium. In this case, we can show that bank 1 (resp. bank 2) has incentive to deviate if  $\tilde{x} \leq 1/2$  (resp.  $\tilde{x} \geq 1/2$ ). If  $\tilde{x} \leq 1/2$ , then bank 1's market share will increase from  $\tilde{x}$  to 1 if the bank deviates from  $\{q_1 > 0 \text{ or } c_1 > \underline{c}\}$  to  $\{q_1 = 0, c_1 = \underline{c}\}$ ; the cost of this deviation

is no higher than  $T(0, \underline{c})$ , while the bank's profit from the incremental market area  $(\tilde{x}, 1]$  must satisfy

$$\int_{\tilde{x}}^1 D(z)\pi_1(z)dz \Big|_{q_1=0, c_1=\underline{c}; q_2>0 \text{ or } c_2>\underline{c}} > \int_0^{1/2} D(z)\pi_1(z)dz \Big|_{q_1=q_2=0, c_1=c_2=\underline{c}}.$$

because  $\tilde{x} \leq 1/2$ . Meanwhile, bank 1's profit from its initial market area  $[0, \tilde{x}]$  will also (weakly) increase as the bank deviates to  $\{q_1 = 0, c_1 = \underline{c}\}$ . Overall, because of the deviation, bank 1's profit at the lending competition stage will increase by more than  $\int_0^{1/2} D(z)\pi_1(z)dz \Big|_{q_1=q_2=0, c_1=c_2=\underline{c}}$ , while the IT investment cost will increase by no more than  $T(0, \underline{c})$ . Then, because we have the condition

$$\Pi_1(0, 0, \underline{c}, \underline{c}) = \int_0^{1/2} D(z)\pi_1(z)dz \Big|_{q_1=q_2=0, c_1=c_2=\underline{c}} - T(0, \underline{c}) > 0,$$

bank 1 will become strictly better off if it deviates to  $\{q_1 = 0, c_1 = \underline{c}\}$ . Therefore, if  $\tilde{x} \leq 1/2$ ,  $\{q_1 > 0 \text{ or } c_1 > \underline{c}\}$  and  $\{q_2 > 0 \text{ or } c_2 > \underline{c}\}$  cannot be an equilibrium.

Reasoning symmetrically,  $\{q_1 > 0 \text{ or } c_1 > \underline{c}\}$  and  $\{q_2 > 0 \text{ or } c_2 > \underline{c}\}$  cannot be an equilibrium if  $\tilde{x} \geq 1/2$  because then bank 2 can be strictly better off by deviating to  $\{q_2 = 0, c_2 = \underline{c}\}$ . Overall, the unique equilibrium is  $\{q_1 = 0, c_1 = \underline{c}\}$  and  $\{q_2 = 0, c_2 = \underline{c}\}$  if we have the condition  $\Pi_1(0, 0, \underline{c}, \underline{c}) > 0$ .

**Proof of Proposition 5.** Here we provide a sketch for the proof. See Online Appendix D for a detailed proof of Proposition 5.

In a symmetric equilibrium, the first order conditions of bank 1 wrt  $q_1$  and  $c_1$  are respectively given by:

$$\frac{\partial \Pi_1}{\partial q_1} \Big|_{q_i=q, c_i=c} = 0 \text{ and } \frac{\partial \Pi_1}{\partial c_1} \Big|_{q_i=q, c_i=c} = 0. \quad (9)$$

Since  $\partial T(q, c)/\partial q = 0$  when  $q \geq \bar{q}$  and  $\lim_{q \rightarrow 0} -q\partial T(q, c)/\partial q$  is large enough, there must exist a  $q^*(c) \in (0, \bar{q})$  that solves  $\frac{\partial \Pi_1}{\partial q_1} \Big|_{q_i=q, c_i=c} = 0$  for any  $c \in [\underline{c}, \bar{c}]$ . The assumption that  $-q \frac{\partial^2 T(q, c)/\partial q^2}{\partial T(q, c)/\partial q}$  is large enough for  $q < \bar{q}$  ensures that such  $q^*(c)$  is unique. Meanwhile, since  $\frac{\partial T(q, c)}{\partial c} = 0$  for  $c \geq \bar{c}$  and  $-c\partial T(q, c)/\partial c$  is large enough when  $c = \underline{c}$ , there must exist a  $c^* \in (\underline{c}, \bar{c})$  that solves  $\frac{\partial \Pi_1}{\partial c_1} \Big|_{q_i=q^*(c), c_i=c} = 0$ . The assumption that  $-c \frac{\partial^2 T(q, c)/\partial c^2}{\partial T(q, c)/\partial c}$  is large enough for  $c < \bar{c}$  ensures that such  $c^*$  is unique. Therefore, the unique solution to (9) is  $\{q_i = q^*(c^*), c_i = c^*\}$ .

In a similar way, we can show that  $\{q_1 = q^*(c^*), c_1 = c^*\}$  is the unique solution to bank 1's first order condition given that bank 2 chooses  $\{q_2 = q^*(c^*), c_2 = c^*\}$ , so  $\{q_i = q^*(c^*), c_i = c^*\}$  indeed constitutes an equilibrium.

**Proof of Proposition 6.** In a symmetric equilibrium  $q$  and  $c$  solves the following system of equations (which is bank 1's FOC):

$$\underbrace{\left( \int_0^{\frac{1}{2}} \frac{R^4(1-q(1-z))z \left( (1-qz) \left( 1+2\sqrt{\frac{q(1-2z)}{1-qz}} \right) + q(1-2z) \right)}{32c^2 \sqrt{\frac{q(1-2z)}{1-qz}} (1-qz)} dz \right.}_{\text{denoted by } L_q(q,c)} + \frac{(2-q)R^2((2-q)R^2-16cf)}{128c^2} \left( \frac{1}{4q} \right) \right) = -\beta_q Q'(q);$$

$$\underbrace{\left( \int_0^{\frac{1}{2}} \frac{R^4(1-q(1-z)) \left( (1-qz) \left( 1+2\sqrt{\frac{q(1-2z)}{1-qz}} \right) + q(1-2z) \right)}{32c^3 \sqrt{\frac{q(1-2z)}{1-qz}}} dz \right.}_{\text{denoted by } L_c(q,c)} + \frac{(2-q)R^2((2-q)R^2-16cf)}{128c^2} \left( \frac{2-q}{4cq} \right) \right) = -\beta_c H'(c).$$

Obviously,  $L_q(q, c)$  is decreasing  $c$ . Note that  $(2-q)R^2 - 16cf \geq 0$  holds because, by assumption, a bank can make non-negative profit at location  $z = 1/2$  when it offers the best loan rate  $R/2$ . Next we show that  $L_c(q, c)$  is decreasing in  $q$ . Obviously the second term of  $L_c(q, c)$  is decreasing in  $q$ . The first term of  $L_c(q, c)$  can be rewritten as

$$\int_0^{\frac{1}{2}} \frac{R^4(1-q(1-z)) \sqrt{1-qz} \left( \left( 2\sqrt{1-qz} - \frac{\sqrt{qz}}{\sqrt{1-2z}} \right) + \frac{1}{\sqrt{q(1-2z)}} + \sqrt{q(1-2z)} \right)}{32c^3} dz,$$

which is also decreasing in  $q$  because  $\frac{1}{\sqrt{q(1-2z)}} + \sqrt{q(1-2z)}$  is decreasing in  $q$  for  $q \leq 1$ . Therefore,  $L_c(q, c)$  is decreasing in  $q$ .

The equation  $L_q(q, c) = -\beta_q Q'(q)$  implies that  $q$  is an implicit function of  $c$  and  $\beta_q$ , and we denote the implicit function as  $q(c, \beta_q)$ . For a given  $c$ , we have  $\partial q(c, \beta_q) / \partial \beta_q > 0$  in the unique symmetric equilibrium (See Inequality (15) in Online Appendix D for more details). Hence  $L_c(q(c, \beta_q), c)$  is decreasing in  $\beta_q$  for a given  $c$ . If  $\beta_q$  increases to some  $\widehat{\beta}_q > \beta_q$  while  $c$  does not change, then we must have  $L_c(q(c, \widehat{\beta}_q), c) < -\beta_c H'(c)$  because  $\beta_c H'(c)$  is not affected by  $\beta_q$ . Since  $-c \frac{\partial^2 T(q,c)/\partial c^2}{\partial T(q,c)/\partial c}$  is large (which means  $-c \frac{\partial^2 H(c)/\partial c^2}{\partial H(c)/\partial c}$  is large) for  $c \in [c, \bar{c})$ , to regain the symmetric equilibrium  $c$  must increase to  $\widehat{c} > c$  such that  $L_c(q(\widehat{c}, \widehat{\beta}_q), \widehat{c}) = -\beta_c H'(\widehat{c})$ . Note that  $\partial q(c, \beta_q) / \partial c > 0$  holds because  $L_q(q, c)$

is decreasing in  $c$ . Hence we must have  $q(\widehat{c}, \widehat{\beta}_q) > q(c, \beta_q)$  because  $\widehat{c} > c$  and  $\widehat{\beta}_q > \beta_q$ . Overall, if  $\beta_q$  increases to some  $\widehat{\beta}_q > \beta_q$ , then  $c$  and  $q = q(c, \beta_q)$  will respectively increase to  $\widehat{c}$  and  $q(\widehat{c}, \widehat{\beta}_q)$ , which means  $\frac{\partial q^*}{\partial \beta_q} > 0$  and  $\frac{\partial c^*}{\partial \beta_q} > 0$ . In a symmetric way, we can show that  $\frac{\partial q^*}{\partial \beta_c} > 0$  and  $\frac{\partial c^*}{\partial \beta_c} > 0$ .

**Proof of Proposition 7.** The second-best socially optimal loan rate of bank  $i$  maximizes  $W$  under the constraint  $m_i(z) = \frac{(1-qs_i)r_i^{\text{SB}}(z)}{c}$ . If  $K = 0$ , then the first order condition satisfied by  $r_i^{\text{SB}}(z)$  is

$$f^{\text{SB}}(r_i^{\text{SB}}(z)) \equiv \frac{r_i^{\text{SB}}(z) R (2R - 3r_i^{\text{SB}}(z)) (1 - qs_i)}{2c} + (2r_i^{\text{SB}}(z) - R) f = 0,$$

which has two solutions.

It must hold that  $1 - qs_i > 0$  because the farthest location bank 1 (or bank 2) finances is  $z = \frac{1}{2}$  in the symmetric case. Therefore, it is clear that  $f^{\text{SB}}(-\infty) \rightarrow -\infty$ ,  $f^{\text{SB}}(\frac{R}{2}) > 0$  and  $f^{\text{SB}}(+\infty) \rightarrow -\infty$ ; This means one solution of the FOC is smaller than  $\frac{R}{2}$ , and the other solution is larger than  $\frac{R}{2}$ . The second order condition (SOC), which is  $\frac{R(2R-6r_i^{\text{SB}}(z))(1-qs_i)}{2c} + 2f < 0$ , is satisfied by the larger solution of the FOC:

$$r_i^{\text{SB}}(z) = \frac{(2R^2(1-qs_i) + 4cf) + \sqrt{(2R^2(1-qs_i) + 4cf)^2 - 24cfR^2(1-qs_i)}}{6R(1-qs_i)} > \frac{R}{2}.$$

The monopoly loan rate  $r_i^m(z)$  is the largest solution (which is larger than  $\frac{R}{2}$ ) of following equation:

$$f(r_i^m(z)) \equiv \frac{(r_i^m(z))^2 (3R - 4r_i^m(z)) (1 - qs_i)}{2c} + (2r_i^m(z) - R) f = 0.$$

Based on the equation above, we have  $r_i^m(z) > \frac{3}{4}R$  because  $f(\frac{3}{4}R) > 0$  and  $f(+\infty) \rightarrow -\infty$  hold. Meanwhile, it is easy to see that  $f(x) > f^{\text{SB}}(x)$  if  $R > x > \frac{3R}{4}$ . Therefore, if  $r_i^m(z) < R$ , we have  $f(r_i^m(z)) = 0 > f^{\text{SB}}(r_i^m(z))$ , which implies  $r_i^{\text{SB}}(z) < r_i^m(z)$ .

If  $r_i^m(z) = R$ , however, it must hold that  $R = \sqrt{\frac{2cf}{1-qs_i}}$ . In this case, bank  $i$ 's best loan rate is also  $\sqrt{\frac{2cf}{1-qs_i}}$ , and it is easy to show that  $f^{\text{SB}}(R) = 0$ , so  $r_i^m(z) = r_i^{\text{SB}}(z) = R$  in this case.

**Proof of Proposition 8.** We consider the limiting case  $q = 0$ . In this case, bank  $i$  must offer its best loan rate in equilibrium because there is no bank differentiation. That is,  $r_i^{\text{comp}}(z) = \frac{R}{2}$  if  $R \geq 2\sqrt{2cf}$  and  $r_i^{\text{comp}}(z) = \sqrt{2cf}$  if  $\sqrt{2cf} < R < 2\sqrt{2cf}$  (see Appendix B for bank  $i$ 's best loan rates when  $R$  is not large). In the case  $R \geq 2\sqrt{2cf}$ , it is easy

to see  $r_i^{\text{comp}}(z) = \frac{R}{2} < r_i^{\text{SB}}(z)$  because  $f^{\text{SB}}\left(\frac{R}{2}\right) > 0$ . So we need only look at the case  $\sqrt{2cf} < R < 2\sqrt{2cf}$ .

In the case  $\sqrt{2cf} < R < 2\sqrt{2cf}$ , we can show that

$$f^{\text{SB}}(r_i^{\text{comp}}(z)) = \frac{2\sqrt{2cf}(R - \sqrt{2cf})^2}{2c},$$

which is positive if  $R > \sqrt{2cf}$  holds. Therefore, we have  $r_i^{\text{comp}}(z) < r_i^{\text{SB}}(z)$  if  $R > \sqrt{2cf}$  and if  $q = 0$ ; this means  $r_i^{\text{comp}}(z) < r_i^{\text{SB}}(z)$  holds when  $q$  is small enough and  $R > \sqrt{2cf}$ .

**Proof of Proposition 9.** In the first-best case, the social planner chooses  $r_i^{\text{FB}}(z)$  and  $m_i^{\text{FB}}(z)$  to maximize  $W$ . The FOC w.r.t.  $r_i(z)$  is

$$-r_i(z)m_i(z) + f + \frac{c}{2(1-qs_i)}(m_i(z))^2 = 0.$$

The FOC w.r.t.  $m_i(z)$  is

$$(R + r_i(z))m_i(z) - f - \frac{3c}{2(1-qs_i)}(m_i(z))^2 = 0.$$

Solving the two FOC equations yields:

$$r_i^{\text{FB}}(z) = \frac{R}{2} + \frac{cf}{(1-qs_i)R}; m_i^{\text{FB}}(z) = \frac{(1-qs_i)R}{c}.$$

We can show that

$$\begin{aligned} f^{\text{SB}}(r_i^{\text{FB}}(z)) &= \frac{r_i^{\text{FB}}(z)R(2R - 3r_i^{\text{FB}}(z))(1-qs_i)}{2c} + (2r_i^{\text{FB}}(z) - R)f \\ &= \frac{\frac{1}{4}((1-qs_i)R^2 - 2cf)^2}{2c(1-qs_i)R}, \end{aligned}$$

which is positive unless  $R = \sqrt{\frac{2cf}{1-qs_i}}$ . As a consequence,  $r_i^{\text{FB}}(z) < r_i^{\text{SB}}(z)$  if  $R \neq \sqrt{\frac{2cf}{1-qs_i}}$ .

If  $R = \sqrt{\frac{2cf}{1-qs_i}}$ , then bank  $i$ 's best loan rate is  $R$  at location  $z$ . In this case we have  $f^{\text{SB}}(r_i^{\text{FB}}(z)) = 0$ , so  $r_i^{\text{FB}}(z) = r_i^{\text{SB}}(z) = r_i^m(z) = R$ .

**Proof of Proposition 10.** We consider the limiting case  $q = 0$ . In this case, bank  $i$  must offer its best loan rate in equilibrium because there is no bank differentiation. That is,  $r_i^{\text{comp}}(z) = \frac{R}{2}$  if  $R \geq 2\sqrt{2cf}$  and  $r_i^{\text{comp}}(z) = \sqrt{2cf}$  if  $\sqrt{2cf} < R < 2\sqrt{2cf}$ . In the case  $R \geq 2\sqrt{2cf}$ , it is easy to see  $r_i^{\text{comp}}(z) = \frac{R}{2} < r_i^{\text{FB}}(z)$  because  $r_i^{\text{FB}}(z) = \frac{R}{2} + \frac{cf}{R}$ . Therefore, we only need to look at the case  $\sqrt{2cf} < R < 2\sqrt{2cf}$ .

In the case  $\sqrt{2cf} < R < 2\sqrt{2cf}$ , we can show that

$$r_i^{\text{FB}}(z) - r_i^{\text{comp}}(z) = \frac{R^2 - 2R\sqrt{2cf} + \sqrt{2cf}\sqrt{2cf}}{2R} = \frac{(R - \sqrt{2cf})^2}{2R} > 0.$$

Therefore,  $r_i^{\text{comp}}(z) < r_i^{\text{FB}}(z)$  holds when  $q$  is small enough.

**Proof of Proposition 11.** In a symmetric competitive equilibrium with  $K = 0$ , social welfare  $W$  can be simplified to

$$W = 2 \int_0^{1/2} \left( \frac{1}{2} (D(z))^2 + D(z) \left( \frac{(r_1(z))^2(1-qz)}{2c} - f \right) \right) dz.$$

If bank 1 has monopoly power in the region  $[0, x^m] \subset [0, 1/2]$ , then following the proof of Proposition 2 we can show that

$$\frac{\partial W}{\partial c} = \left( \begin{array}{l} 2 \int_0^{x^m} \frac{\partial \left( \left( \frac{1}{2} (D(z))^2 + D(z) \left( \frac{(r_1^m(z))^2(1-qz)}{2c} - f \right) \right) \right)}{\partial c} dz \\ + 2 \int_{x^m}^{1/2} \frac{\partial \left( \left( \frac{1}{2} (D(z))^2 + D(z) \left( \frac{(r_1^{\text{com}}(z))^2(1-qz)}{2c} - f \right) \right) \right)}{\partial c} dz \end{array} \right).$$

For  $z \in [0, x^m]$ ,  $D(z) = \frac{r_1^m(z)(1-qz)}{c} (R - r_1^m(z))$  is decreasing in  $c$  because  $r_1^m(z)$  is increasing in  $c$  (Proposition 13); meanwhile,  $D(z) \left( \frac{(r_1^m(z))^2(1-qz)}{2c} - f \right)$  is also decreasing in  $c$  according to the proof of Proposition 2. Therefore, the first term of  $\frac{\partial W}{\partial c}$  is negative. For  $z \in (x^m, 1/2]$ ,  $D(z) = \frac{(1-q(1-z))R^2}{4c}$  is obviously decreasing in  $c$ ; meanwhile,  $D(z) \left( \frac{(r_1^{\text{com}}(z))^2(1-qz)}{2c} - f \right)$  is also decreasing in  $c$  according to the proof of Proposition 2. Therefore, the second term of  $\frac{\partial W}{\partial c}$  is also negative. Overall, we have  $\frac{\partial W}{\partial c} < 0$ , which means social welfare is decreasing in  $c$ .

Next we look at the effect of  $q$ . If  $q$  is small enough, bank competition is effective at all locations (i.e.,  $x^m = 0$ ). In this case, we can show that

$$\frac{\partial W}{\partial q} = 2 \int_0^{1/2} \left( \frac{R^4 \sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} + \mu_W(q, c, z) \right) dz,$$

where  $\mu_W(q, c, z)$  is a term that is finite for  $q \rightarrow 0$ . For  $z < 1/2$ , we have  $\lim_{q \rightarrow 0} \frac{R^4 \sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} \rightarrow +\infty$ . For  $z = 1/2$ , we have  $\frac{R^4 \sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} = 0$ . Therefore,  $\lim_{q \rightarrow 0} \frac{\partial W}{\partial q} \rightarrow +\infty$  must hold. As a consequence, social welfare is increasing in  $q$  if  $q$  is sufficiently small.

## Appendix LM: Local monopoly equilibrium

In this appendix we consider the local monopoly equilibrium, where the two banks do not compete with each other. Studying this equilibrium requires us to abandon the assumption that  $R$  is large (i.e., that  $R \geq \max\{\sqrt{8c_1f/(1-q_1)}, \sqrt{8c_2f/(1-q_2)}\}$ ); otherwise, there will exist no local monopoly equilibria. The reason is that such an equilibrium exists only if banks are unwilling to finance far-away entrepreneurs even when the loan rate is  $R$ , which contradicts the condition  $R \geq \max\{\sqrt{8c_1f/(1-q_1)}, \sqrt{8c_2f/(1-q_2)}\}$  that ensures banks are willing to offer the loan rate  $R/2$  to any entrepreneur.

Since the two banks are symmetric, we focus on bank 1. If entrepreneurs at  $z$  are target clients of bank 1 and if there is no bank competition, then bank 1 must guarantee that the expected profit of an entrepreneur at  $z$  who borrows from bank 1 is non-negative; otherwise, no entrepreneur at  $z$  would want to be served by bank 1. If bank 1's loan rate for entrepreneurs at  $z$  is  $r_1(z)$ , then an entrepreneur's expected profit at that location is

$$(R - r_1(z)) \frac{r_1(z)(1 - q_1z)}{c_1},$$

which is always non-negative for  $r_1(z) \in [0, R]$ . In other words, bank 1 can serve all locations by offering a loan rate  $r_1(z) \in [0, R]$ .<sup>30</sup>

Yet in a local monopoly equilibrium, there must exist locations that bank 1 is not willing to serve. If entrepreneurs at  $z$  are clients that bank 1 does not want to finance, then bank 1's expected profit from financing an entrepreneur at that location must be negative even if bank 1 sets  $r_1(z) = R$ , which implies the following inequality:

$$z > \frac{R^2 - 2c_1f}{q_1R^2}. \quad (10)$$

Inequality (10) implies that bank 1 is willing to serve entrepreneurs in  $[0, \frac{R^2 - 2c_1f}{q_1R^2}]$  if  $\frac{R^2 - 2c_1f}{q_1R^2} \geq 0$ . By symmetric reasoning, bank 2 is willing to serve entrepreneurs in  $[1 - \frac{R^2 - 2c_2f}{q_2R^2}, 1]$  if  $1 - \frac{R^2 - 2c_2f}{q_2R^2} \leq 1$ . To ensure that the equilibrium is indeed of the local monopoly type, there cannot exist a location that both banks are willing to serve. Hence the local monopoly equilibrium exists if

$$\frac{R^2 - 2c_1f}{q_1R^2} + \frac{R^2 - 2c_2f}{q_2R^2} < 1.$$

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<sup>30</sup>When  $r_1(z) = R$ , an entrepreneur with  $u = 0$  is willing to accept the offer of bank 1.

In such an equilibrium, there is no competition between banks and so bank  $i$ 's equilibrium loan rate for an entrepreneur at  $z$  is the monopoly loan rate  $r_i^m(z)$ .

We summarize the foregoing analysis in our next proposition.

**Proposition 12.** *Let  $\frac{R^2-2c_i f}{q_i R^2} \geq 0$ ,  $i = 1, 2$ , and  $\frac{R^2-2c_1 f}{q_1 R^2} + \frac{R^2-2c_2 f}{q_2 R^2} < 1$ . Then there exists a local monopoly equilibrium where bank  $i$ 's loan rate schedule is given by*

$$r_i^{\text{local}}(z) = r_i^m(z).$$

*Bank 1 serves entrepreneurs in  $[0, \frac{R^2-2c_1 f}{q_1 R^2}]$  while bank 2 serves entrepreneurs in  $[1 - \frac{R^2-2c_2 f}{q_2 R^2}, 1]$ .*

According to Proposition 12, a local monopoly equilibrium will arise when  $R$  is not large yet  $q_i$  and  $c_i$  are sufficiently large. Corollary 5 shows how  $r_1^m(z)$  varies with entrepreneurial location  $z$ ; a symmetric result holds for  $r_2^m(z)$ .

**Corollary 5.** *In the local monopoly equilibrium, bank 1's equilibrium loan rate  $r_1^m(z)$  is increasing in  $z$  when  $z \in [0, \frac{R^2-2c_1 f}{q_1 R^2}]$ . At the location  $z = \frac{R^2-2c_1 f}{q_1 R^2}$ , we have  $r_1^m(z) = R$ .*

Note that the pattern of bank 1's loan rate with respect to  $z$  in the local monopoly equilibrium is different from that in the case with bank competition (see Corollary 1). The reason is that the determinants of loan rates are completely different in the two types of equilibria. When the two banks compete for entrepreneurs at  $z$ , what determines the equilibrium loan rate is the intensity of bank competition. In this case, the equilibrium loan rate is higher at the locations where the competition is less intense. In the local monopoly equilibrium, however, banks no longer compete with each other and so the equilibrium loan rate reflects banks' costs of providing loans (monitoring and funding costs) instead of competition intensity.

**Information technology and monopoly loan rates.** The following proposition shows how information technology affects loan rates in the local monopoly equilibrium.

**Proposition 13.** *In the local monopoly equilibrium, bank 1's equilibrium loan rate  $r_1^m(z)$  is increasing in  $c_1$  and  $q_1$  when  $z \in [0, \frac{R^2-2c_1 f}{q_1 R^2})$ .*

In the local monopoly equilibrium information technology progress (i.e., reducing  $c_1$  or  $q_1$ ) simply makes monitoring cheaper for bank 1, which increases bank 1's profit per unit of loans and hence induces bank 1 to be more concerned about total funding demand

at  $z$ . As a result, bank 1 decreases its loan rate in order to increase the funding demand and maximize its monopoly profit at location  $z$ .

**Bank stability under local monopoly.** In a local monopoly equilibrium, bank 1 is not affected by  $q_2$  or  $c_2$ ; therefore, we need only look at the effects of  $q_1$  and  $c_1$  on bank 1's stability. Proposition 14 gives a relevant result.

**Proposition 14.** *In the local monopoly equilibrium, bank 1's probability of default is independent of  $q_1$ .*

A higher  $q_1$  has two competing effects on bank 1's stability. The first one is a direct cost effect: increasing  $q_1$  makes monitoring more costly, which reduces the intensity of bank 1's monitoring and thus reduces bank stability. The second effect is an indirect market area effect: the region that bank 1 serves will shrink as  $q_1$  increases, which promotes the bank's stability because it can then concentrate more on nearby entrepreneurs (who are easier to monitor). Proposition 14 means that the market area effect exactly offsets the cost effect.<sup>31</sup>

Increasing  $c_1$  induces a cost effect and a market area effect, just as changing  $q_1$  does. Yet because  $c_1$  significantly affects monitoring costs for all locations,<sup>32</sup> the cost effect of  $c_1$  is stronger than that of  $q_1$ . A numerical study establishes that the cost effect dominates as  $c_1$  increases.

**Welfare analysis of the local monopoly equilibrium.** In Proposition 7, we have shown that  $R/2 < r_i^{\text{SB}}(z) \leq r_i^m(z)$  holds. According to Proposition 12, bank  $i$ 's equilibrium loan rate in the local monopoly equilibrium exactly equals  $r_i^m(z)$ , so we have the following corollary.

**Corollary 6.** *Let  $K = 0$ . Then, in a local monopoly equilibrium where bank 1 serves the region  $[0, \frac{R^2-2cf}{qR^2}]$ , bank 1's equilibrium loan rate is higher than  $r_1^{\text{SB}}(z)$  when  $z \in [0, \frac{R^2-2cf}{qR^2})$  – provided that  $\frac{R^2-2cf}{qR^2} > 0$  – and is equal to  $r_1^{\text{SB}}(z)$  ( $= R$ ) at  $z = \frac{R^2-2cf}{qR^2}$ . A symmetric result holds for bank 2.*

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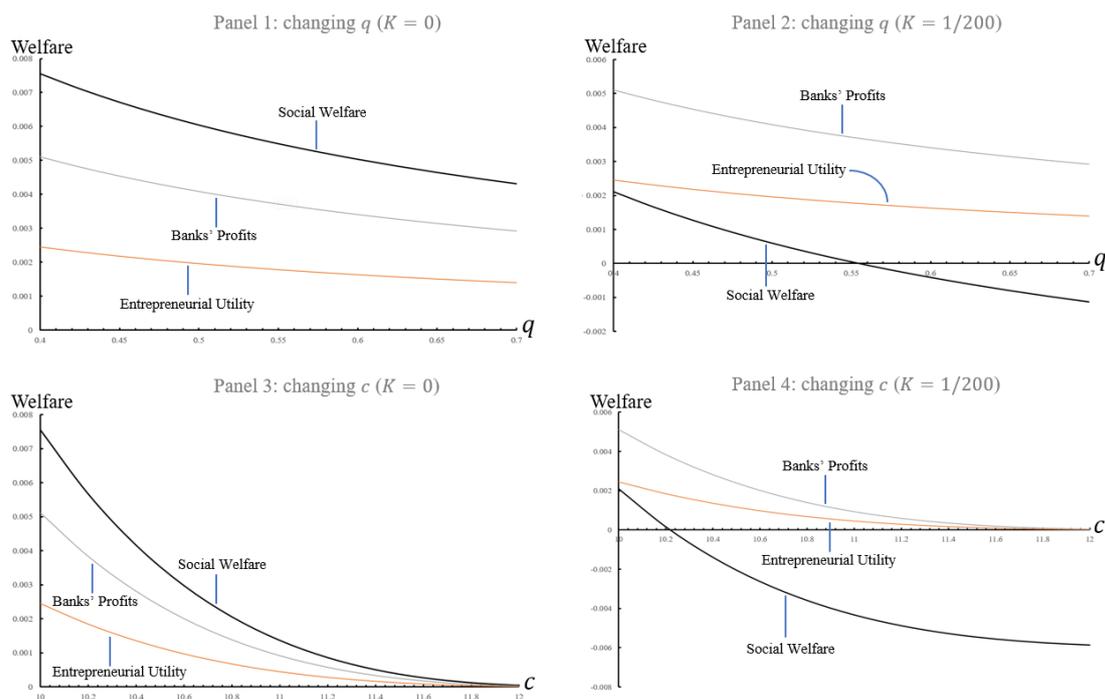
<sup>31</sup>The market area effect in our model is in line with empirical evidence. Acharya et al. (2006) find that geographic expansion does not guarantee greater safety for banks. Deng and Elyasiani (2008) document that increased distance between a bank holding company (BHC) and its branches is associated with BHC value reduction and risk increase. Loutskina and Strahan (2011) find that geographically concentrated lenders have higher profits and are more stable than diversified lenders because geographic diversification leads to a decline in screening by lenders. Blickle et al. (2021) report that specialized banks earn more stable returns and charge-off fewer loans.

<sup>32</sup>In contrast,  $q_1$  does not significantly affect bank 1's monitoring costs for given monitoring intensity when  $z$  is close to zero.

Next we analyze how the development and diffusion of information technology affect social welfare in the local monopoly equilibrium. The following proposition shows how social welfare is affected by  $q$  and  $c$  when there is no social cost of bank failure.

**Proposition 15.** *Let  $K = 0$ . Social welfare is decreasing in  $q$  and  $c$  in the local monopoly equilibrium.*

In a local monopoly equilibrium, the welfare effects of  $q$  and  $c$  are not qualitatively different. A marginal decrease in  $q$  or  $c$  brings only cost-saving effect in this equilibrium, which promotes entrepreneurial utility, banks' profits, and social welfare (Panels 1 and 3 of Figure 11). Taking bankruptcy cost  $K$  into consideration strengthens (resp., does not change) the welfare-improving effect of decreasing  $c$  (resp.,  $q$ ) because, when there is no bank competition, a smaller  $c$  (resp.,  $q$ ) enhances (resp., does not affect) bank stability; see Panels 2 and 4 of Figure 11.



**Figure 11: Social Welfare and Banking Sector's Information Technology under Local Monopoly.** This figure plots social welfare, entrepreneurial utility, and banks' profits against  $c$  and  $q$  in the local monopoly equilibrium. The parameter values are:  $R = 5$  and  $f = 1$  in all panels;  $c = 10$  in Panels 1 and 2;  $q = 0.4$  in Panels 3 and 4;  $K = 0$  in Panels 1 and 3; and  $K = 1/200$  in Panels 2 and 4.

## Appendix B: Insufficiently large $R$

In this part we consider bank competition under a general  $R$  that need not be large (i.e.,  $R \geq \max \left\{ \sqrt{\frac{8c_1 f}{1-q_1}}, \sqrt{\frac{8c_2 f}{1-q_2}} \right\}$  need not hold). In this case,  $\frac{R}{2}$  may not guarantee banks a non-negative profit at  $z$ . Specifically, bank 1's expected profit from financing an entrepreneur at  $z$  is given by:

$$\pi_1(z) = \frac{(r_1(z))^2(1-q_1z)}{2c_1} - f$$

when bank 1 posts loan rate  $r_1(z)$  for the entrepreneur. If  $\pi_1(z)$  is positive when  $r_1(z) = \frac{R}{2}$ , then bank 1's best loan rate at location  $z$  is still  $\frac{R}{2}$ . However, if  $\pi_1(z)$  is negative when  $r_1(z) = \frac{R}{2}$ , then  $\frac{R}{2}$  is no longer bank 1's best loan rate. A symmetric result holds for bank 2. When  $\frac{R}{2}$  is too low to be bank 1's best loan rate, the lowest acceptable loan rate for bank 1 is determined by

$$\pi_1(z) = 0,$$

which yields:

$$r_1(z) = \bar{r}_1(z) \equiv \sqrt{\frac{2c_1 f}{1-q_1 z}}.$$

Similarly, the lowest acceptable loan rate for bank 2 equals  $\bar{r}_2(z) \equiv \sqrt{\frac{2c_2 f}{1-q_2(1-z)}}$  if  $\frac{R}{2}$  is too low to be the best loan rate. As a result, bank  $i$ 's best loan rate at location  $z$  is given by

$$r_i^b(z) = \max \left\{ \frac{R}{2}, \bar{r}_i(z) \right\}.$$

Because the two banks are symmetric, we need only look at how bank 1 chooses its loan rates at locations it serves. If bank 1 does not face enough competition pressure from bank 2, then bank 1 will maintain its monopoly loan rate  $r_1^m(z)$  for entrepreneurs at  $z$ .

If bank 1 faces effective competition at  $z$ , and wants to attract entrepreneurs who want to undertake investment projects at the location, then it must be able to offer entrepreneurs at  $z$  a loan rate that is more attractive than  $r_2^b(z)$  offered by bank 2. If bank 1 cannot do so, then location  $z$  will be served by bank 2. If bank 1 can do so, then its strategy is to maximize its own profit, subject to the constraint that an entrepreneur at  $z$ 's expected utility is no less than what she would derive from accepting  $r_2^b(z)$  offered by bank 2. Following this reasoning, the equilibrium loan rate offered by bank 1, if there

is effective competition between banks, is determined by the following equation:

$$(R - r_1(z)) \frac{r_1(z)(1 - q_1 z)}{c_1} - \underline{u} = (R - r_2^b(z)) \frac{r_2^b(z)(1 - q_2(1 - z))}{c_2} - \underline{u},$$

which yields

$$r_1^{\text{comp}}(z) = \frac{R}{2} + \frac{1}{2} \sqrt{R^2 - 4 \frac{c_1}{c_2} \frac{1 - q_2(1 - z)}{1 - q_1 z} (R - r_2^b(z)) r_2^b(z)}.$$

In a similar way, bank 2's loan rate, if there is effective competition between banks, is given by

$$r_2^{\text{comp}}(z) = \frac{R}{2} + \frac{1}{2} \sqrt{R^2 - 4 \frac{c_2}{c_1} \frac{1 - q_1 z}{1 - q_2(1 - z)} (R - r_1^b(z)) r_1^b(z)}.$$

The indifference entrepreneur is located at the point  $\tilde{x}$  where an entrepreneur feels indifferent about which bank to choose and meanwhile both banks offer their best loan rate. Therefore,  $\tilde{x}$  is determined by the following equation:

$$(R - r_1^b(\tilde{x})) \frac{r_1^b(\tilde{x})(1 - q_1 \tilde{x})}{c_1} - \underline{u} = (R - r_2^b(\tilde{x})) \frac{r_2^b(\tilde{x})(1 - q_2(1 - \tilde{x}))}{c_2} - \underline{u}. \quad (11)$$

Equation (11) does not yield a closed-form solution. However, at locations where both banks are willing to serve,  $\frac{R}{2} \leq r_i^b(z) \leq R$  must hold, so the left hand side of Equation (11) is decreasing in  $\tilde{x}$ , and the right hand side is increasing in  $\tilde{x}$ . Therefore, whenever there exists a solution  $\tilde{x} \in [0, 1]$  that solves equation (11), such a solution must be unique.

It is possible that equation (11) yields no solution in the region  $[0, 1]$ . If this occurs, then it means one bank dominates the entire lending market. We focus on the interesting case that both banks can serve a positive measure of locations in equilibrium, and so summarize our foregoing analysis with the following proposition:

**Proposition 16.** *Define*

$$r_1^b(z) \equiv \max \left\{ \frac{R}{2}, \bar{r}_1(z) \right\}, r_2^b(z) \equiv \max \left\{ \frac{R}{2}, \bar{r}_2(z) \right\},$$

$$r_1^{\text{comp}}(z) \equiv \frac{R}{2} + \frac{1}{2} \sqrt{R^2 - 4 \frac{c_1}{c_2} \frac{1 - q_2(1 - z)}{1 - q_1 z} (R - r_2^b(z)) r_2^b(z)},$$

$$r_2^{\text{comp}}(z) \equiv \frac{R}{2} + \frac{1}{2} \sqrt{R^2 - 4 \frac{c_2}{c_1} \frac{1 - q_1 z}{1 - q_2(1 - z)} (R - r_1^b(z)) r_1^b(z)}.$$

Assume that there exists an  $\tilde{x} \in (0, 1)$  solving

$$(R - r_1^b(\tilde{x})) \frac{r_1^b(\tilde{x})(1 - q_1 \tilde{x})}{c_1} = (R - r_2^b(\tilde{x})) \frac{r_2^b(\tilde{x})(1 - q_2(1 - \tilde{x}))}{c_2}.$$

Then there exists an equilibrium where entrepreneurs located in  $[0, \tilde{x}]$  are served by bank 1, while the other locations are served by bank 2. Bank 1 and bank 2's equilibrium loan rates,  $r_1^*(z)$  and  $r_2^*(z)$ , are respectively given by the following two equations:

$$r_1^*(z) = \min \{r_1^{\text{comp}}(z), r_1^m(z)\}, z \in [0, \tilde{x}]$$

$$r_2^*(z) = \min \{r_2^{\text{comp}}(z), r_2^m(z)\}, z \in (\tilde{x}, 1].$$

We need only focus on bank 1 because the two banks are symmetric. Note that if  $r_2^b(z) = \frac{R}{2}$ , then  $r_1^{\text{comp}}(z)$  exactly equals

$$\frac{R}{2} \left( 1 + \sqrt{1 - \frac{c_1}{c_2} \frac{1 - q_2(1 - z)}{1 - q_1 z}} \right),$$

which is what we have in Proposition 1. Therefore, in this appendix, we focus on the case  $r_2^b(z) = \bar{r}_2(z)$ , which implies

$$r_1^{\text{comp}}(z) = \frac{R}{2} + \frac{1}{2} \sqrt{R^2 - 4 \frac{c_1}{c_2} \frac{1 - q_2(1 - z)}{1 - q_1 z} (R - \bar{r}_2(z)) \bar{r}_2(z)}.$$

The following corollary characterizes  $r_1^{\text{comp}}(z)$  when  $r_2^b(z) = \bar{r}_2(z)$ .

**Corollary 7.** *If  $0 < \tilde{x} < 1$  and if  $r_2^b(z) = \bar{r}_2(z)$ , then  $r_1^{\text{comp}}(z)$  is decreasing in  $z$  when  $z \in [0, \tilde{x}]$ . At the location  $z = \tilde{x}$ ,  $r_1^{\text{comp}}(z) = r_1^b(z)$ .*

This corollary is consistent with Corollary 1 except that the best loan rate offered by bank 1 at  $z = \tilde{x}$  is  $r_1^b(z)$  here, instead of  $\frac{R}{2}$ .

**Comparative statics.** Now we analyze how the foregoing equilibrium is affected by parameters. The next corollary gives the result:

**Corollary 8.** *When  $z \in (0, \tilde{x})$ , if  $r_2^b(z) = \bar{r}_2(z)$  and if there is effective bank competition at  $z$  (i.e.,  $r_1^{\text{comp}}(z) < r_1^m(z)$ ), then bank 1's equilibrium loan rate  $r_1^{\text{comp}}(z)$  is decreasing in  $c_1$  and  $q_1$ , but is increasing in  $c_2$  and  $q_2$ .*

This corollary shares the same intuition with Corollary 3. So we do not repeat the intuition here.

Letting  $c_1 = c_2 = c$  and  $q_1 = q_2 = q$ , we can study how the change of the bank sector's information technology affects the equilibrium. The following corollary gives the result:

**Corollary 9.** *Let  $c_1 = c_2 = c$  and  $q_1 = q_2 = q$ . If there is effective bank competition at  $z$  (i.e., if  $r_1^{\text{comp}}(z) < r_1^m(z)$ ) and if  $r_2^b(z) = \bar{r}_2(z)$ , then bank 1's equilibrium loan rate  $r_1^{\text{comp}}(z)$  is increasing in  $c$  and  $q$  at  $z \in [0, \frac{1}{2}]$ . A symmetric result holds for bank 2.*

Different from Corollary 4, if  $r_2^b(z) = \bar{r}_2(z)$  (i.e., if  $R$  is not large enough to make  $\frac{R}{2}$  the best loan rate of bank 2 at  $z$ ), then  $r_1^{\text{comp}}(z)$  is increasing in  $c$ . The reason is that now the lowest loan rate bank 2 can offer is  $\bar{r}_2(z)$ , rather than  $\frac{R}{2}$ . If  $c$  increases, then  $\bar{r}_2(z)$  will also increase, which decreases the competition pressure bank 2 puts on bank 1 when bank 1 chooses loan rates for its entrepreneurs. As a consequence, bank 1 is able to choose a higher  $r_1^{\text{comp}}(z)$ . Symmetrically, bank 2 also faces less competition from bank 1 if  $c$  increases, so  $r_2^{\text{comp}}(z)$  is increasing in  $c$  at  $z \in (\frac{1}{2}, 1]$ .

# Online Appendix

## Appendix C: Supplementary results for Section 4

In this appendix, we provide complementary explanations for Proposition 4 and for Numerical Result 3.

**About Proposition 4** If we restrict our attention to the case  $c_1 = c_2$ , which will hold in a symmetric equilibrium, then we have the following limiting result.

**Numerical Result 4.** <sup>33</sup> *If bank competition is effective at all locations and if  $c_1 = c_2$ , then for  $q_2 > 0$  we have:*

$$\lim_{q_1 \rightarrow 0} \frac{\partial^2 \Pi_1}{\partial q_1 \partial q_2} > 0 \text{ and } \lim_{q_2 \rightarrow 0} \left( \lim_{q_1 \rightarrow 0} \frac{\partial^2 \Pi_1}{\partial q_1 \partial q_2} \right) \rightarrow +\infty;$$

$$\lim_{q_1 \rightarrow 0} \frac{\partial^2 \Pi_1}{\partial c_1 \partial q_2} > 0 \text{ and } \lim_{q_2 \rightarrow 0} \left( \lim_{q_1 \rightarrow 0} \frac{\partial^2 \Pi_1}{\partial c_1 \partial q_2} \right) \rightarrow +\infty.$$

The restriction  $c_1 = c_2$  ensures  $0 < \tilde{x} < 1$  no matter how  $q_1$  and  $q_2$  vary.<sup>34</sup> Numerical Result 4 states that if there is no gap between the two banks' general monitoring efficiency (i.e., if  $c_1 = c_2$ ) and if  $q_1 \rightarrow 0$ , then  $q_2$  and the IT of bank 1 are strategic complements. The reason is that the share sensitivity effect of decreasing  $q_2$  becomes strategically complementary if  $q_1 \rightarrow 0$ .<sup>35</sup> The share sensitivity effect, together with the boundary profit effect, dominate the share squeezing effect in this limiting case. Furthermore, the strategically complementary share sensitivity effect is infinitely large if  $q_2$  also approaches 0, because then bank differentiation almost disappears. Then bank 1's market share is infinitely sensitive to its IT investment. Numerical Result 4 is relevant to understand Proposition 4 where the two banks are trapped in a limiting (boundary) equilibrium.

**Explanation for Numerical Result 3.** First, note that Numerical Result 2 has already shown that  $\partial^2 \Pi_1 / (\partial q_1 \partial c_2) > 0$  holds in more general cases because the share

<sup>33</sup>The grid of parameters is as follows:  $R$  ranges from 15 to 100;  $\underline{c} = 1.01R$ ;  $q_2$  ranges from 0 to 0.3;  $f$  ranges from 0.8 to 1.2;  $c_1 (= c_2)$  ranges from  $\underline{c}$  to  $1.3R$ .

<sup>34</sup>Without the restriction  $c_1 = c_2$ , as  $q_1$  and  $q_2$  approach 0, bank 1 will drive out (resp. be driven out by) bank 1 if  $c_1 < c_2$  (resp.  $c_1 > c_2$ ).

<sup>35</sup>We can show that  $\lim_{q_1 \rightarrow 0} \partial^2 \tilde{x} / (\partial q_1 \partial q_2) > 0$ ,  $\lim_{q_1 \rightarrow 0} \partial^2 \tilde{x} / (\partial c_1 \partial q_2) > 0$ ,  $\lim_{q_2 \rightarrow 0} \left( \lim_{q_1 \rightarrow 0} \partial^2 \tilde{x} / (\partial q_1 \partial q_2) \right) \rightarrow +\infty$  and  $\lim_{q_2 \rightarrow 0} \left( \lim_{q_1 \rightarrow 0} \partial^2 \tilde{x} / (\partial c_1 \partial q_2) \right) \rightarrow +\infty$  if  $c_1 = c_2$ .

squeezing effect is dominant; hence it is natural that  $\partial^2\Pi_1/(\partial q_1\partial c_2) > 0$  holds in the interior symmetric case. Meanwhile, it is easy to show that  $\partial^2\tilde{x}/(\partial q_1\partial c_2) < 0$  when  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold; this means the share sensitivity effect of  $c_2$  on  $q_1$  is strategically substitutive, which strengthens the share squeezing effect. The strategically complementary boundary profit effect is dominated.

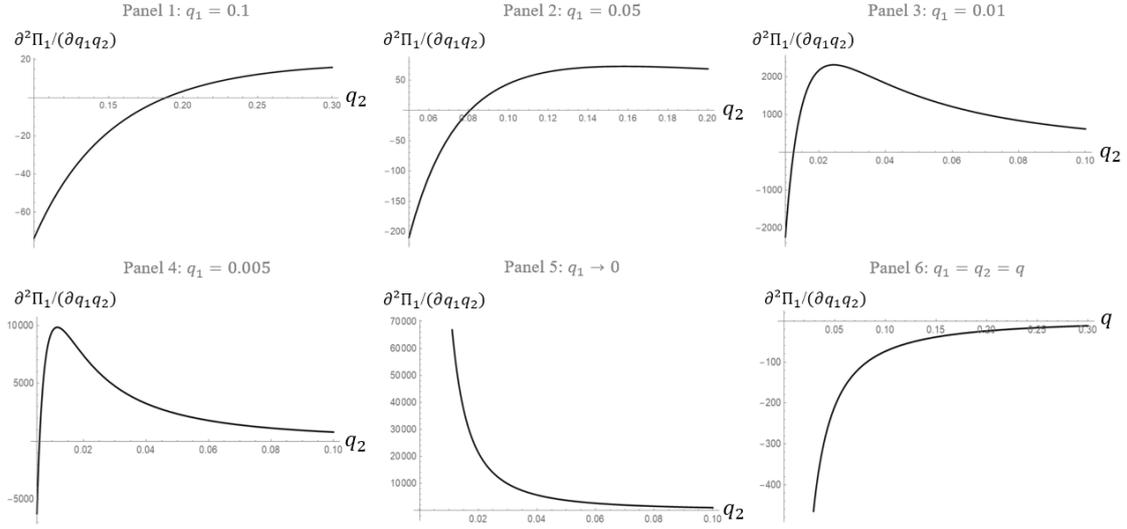
For the strategic relation between  $c_1$  and  $q_2$ , we can show that  $\partial^2\tilde{x}/(\partial c_1\partial q_2) > 0$  when  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold; this means the share sensitivity effect of  $q_2$  on  $c_1$  is strategically complementary. The share sensitivity effect, together with the boundary profit effect, dominates the strategically substitutive share squeezing effect, so  $c_1$  and  $q_2$  are strategic complements for bank 1 in the interior symmetric case.

For  $q_1$  and  $q_2$ , the share squeezing effect is dominant in the interior symmetric case, so  $q_1$  and  $q_2$  are strategic substitutes for bank 1. We can show that  $\partial^2\tilde{x}/(\partial q_1\partial q_2) > 0$  when  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold; this means the share sensitivity effect of  $q_2$  on  $q_1$  is strategically complementary. However, the share sensitivity effect, together with the boundary profit effect, is not strong enough to dominate the share squeezing effect.

Finally, we look at the strategic relation between  $c_1$  and  $c_2$ . We can show that  $\partial^2\tilde{x}/(\partial c_1\partial c_2) = 0$  when  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold; this means the share sensitivity effect of  $c_2$  on  $c_1$  is null.  $c_1$  and  $c_2$  are strategic substitutes for bank 1 in the interior symmetric case because the share squeezing effect dominates the boundary profit effect.

**A discussion on the strategic relation between  $q_1$  and  $q_2$ .** Note that Numerical Result 3 shows that  $q_1$  and  $q_2$  are strategic substitutes when  $q_1 = q_2 > 0$  and  $c_1 = c_2$  (the interior symmetric equilibrium belongs to this case); however, Numerical Result 4 shows that  $q_1$  and  $q_2$  are strategic complements in the limiting case  $q_1 \rightarrow 0$ . Those are not contradictory results. The complementarity displayed in Numerical Result 4 highly relies on the condition  $q_1 \rightarrow 0$ ; therefore, it is useful only when describing bank 1's marginal benefit of IT investment in boundary case  $q_1 = 0$ . Proposition 4 exactly provides an equilibrium that belongs to the boundary case.

In contrast, Proposition 6 describes a symmetric interior equilibrium, which is beyond the scope of Numerical Result 4. In a symmetric interior equilibrium,  $q_1 = q_2 > 0$  and  $c_1 = c_2$  hold, so we can use Numerical Result 3 to understand the strategic relation between  $q_1$  and  $q_2$ . Figure 12 reconciles Numerical Result 4 with Numerical Result 3. Panel 6 of Figure 12 shows that  $\partial^2\Pi_1/(\partial q_1\partial q_2)$  is always negative when  $q_1 = q_2 = q > 0$  and  $c_1 = c_2$ . However, if we remove the restriction  $q_1 = q_2$  and gradually let  $q_1$  approach 0 (from Panel 1 to Panel 5), we can find that the sign of  $\partial^2\Pi_1/(\partial q_1\partial q_2)$  gradually evolves from being ambiguous to being positive.



**Figure 12: The Effects of  $q_2$  on Bank 1's Marginal Benefit of reducing  $q_1$ .** This figure shows how the sign of  $\partial^2\Pi_1/(\partial q_1\partial q_2)$  varies with parameters when bank competition is effective at all locations and  $0 < \tilde{x} < 1$ . The parameter values are  $R = 20$ ,  $f = 1$ ,  $c_1 = 1.01R$ ,  $c_2 = 1.01R$ .

## Appendix D: Detailed proof of Proposition 5

In this appendix, we provide a detailed proof for Proposition 5. The first order conditions of bank 1 wrt  $q_1$  and  $c_1$  are respectively:

$$\frac{\partial\Pi_1(q_1, q_2, c_1, c_2)}{\partial q_1} = 0 \text{ and } \frac{\partial\Pi_1(q_1, q_2, c_1, c_2)}{\partial c_1} = 0.$$

In a symmetric equilibrium, the two equations above must hold with  $q_1 = q_2 = q$  and  $c_1 = c_2 = c$ , which implies

$$\underbrace{\frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1}}_{\left. \frac{\partial\Pi_1(q_1, q_2, c_1, c_2)}{\partial q_1} \right|_{q_i=q, c_i=c}} \bigg|_{q_i=q, c_i=c} - \frac{\partial T(q, c)}{\partial q} = 0; \quad \underbrace{\frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial c_1}}_{\left. \frac{\partial\Pi_1(q_1, q_2, c_1, c_2)}{\partial c_1} \right|_{q_i=q, c_i=c}} \bigg|_{q_i=q, c_i=c} - \frac{\partial T(q, c)}{\partial c} = 0 \quad (12)$$

where

$$\frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1} \bigg|_{q_i=q, c_i=c} = \left( \int_0^{\frac{1}{2}} - \frac{R^4(1-q(1-z))z \left( (1-qz) \left( 1 + 2\sqrt{\frac{q(1-2z)}{1-qz}} \right) + q(1-2z) \right)}{32c^2 \sqrt{\frac{q(1-2z)}{1-qz}} (1-qz)} dz \right);$$

$$+ \frac{(2-q)R^2((2-q)R^2 - 16cf)}{128c^2} \left( -\frac{1}{4q} \right)$$

$$\frac{\partial \int_0^{\bar{x}} D(z)\pi_1(z)dz}{\partial c_1} \Big|_{q_i=q, c_i=c} = \left( \int_0^{\frac{1}{2}} - \frac{R^4(1-q(1-z)) \left( (1-qz) \left( 1+2\sqrt{\frac{q(1-2z)}{1-qz}} \right) + q(1-2z) \right)}{32c^3 \sqrt{\frac{q(1-2z)}{1-qz}}} dz \right) + \frac{(2-q)R^2((2-q)R^2-16cf)}{128c^2} \left( -\frac{2-q}{4cq} \right).$$

We prove the proposition with two steps: first, we show that the system of equations (12) has a unique solution; second, we prove that the solution is indeed an equilibrium.

**Step 1.** Now we show that the system of equations (12) indeed has a unique solution. First, we show there exist a unique  $q$  that solves

$$- \frac{\partial \int_0^{\bar{x}} D(z)\pi_1(z)dz}{\partial q_1} \Big|_{q_i=q, c_i=c} = - \frac{\partial T(q, c)}{\partial q} \quad (13)$$

for a given  $c \in [c, \bar{c}]$ . The left hand side (LHS) of Equation (13) is bank 1's marginal benefit of decreasing  $q_1$  (under the restriction  $q_i = q$  and  $c_i = c$ ), while the right hand side (RHS) is marginal cost of doing so. Obviously, both sides of Equation (13) are positive. Equation (13) is equivalent to

$$- q \frac{\partial \int_0^{\bar{x}} D(z)\pi_1(z)dz}{\partial q_1} \Big|_{q_i=q, c_i=c} = -q \frac{\partial T(q, c)}{\partial q} \quad (14)$$

if  $q > 0$ . Obviously, we have that

$$- q \frac{\partial \int_0^{\bar{x}} D(z)\pi_1(z)dz}{\partial q_1} \Big|_{q_i=q>0, c_i=c} > 0 \text{ and}$$

$$\lim_{q \rightarrow 0} \left( - q \frac{\partial \int_0^{\bar{x}} D(z)\pi_1(z)dz}{\partial q_1} \Big|_{q_i=q>0, c_i=c} \right) = \frac{R^2(R^2 - 8cf)}{128c^2} < +\infty$$

for all  $c \in [c, \bar{c}]$ . Since  $\partial T(q, c)/\partial q = 0$  when  $q \geq \bar{q}$  and  $\lim_{q \rightarrow 0} -q\partial T(q, c)/\partial q$  is large enough, there must exist a  $q \in (0, \bar{q})$  that solves Equation (14) for any  $c \in [c, \bar{c}]$ . We denote the largest solution as  $q(c)$  and let  $q_{\max} \equiv \max_{c \in [c, \bar{c}]} q(c)$ . The assumption  $\lim_{q \rightarrow 0} -q\partial T(q, c)/\partial q$  is large ensures that  $q_{\max}$  must belong to the open interval  $(0, \bar{q})$ .

Next we need to show that  $q(c)$  is the unique solution to Equation (14) when  $-q \frac{\partial^2 T(q, c)/\partial q^2}{\partial T(q, c)/\partial q}$  is large enough for  $q < \bar{q}$ . Note that  $q(c)$  must be the unique solution if  $-q\partial T(q, c)/\partial q$  increases faster than  $-q\partial \int_0^{\bar{x}} D(z)\pi_1(z)dz/\partial q_1 \Big|_{q_i=q, c_i=c}$  as  $q$  decreases in the interval

$(0, q(c)]$ , which means:

$$\frac{\partial T(q, c)}{\partial q} + q \frac{\partial^2 T(q, c)}{\partial q^2} > \partial \left( q \frac{\partial \int_0^{\bar{x}} D(z) \pi_1(z) dz}{\partial q_1} \Big|_{q_i=q, c_i=c} \right) / \partial q$$

holds for  $q \in (0, q(c)]$ . The inequality above can be written as

$$-1 - q \frac{\partial^2 T(q, c) / \partial q^2}{\partial T(q, c) / \partial q} > \frac{\partial \left( q \frac{\partial \int_0^{\bar{x}} D(z) \pi_1(z) dz}{\partial q_1} \Big|_{q_i=q, c_i=c} \right) / \partial q}{-\partial T(q, c) / \partial q} \quad (15)$$

for  $q \in (0, q(c)]$ . The assumption that  $-q \frac{\partial^2 T(q, c) / \partial q^2}{\partial T(q, c) / \partial q}$  is large enough for  $q < \bar{q}$  means the LHS of Inequality (15) is large enough for  $q \in (0, q(c)]$ . This means Inequality (15) will hold if the RHS of (15) is smaller than  $+\infty$  for  $q \in (0, q(c)]$ . Since  $-\partial T(q, c) / \partial q > 0$  must hold for  $q \leq q_{\max} < \bar{q}$ , we need only show that

$$\partial \left( q \frac{\partial \int_0^{\bar{x}} D(z) \pi_1(z) dz}{\partial q_1} \Big|_{q_i=q, c_i=c} \right) / \partial q < +\infty \quad (16)$$

holds for  $q \in (0, q(c)]$ . Note that

$$= \left( \begin{array}{c} q \frac{\partial \int_0^{\bar{x}} D(z) \pi_1(z) dz}{\partial q_1} \Big|_{q_i=q, c_i=c} \\ - \int_0^{\frac{1}{2}} q \frac{R^4 (1 - q(1 - z)) z \left( (1 - qz) \left( 1 + 2\sqrt{\frac{q(1-2z)}{1-qz}} \right) + q(1 - 2z) \right)}{32c^2 \sqrt{\frac{q(1-2z)}{1-qz}} (1 - qz)} dz \\ \underbrace{\hspace{15em}}_{\text{denoted by } RHS_1^q} \\ \underbrace{\frac{1}{4} \frac{(2 - q) R^2 ((2 - q) R^2 - 16cf)}{128c^2}}_{\text{denoted by } RHS_2^q} \end{array} \right).$$

It is clear that  $\partial RHS_2^q / \partial q < +\infty$ . Since it holds that

$$RHS_1^q < 0 \text{ and } \lim_{q \rightarrow 0} RHS_1^q = 0,$$

we must have  $\lim_{q \rightarrow 0} \frac{\partial RHS_1^q}{\partial q} < 0 < +\infty$ . Therefore, Inequality (16) indeed holds. As a consequence,  $q(c)$  is the unique solution to Equation (14) when  $-q \frac{\partial^2 T(q, c) / \partial q^2}{\partial T(q, c) / \partial q}$  is large

enough for  $q < \bar{q}$ . Meanwhile, by implicit function theorem and Inequality (15), we can show that  $\max_{c \in [\underline{c}, \bar{c}]} \partial q(c) / \partial c$  is finite.

To show that the system of equations (12) has a solution, next we need to show that there exists a unique  $c \in (\underline{c}, \bar{c})$  that solves

$$-c \frac{\partial \int_0^{\tilde{x}} D(z) \pi_1(z) dz}{\partial c_1} \Big|_{q_i=q(c), c_i=c} = -c \frac{\partial T(q, c)}{\partial c} \Big|_{q=q(c)} \quad (17)$$

given that  $q$  is equal to  $q(c)$ . The LHS of Equation (17) must be positive and finite on the close interval  $[\underline{c}, \bar{c}]$ . Since  $\frac{\partial T(q, c)}{\partial c} = 0$  for  $c \geq \bar{c}$  and  $-c \partial T(q, c) / \partial c$  is large enough when  $c = \underline{c}$ , there must at least exist a  $c \in (\underline{c}, \bar{c})$  that solves Equation (17). We denote the largest solution to (17) as  $c^* \in (\underline{c}, \bar{c})$ . Meanwhile,  $c^*$  must be the unique solution if  $-c \partial T(q, c) / \partial c$  increases faster than  $-c \partial \int_0^{\tilde{x}} D(z) \pi_1(z) dz / \partial c_1 \Big|_{q_i=q(c), c_i=c}$  as  $c$  decreases in the interval  $[\underline{c}, c^*]$ , which means:

$$\frac{\partial T(q(c), c)}{\partial c} + c \frac{\partial^2 T(q(c), c)}{\partial c^2} + \frac{\partial^2 T(q(c), c)}{\partial q \partial c} \frac{\partial q(c)}{\partial c} > \frac{\partial \left( c \frac{\partial \int_0^{\tilde{x}} D(z) \pi_1(z) dz}{\partial c_1} \Big|_{q_i=q(c), c_i=c} \right)}{\partial c}$$

holds for  $c \in [\underline{c}, c^*]$ . The inequality above can be written as

$$-1 - c \frac{\partial^2 T(q(c), c) / \partial c^2}{\partial T(q(c), c) / \partial c} - c \frac{\frac{\partial^2 T(q(c), c)}{\partial q \partial c} \frac{\partial q(c)}{\partial c}}{\partial T(q(c), c) / \partial c} > \frac{\partial \left( c \frac{\partial \int_0^{\tilde{x}} D(z) \pi_1(z) dz}{\partial c_1} \Big|_{q_i=q(c), c_i=c} \right) / \partial c}{-\partial T(q(c), c) / \partial c} \quad (18)$$

Since  $\max_{c \in [\underline{c}, \bar{c}]} \partial q(c) / \partial c$  is finite,  $\partial \left( c \frac{\partial \int_0^{\tilde{x}} D(z) \pi_1(z) dz}{\partial c_1} \Big|_{q_i=q(c), c_i=c} \right) / \partial c$  must be finite for all  $c \in [\underline{c}, \bar{c}]$  because it is a continuous function of  $c$  on the close interval  $[\underline{c}, \bar{c}]$ . Meanwhile, the assumption that  $-c \frac{\partial^2 T(q, c) / \partial c^2}{\partial T(q, c) / \partial c}$  is large enough for  $c \in [\underline{c}, \bar{c}]$  ensures that the LHS of Inequality (18) is large enough for  $\underline{c} \leq c \leq c^*$ ; this means Inequality (18) indeed holds if  $-c \frac{\partial^2 T(q, c) / \partial c^2}{\partial T(q, c) / \partial c}$  is large enough for  $c \in [\underline{c}, \bar{c}]$ . Therefore,  $c^*$  is the unique solution to Equation (17). Overall, there exists a unique solution  $\{c^*, q^* \equiv q(c^*)\} \in (\underline{c}, \bar{c}) \times (0, \bar{q})$  that solves the system of equations (12). This means in a symmetric equilibrium we must have  $q_i = q^* \in (0, \bar{q})$  and  $c_i = c^* \in (\underline{c}, \bar{c})$ .

**Step 2.** Next, we need to show that  $q_i = q^*$  and  $c_i = c^*$  indeed constitute an equilibrium. To do this, we need to show that bank 1's optimal IT investment is  $c_1 = c^*$  and  $q_1 = q^*$  if bank 2's investment is represented by  $c_2 = c^*$  and  $q_2 = q^*$ . Given that

$c_2 = c^*$  and  $q_2 = q^*$ , the first order conditions of bank 1 are

$$\underbrace{-q_1 \frac{\partial \int_0^{\bar{x}} D(z) \pi_1(z) dz}{\partial q_1} \Big|_{q_2=q^*, c_2=c^*}}_{\text{denoted by } MB_{q_1}} = -q_1 \frac{\partial T(q_1, c_1)}{\partial q_1} \quad \text{and} \quad (19)$$

$$\underbrace{-c_1 \frac{\partial \int_0^{\bar{x}} D(z) \pi_1(z) dz}{\partial c_1} \Big|_{q_2=q^*, c_2=c^*}}_{\text{denoted by } MB_{c_1}} = -c_1 \frac{\partial T(q_1, c_1)}{\partial c_1} \quad (20)$$

where

$$MB_{q_1} = -q_1 \left( \int_0^{\bar{x}} \frac{R^4(1-q_2(1-z))z \left( c_1+c_1q_2(-1+z)+2c_2(-1+q_1z) \left( 1+\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}} \right) \right)}{32c_1(c_2)^2(1-q_1z)\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}}} dz \right. \\ \left. + \frac{(q_1(-1+q_2)-q_2)R^2(8c_2q_1f+8c_1q_2f+(-q_1+(-1+q_1)q_2)R^2)}{32(c_2q_1+c_1q_2)^2} - \frac{c_2(c_2+c_1(-1+q_2))}{(c_2q_1+c_1q_2)^2} \right);$$

$$MB_{c_1} = -c_1 \left( \int_0^{\bar{x}} \frac{R^4(1-q_2(1-z)) \left( c_1+c_1q_2(-1+z)+2c_2(-1+q_1z) \left( 1+\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}} \right) \right)}{32(c_1)^2(c_2)^2\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}}} dz \right. \\ \left. + \frac{(q_1(-1+q_2)-q_2)R^2(8c_2q_1f+8c_1q_2f+(-q_1+(-1+q_1)q_2)R^2)}{32(c_2q_1+c_1q_2)^2} - \frac{c_2(q_2-q_1(-1+q_2))}{(c_2q_1+c_1q_2)^2} \right).$$

For a given  $c \in [\underline{c}, \bar{c}]$ , we can find that  $MB_{q_1} > 0$  and  $\lim_{q_1 \rightarrow 0} MB_{q_1} = 0$  hold, which implies

$$-\partial MB_{q_1} / \partial q_1 = \partial \left( q_1 \frac{\partial \int_0^{\bar{x}} D(z) \pi_1(z) dz}{\partial q_1} \Big|_{q_2=q^*, c_2=c^*} \right) / \partial q_1 < +\infty$$

for  $q_1 \in (0, \bar{q}]$ . Therefore, following the way in which we show the existence and uniqueness of the solution to (12), we can also show that the solution to equations (19) and (20) exists and is unique if  $\lim_{q \rightarrow 0} -q \partial T(q, c) / \partial q$  and  $-c \partial T(q, c) / \partial c|_{c=\underline{c}}$  are large enough and if  $-q \frac{\partial^2 T(q, c) / \partial q^2}{\partial T(q, c) / \partial q}$  (resp.  $-c \frac{\partial^2 T(q, c) / \partial c^2}{\partial T(q, c) / \partial c}$ ) is large enough for  $q \in (0, \bar{q})$  (resp.  $c \in [\underline{c}, \bar{c})$ ); in this case, the solution must be  $q_1 = q^*$  and  $c_1 = c^*$ . Therefore, given that  $c_2 = c^*$  and  $q_2 = q^*$ , bank 1's best response is to choose  $c_1 = c^*$  and  $q_1 = q^*$ ; this means  $q_i = q^*$  and  $c_i = c^*$  indeed constitute an equilibrium.