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, investment, stability and welfare. An IT improvement spurs entrepreneurs' investment. Other effects of the 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. Our results are consistent with received empirical work on SMEs.

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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.[1] 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). Such a transformation spurs the banking sector to invest increasingly in IT, which 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 services to entrepreneurs. In particular, our model will illuminate the following empirical results:

- Small business lending by banks with better IT adoption is less affected by the distance between the banks (or bank headquarters) and their borrowers (DeYoung et al., 2011; Ahnert et al., 2022).
- Increased bank/branch specialization in export/SME lending curtails bank competition (Paravisini et al., 2021; Duquerroy et al., 2022).
- Banks with better IT originate more "paycheck protection program" loans to SMEs – especially in areas with more intense bank competition (Kwan et al., 2021).
- Entrepreneurship (proxied by job creation by young enterprises) is stronger in US counties that are more exposed to IT-intensive banks (Ahnert et al., 2022).

[1] 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, almost one third of small and medium firms that sought financing applied with a FinTech firm or online lender, up from 19% in 2016 (US Federal Reserve's Small Business Credit Survey 2019). The annual growth rate of FinTech business lending volume in US was over 40% from 2016 to 2020 (Berg et al., 2021).

- Banks with higher pre-crisis IT adoption had fewer non-performing loans during the crisis (Pierri and Timmer, 2021).

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. We take as given that IT is advanced enough so that banks can price flexibly. 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). Monitoring is more costly for a bank if there is more distance between the bank and the monitored entrepreneur. This distance can be physical[2] or in characteristics space from the expertise of the bank on certain sectors or industries.[3]

Information technology improvements can generate two types of outcomes. The first is by lowering the costs of monitoring an entrepreneur without affecting banks' relative cost advantage in different locations – for example, by making improvements in the ability to process information with better computer hardware or information management software (e.g. desktop applications). The second is by reducing the effect of bank–borrower distance on monitoring costs. For example, better internet connectivity and communication technology (e.g. video conferencing) reduces the physical distance friction. Credit scoring hardens soft information and reduces the expertise distance friction. Big Data and machine learning techniques may influence both types of outcomes.[4]

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

[2]There is evidence that firm–bank *physical* distance 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).

[3]Blickle et al. (2021) find that a bank "specializes" by concentrating its lending disproportionately on one industry about which the bank has better knowledge. Paravisini et al. (2021) document that exporters to a given country are more likely to be financed by a bank that has better expertise in the country. Duquerroy et al. (2022) find that in local markets there exist specialized bank branches that concentrate their SME lending on certain industries.

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

rates (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 offer 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. Both types of IT progress will make entrepreneurs better off and hence spur more entrepreneurs to undertake investment projects.

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 and hence spurs their investment. 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 hence 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, and the market is extended (i.e., financial inclusion improved).

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 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 discriminate.[5] 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. Several papers have emphasized the importance of monitoring in banking.[6] 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

[5] 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.

[6] See, e.g., Diamond (1984) and Holmstrom and Tirole (1997) for pioneering work.

Vives, 2016).

Our study also belongs to the literature that studies information technology and bank competition. Hauswald and Marquez (2003) in an adverse selection model find that improving an informed bank's ability to process information strengthens the "winner's curse" faced by an uninformed bank, decreases the intensity of bank competition, and increases the loan rate that borrowers are expected to pay. 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).[7] However, the mechanism behind our results differs since there is no scope for a winners' curse in our model.

Our results differ from the models of Hauswald and Marquez 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.

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).[8] To start with, there is considerable evidence showing that IT makes non-traditional data – such as soft information (Iyer et al., 2016),

[7]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.

[8]Philippon (2016) claims that the existing financial system's inefficiency can explain the emergence of new entrants that bring novel technology to the sector. Gopal and Schnabl (2022) show that most of the increase in fintech lending to SMEs after 2008 financial crisis substituted for a reduction in lending by banks.

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 (Agarwal et al., 2020; Berg et al., 2020), and cashless payment information (Ghosh et al., 2021; Ouyang, 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 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.[9]

Several papers provide evidence consistent with our results. 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. DeYoung et al. (2011) find that banks adopting Small Business Credit Score (SBCS) to access borrowers have a higher bank-borrower distance; similarly, Ahnert et al. (2022) 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 findings since we show that a bank's geographic reach will be extended if the bank adopts better information technology. Ahnert et al. (2022) find that job creation by young enterprises, a proxy for entrepreneurship, is stronger in US counties that are more exposed to IT-intensive banks; consistent with this finding, our model shows that an improvement in the banking sector's IT will spur more entrepreneurs to undertake investment projects. 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.

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.

[9]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.

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 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, geographical position, industry, . . .) at this location, and two close points mean that the entrepreneurs in those locations are similar.

There are two banks, labeled by $i = \{1, 2\}$, located at the two extremes of the city. Hence a bank is closer to some entrepreneurs than to others. This means, for example, that banks are specialized in different sectors of the economy (see Paravisini et al., 2021 for export-related lending and Duquerroy et al., 2022 for SME lending). 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.

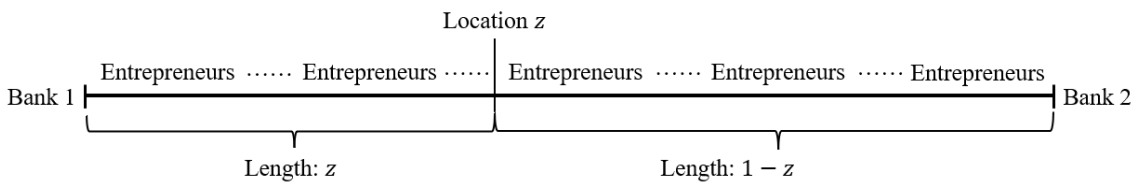

Figure 1: The Economy.

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:

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

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 θ 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 θ 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 own capital to finance their loans, so they must attract 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 promised (nominal) 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' investment decisions and 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, so she seeks funding if and only if $\pi^e(z) \geq \underline{u}$. Here $\underline{u}$ is the reservation utility (i.e., opportunity cost) 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 mass of entrepreneurs who undertake investment projects) 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 is monitored with intensity $m_i(z)$, then the bank incurs the non-pecuniary quadratic monitoring cost

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

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 location 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 is the slope of marginal monitoring costs when bank-borrower distance is zero. Parameter q_i measures the negative effect of bank-borrower distance (i.e., "distance friction") on the bank's information collection and data analysis (see below for a discussion of parameters).[10] 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 entrepreneur(s) 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:

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

[10] A similar classification of technology can be found in Boot et al. (2020).

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

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

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, a higher q not only makes monitoring more costly but also magnifies the importance of bank specialization by increasing the importance of distance in determining the relative cost advantage of a bank's monitoring.

Interpretation of monitoring. Banks do not directly participate in firms' management but they can collect firm data and assess whether a firm is acting appropriately to return its loan, which disciplines firms' management.[11] This type of monitoring relies on collecting and processing information about the firm, so it is facilitated by advancements in the lending bank's information technology. In our model, monitoring benefits both banks and entrepreneurs; hence we can view it as banks' expertise-based advising, mentoring or/and information production that is helpful for entrepreneurs. There is evidence that banks specialize and that borrowers do value the expertise of lenders. Paravisini et al. (2021) find that an exporter prefers borrowing from a bank with better expertise in the target market. Duquerroy et al. (2022) document that an SME borrows less if its account is reallocated from a branch with expertise in the SME's industry to one without such expertise.

Next we give a more specific interpretation to parameters q_i and c_i of the monitoring cost function (1). The parameter c_i controls the marginal cost of monitoring when bank-borrower distance is zero. If bank-borrower distance is positive, then the bank's ability to collect and analyze information depends also on q_i, which represents the magnitude of distance friction on information collection and data analysis.

Bank-borrower distance in our model can be viewed as either the "physical distance" between a bank's geographic location and the monitored borrower's, or the "expertise gap" between the bank's specialized area and the borrower's characteristics. Physical distance will reduce monitoring efficiency in two ways: First, face-to-face communication is often essential for gathering first-hand information about a firm; the cost of doing

[11] 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.

so is higher when the firm is more distant from the lending bank. Second, after first-hand information is gathered, such information often contains soft information and hence is hard to convey back to loan officers (see Liberti and Petersen, 2019); hence rounds of internal information exchange are needed for loan officers to digest the information gathered, which is also a costly process. In contrast, if the firm is physically close to the bank, then loan officers can directly communicate with the firm and collect first-hand information, avoiding rounds of information exchange. The expertise gap will reduce monitoring efficiency because a loan officer needs more time and effort to analyze a firm that he/she is not specialized in. For example, the framework for assessing a food company is completely different from that of analyzing a real estate company, so a loan officer who specializes in the latter firm must spend additional effort when monitoring a food company.

Technologies that decrease c_i are related to improvements in processing information as shown in the following examples: Advances in chip technology and cloud computing/storage increase the computing and storage ability of banks; adopting better software (e.g. desktop applications) improves the efficiency of document assembly and information classification and processing (see e.g., He et al., 2021); analyzing unconventional information, like digital footprints (see Berg et al., 2020) with AI and machine learning techniques helps assessing borrowers.

Technologies that decrease q_i can diminish the physical distance friction (e.g., improvements in communication) or the expertise friction (such as extending the competence of human capital or hardening soft information). The diffusion of internet allows face-to-face communication to take place remotely, reducing the negative effect of physical distance on information gathering. The development of communication technology (like smart phones, mobile apps, social media, or video conferencing) facilitates remote information collection and exchange, and hence reduces the friction caused by the bank-borrower physical distance. In addition, internal information exchange will be easier for a bank with the help of better communication technology. The effect of the expertise gap can be weakened if an IT improvement can facilitate banks to extend their specialized areas. For example, improvements in human capital (facilitated by remote learning) make it easier for loan officers to assess firms they do not specialize in, thereby decreasing q_i. The development of code sharing platforms (like Github) is another example that can facilitate banks' expertise extension. Furthermore, technologies such as credit scoring systems make it possible to harden soft information that is at the base of relationship banking, which reduces the expertise gap and hence lowers q_i.

Table 1: **Technology Improvements and Monitoring Efficiency.**

Improvement of efficiency	Related technology
Decreasing c_i (improvement in processing information)	AI, ML with big/unconventional data advances in cloud storage and computing, information management software
Decreasing q_i (physical distance friction) (improvement in communication)	diffusion of internet, video conferencing, smart phone, mobile apps, social media
Decreasing q_i (expertise friction) (extending competence of human capital/ hardening soft information)	AI, ML with big/unconventional data, credit scoring, remote learning and code sharing

There are also technologies that decrease both c_i and q_i: AI and machine learning with big data decrease c_i by improving bank i's ability to process data. At the same time, they make it possible to harden soft information (like, e.g., digital footprints), which reduces q_i. See Table 1 for a summary of aforementioned technology improvements and the corresponding effects on monitoring efficiency.

Competition with discriminatory loan pricing. When 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.[12]

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.

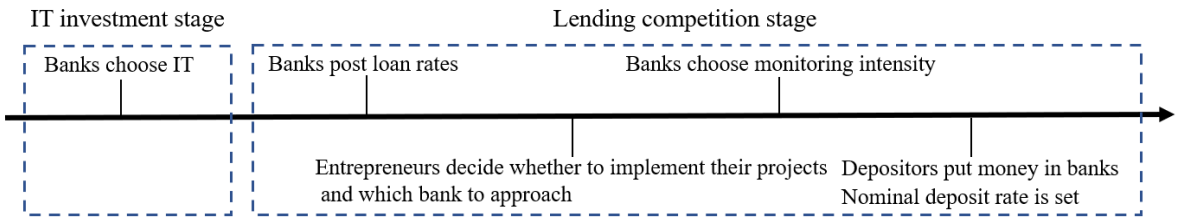

Figure 2: Timeline.

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

[12]Degryse and Ongena (2005) document spatial discrimination in loan pricing. See also Agarwal and Hauswald (2010).

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 the 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 paper we focus mostly on the equilibrium with direct competition but we also characterize the local monopoly equilibrium in Appendix C.

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.

3.1 Optimal monitoring intensity

We solve the equilibrium by backward induction and so first examine how banks choose their monitoring intensities. Bank i's loan rate and monitoring intensity for entrepreneurs at z are denoted by $r_i(z)$ and $m_i(z)$, respectively.

According to the timeline, an entrepreneur at z has 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

$$\pi_1(z) \equiv r_1(z)m_1(z) - f - \frac{c_1}{2(1-q_1 z)}(m_1(z))^2. \tag{3}$$

The first term of $\pi_1(z)$ is the expected loan repayment from the 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 expected funding costs by borrowing from depositors. Note that what

determines bank 1's expected 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.

Bank 1 chooses its optimal monitoring intensity $m_1(z)$ to maximize its expected profit $\pi_1(z)$, 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*

$$m_1(z) = \frac{r_1(z)(1 - q_1 z)}{c_1}.$$

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 (when $q_1 > 0$) because monitoring an entrepreneur is more costly 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 $r_1(z)$ is, the more bank 1 can receive from the entrepreneur's loan repayment when her project succeeds and so the more incentive bank 1 has to increase its intensity of monitoring.[13]

3.2 Equilibrium loan rate

In this section we study how banks determine their loan rates in equilibrium. We look first at how entrepreneurs decide which bank to approach after observing banks' loan rates.

Entrepreneurs' decisions. After observing the loan rates posted by banks, an entrepreneur will approach the bank that can provide higher expected utility. If bank i offers loan rate $r_i(z)$ at z, then entrepreneurs can expect that the bank's monitoring intensity $m_i(z)$ equals $r_i(z)(1 - q_i s_i)/c_i$ at this location. Hence entrepreneurs at z will

[13] According to Lemma 1, bank 1's promised nominal 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" (loan income *minus* its promised payment to depositors). In this case, a higher nominal deposit rate will reduce the marginal benefit of monitoring. Yet in our paper, d_i is adjusted to bank i's risk because its monitoring intensity is observable to depositors.

consider bank 1 for loans if and only if they derive higher (gross) expected utility by approaching bank 1 instead of bank 2:

$$(R - r_1(z))m_1(z) \geq (R - r_2(z))m_2(z). \tag{4}$$

If Inequality (4) holds, then an entrepreneur at z will approach bank 1 if $\pi^e(z) = (R - r_1(z))m_1(z)$ is no smaller than her reservation utility $\underline{u}$.

Note that increasing bank i's loan rate has two competing effects on entrepreneurial utility at z: First, the residual payoff $R - r_i(z)$ will decrease, which reduces entrepreneurs' utility. However, bank i will increase its monitoring intensity $m_i(z)$, which increases the success probability of entrepreneurs who approach the bank. Therefore, entrepreneurs do not simply choose the bank whose loan rate is lower. Since bank i's monitoring intensity is affected by q_i and c_i, banks' IT is important in determining which bank can bring entrepreneurs (at z) higher expected utility.

Best loan rate. The competitiveness of a bank can be represented by its best loan rate, which is defined as follows:

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

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

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

Bank 1's expected profit from financing an entrepreneur at z (viz. $\pi_1(z)$) is given in (3). By Lemma 1, $\pi_1(z)$ is equal to $(r_1(z))^2(1 - q_1 z)/(2c_1) - f$, which is positive

when both $r_1(z) = R/2$ and $R \geq \sqrt{8c_1 f/(1-q_1)}$ hold. Therefore, the best loan rate is acceptable to bank 1. In a symmetric way, we can show the result for bank 2.

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 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 increase its attractiveness 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 $R/2$.[14] 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 C we show that this assumption eliminates the possibility of local monopoly equilibria.

Monopoly loan rate. Throughout the paper we use $r_i^m(z)$ to denote bank i's monopoly loan rate, which is defined as follows:

Definition 2. *The monopoly loan rate $r_i^m(z)$ of bank i at location z is the loan rate the bank would choose if it faced no competition at the location.*

At location z, bank i would never offer a loan rate that is higher than its monopoly loan rate $r_i^m(z)$. While the best loan rate is the *lower* bound of a bank's loan rate, the monopoly loan rate is the *upper* bound. In Lemma 5 of Appendix A we show that $r_i^m(z) > R/2$ must hold, so 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 1 and 2, 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 (at z) who decides to undertake a project, it must offer the entrepreneur a loan rate that is more attractive than the best loan 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

[14] A bank's best loan rate is higher than $R/2$ at some or even all locations when R is not large enough.

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* $R \geq \sqrt{8c_i f/(1-q_i)}, i = \{1,2\}$. *Let*

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

When $0 < \tilde{x} < 1$, *there exists a unique 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:*

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

Proposition 1 describes the equilibrium with direct bank competition. The restriction $0 < \tilde{x} < 1$ guarantees that both banks can attract a positive mass of entrepreneurs in equilibrium. If this restriction does not hold (which occurs when the difference between the two banks' IT is sufficiently large), then one bank will dominate the lending market and drive the other bank out in equilibrium; in this case, banks' pricing policy displayed in Proposition 1 is still robust for the dominant bank.[15] For convenience, we focus on the case $0 < \tilde{x} < 1$ for the rest of the paper.

Proposition 1 implies that bank-borrower distance matters for bank lending if $q_i > 0$ holds for some i (i.e., if distance friction exists in the market). Since monitoring benefits entrepreneurs, attracting an entrepreneur will be harder for a bank if the entrepreneur is

[15]For example, if c_2 is much larger than c_1, then $\tilde{x} \geq 1$ will hold; in this case, bank 1 is the dominant bank that serves all locations of the city; the monitoring intensity of bank 2 is too low, so it cannot attract any entrepreneur even if its best loan rate $R/2$ is offered. The equilibrium loan rate of bank 1 at z still equals $r_1^*(z)$, because bank 2's competitive pressure still exists despite that bank 2 serves no locations.

located father away, which means that the bank's relative cost advantage in monitoring is smaller. As a result, 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. The location $z = \tilde{x}$ is the "indifference location" where neither bank has a cost advantage in monitoring, that is:

$$\frac{1 - q_1\tilde{x}}{c_1} = \frac{1 - q_2(1 - \tilde{x})}{c_2}.$$

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 consistent with DeYoung et al. (2011) who document that banks adopting Small Business Credit Score (SBCS) to assess borrowers – which can be viewed as a reduction in q_i – have a higher bank-borrower distance; Ahnert et al. (2022) find a similar result: small business lending by banks with higher IT adoption is less affected by the distance between the bank headquarters and their borrowers.

Next we look at banks' pricing strategies. Proposition 1 states that two cases may arise when bank 1 chooses its loan rate for entrepreneurs at $z \in [0, \tilde{x}]$. In the first case, which occurs when $\frac{c_1}{c_2}\frac{1-q_2(1-z)}{1-q_1 z}$ is sufficiently small, bank 2 cannot put enough competitive pressure on bank 1 because the latter's competitive advantage is too high at this location. As a result, bank 1 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 at location z. In the second case, which occurs when bank 1's competitive advantage at z is not so high, bank 2 can exert sufficient competitive pressure, so bank 1 can no longer maintain its monopoly loan rate at z; instead, bank 1's loan rate at the location 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). Bank 2's pricing strategy follows the same logic.

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 $r_2^{\text{comp}}(z)$.[16]

Corollary 1. *Let $q_i > 0$ for some $i \in \{1, 2\}$. With effective bank competition at z (i.e., if $r_1^{\text{comp}}(z) < r_1^m(z)$), bank 1's equilibrium loan rate $r_1^{\text{comp}}(z)$ is decreasing in z when $z \in [0, \tilde{x}]$. At the indifference location $z = \tilde{x}$, $r_1^{\text{comp}}(z) = R/2$ holds.*

If $q_i > 0$ for some $i \in \{1, 2\}$, then there exists distance friction on monitoring efficiency

[16] See Appendix C for details about $r_i^m(z)$.

for at least one bank. In this case, a larger $z \in [0, \tilde{x}]$ will decrease bank 1's competitive advantage over bank 2 because the distance between bank 1 (resp. bank 2) and location z will increase (resp. decrease). As a consequence, bank 1's market power and competitive loan rate $r_1^{\text{comp}}(z)$ are decreasing in z in the region $[0, \tilde{x}]$. At the indifference location $z = \tilde{x}$, neither bank has a cost advantage in monitoring, so the intensity of bank competition is maximal there; bank 1 must offer its the best loan rate $R/2$ to attract entrepreneurs at the indifference location. Figure 3 graphically illustrates banks' equilibrium rates when $q_i > 0$.

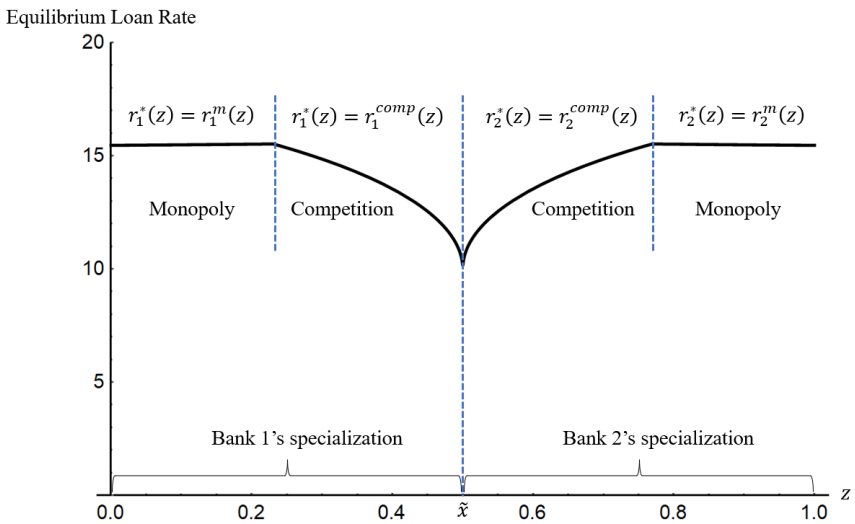

Figure 3: Equilibrium Loan Rates for Different Locations. This figure plots the equilibrium loan rate against the entrepreneurial location in the equilibrium under direct bank competition. The parameter values are $R = 20$, $f = 1$, $c_1 = 1.01R$, $c_2 = 1.01R$, $q_1 = 0.5$, and $q_2 = 0.5$.

The case with no distance friction ($q_1 = q_2 = 0$). If $c_1 = c_2$ holds, then the two banks have the same monitoring efficiency at all locations, which means competition intensity is infinitely high everywhere. In this case, every location is an indifference location with both banks offering the best loan rate $R/2$; we let $\tilde{x} = 1/2$ still hold (since this is the natural limit by letting $q_1 = q_2$ tend to 0). Then the pricing strategies displayed in Proposition 1 hold: Bank 1's (resp. bank 2's) equilibrium loan rate is $r_1^{\text{comp}}(z) = R/2$ at $z \in [0, 1/2]$ (resp. $r_2^{\text{comp}}(z) = R/2$ at $z \in (1/2, 1]$).[17]

Locations with no effective competition. At such a location served by bank i,

[17] If $q_1 = q_2 = 0$ and $c_1 \neq c_2$ hold, then the bank with better IT (i.e., higher monitoring efficiency) will dominate the entire lending market and so drive out the other bank. In this case, the equilibrium loan rate of the dominant bank still follows the pricing policy in Proposition 1 and is invariant to z because locations will not affect a bank's competitive advantage when distance friction is absent.

the equilibrium loan rate is $r_i^m(z)$ (Proposition 1). In Appendix C we show that $r_i^m(z)$ is increasing in the corresponding bank-borrower distance if $q_i > 0$ (e.g., $r_1^m(z)$ is increasing in z if $q_1 > 0$). The reason is that $r_i^m(z)$ only reflects bank i's costs of serving entrepreneurs when competition is absent. As the bank's lending distance increases, monitoring will be more costly if $q_i > 0$, so the monopolistic loan rate $r_i^m(z)$ will increase in response to the rising cost. Figure 3 illustrates how $r_i^m(z)$ varies with z when $q_i > 0$. More properties of $r_i^m(z)$ are displayed in Appendix C, where $q_i > 0$ must hold to ensure the existence of a local monopoly equilibrium.

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

Corollary 2. *Let $q_2 > 0$ hold. With effective bank competition at z (i.e., if $r_1^{\text{comp}}(z) < r_1^m(z)$), the funding demand of entrepreneurs at z is increasing in z when $z \in [0, \tilde{x}]$.*

If $q_2 > 0$, bank 2 can provide strictly higher expected utility to entrepreneurs as z increases in the region $[0, \tilde{x}]$, because then the distance between bank 2 and location z becomes smaller. To ensure that entrepreneurs do not approach bank 2, bank 1 must provide strictly higher expected utility to entrepreneurs as z increases in the region $[0, \tilde{x}]$, which induces more entrepreneurs to undertake investment projects and to demand funding from banks.[18] A symmetric result holds for bank 2's region $(\tilde{x}, 1]$.

Note from Corollary 2 that entrepreneurs' funding demand is highest at $z = \tilde{x}$ if both q_1 and q_2 are positive. The reason is that the intensity of bank competition is maximal at the indifference location where neither bank has a cost advantage in monitoring, so entrepreneurs there derive the highest expected utility.

3.3 Information technology and bank competition

In this section we study how bank competition is affected by a change in information technology. The following corollary shows how bank 1's loan rate schedule (under effective competition) is affected by the bank's IT. A symmetric result holds for bank 2.

Corollary 3. *With effective bank competition at $z \in [0, \tilde{x})$ (i.e., if $r_1^{\text{comp}}(z) < r_1^m(z)$), bank 1's equilibrium loan rate $r_1^{\text{comp}}(z)$ is increasing in the bank's competitive advantage, be it due to better basic monitoring technology (i.e., lower c_1/c_2) or to higher local expertise (i.e., lower $\frac{1-q_2(1-z)}{1-q_1 z}$).*

[18] If $q_2 = 0$, however, there is no distance friction for bank 2. In this case, the expected utility bank 2 can provide is invariant to z. As a result, bank 1 need not provide higher expected utility to entrepreneurs as z increases, which implies that entrepreneurs' funding demand does not vary with z in the region $[0, \tilde{x}]$.

Corollary 3 states that bank 1's equilibrium loan rate is decreasing in c_1 and q_1 (except for location $z = 0$ where q_1 has no effect) 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, bank 2's competitive advantage will decrease, which allows bank 1 to increase its loan rate.

We have witnessed the development and diffusion of information technology throughout the entire banking sector. We check now the implications for bank competition. 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 determine the banking sector's information technology.

Corollary 4. *Let $c_1 = c_2 = c$ and $q_1 = q_2 = q$. With effective bank competition at z (i.e., if $r_i^{\text{comp}}(z) < r_i^m(z)$), bank i's equilibrium loan rate $r_i^{\text{comp}}(z)$ is increasing in q (except for $z = 1/2$ where $r_i^{\text{comp}}(z) = R/2$) 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 contrast, if c increases then banks' monitoring costs increase but their differentiation is unaffected; hence equilibrium loan rates are not affected. In sum: increasing q not only makes monitoring more costly but also increases banks' differentiation, and the latter effect renders bank competition less intense.[19] This result is consistent with Duquerroy et al. (2022) who find that increased branch specialization in SME lending – which can be viewed as an increase in q – substantially curtails the intensity of bank competition. Paravisini et al. (2021) find a similar result in the credit market for export-related loans.

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 more general cost function $C_i(m_i, z) = g(c_i, q_i, s_i)m_i^2$ that satisfies

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

[19] 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.

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

Information technology and local monopoly equilibrium. When bank competition is absent, bank i's equilibrium loan rate $r_i^m(z)$ depends only on its own IT. In Appendix C we show that $r_i^m(z)$ is increasing in q_i (when lending distance is positive) and c_i. The reason is that an IT improvement (i.e., decreasing q_i or/and c_i) in the local monopoly equilibrium has no competition effect; instead, it only makes monitoring less costly, which is reflected in bank i's lower loan rates. Better IT allows bank i to serve farther entrepreneurs, which improves financial inclusion because some locations that are not covered by any bank will gain access to bank finance because of the IT progress. See Proposition 18 and Corollary 10 in Appendix C for more details.

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

Information technology and lending volume. Does the progress of information technology spur entrepreneurship? To shed light on this question, first we study how the IT progress of a bank affects the mass of entrepreneurs it serves. The mass of entrepreneurs financed by bank 1 (resp. bank 2) – which is also the bank's aggregate loan volume – equals $L_1 \equiv \int_0^{\tilde{x}} D(z)dz$ (resp. $L_2 \equiv \int_{\tilde{x}}^1 D(z)dz$) and is characterized in the following proposition.

Proposition 3. *Bank i's aggregate loan volume L_i is decreasing in q_i and c_i. If $q_1 = q_2 = q$ and if there is effective bank competition at all locations (i.e., if $r_i^{\text{comp}}(z) < r_i^m(z)$ holds for all $z \in [0,1]$), then 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 states that the progress of a bank's IT, whatever its type, will induce the bank to serve more entrepreneurs (i.e., to provide more loans). We explain the result by looking at the IT progress of bank 1 (i.e., a decrease in q_1 or c_1): First, bank 1 will extend its market area (i.e., $\tilde{x}$ will increase) since its competitiveness is increased by the IT progress. Second, at a location served by bank 1, entrepreneurs' funding demand will not be affected by the bank's IT progress; the reason is that an entrepreneur's utility at that location is determined by the threat of bank 2 (i.e., the highest utility bank 2 can provide), which is not affected by bank 1's IT progress. As a result, bank 1's aggregate loan volume will increase as the bank's IT improves.

The second part (i.e., $\left.\frac{\partial^2 L_i}{\partial c_i \partial q}\right|_{q_i=q} > 0$) of Proposition 3 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 higher (i.e., when q is smaller). Two reasons contribute to the result. First of all, a bank's marginal expansion of market area (which is caused by the bank's IT progress) will bring more loans to the bank if q is smaller because entrepreneurs are better off and hence demand more funding at each location when banks compete more intensely. Second, a bank's marginal IT progress will lead to a larger market area expansion if q is smaller (i.e., $\left.\frac{\partial^2 \tilde{x}}{\partial c_1 \partial q}\right|_{q_i=q} > 0$) because the IT progress can affect more (distant) entrepreneurs' decisions when bank differentiation is smaller. Proposition 3 is consistent with Kwan et al. (2021) who find that banks with better IT originate more "paycheck protection program" loans to SMEs, especially in areas with more intense bank competition.

Next we analyze how the total mass of entrepreneurs undertaking investment projects (i.e., $L_1 + L_2$) is affected by the banking sector's IT.

Proposition 4. *Let $c_1 = c_2 = c$ and $q_1 = q_2 = q$. The total mass of entrepreneurs undertaking investment projects (i.e., $L_1 + L_2$) is decreasing in q and c.*

Proposition 4 states that the progress of the banking sector's IT, whatever its type, will promote entrepreneurs' investment. A decrease in q has two effects that spur entrepreneurship. First, there is a (competition) differentiation effect: Decreasing q diminishes bank differentiation and hence increases the intensity of bank competition. A more intense competition forces banks to provide higher expected utility to entrepreneurs, which induces more entrepreneurs to undertake their projects. Second, there is a cost-saving effect: A decrease in q makes monitoring less costly, so banks will choose higher monitoring intensity for a given loan rate, which benefits entrepreneurs and hence promotes their investment. Decreasing c does not have the differentiation effect, but the cost-saving effect still works. Proposition 4 is consistent with Ahnert et al. (2022) who find that job creation by young enterprises, which is an indirect measure of entrepreneurial investment, is higher in US counties that are more exposed to IT-intensive banks.

What happens when R is not large enough? In Appendix B we consider the case when R is not large enough and so at some locations bank i cannot make a non-negative profit by posting the loan rate $R/2$. For such a location, the best loan rate bank i can offer to entrepreneurs equals the loan rate that exactly brings bank i zero profit. 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 when R is not large enough because increasing c_i or q_i makes monitoring more costly for bank i and reduces its market power – 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 the higher c is, the higher a best loan rate bank i must charge in order to guarantee a non-negative profit, which reduces the attractiveness of bank i's best loan rate. Therefore, at a location served by bank j ($j \neq i$), bank j will face less competitive pressure from bank i and hence can set a higher loan rate as c (and bank i's best loan rate) increase. Propositions 2 to 4 are robust when R is not large (See Propositions 14 to 16 in Appendix B).

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.

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 (3) because bank risk will be appropriately priced when there is fairly priced deposit insurance, even if depositors cannot observe bank risk. It follows that all propositions based on Equation (3) are valid also in the case with fairly priced deposit insurance.[20]

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., $R \geq \sqrt{8c_i f/(1-q_i)}$) 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 $T(q_i, c_i) \geq 0$ at the IT investment stage. We assume that $T(q_i, c_i)$ is differentiable 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 lending profit at the lending competition stage. Sometimes $\Pi_1(q_1, q_2, c_1, c_2)$ is also written as Π_1 for short. In a symmetric way we

[20] The model with fair deposit insurance is available upon request.

can define bank 2's first-stage profit (i.e., Π_2).

4.1 Bank IT investment: substitutes or complements?

Are the two types of bank i's own IT investment, 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 investment: substitutes or complements? Let's 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. [21] *Let bank competition be effective at all locations. 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, bank 1's monitoring efficiency at location z is determined by $\frac{1-q_1 z}{c_1}$, 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).[22] As a consequence, q_1 and c_1 are complements if $T(q_1, c_1)$ is submodular.

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

[21] 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 $max\{c_1 - c_1 q_2, \underline{c}\}$ to $c_1/(1-q_1)$, which ensures that $0 < \tilde{x} < 1$.

[22] 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. [23] *If bank competition is effective at all locations, then q_1 and c_2 are strategic substitutes for bank 1: $\partial^2\Pi_1/(\partial q_1 \partial c_2) < 0$, 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 $\partial^2\Pi_1/(\partial q_1 \partial q_2)$ 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 that 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; this effect 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 lending profit at the indifference location $z = \tilde{x}$ will increase as q_2 or/and c_2 decreases, because then bank 1 can specialize in a smaller area.[24] 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 our 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

[23] 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 $max\{c_1 - c_1 q_2, \underline{c}\}$ to $c_1/(1-q_1)$, which ensures that $0 < \tilde{x} < 1$.

[24] 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.

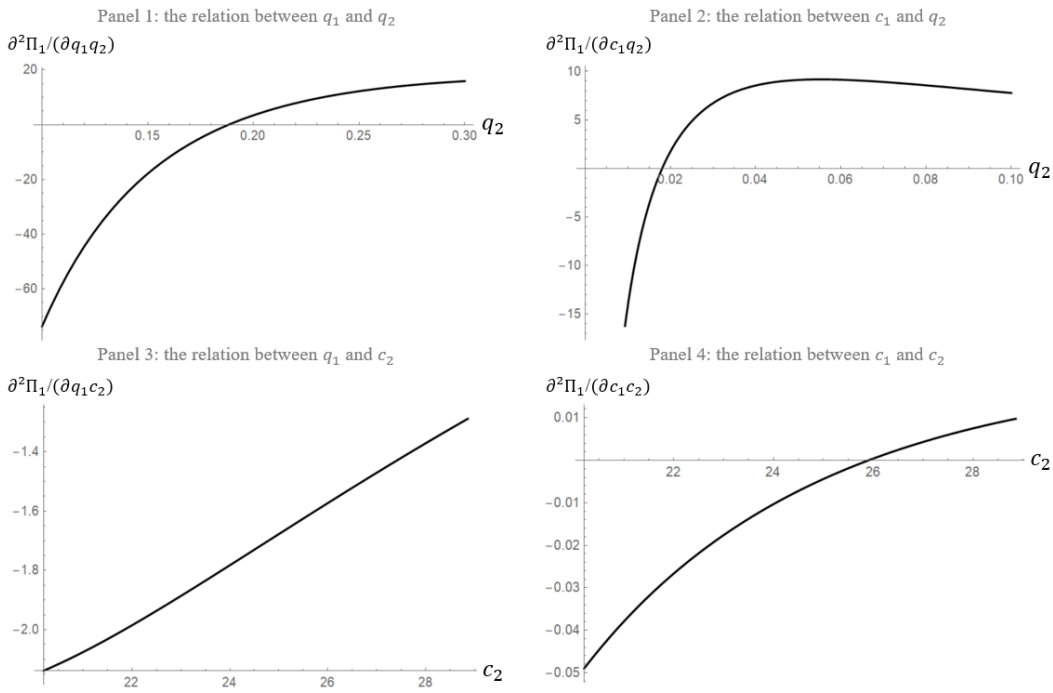

Figure 4: The Effects of q_2 and c_2 on Bank 1's Marginal Benefit of IT investment. This figure shows how the sign of $\partial^2\Pi_1/\left(\partial IT_1 \partial IT_2\right)$ varies with parameters when bank competition is effective at all locations and $0 < \tilde{x} < 1$, where $IT_1 = q_1$ or c_1 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 5. *If*

$$\Pi_i\left(0, 0, \underline{c}, \underline{c}\right) = \frac{R^2}{8\underline{c}}\left(\frac{R^2}{8\underline{c}} - f\right) - T\left(0, \underline{c}\right) > 0, \tag{5}$$

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

Condition (5) means that each bank can still make a positive ex ante profit when both banks acquire the best possible information technology. If Condition (5) is satisfied, we say IT is "cheap" to acquire. Proposition 5 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 lending profit at the lending

competition stage is equal to $\frac{R^2}{8\underline{c}}\left(\frac{R^2}{8\underline{c}} - f\right)$).

We prove here that $\{q_i = 0, c_i = \underline{c}\}$ is indeed an equilibrium under Condition (5). 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 (5). If bank 1 deviates (from $q_1 = 0$ and/or $c_1 = \underline{c}$), it will lose all its market share and so make a non-positive 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 (5) a bank will have the ability to dominate the entire 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.[25]

When IT is not cheap. Now we look at banks' IT investment when Condition (5) is not satisfied. We impose some 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 $\overline{q} > 0$ and $\overline{c} > \underline{c}$ such that $\partial T(q_i, c_i)/\partial q_i = 0$ for $q_i \geq \overline{q}$ and $\partial T(q_i, c_i)/\partial c_i = 0$ for $c_i \geq \overline{c}$. This assumption implies that bank i need only consider information technology that satisfies $q_i \times c_i \in [0, \overline{q}] \times [\underline{c}, \overline{c}]$. Finally, we assume $\overline{q}$ and $\overline{c}$ are sufficiently small so that bank competition is effective for all locations at the lending competition stage. Then we have the following (technical) result.

Lemma 3. *If* $\lim_{q_i \to 0} - q_i \partial T(q_i, c_i)/\partial q_i$ *(resp.* $-c_i \partial T(q_i, c_i)/\partial c_i|_{c_i = \underline{c}}$*) is large enough for any* $c_i \in [\underline{c}, \overline{c})$ *(resp. for any* $q_i \in [0, \overline{q})$*) 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* $q_i \times c_i \in (0, \overline{q}) \times [\underline{c}, \overline{c})$*, then there exists a unique symmetric interior equilibrium:* $q_i = q^* \in (0, \overline{q})$ *and* $c_i = c^* \in (\underline{c}, \overline{c})$*.*

Lemma 3 states that when the slope of $T(q_i, c_i)$ with respect to q_i and c_i fulfills a boundary condition and when its relative convexity with respect to q_i and c_i is large enough, a unique symmetric interior IT investment equilibrium will arise.[26]

[25] 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 D). 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.

[26] The assumption that $\lim_{q_i \to 0} -q_i \partial T(q_i, c_i)/\partial q_i$ and $-c_i \partial T(q_i, c_i)/\partial c_i|_{c_i = \underline{c}}$ are large enough ensures the

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

$$T(q_i, c_i) \equiv \beta_q Q(q_i) + \beta_c H(c_i), \tag{6}$$

where $Q(\cdot) \geq 0$, $H(\cdot) \geq 0$, are differentiable with $Q'(\cdot) \leq 0$ and $H'(\cdot) \leq 0$. The cost function (6) implies that the costs of the two types of IT are independent, so $T(q_i, c_i)$ itself cannot induce any interaction between the two types of information technology. 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 β_q and β_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 Lemma 3, at the 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) will co-move in response to a cost shock in the symmetric interior equilibrium. Yet 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 Lemma 3 and Proposition 6 belong to this symmetric case.

Numerical Result 3. [27] *If bank competition is effective at all locations and if $q_1 = q_2 > 0$ and $c_1 = c_2$ hold, then:*

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

existence of an interior solution $\{q^*, c^*\}$ that satisfies both banks' first order conditions. The assumption that $\lim_{q_i \to 0} -q_i \partial T(q_i, c_i)/\partial q_i$ is large enough for any $c_i \in [\underline{c}, \overline{c})$ ensures that Condition (5) cannot hold. A large $\lim_{q_i \to 0} -q_i \partial T(q_i, c_i)/\partial q_i$ 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: $T(0, c_i) = -\int_0^{\overline{q}} \frac{\partial T(q_i, c_i)}{\partial q_i} dq_i = +\infty$. 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 $\{q^*, c^*\}$ is unique and indeed constitutes an equilibrium.

[27] 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 $1.3R$.

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 2. In Online Appendix D there is a more detailed explanation.

Table 2: 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

As β_q decreases, bank 1 reduces q_1 because the direct effect of reducing β_q dominates the strategic substitutability effects of lower q_2 and c_2 (and is reinforced by the complementary effect of the decrease in c_1); bank 1 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 β_c decreases, bank 1 reduces c_1 because the direct effect of reducing β_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); bank 1 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

In this section 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. At the lending competition stage, banks have no own capital, so a bank will default if and only if the aggregate loan repayment it receives cannot cover its promised return to depositors. The probability of bank i's default is denoted by θ_i^*, 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 location $z \in [0, \tilde{x}]$. Then bank 1's default probability θ_1^* is determined by the following equation:*

$$\int_0^{\theta_1^*} \int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta\right\}} \, dz \, d\theta$$
$$+ (1 - \theta_1^*) \int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta_1^*\right\}} \, dz - f \int_0^{\tilde{x}} D(z) \, dz = 0,$$

where $1_{\{\cdot\}}$ *is an indicator function that equals* 1 *if the condition in* $\{\cdot\}$ *holds and equals* 0 *otherwise. Bank 2's default probability* θ_2^* *can be determined in a symmetric way.*

To see what is behind Lemma 4, we prove it here. Since the risk factor θ is assumed to be uniformly distributed on $[0, 1]$, it follows that bank 1 would default when $\theta < \theta_1^*$ if the bank's default probability is equal to θ_1^*. So for a given θ_1^*, the break-even condition for depositors is

$$\int_0^{\theta_1^*} \int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta\right\}} \, dz \, d\theta + (1 - \theta_1^*) d_1 \int_0^{\tilde{x}} D(z) \, dz = f \int_0^{\tilde{x}} D(z) \, dz. \quad (7)$$

Equation (7) is interpreted to mean that bank 1's actual expected payment to depositors must equal their required expected (gross) return. To understand the equation, we start by looking at its right-hand side: $\int_0^{\tilde{x}} D(z) \, dz$ is the aggregate funding amount that bank 1 raises from its depositors and f is the minimum expected return required by those depositors for a unit of funding. Thus $f \int_0^{\tilde{x}} D(z) \, dz$ is the minimum expected gross return required by depositors. The left-hand side of Equation (7) represents bank 1's actual expected payment to depositors: When θ is not lower than θ_1^*, bank 1 stays solvent and hence can pay all of $d_1 \int_0^{\tilde{x}} D(z) \, dz$ (the promised nominal return) back to the depositors. However, if $\theta < \theta_1^*$ 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 the bank receives from entrepreneurs. The indicator function $1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta\right\}}$ appears in (7) 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 (7).

Furthermore, bank 1 defaults if and only if $\theta < \theta_1^*$; this means that, when $\theta = \theta_1^*$, the aggregate loan repayment received by bank 1 should exactly equal the bank's promised payment to depositors, implying

$$\int_0^{\tilde{x}} D(z) r_1(z) 1_{\left\{1 - \frac{r_1(z)(1-q_1 z)}{c_1} \leq \theta_1^*\right\}} \, dz = d_1 \int_0^{\tilde{x}} D(z) \, dz. \quad (8)$$

Equations (7) and (8) together determine d_1 and θ_1^*. Inserting (8) into (7) yields the equation displayed in Lemma 4.

Bank stability when R is large. Lemma 4 does not yield a closed-form solution for θ_1^*, 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.

A numerical study shows that 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 improves 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 and/or c_1 increases bank 1's monitoring cost and so decreases the bank'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 increase, 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.

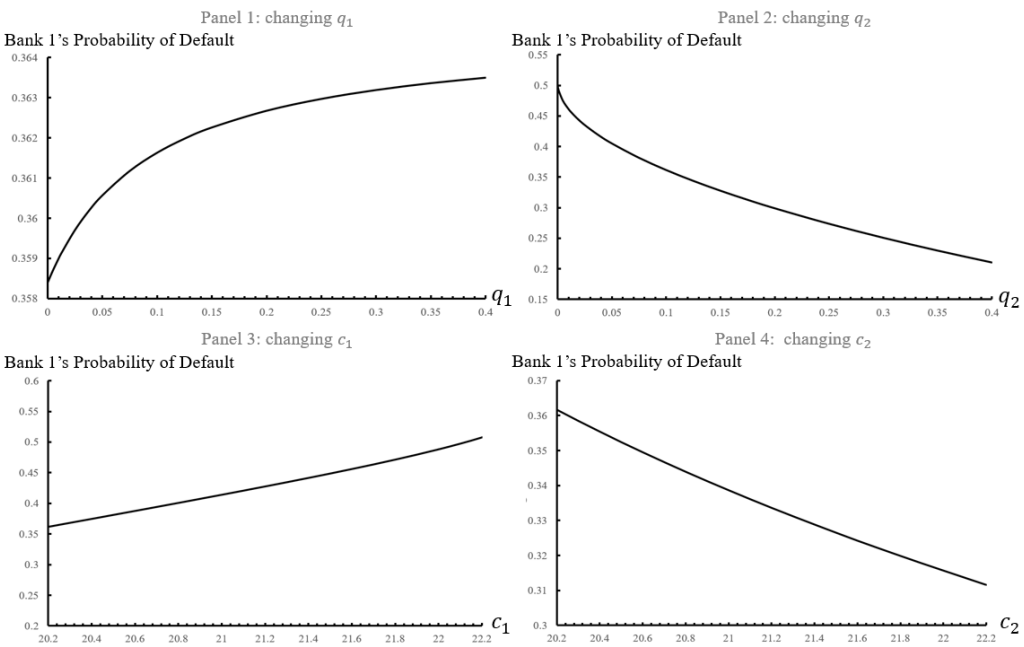

Figure 5: Bank 1's Probability of Default (w.r.t. q_i and c_i). This figure plots bank 1's probability of default against q_i and c_i in the equilibrium under direct bank competition. Except when used as a panel's independent variable, the parameter values are $R = 20$, $f = 1$, $c_1 = 1.01R$, $c_2 = 1.01R$, $q_1 = 0.1$, 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 advantage (Corollary 3) and enables bank 1 to set higher loan rates – 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.

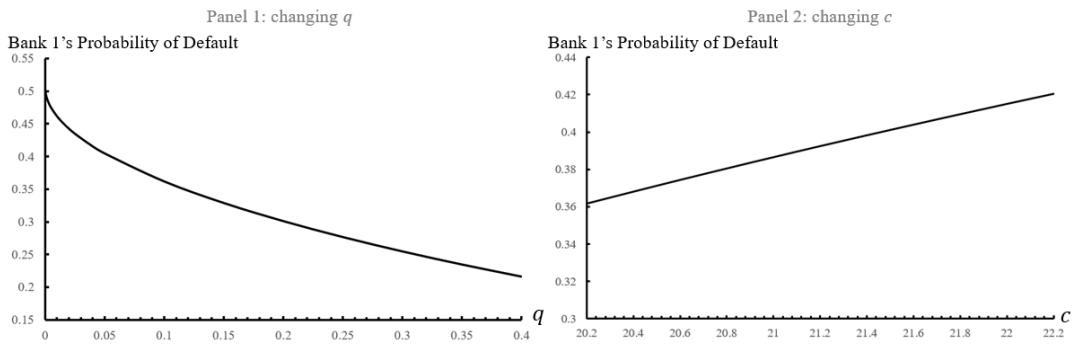

Figure 6: Bank 1's Probability of Default (w.r.t. q and c). This figure plots bank 1's probability of default against q and c with the restriction that $q_1 = q_2 = q$ and $c_1 = c_2 = c$ in the equilibrium under direct bank competition. Except when used as a panel's independent variable, the parameter 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.[28] In contrast, an increase in c does not have this kind of differentiation effect, so the direct cost effect reduces bank stability.

Bank stability when R is not large. If $R \geq \sqrt{8c_i f/(1-q_i)}$ is not satisfied (i.e., if R is not large), then the net effect of IT progress on bank stability is more complex.

[28] 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.

In Appendix C, 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 17). 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 (a) whether or not banks enjoy local monopolies and (b) the extent of bank competition. Figure 7 graphically illustrates 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 19 in Appendix C 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 such an equilibrium, 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 decreasing q on bank stability is reversed when q is small enough.[29]

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

[29]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. The reason is that a large R ensures effective bank competition for a significant range of (or even for all) locations.

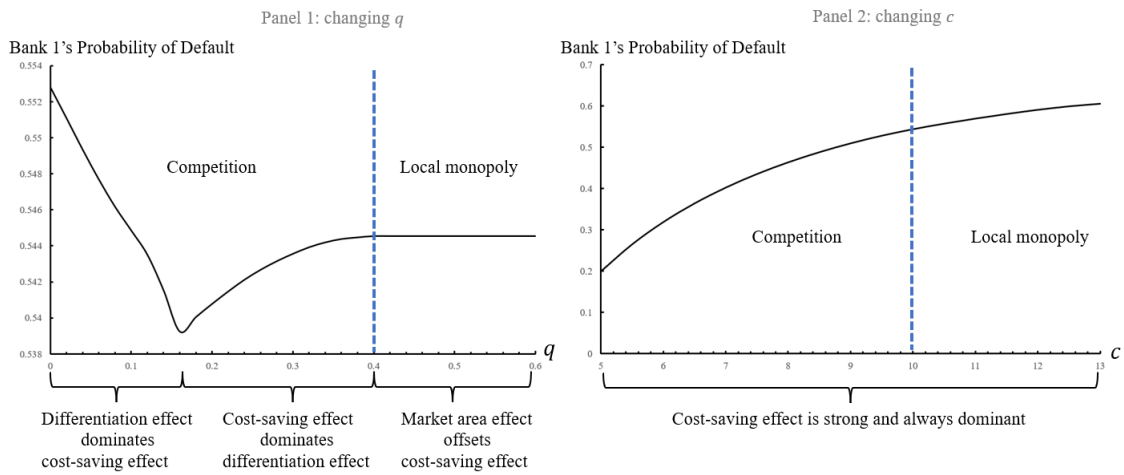

Figure 7: Bank 1's Probability of Default (w.r.t. q and c) when R is not large. This figure plots bank 1's probability of default against q and c with the restriction that $q_1 = q_2 = q$ and $c_1 = c_2 = c$. Except when used as a panel's independent variable, the parameter values are $R = 5$, $f = 1$,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

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 return 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.

6 Welfare analysis

In this section we analyze the social planner's problem. 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 C, the welfare effect of IT progress in the local monopoly equilibrium is analyzed and the main results are presented in the text. 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 $\Omega \subseteq [0,1]$ is the set of locations that are served and if entrepreneurs at location z are financed by bank i,[30] then social welfare is given by

$$\underbrace{\int_\Omega D(z)Rm_i(z)\,dz}_{\text{Social benefits}} - \underbrace{\begin{pmatrix} \int_\Omega D(z)f\,dz + \int_\Omega \frac{D(z)c}{2(1-qs_i)}(m_i(z))^2\,dz \\ + \int_\Omega \int_0^{D(z)} \underline{u}\,d\underline{u}\,dz + (\theta_1^* + \theta_2^*)K \end{pmatrix}}_{\text{Social costs}}. \tag{9}$$

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, θ_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 $\int_0^{D(z)} \underline{u}\,d\underline{u} = (D(z))^2/2$ and $D(z) = (R - r_i(z))m_i(z)$. Then we can reorganize (9) as follows:

$$\begin{aligned} W = & \underbrace{\int_\Omega \frac{\big((R - r_i(z))m_i(z)\big)^2}{2}\,dz}_{\text{Entrepreneurs' aggregate expected utility}} \\ & + \underbrace{\int_\Omega D(z)\left(r_i(z)m_i(z) - f - \frac{c(m_i(z))^2}{2(1-qs_i)}\right)dz}_{\text{Banks' expected profits}} - \underbrace{(\theta_1^* + \theta_2^*)K}_{\text{Deadweight loss of bankruptcy}} . \end{aligned} \tag{10}$$

This expression divides social welfare into three components: entrepreneurs' aggregate utility, banks' profits, and the expected deadweight loss due to banks' failure. Using Equation (10), we can analyze the relation between equilibrium loan rates and socially optimal ones.

Second best rates. First we consider the second-best case where the social planner

[30] We will show below that it is socially optimal that a location in Ω is served by the bank with (weakly) smaller lending distance.

can (a) determine the locations each bank serves and (b) choose the second-best socially optimal loan rate schedule of bank i, denoted by $\{r_i^{\mathrm{SB}}(z)\}$, to maximize social welfare under the constraint that bank i's monitoring intensity at z is equal to $r_i^{\mathrm{SB}}(z)(1-qs_i)/c$. In this case the social planner cannot control banks' monitoring intensities, which hence must be as described in Lemma 1. Our next proposition gives the basic properties of the second-best case.

Proposition 7. *Let $K=0$. In the second-best case it is socially optimal to let bank i serve locations that it would serve in equilibrium.*[31] *The second-best socially optimal loan rate $r_i^{\mathrm{SB}}(z)$ at location z (served by bank i) is given by*

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

which satisfies $R/2<r_i^{\mathrm{SB}}(z)\leq r_i^m(z)$.[32]

Since monitoring will incur social costs, for each location it is always socially more desirable to assign the bank with better monitoring efficiency (i.e., with smaller lending distance). If there exist locations that neither bank is willing to serve in equilibrium (see Appendix C), then it means that projects in those locations cannot generate positive expected values net of monitoring and funding costs; hence the social planner will not let either bank serve such locations. Overall, the social planner will let bank i serve locations that it would serve in equilibrium. This result holds also in the first-best case (to be characterized in Proposition 9) for the same reason.

From the perspective of social welfare, lowering $r_i^{\mathrm{SB}}(z)$ will decrease bank i incentive to monitor, which will reduce the expected value of projects financed by bank i. Yet as $r_i^{\mathrm{SB}}(z)$ decreases, an entrepreneur's utility will increase (since $r_i^{\mathrm{SB}}(z)\geq R/2$), which will increase the mass of entrepreneurs undertaking investment projects. Hence a social planner must balance the social benefits (i.e., investment-spurring effect) and costs (i.e., monitoring-reducing effect) of decreasing $r_i^{\mathrm{SB}}(z)$ – here $R/2$ is one extreme loan rate, which maximizes entrepreneurs' utility and investment at z; the monopoly loan rate $r_i^m(z)$ is the other extreme, which maximizes bank i's profit and hence incentivizes the bank to choose a high monitoring intensity – leading to the relation $R/2<r_i^{\mathrm{SB}}(z)\leq r_i^m(z)$.

[31] If there is direct bank competition in equilibrium, then in the second-best case it is socially optimal to let bank 1 (resp. bank 2) serve the region $[0,1/2]$ (resp. $(1/2,1]$); if there is no bank competition in equilibrium (see Appendix C), then it is socially optimal to let bank 1 (resp. bank 2) serve the region $[0,\frac{R^2-2cf}{qR^2}]$ (resp. $[1-\frac{R^2-2cf}{qR^2},1]$)

[32] The equality $r_i^{\mathrm{SB}}(z)=r_i^m(z)$ holds only when bank i's best loan rate at z is R.

In a local monopoly equilibrium, bank i's loan rate at z equals $r_i^m(z)$. Hence Proposition 7 implies that in such an equilibrium bank i's loan rates are higher than the second-best ones (except for the boundary location where $r_i^{\mathrm{SB}}(z) = r_i^m(z)$ holds). See Corollary 11 in Appendix C for more details.

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

Proposition 8. *Let $K = 0$. If $R > \sqrt{2cf}$ and if location z is served by bank i, then the inequality $r_i^{\mathrm{comp}}(z) < r_i^{\mathrm{SB}}(z)$ holds for all locations when q is small enough.*[33]

Proposition 8 states that the intensity of bank competition will be too high when q (the differentiation between banks) is sufficiently low. Entrepreneurs will be better-off as the intensity of bank competition increases, which will increase the mass of entrepreneurs undertaking investment projects; but banks will then be worse-off and monitoring intensities will decline, which will reduce the expected value of financed projects.[34] When q is too low, the monitoring-reducing effect dominates the investment-spurring effect, so the equilibrium loan rate is lower than the socially optimal one. Figure 8 provides a graphic presentation of this result.

First-best rates. Now we consider the first-best socially optimal case, where the social planner can (a) determine the locations each bank serves, (b) choose the first-best socially optimal loan rate schedule (denoted by $\{r_i^{\mathrm{FB}}(z)\}$) of bank i, and (c) set banks' monitoring intensities. The monitoring intensities chosen by the social planner are observable for entrepreneurs, so they can have a correct expectation about investment returns and make decisions accordingly. In the first best case, banks' monitoring intensities are no longer constrained by Lemma 1. The following proposition characterizes the first-best case.

Proposition 9. *Let $K = 0$. In the first-best case it is socially optimal to let bank i serve locations that it would serve in equilibrium. At location z (served by bank i), the first-best*

[33] 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 $r_i^{\mathrm{comp}}(z) = r_i^{\mathrm{SB}}(z) = r_i^m(z) = R$ at locations served by bank i.

[34] Gehrig (1998) also finds that under certain conditions competition will decrease banks' efforts, and so reduce the quality of the overall loan portfolio.

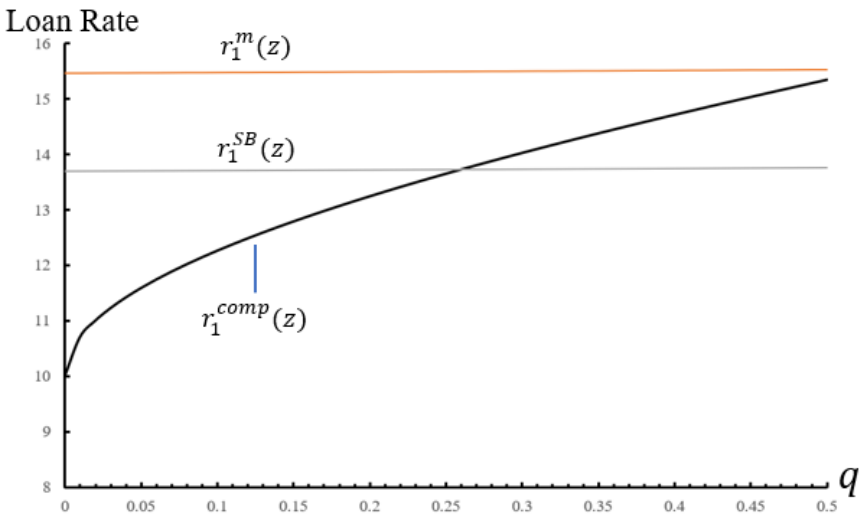

Figure 8: Comparing $r_1^{\text{comp}}(z)$, $r_1^m(z)$, and $r_1^{\text{SB}}(z)$. This figure plots $r_1^{\text{comp}}(z)$, $r_1^m(z)$, and $r_1^{\text{SB}}(z)$ against q. The parameter values are $R = 20$, $f = 1$, $c = 1.01R$, and $z = 0.25$.

socially optimal loan rate $r_i^{\text{FB}}(z)$ and monitoring intensity $m_i^{\text{FB}}(z)$ are given by

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

here $r_i^{\text{FB}}(z) \leq r_i^{\text{SB}}(z)$.[35]

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 $(1 - qs_i)R/c$, which is the monitoring intensity 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

[35] We have that $r_i^{\text{FB}}(z) = r_i^{\text{SB}}(z)$ holds only when bank i's best loan rate at z is R.

higher monitoring intensity benefits entrepreneurs, the social planner must control $r_i^{\mathrm{FB}}(z)$ in order to avoid inefficiently excessive funding demand (i.e., excessive investment) at location z – which means that $r_i^{\mathrm{FB}}(z)$ cannot be too low. So when bank competition is intense enough (i.e., when q is small enough), the equilibrium loan rate $r_i^{\mathrm{comp}}(z)$ will be lower than $r_i^{\mathrm{FB}}(z)$. Figure 9 illustrates the relations involving $r_1^{\mathrm{comp}}(z)$, $r_1^{\mathrm{SB}}(z)$, and $r_1^{\mathrm{FB}}(z)$ in $z \times q$ space.

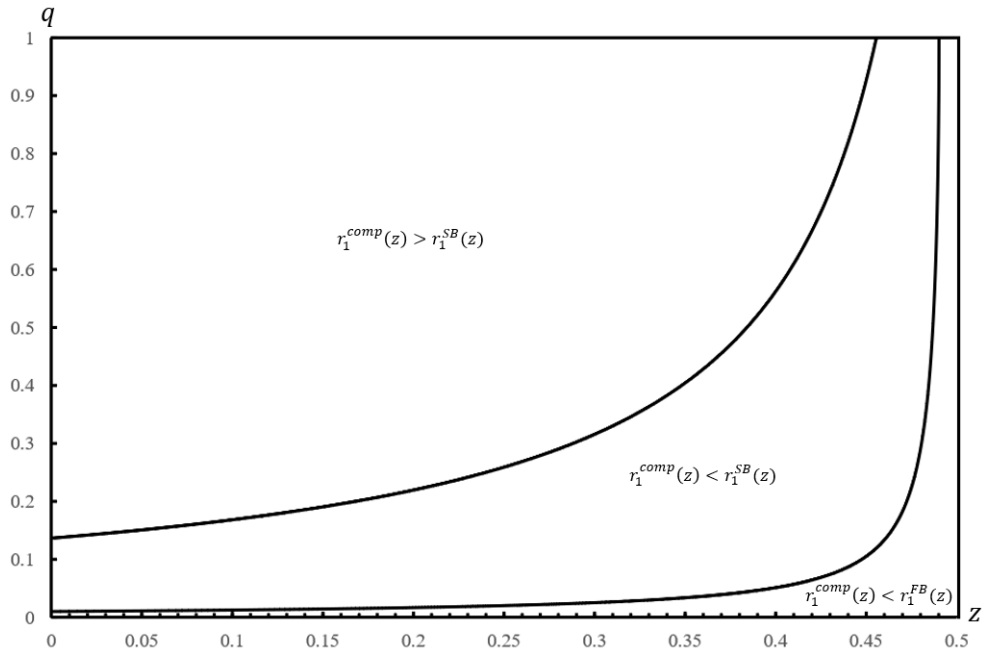

Figure 9: Relations among $r_1^{\mathrm{comp}}(z)$, $r_1^{\mathrm{SB}}(z)$, and $r_1^{\mathrm{FB}}(z)$ in $z \times q$ space. This figure compares $r_1^{comp}(z)$ with $r_1^{\mathrm{SB}}(z)$ and $r_1^{\mathrm{FB}}(z)$ in $z \times q$ space. The parameter values are $R = 20$, $c = 1.01R$, and $f = 1$.

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 (together with a higher monitoring efficiency) translates into banks offering better loan rates, which always boosts entrepreneurs' utility and spurs investment. So as can be seen in Panels 1 and 2 of Figure 10, entrepreneurial utility increases if q decreases. From the banks' perspective, reducing q has two opposing effects.

The first is a 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 for q small enough, even if bank failure incurs no social costs (i.e., if $K = 0$; see Panel 1 of Figure 10).

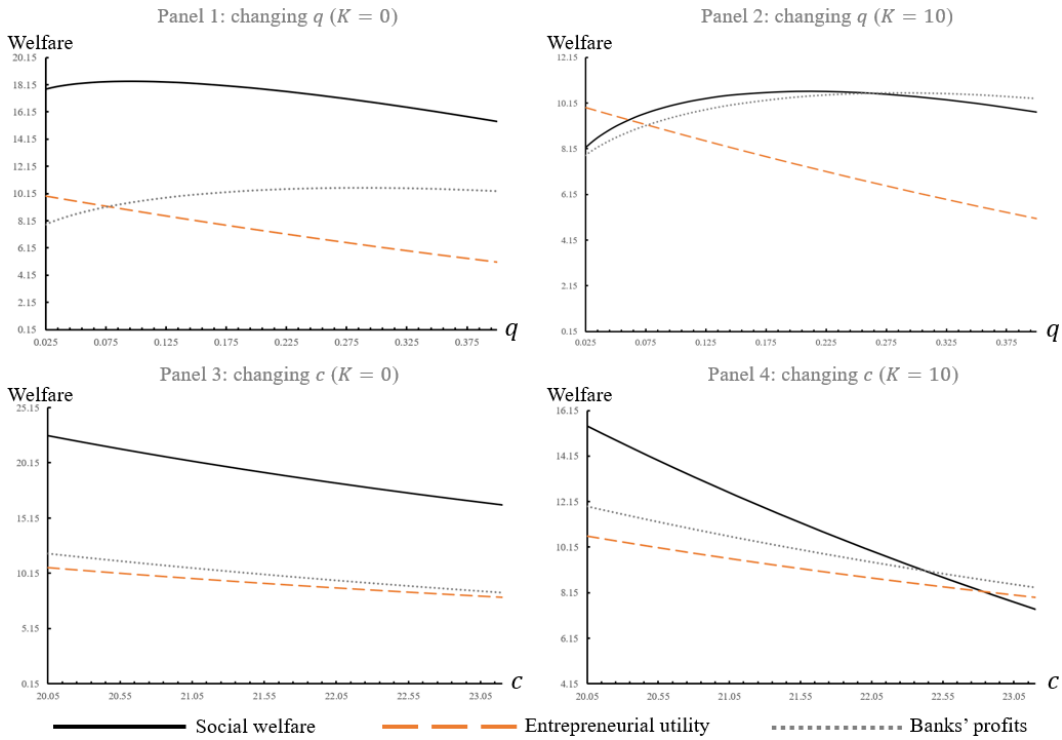

Figure 10: Social Welfare and Banking Sector's Information Technology under Competition. This figure plots social welfare, entrepreneurial utility, and banks' profits against c and q in the equilibrium under bank competition. The parameter values are: $R = 20$ and $f = 1$ in all panels; $c = 22$ in Panels 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 part (i.e., the result about q) of 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 and investment-spurring effects 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 lower monitoring intensities; 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.

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.

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 Proposition 20 in Appendix C).

Deposit insurance: The formula for social welfare W, Equation (10), 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 the deposit insurance has no effect on social welfare. Because bank stability is no longer determined by Lemma 4 when deposits are insured, the fairly priced deposit insurance

will increase social welfare by reducing banks' probability of default θ_i^* if there is a positive deadweight loss associated with bank failure (i.e., if $K > 0$). Yet this section's results – on how IT progress affects social welfare – are robust in the case with a fairly priced deposit insurance and a positive deadweight loss of bank failure.

6.2.1 Welfare analysis with IT investment costs

Finally we take into consideration the IT investment cost $T(q, c)$ when analyzing the welfare effect of changing q and c.

IT is cheap. In this case $q = 0$ and $c = \underline{c}$ will arise endogenously (Proposition 5). According to Proposition 11, the monitoring-reducing effect will dominate the cost-saving and invest-spurring effects when q is sufficiently small, so banks' endogenous IT investment will induce excessively low levels of differentiation (i.e., too low a q) from the social point of view. Taking IT investment costs into consideration strengthens the negative effect of decreasing q (Panel 1 of Figure 11).

As for c, note that the cheap IT condition (5) does not restrict the marginal cost of decreasing c, so $c = \underline{c}$ (which is banks' endogenous choice) will be lower than the socially optimal level if $\lim_{c \to \underline{c}} \partial T(q, c)/\partial c \leq 0$ is low enough. The reason is that the marginal benefit (cost-saving effect) of decreasing c is always finite from the social planner's perspective. Panel 2 of Figure 11 gives an example in which $c = \underline{c}$ is excessively low; in this figure $\lim_{c \to \underline{c}} \partial T(q, c)/\partial c = -\infty$.

The cheap-IT scenario can arise for example if information technology is highly advanced in non-financial sectors and then it spills over the banking sector.

IT is not cheap. As in Lemma 3, we focus on the case that $\partial T(q, c)/\partial q = 0$ (resp. $\partial T(q, c)/\partial c = 0$) for $q \geq \overline{q}$ (resp. $c \geq \overline{c}$). Then we have the following result.

Proposition 12. *Let $K = 0$ and $T(q, c)$ be submodular. Under the assumptions of Lemma 3, if $\overline{q}$ is sufficiently small, then q^* and c^* (i.e., banks' IT choice in the unique symmetric interior equilibrium) are excessively low from the social planner's perspective.*

A bank and the social planner have different marginal benefits of IT investment. A bank cares only about its own lending profit, so the marginal benefit of IT investment for the bank consists of a cost-saving effect on monitoring and a *business stealing effect*. The latter means that by adopting better IT the bank will have a higher competitive advantage and erode the rival bank's lending profit. In contrast, the social planner cares about entrepreneurial utility and both banks' profits, so it does not value the business stealing effect.

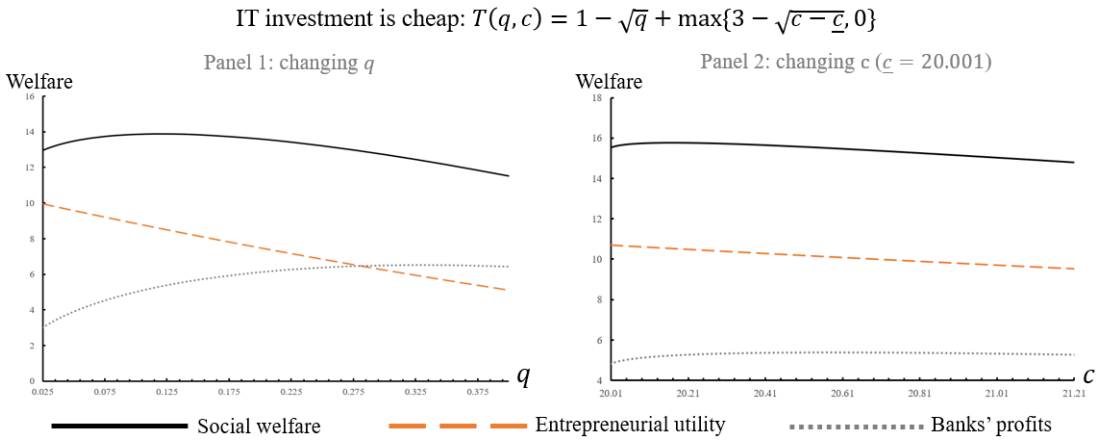

Figure 11: Social Welfare and Banking Sector's Information Technology with Competition and Cheap IT. This figure plots social welfare, entrepreneurial utility, and banks' profits against c and q in the equilibrium with bank competition and cheap IT. The parameter values are: $R = 20$, $K = 0$ and $f = 1$ in both panels; $c = 22$ in Panel 1; $q = 0.1$ in Panel 2.

Because of the cost-saving and business stealing effects, investing in IT always has a positive marginal benefit for a bank, so q^* is always lower than $\overline{q}$ no matter how small $\overline{q}$ is. For the social planner, however, the marginal benefit of decreasing q will turn negative when q is sufficiently small (Proposition 11). Hence q^* must be excessively low from the social planner's perspective when $\overline{q}$ is sufficiently small.

With sufficiently low $\overline{q}$ (and hence q^*), banks' endogenous IT investment will induce very low levels of bank differentiation, which will lead to a very strong business stealing effect. In this case, a bank's small IT improvement will increase the bank's profit by a lot (through eroding the rival's market share).[36] Such a large business stealing effect will give bank i quite strong incentive to reduce c_i, which will lead to an excessively low c^* from the social planner's perspective if $T(q, c)$ is submodular (i.e., if a lower q does not increase the marginal cost of decreasing c).

Local monopoly equilibrium with endogenous IT investment. In this case investing in IT, whatever its type, has a higher marginal benefit for the social planner than for a bank, because a bank does not internalize that a higher monitoring efficiency also benefits entrepreneurs. Therefore, banks' endogenous IT investment will lead to excessively high q and c from the social planner's perspective if $T(q, c)$ is submodular.

[36] An extreme example is the case where $\overline{q}$ (and hence q^*) approach 0. In this case bank differentiation almost disappears, so bank 1 can gain a lot of market share if it slightly decreases c_1 (from $c_1 = c_2 = c^*$), which implies that the business stealing effect is nearly infinitely strong for the bank.

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 an entrepreneur without altering banks' relative cost advantage (i.e., lower c), then 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 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 have the testable implication that a technologically more advanced bank – regardless of how changes in IT affect bank differentiation – specializes less (i.e. lends to more industries/locations), commands greater market power and is more stable. We find also that in locations (or industries) with effective bank competition (proxied by low bank concentration), a bank's loan rate will increase after the bank's IT improves relative to other banks, while if the bank has monopoly power it will decrease its loan rate.

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. The testable implication then is that investment in different types of IT are complements.

We find that the welfare effect of information technology progress is ambiguous when it weakens the influence of bank–entrepreneur distance on monitoring 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; in this case banks' IT investment is inefficiently low because they cannot internalize the benefit of IT improvement on entrepreneurs.

References

Acharya, V. V., I. Hasan, and A. Saunders (2006): "Should banks be diversified? Evidence from individual bank loan portfolios," *The Journal of Business*, 79, 1355–1412.

Agarwal, S., S. Alok, P. Ghosh, and S. Gupta (2020): "Fintech and credit scoring for the millennials: evidence using mobile and social footprints," *SSRN Electronic Journal*.

Agarwal, S. and R. Hauswald (2010): "Distance and private information in lending," *The Review of Financial Studies*, 23, 2757–2788.

Ahnert, T., S. Doerr, N. Pierri, and Y. Timmer (2022): "Does IT help startups? Information Technology in Banking and Entrepreneurship," *Working Paper*.

Almazan, A. (2002): "A model of competition in banking: Bank capital vs expertise," *Journal of Financial Intermediation*, 11, 87–121.

Berg, T., V. Burg, A. Gombović, and M. Puri (2020): "On the rise of fintechs: Credit scoring using digital footprints," *The Review of Financial Studies*, 33, 2845–2897.

Berg, T., A. Fuster, and M. Puri (2021): "FinTech Lending," *NBER Working Paper*.

Björkegren, D. and D. Grissen (2020): "Behavior revealed in mobile phone usage predicts credit repayment," *The World Bank Economic Review*, 34, 618–634.

Blickle, K., C. Parlatore, and A. Saunders (2021): "Specialization in Banking," *FRB of New York Staff Report*.

Boot, A. W., P. Hoffmann, L. Laeven, L. Ratnovski, et al. (2020): "Financial intermediation and technology: what's old, what's new?" *European Central Bank, Working Paper*.

Brevoort, K. P. and J. D. Wolken (2009): "Does distance matter in banking?" in *The changing geography of banking and finance*, Springer, 27–56.

Buchak, G., G. Matvos, T. Piskorski, and A. Seru (2018): "Fintech, regulatory arbitrage, and the rise of shadow banks," *Journal of Financial Economics*, 130, 453–483.

Carletti, E., S. Claessens, A. Fatas, and X. Vives (2020): "The bank business model in the post-Covid-19 world," *The Future of Banking, Centre for Economic Policy Research.*

Cordella, T. and E. L. Yeyati (2002): "Financial opening, deposit insurance, and risk in a model of banking competition," *European Economic Review*, 46, 471–485.

Degryse, H. and S. Ongena (2005): "Distance, lending relationships, and competition," *The Journal of Finance*, 60, 231–266.

Deng, S. and E. Elyasiani (2008): "Geographic diversification, bank holding company value, and risk," *Journal of Money, Credit and Banking*, 40, 1217–1238.

DeYoung, R., W. S. Frame, D. Glennon, and P. Nigro (2011): "The information revolution and small business lending: The missing evidence," *Journal of Financial Services Research*, 39, 19–33.

Diamond, D. W. (1984): "Financial intermediation and delegated monitoring," *The Review of Economic Studies*, 51, 393–414.

Dorfleitner, G., C. Priberny, S. Schuster, J. Stoiber, M. Weber, I. de Castro, and J. Kammler (2016): "Description-text related soft information in peer-to-peer lending–Evidence from two leading European platforms," *Journal of Banking & Finance*, 64, 169–187.

Duquerroy, A., C. Mazet-Sonilhac, J.-S. Mésonnier, D. Paravisini, et al. (2022): "Bank Local Specialization," *Working Paper.*

Frost, J., L. Gambacorta, Y. Huang, H. S. Shin, and P. Zbinden (2019): "BigTech and the changing structure of financial intermediation," *Economic Policy.*

FSB (2019): "FinTech and market structure in financial services: Market developments and potential financial stability implications," *Financial Innovation Network, Financial Stability Board, Basel, Switzerland.*

Fuster, A., M. Plosser, P. Schnabl, and J. Vickery (2019): "The role of technology in mortgage lending," *The Review of Financial Studies*, 32, 1854–1899.

Gao, Q., M. Lin, and R. W. Sias (2018): "Words matter: The role of texts in online credit markets," *Working Paper*.

Gehrig, T. (1998): "Screening, cross-border banking, and the allocation of credit," *Research in Economics*, 52, 387–407.

Ghosh, P., B. Vallee, and Y. Zeng (2021): "FinTech Lending and Cashless Payments," *Working Paper*.

Gopal, M. and P. Schnabl (2022): "The rise of finance companies and fintech lenders in small business lending," *The Review of Financial Studies, forthcoming*.

Hauswald, R. and R. Marquez (2003): "Information technology and financial services competition," *The Review of Financial Studies*, 16, 921–948.

——— (2006): "Competition and strategic information acquisition in credit markets," *The Review of Financial Studies*, 19, 967–1000.

He, Z., J. Huang, and J. Zhou (2020): "Open banking: Credit market competition when borrowers own the data," *National Bureau of Economic Research, Working Paper, No. 28118*.

He, Z., S. Jiang, D. Xu, and X. Yin (2021): "Investing in Lending Technology: IT Spending in Banking," *University of Chicago, Becker Friedman Institute for Economics Working Paper*.

Hertzberg, A., A. Liberman, and D. Paravisini (2016): "Adverse selection on maturity: Evidence from online consumer credit?" *Financial innovation online lending to households and small businesses*, 1–66.

Holmstrom, B. and J. Tirole (1997): "Financial intermediation, loanable funds, and the real sector," *The Quarterly Journal of Economics*, 112, 663–691.

Hotelling, H. (1929): "Stability in Competition," *The Economic Journal*, 39, 41–57.

Iyer, R., A. I. Khwaja, E. F. Luttmer, and K. Shue (2016): "Screening peers softly: Inferring the quality of small borrowers," *Management Science*, 62, 1554–1577.

Jiang, L., R. Levine, and C. Lin (2017): "Does competition affect bank risk?" *National Bureau of Economic Research, Working Paper, No. 23080.*

Kawai, K., K. Onishi, and K. Uetake (2014): "Signaling in online credit markets," *Working Paper.*

Kwan, A., C. Lin, V. Pursiainen, and M. Tai (2021): "Stress testing banks' digital capabilities: Evidence from the COVID-19 Pandemic," *Working Paper.*

Liberti, J. M. and M. A. Petersen (2019): "Information: Hard and soft," *Review of Corporate Finance Studies*, 8, 1–41.

Lin, M., N. R. Prabhala, and S. Viswanathan (2013): "Judging borrowers by the company they keep: Friendship networks and information asymmetry in online peer-to-peer lending," *Management Science*, 59, 17–35.

Martinez-Miera, D. and R. Repullo (2019): "Monetary policy, macroprudential policy, and financial stability," *Annual Review of Economics*, 11, 809–832.

Matutes, C. and X. Vives (1996): "Competition for deposits, fragility, and insurance," *Journal of Financial Intermediation*, 5, 184–216.

Netzer, O., A. Lemaire, and M. Herzenstein (2019): "When words sweat: Identifying signals for loan default in the text of loan applications," *Journal of Marketing Research*, 56, 960–980.

Ouyang, S. (2021): "Cashless Payment and Financial Inclusion," *Available at SSRN 3948925.*

Paravisini, D., V. Rappoport, and P. Schnabl (2021): "Specialization in Bank Lending: Evidence from Exporting Firms," *Working Paper.*

Petersen, M. A. and R. G. Rajan (2002): "Does distance still matter? The information revolution in small business lending," *The Journal of Finance*, 57, 2533–2570.

Philippon, T. (2016): "The fintech opportunity," *National Bureau of Economic Research, Working Paper, No. 22476.*

Pierri, N. and Y. Timmer (2021): "The importance of technology in banking during a crisis," *ESRB: Working Paper Series 2021/117.*

Thisse, J.-F. and X. Vives (1988): "On the strategic choice of spatial price policy," *The American Economic Review*, 122–137.

Tirole, J. (2010): *The theory of corporate finance*, Princeton University Press.

Villas-Boas, J. M. and U. Schmidt-Mohr (1999): "Oligopoly with asymmetric information: Differentiation in credit markets," *The RAND Journal of Economics*, 375–396.

Vives, X. (2016): *Competition and stability in banking: The role of regulation and competition policy*, Princeton University Press.

——— (2019): "Digital disruption in banking," *Annual Review of Financial Economics*, 11, 243–272.

Appendix A: Proofs

Proof of Equation (3). Let Ω_1 denote the the set of locations served by bank 1. When the common risk factor is θ, the aggregate loan repayment bank 1 receives from entrepreneurs is equal to $\int_{z\in\Omega_1} D(z)r_1(z)1_{\{1-m_1(z)\leq\theta\}}\,dz$, which is (weakly) increasing in θ. Meanwhile the bank must raise $\int_{z\in\Omega_1} D(z)\,dz$ units of funding from depositors to finance its loans. Thus the bank must promise to pay back $d_1\int_{z\in\Omega_1} D(z)\,dz$ (here d_1 is endogenous). Then when θ is small enough, the bank cannot fully pay back the promised return to depositors.

Let θ_1^* denote the cut-off risk factor such that the bank can fully pay back depositors if and only if $\theta \geq \theta_1^*$. Then the bank's expected aggregate lending profit is

$$AP_1 = \left(\begin{array}{c} \int_{\theta_1^*}^1 \left(\int_{z\in\Omega_1} D(z)r_1(z)1_{\{1-m_1(z)\leq\theta\}}\,dz - d_1\int_{z\in\Omega_1} D(z)\,dz \right) d\theta \\ -\int_{z\in\Omega_1} D(z)C_1\left(m_1\left(z\right),z\right)\,dz \end{array} \right).$$

Since the value of d_1 must ensure that the expected return to depositors is f for each unit of funding, we must have the following equation:

$$\int_0^{\theta_1^*}\int_{z\in\Omega_1} D(z)r_1(z)1_{\{1-m_1(z)\leq\theta\}}\,dz\,d\theta + \int_{\theta_1^*}^1\int_{z\in\Omega_1} d_1 D(z)\,dzd\theta = f\int_{z\in\Omega_1} D(z)\,dz. \quad \text{(A.1)}$$

The intuition behind (A.1) is explained after Lemma 4. Inserting (A.1) into AP_1 to cancel d_1, we can show that

$$AP_1 = \int_{z\in\Omega_1} D(z)\underbrace{\left(r_1(z)m_1\left(z\right) - f - C_1\left(m_1\left(z\right),z\right)\right)}_{\pi_1(z)}dz$$

because $\int_0^1\int_{z\in\Omega_1} D(z)r_1(z)1_{\{1-m_1(z)\leq\theta\}}\,dzd\theta = \int_{z\in\Omega_1} D(z)r_1(z)m_1\left(z\right)\,dz$ holds. Therefore, the bank's profit from financing an entrepreneur at z is given by Equation (3).

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

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

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

Some proofs in the appendix will use the following lemma.

Lemma 5. *The monopoly loan rate $r_1^m(z)$ of bank 1 for entrepreneurs at z is the largest solution of the following equation:*

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

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

Proof of Lemma 5. 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:

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

It is clear that $h(-\infty)\to+\infty$, $h(0)=-Rf<0$ and $h\left(\frac{R}{2}\right)=\frac{\left(\frac{R}{2}\right)^2R(1-q_1z)}{2c_1}>0$. Therefore, within $(-\infty,0)$ and $\left(0,\frac{R}{2}\right)$, there exist two roots for $h(r_1(z))=0$. 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 $h(+\infty)\to-\infty$. So there must exist a third root, denoted by r^{3rd}, within $\left(\frac{R}{2},+\infty\right)$. 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 $\left(\frac{R}{2},R\right]$, 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. 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 $\tilde{x}$:

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

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 $r_1\left(z\right)$ 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 $r_1\left(z\right)$ as high as possible; this implies the following equation:

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

The equation yields $r_1\left(z\right)=r_1^{\text{comp}}(z)$. However, if $r_1^{\text{comp}}(z)$ is higher than bank 1's monopoly loan rate $r_1^m(z)$, then bank 1 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 $r_1^*\left(z\right)=\min\left\{r_1^{\text{comp}}(z),r_1^m(z)\right\}$ for entrepreneurs located in $[0,\tilde{x}]$. Similarly, we can derive bank 2's equilibrium loan rate $r_2^*\left(z\right)$.

Proof of Corollary 2. 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 $D\left(z\right)=(R-r_1^{\text{comp}}(z))m_1(z)$.We can show that $D\left(z\right)=\frac{(1-q_2(1-z))R^2}{4c_2}$, which is increasing in $z\in[0,\tilde{x}]$ when $q_2>0$. 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 when $q_1>0$.

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

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

We can show that

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

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 $r_1^{\text{comp}}(x^m)$. 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 $\partial\left(D(z)\left(\frac{(r_1^{\text{comp}}(z))^2(1-qz)}{2c}-f\right)\right)/\partial c < 0$ because $D(z) = \frac{(1-q(1-z))R^2}{4c}$ is decreasing in c (see the proof of Corollary 2) while $r_1^{\text{comp}}(z)$ 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 $q \to 0$. For $z < 1/2$, it is easy to show $\lim_{q\to 0}\frac{R^4\sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} \to +\infty$. If $z = 1/2$, we have $\frac{R^4\sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} = 0$. Therefore, we must have $\lim_{q\to 0}\frac{\partial AP_1}{\partial q} \to +\infty$. As a result, bank 1's aggregate profit is increasing in q if q is sufficiently small.

Proof of Proposition 3. First we calculate $\frac{\partial L_1}{\partial q_1}$ and $\frac{\partial L_1}{\partial c_1}$. A symmetric result holds for bank 2. If bank 1 has monopoly power in the region $[0, x^m] \subset [0, \tilde{x}]$, then

$$L_1 = \int_0^{x^m} \frac{(1-q_1 z)\, r_1^m(z)\,(R - r_1^m(z))}{c_1}dz + \int_{x^m}^{\tilde{x}} \frac{(1-q_2(1-z))\, R^2}{4c_2}dz.$$

If $x^m = 0$, then obviously $\frac{\partial L_1}{\partial q_1} < 0$ and $\frac{\partial L_1}{\partial c_1} < 0$ hold because $\frac{\partial \tilde{x}}{\partial q_1} < 0$ and $\frac{\partial \tilde{x}}{\partial c_1} < 0$ hold. If $\tilde{x} > x^m > 0$, then

$$\frac{\partial L_1}{\partial q_1} = \int_0^{x^m} \frac{\partial\left(\frac{(1-q_1 z)r_1^m(z)\left(R-r_1^m(z)\right)}{c_1}\right)}{\partial q_1}dz + \underbrace{\frac{(1-q_2(1-\tilde{x}))\, R^2}{4c_2}\frac{\partial \tilde{x}}{\partial q_1}}_{<0} \tag{A.3}$$

because $r_1^m(x^m) = r_1^{\text{comp}}(x^m)$. According to Equation (A.2), $r_1^m(z)$ is increasing in q_1 for $z > 0$; an increase in $q_1 z$ will make $h\left(r_1^m(z)\right)$ positive, so $r_1^m(z)$ must increase to keep $h\left(r_1^m(z)\right) = 0$ holding. Hence the first term of Equation (A.3) is negative. Therefore $\frac{\partial L_1}{\partial q_1} < 0$ must hold. In the same way, we can show that $\frac{\partial L_1}{\partial c_1} < 0$ holds.

Next we look at $\left.\frac{\partial^2 L_i}{\partial c_i \partial q}\right|_{q_i=q}$. We need only look at L_1 since the two banks are symmetric. When there is effective bank competition at all locations, it can be shown that

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

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

Proof of Proposition 4. When $q_i = q$ and $c_i = c$, we must have $L_1 = L_2$ and $\tilde{x} = 1/2$, so we need only calculate $\frac{\partial L_1}{\partial q}$ and $\frac{\partial L_1}{\partial c}$. If bank 1 has monopoly power in the region $[0, x^m] \subset [0, \tilde{x}]$, then

$$L_1|_{q_i=q, c_i=c} = \int_0^{x^m} \frac{(1-qz)\, r_1^m(z)\left(R - r_1^m(z)\right)}{c} dz + \int_{x^m}^{1/2} \frac{\left(1-q(1-z)\right)R^2}{4c} dz.$$

If $x^m = 0$, then obviously $\frac{\partial L_1}{\partial q} < 0$ and $\frac{\partial L_1}{\partial c_1} < 0$ hold because $\frac{(1-q(1-z))R^2}{4c}$ is decreasing in q and c. If $\tilde{x} > x^m > 0$, then

$$\frac{\partial L_1}{\partial c} = \int_0^{x^m} \frac{\partial\left(\frac{(1-qz)r_1^m(z)\left(R-r_1^m(z)\right)}{c}\right)}{\partial c} dz + \underbrace{\int_{x^m}^{1/2} \frac{\partial\left(\frac{(1-q(1-z))R^2}{4c}\right)}{\partial c} dz}_{<0} \tag{A.4}$$

because $r_1^m(x^m) = r_1^{\text{comp}}(x^m)$. According to Equation (A.2), $r_1^m(z)$ is increasing in c; an increase in c will make $h\left(r_1^m(z)\right)$ positive, so $r_1^m(z)$ must increase to keep $h\left(r_1^m(z)\right) = 0$ holding. Hence the first term of Equation (A.4) is negative. Therefore $\frac{\partial L_1}{\partial c} < 0$ must hold. In the same way, we can show that $\frac{\partial L_1}{\partial q} < 0$ holds.

Proof of Proposition 5. 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 $\Pi_1\left(0, 0, \underline{c}, \underline{c}\right) > 0$. 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

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

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 Lemma 3. Here we provide a sketch for the proof. See Online Appendix E for a detailed proof of Lemma 3.

In a symmetric equilibrium, the first order conditions of bank 1 w.r.t q_1 and c_1 are

respectively given by:

$$\left.\frac{\partial \Pi_1}{\partial q_1}\right|_{q_i=q,c_i=c}=0 \text{ and } \left.\frac{\partial \Pi_1}{\partial c_1}\right|_{q_i=q,c_i=c}=0. \tag{A.5}$$

Since $\partial T(q,c)/\partial q=0$ when $q\geq\overline{q}$ and $\lim_{q\to 0}-q\partial T(q,c)/\partial q$ is large enough, there must exist a $q^*(c)\in(0,\overline{q})$ that solves $\left.\frac{\partial \Pi_1}{\partial q_1}\right|_{q_i=q,c_i=c}=0$ for any $c\in[\underline{c},\overline{c}]$. The assumption that $-q\frac{\partial^2 T(q,c)/\partial q^2}{\partial T(q,c)/\partial q}$ is large enough for $q<\overline{q}$ ensures that such $q^*(c)$ is unique. Meanwhile, since $\frac{\partial T(q,c)}{\partial c}=0$ for $c\geq\overline{c}$ and $-c\partial T(q,c)/\partial c$ is large enough when $c=\underline{c}$, there must exist a $c^*\in(\underline{c},\overline{c})$ that solves $\left.\frac{\partial \Pi_1}{\partial c_1}\right|_{q_i=q^*(c),c_i=c}=0$. The assumption that $-c\frac{\partial^2 T(q,c)/\partial c^2}{\partial T(q,c)/\partial c}$ is large enough for $c<\overline{c}$ ensures that such c^* is unique. Therefore, the unique solution to (A.5) 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):

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

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

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

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

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

The equation $L_q\left(q,c\right)=-\beta_q Q'\left(q\right)$ implies that q is an implicit function of c and β_q, and we denote the implicit function as $q\left(c,\beta_q\right)$. For a given c, we have $\partial q\left(c,\beta_q\right)/\partial\beta_q>0$ in the unique symmetric equilibrium (See Inequality (E.4) in Online Appendix E for more details). Hence $L_c\left(q\left(c,\beta_q\right),c\right)$ is decreasing in β_q for a given c. If β_q increases to some $\widehat{\beta}_q>\beta_q$ while c does not change, then we must have $L_c\left(q\left(c,\widehat{\beta}_q\right),c\right)<-\beta_c H'\left(c\right)$ because $\beta_c H'\left(c\right)$ is not affected by β_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 $c\in[\underline{c},\overline{c})$, to regain the symmetric equilibrium c must increases to $\widehat{c}>c$ such that $L_c\left(q\left(\widehat{c},\widehat{\beta}_q\right),\widehat{c}\right)=-\beta_c H'\left(\widehat{c}\right)$. Note that $\partial q\left(c,\beta_q\right)/\partial c>0$ holds because $L_q\left(q,c\right)$ is decreasing in c. Hence we must have $q\left(\widehat{c},\widehat{\beta}_q\right)>q\left(c,\beta_q\right)$ because $\widehat{c}>c$ and $\widehat{\beta}_q>\beta_q$. Overall, if β_q increases to some $\widehat{\beta}_q>\beta_q$, then c and $q=q\left(c,\beta_q\right)$ will respectively increase to $\widehat{c}$ and $q\left(\widehat{c},\widehat{\beta}_q\right)$, 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. If an entrepreneur at location $z\in[0,1/2]$ is served by bank 2 with loan rate $r_2\left(z\right)$ and monitoring intensity $\frac{r_2(z)(1-q(1-z))}{c}$, then the entrepreneur can derive expected utility $\frac{r_2(z)(R-r_2(z))(1-q(1-z))}{c}-\underline{u}$, while the bank's expected profit is $\frac{(r_2(z))^2(1-q(1-z))}{2c}-f$. If bank 1 serves the same entrepreneur with loan rate $r_2\left(z\right)$, then the entrepreneur's utility and the bank profit from serving her will both (weakly) increase because $z\in[0,1/2]$. Therefore, the social planner will let bank 1 (resp. bank 2) serve the region $[0,1/2]$ (resp. $(1/2,1]$) if banks are willing to serve all locations.

If bank i serves an entrepreneur at z, then the total surplus generated (the entrepreneur's utility plus the bank's profit) is

$$\frac{r_i\left(z\right)\left(R-r_i\left(z\right)\right)\left(1-qs_i\right)}{c}-\underline{u}+\frac{\left(r_i\left(z\right)\right)^2\left(1-qs_i\right)}{2c}-f,$$

which is maximized when $r_i\left(z\right)=R$; the resulting maximum surplus is $\frac{(R)^2(1-qs_i)}{2c}-\underline{u}-f$. If neither bank is willing to serve location z, then it means $\frac{(R)^2(1-qs_i)}{2c}-f<0$ (bank profit from serving an entrepreneur at z with loan rate R) holds for $i=1,2$; in this case, the social planner will not let either bank to serve location z because $\frac{(R)^2(1-qs_i)}{2c}-\underline{u}-f$ must be negative for any $\underline{u}\geq 0$.

The second-best socially optimal loan rate of bank i maximizes W under the constraint

$m_i(z) = \frac{(1-qs_i)r_i^{\mathrm{SB}}(z)}{c}$. If $K = 0$, then the first order condition satisfied by $r_i^{\mathrm{SB}}(z)$ is

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

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 $h^{\mathrm{SB}}(-\infty) \to -\infty$, $h^{\mathrm{SB}}\left(\frac{R}{2}\right) > 0$ and $h^{\mathrm{SB}}(+\infty) \to -\infty$; 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 $\frac{R\left(2R-6r_i^{\mathrm{SB}}(z)\right)(1-qs_i)}{2c} + 2f < 0$, is satisfied by the larger solution of the FOC:

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

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

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

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

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 $h^{\mathrm{SB}}(R) = 0$, so $r_i^m(z) = r_i^{\mathrm{SB}}(z) = R$ 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, $r_i^{\mathrm{comp}}(z) = \frac{R}{2}$ if $R \geq 2\sqrt{2cf}$ and $r_i^{\mathrm{comp}}(z) = \sqrt{2cf}$ 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 $r_i^{\mathrm{comp}}(z) = \frac{R}{2} < r_i^{\mathrm{SB}}(z)$ because $h^{\mathrm{SB}}\left(\frac{R}{2}\right) > 0$. 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

$$h^{\mathrm{SB}}\left(r_i^{\mathrm{comp}}(z)\right) = \frac{2\sqrt{2cf}\left(R - \sqrt{2cf}\right)^2}{2c},$$

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. If an entrepreneur at location $z \in [0, 1/2]$ is served by bank 2 with loan rate $r_2(z)$ and monitoring intensity $m_2(z)$, then the entrepreneur can derive expected utility $(R - r_2(z))\, m_2(z) - \underline{u}$, while the bank's expected profit is $r_2(z)\, m_2(z) - f - \frac{c(m_2(z))^2}{2(1-q(1-z))}$. If bank 1 serves the same entrepreneur with loan rate $r_2(z)$ and monitoring intensity $m_2(z)$, then the entrepreneur's utility stays the same, but the bank profit from serving her will (weakly) increase because the monitoring cost will be (weakly) lower. Therefore, the social planner will let bank 1 (resp. bank 2) serve the region $[0, 1/2]$ (resp. $(1/2, 1]$) if banks are willing to serve all locations.

If bank i serves an entrepreneur at z (with loan rate $r_i(z)$ and monitoring intensity $m_i(z)$), then the total surplus generated (the entrepreneur's utility plus the bank's profit) is

$$Rm_i(z) - \underline{u} - f - \frac{c(m_i(z))^2}{2(1 - qs_i)},$$

which is maximized when $m_i(z) = \frac{R(1-qs_i)}{c}$; the resulting maximum surplus is $\frac{R^2(1-qs_i)}{2c} - \underline{u} - f$. If neither bank is willing to serve location z in equilibrium, then it means $\frac{(R)^2(1-qs_i)}{2c} - f < 0$ (bank profit from serving an entrepreneur at z with loan rate R) holds for $i = 1, 2$; in this case, the social planner will not let either bank to serve location z because $\frac{(R)^2(1-qs_i)}{2c} - \underline{u} - f$ must be negative for any $\underline{u} \geq 0$.

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

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

which is positive unless $R = \sqrt{\frac{2cf}{1-qs_i}}$. As a consequence, $r_i^{\mathrm{FB}}(z) < r_i^{\mathrm{SB}}(z)$ 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 $h^{\mathrm{SB}}\left(r_i^{\mathrm{FB}}(z)\right) = 0$, so $r_i^{\mathrm{FB}}(z) = r_i^{\mathrm{SB}}(z) = r_i^m(z) = R$.

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, $r_i^{\mathrm{comp}}(z) = \frac{R}{2}$ if $R \geq 2\sqrt{2cf}$ and $r_i^{\mathrm{comp}}(z) = \sqrt{2cf}$ if $\sqrt{2cf} < R < 2\sqrt{2cf}$. In the case $R \geq 2\sqrt{2cf}$, it is easy to see $r_i^{\mathrm{comp}}(z) = \frac{R}{2} < r_i^{\mathrm{FB}}(z)$ because $r_i^{\mathrm{FB}}(z) = \frac{R}{2} + \frac{cf}{R}$. 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

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

Therefore, $r_i^{\mathrm{comp}}(z) < r_i^{\mathrm{FB}}(z)$ 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

$$\frac{\partial W}{\partial c} = \begin{pmatrix} 2\int_0^{x^m} \frac{\partial\left(\left(\frac{1}{2}(D(z))^2 + D(z)\left(\frac{(r_1^m(z))^2(1-qz)}{2c} - f\right)\right)\right)}{\partial c} dz \\ +2\int_{x^m}^{1/2} \frac{\partial\left(\left(\frac{1}{2}(D(z))^2 + D(z)\left(\frac{(r_1^{com}(z))^2(1-qz)}{2c} - f\right)\right)\right)}{\partial c} dz \end{pmatrix}. \tag{A.6}$$

For $z \in [0, x^m]$, $D(z) = \frac{r_1^m(z)(1-qz)}{c}\left(R - r_1^m(z)\right)$ is decreasing in c because $r_1^m(z)$ is increasing in c (Proposition 18); 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 nega-

tive. For $z \in (x^m, 1/2]$, $D(z) = \frac{(1-q(1-z))R^2}{4c}$ is obviously decreasing in c; meanwhile, $D(z)\left(\frac{(r_1^{com}(z))^2(1-qz)}{2c} - f\right)$ 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 $q \to 0$. For $z < 1/2$, we have $\lim_{q\to 0}\frac{R^4\sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} \to +\infty$. For $z = 1/2$, we have $\frac{R^4\sqrt{\frac{q(1-2z)}{1-qz}}}{32c^2q} = 0$. Therefore, $\lim_{q\to 0}\frac{\partial W}{\partial q} \to +\infty$ must hold. As a consequence, social welfare is increasing in q if q is sufficiently small.

Proof of Proposition 12. Since $q^* \in (0, \overline{q})$, obviously q^* is excessively low if $\overline{q}$ is sufficiently close to zero (Proposition 11). When banks endogenously choose their IT, bank i's marginal benefit of decreasing c_i at the symmetric equilibrium is $L_c(q^*, c^*)$ (see the proof of Proposition 6). c^* is determined by

$$L_c(q^*, c^*) = -\left.\frac{\partial T(q^*, c)}{\partial c}\right|_{c=c^*}.$$

From the perspective of the social planner, the marginal benefit of decreasing c is $-\frac{\partial W}{\partial c}$ (see Equation A.6 in the proof of Proposition 11). Let q^o denote the social planner's choice of q, then the social planner's choice about c (denoted by c^o) is determined by

$$-\left.\frac{\partial W}{\partial c}\right|_{q=q^o, c=c^o} = -\left.\frac{\partial T(q^o, c)}{\partial c}\right|_{c=c^o}.$$

Note that $\left.\frac{\partial W}{\partial c}\right|_{q=q^o}$ is finite for any $q^o \geq 0$ and $c \geq \underline{c} > R$. However, it is clear that $\lim_{q^*\to 0} L_c(q^*, c^*) = +\infty$. When $\overline{q}$ is sufficiently small, both $L_c(q^*, c^*) > \left.\frac{\partial W}{\partial c}\right|_{q=q^o}$ and $q^* < q^o$ will hold; in this case, the following inequality must hold

$$\left.\frac{\partial T(q^*, c)}{\partial c}\right|_{c=c^*} < \left.\frac{\partial T(q^o, c)}{\partial c}\right|_{c=c^o} < 0,$$

which implies $c^* < c^o$ if $\frac{\partial^2 T(q,c)}{\partial q \partial c} \leq 0$ (i.e., if $T(q,c)$ is submodular).

Appendix B: Insufficiently large R

In this part we consider bank competition under a general R that need not be large (i.e., $R \geq \sqrt{8c_i f/(1-q_i)}$ 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:

$$\pi_1(z) = \frac{(r_1(z))^2 (1-q_1 z)}{2c_1} - f$$

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:

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

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

$$r_i^b(z) = \max\left\{\frac{R}{2}, \overline{r}_i(z)\right\}. \tag{B.1}$$

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:

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

which yields

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

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

$$r_2^{\text{comp}}(z) = \frac{R}{2} + \frac{1}{2}\sqrt{R^2 - 4\frac{c_2}{c_1}\frac{1-q_1 z}{1-q_2(1-z)}\left(R - r_1^b(z)\right)r_1^b(z)}. \tag{B.3}$$

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:

$$\left(R - r_1^b(\tilde{x})\right)\frac{r_1^b(\tilde{x})(1-q_1\tilde{x})}{c_1} - \underline{u} = \left(R - r_2^b(\tilde{x})\right)\frac{r_2^b(\tilde{x})(1-q_2(1-\tilde{x}))}{c_2} - \underline{u}. \tag{B.4}$$

Equation (B.4) 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 (B.4) is weakly decreasing in $\tilde{x}$, and the right hand side is weakly increasing in $\tilde{x}$. If $q_i > 0$ for some i, then whenever there exists a solution $\tilde{x} \in [0,1]$ that solves equation (B.4), such a solution must be unique (If $q_1 = q_2 = 0$ and $c_1 = c_2$ hold, then we let $\tilde{x} = 1/2$).

It is possible that Equation (B.4) 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 13. *Assume that there exists an $\tilde{x} \in (0,1)$ solving Equation (B.4). 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:*

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

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

where r_i^{comp} is defined by Equations (B.2) and (B.3).

We need only focus on bank 1 because the two banks are symmetric. Note that if $r_2^b(z) = R/2$, 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 $r_2^b(z) = \overline{r}_2(z)$, which implies

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

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

Corollary 5. *If $r_2^b(z) = \overline{r}_2(z)$ and if $q_i > 0$ for some i, 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 $R/2$.

Corollary 6. *Let $q_2 > 0$ and $r_2^b(z) = \overline{r}_2(z)$ hold. With effective bank competition at z (i.e., if $r_1^{\text{comp}}(z) < r_1^m(z)$), the funding demand of entrepreneurs at z is increasing in z when $z \in [0, \tilde{x}]$.*

The intuition underlying Corollary 2 directly applies here.

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

Corollary 7. *Let $z \in (0, \tilde{x})$ and $r_2^b(z) = \overline{r}_2(z)$ hold. With effective bank competition at z (i.e., $r_1^{\text{comp}}(z) < r_1^m(z)$), 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 8. *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 $r_2^b(z) = \overline{r}_2(z)$, then bank 1's equilibrium loan rate $r_1^{\text{comp}}(z)$ is increasing in c and q at $z \in \left[0, \frac{1}{2}\right]$. A symmetric result holds for bank 2.*

Different from Corollary 4, if $r_2^b(z) = \overline{r}_2(z)$ (i.e., if R is not large enough to make $R/2$ 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 $\overline{r}_2(z)$, rather than $\frac{R}{2}$. If c increases, then $\overline{r}_2(z)$ 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 $z \in (1/2, 1]$.

Proposition 14. *Let $c_1 = c_2 = c$ and $q_1 = q_2 = q$. If $r_i^b(z) = \overline{r}_i(z)$ holds for $i = \{1, 2\}$, then bank i's aggregate lending profit from all locations is increasing in q if q is sufficiently small; a numerical study finds that bank i's aggregate lending profit is decreasing in c.*

This result confirms the robustness of Proposition 2. As parameter q approaches 0, bank differentiation will disappear, which will dominate cost-saving effect and thereby reduce bank profit. Decreasing c will intensify bank competition by decreasing the value of $\overline{r}_i(z)$, but this effect is dominated by cost-saving effect according to the numerical study.

Proposition 15. *Let $r_i^b(z) = \overline{r}_i(z)$ holds for $i = \{1, 2\}$. Bank i's aggregate loan volume L_i is decreasing in q_i and c_i. If $q_1 = q_2 = q$ and if there is effective bank competition at all locations (i.e., if $r_i^{\text{comp}}(z) < r_i^m(z)$ holds for all $z \in [0, 1]$), then 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 intuition of Proposition 3 directly applies here.

Proposition 16. *Let $c_1 = c_2 = c$ and $q_1 = q_2 = q$. If $r_i^b(z) = \overline{r}_i(z)$ holds for $i = \{1, 2\}$, then the total mass of entrepreneurs undertaking investment projects (i.e., $L_1 + L_2$) is decreasing in q and c.*

This result means Proposition 4 is robust for the case without large R. The intuition is that both a higher competition intensity and a better monitoring efficiency are beneficial for entrepreneurs.

Appendix C: 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 $R \geq \sqrt{8c_i f/(1-q_i)}$ for $i = \{1,2\}$); 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 $R \geq \sqrt{8c_i f/(1-q_i)}$ ($i = \{1,2\}$) 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

$$(R - r_1(z))\frac{r_1(z)(1-q_1 z)}{c_1},$$

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 $r_1(z) \in [0, R]$.[37]

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:

$$z > \frac{R^2 - 2c_1 f}{q_1 R^2}. \tag{C.1}$$

Inequality (C.1) implies that bank 1 is willing to serve entrepreneurs in $\left[0, \frac{R^2-2c_1 f}{q_1 R^2}\right]$ if $\frac{R^2-2c_1 f}{q_1 R^2} \geq 0$. By symmetric reasoning, bank 2 is willing to serve entrepreneurs in $\left[1 - \frac{R^2-2c_2 f}{q_2 R^2}, 1\right]$ if $1 - \frac{R^2-2c_2 f}{q_2 R^2} \leq 1$. 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

$$\frac{R^2 - 2c_1 f}{q_1 R^2} + \frac{R^2 - 2c_2 f}{q_2 R^2} < 1. \tag{C.2}$$

[37] When $r_1(z) = R$, an entrepreneur with $\underline{u} = 0$ 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 17. *Let* $\frac{R^2-2c_if}{q_iR^2} \geq 0$, $i = 1, 2$, *and* $\frac{R^2-2c_1f}{q_1R^2} + \frac{R^2-2c_2f}{q_2R^2} < 1$. *Then there exists a local monopoly equilibrium where bank i's loan rate at z equals* $r_i^m(z)$. *Bank 1 serves entrepreneurs in* $\left[0, \frac{R^2-2c_1f}{q_1R^2}\right]$ *while bank 2 serves entrepreneurs in* $\left[1 - \frac{R^2-2c_2f}{q_2R^2}, 1\right]$.

According to Proposition 17, a local monopoly equilibrium will arise when R is not large yet q_i and c_i are sufficiently large.

Corollary 9 shows how $r_1^m(z)$ varies with entrepreneurial location z; a symmetric result holds for $r_2^m(z)$.

Note that $q_i > 0, i = \{1, 2\}$ must hold in such an equilibrium; otherwise Condition (C.2) will be violated. Therefore we have the following corollary.

Corollary 9. *In the local monopoly equilibrium (which ensures* $q_i > 0$*), bank 1's equilibrium loan rate* $r_1^m(z)$ *is increasing in z when* $z \in \left[0, \frac{R^2-2c_1f}{q_1R^2}\right]$. *At the location* $z = \frac{R^2-2c_1f}{q_1R^2}$, *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 local monopoly equilibrium. The following proposition shows how information technology affects loan rates in the local monopoly equilibrium.

Proposition 18. *In the local monopoly equilibrium, bank 1's equilibrium loan rate* $r_1^m(z)$ *is increasing in* c_1 *and* q_1 *when* $z \in \left(0, \frac{R^2-2c_1f}{q_1R^2}\right)$.

In the local monopoly equilibrium information technology progress (i.e., reducing c_1 or q_1) simply makes monitoring cheaper for bank 1 (except for the special location $z = 0$ where reducing q_1 has no effect on bank 1's monitoring efficiency), which increases

bank 1's profit per unit of loans and hence induces the bank to be more concerned about total funding demand. As a result, bank 1 decreases its loan rates in order to increase the funding demand and maximize its monopoly profit.

The following corollary shows how information technology affects the market area a bank can serve.

Corollary 10. *In the local monopoly equilibrium, the market area served by bank 1 (i.e.,* $[0, \frac{R^2-2c_1 f}{q_1 R^2}]$*) will shrink as* q_1 *or/and* c_1 *increases.*

The local monopoly equilibrium arises only when both banks find it too costly to serve sufficiently distant entrepreneurs. As bank 1's IT improves (i.e., q_1 or/and c_1 decreases), the bank will reach farther locations because monitoring becomes less costly. Corollary 10 implies that in the local monopoly equilibrium IT progress of banks will improve financial inclusion by enabling banks to cover more locations.

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 19 gives a relevant result.

Proposition 19. *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 19 means that the market area effect exactly offsets the cost effect.[38]

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,[39] 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.

[38]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. .

[39]In contrast, q_1 does not significantly affect bank 1's monitoring costs for given monitoring intensity when z is close to zero.

Welfare analysis of the local monopoly equilibrium. In Proposition 7, we have shown that $R/2 < r_i^{\mathrm{SB}}(z) \leq r_i^m(z)$ holds. According to Proposition 17, bank i's equilibrium loan rate in the local monopoly equilibrium exactly equals $r_i^m(z)$, so we have the following corollary.

Corollary 11. *Let $K = 0$. Then, in a local monopoly equilibrium where bank 1 serves the region $\left[0, \frac{R^2-2cf}{qR^2}\right]$, bank 1's equilibrium loan rate is higher than $r_1^{\mathrm{SB}}(z)$ when $z \in \left[0, \frac{R^2-2cf}{qR^2}\right)$ – provided that $\frac{R^2-2cf}{qR^2} > 0$ – and is equal to $r_1^{\mathrm{SB}}(z)$ $(= R)$ at $z = \frac{R^2-2cf}{qR^2}$. A symmetric result holds for bank 2.*

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 20. *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 C.1). 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 C.1.

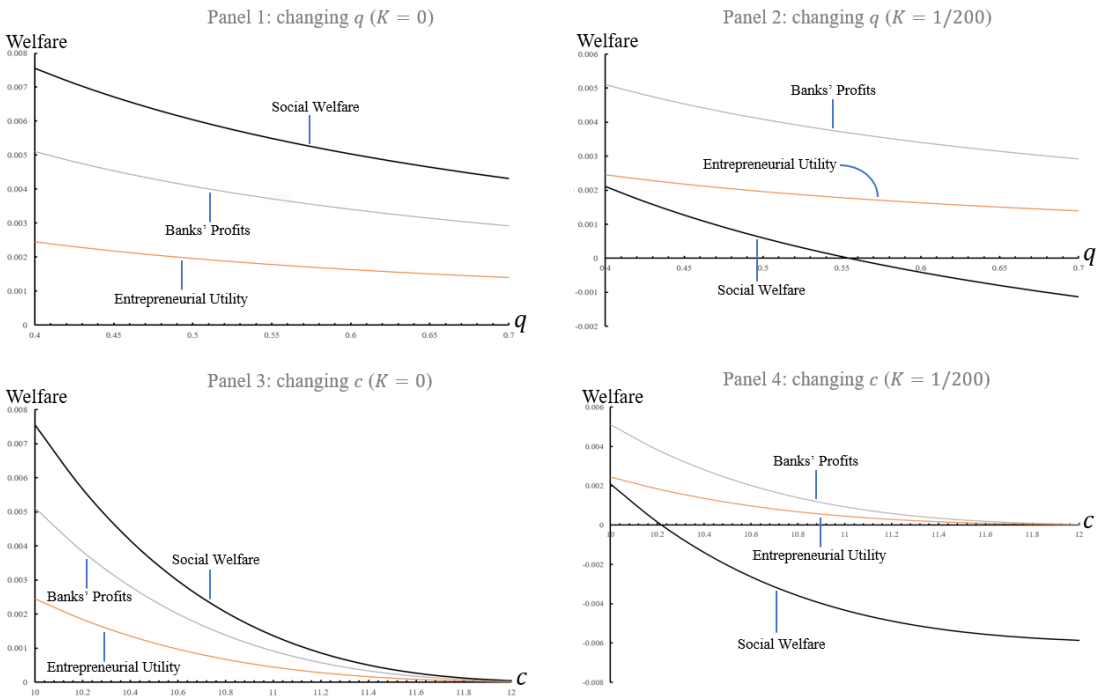

Figure C.1: Social Welfare and Banking Sector's Information Technology under Local Monopoly. This figure plots social welfare, entrepreneurial utility, and banks' profits against c and q in the local monopoly equilibrium. The parameter values are: $R = 5$ and $f = 1$ in all panels; $c = 10$ in Panels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

Online Appendix

Appendix D: Supplementary results for Section 4

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

About Proposition 5. 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. [40] *If bank competition is effective at all locations and if $c_1 = c_2$, then for $q_2 > 0$ we have:*

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

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

The restriction $c_1 = c_2$ ensures $0 < \tilde{x} < 1$ no matter how q_1 and q_2 vary.[41] Numerical Result 4 states that if there is no gap between the two banks' basic monitoring efficiency (i.e., if $c_1 = c_2$) and if $q_1 \to 0$, 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 $q_1 \to 0$.[42] 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 5 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

[40] 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 $1.3R$.

[41] 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. $c_1 > c_2$).

[42] We can show that $\lim_{q_1 \to 0} \partial^2 \tilde{x} / (\partial q_1 \partial q_2) > 0$, $\lim_{q_1 \to 0} \partial^2 \tilde{x} / (\partial c_1 \partial q_2) > 0$, $\lim_{q_2 \to 0} \left(\lim_{q_1 \to 0} \partial^2 \tilde{x} / (\partial q_1 \partial q_2) \right) \to +\infty$ and $\lim_{q_2 \to 0} \left(\lim_{q_1 \to 0} \partial^2 \tilde{x} / (\partial c_1 \partial q_2) \right) \to +\infty$ 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 $q_1 \to 0$. Those are not contradictory results. The complementarity displayed in Numerical Result 4 highly relies on the condition $q_1 \to 0$; therefore, it is useful only when describing bank 1's marginal benefit of IT investment in boundary case $q_1 = 0$. Proposition 5 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 D.1 reconciles Numerical Result 4 with Numerical Result 3. Panel 6 of Figure D.1 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.

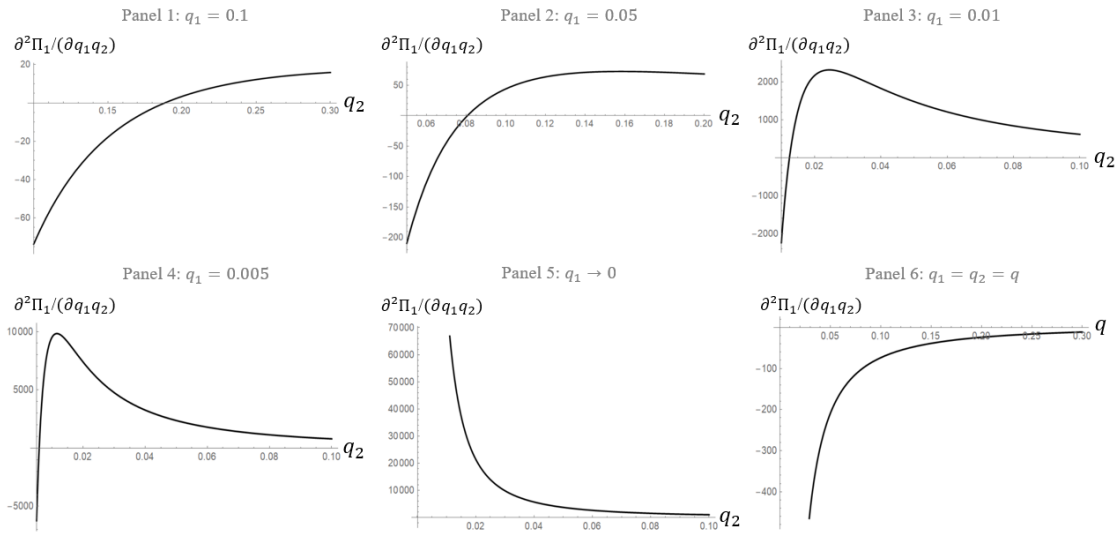

Figure D.1: The Effects of q_2 on Bank 1's Marginal Benefit of reducing q_1. This figure shows how the sign of $\partial^2\Pi_1/(\partial q_1 \partial q_2)$ varies with parameters when bank competition is effective at all locations and $0 < \tilde{x} < 1$. The parameter values are $R = 20$, $f = 1$,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

Appendix E: Detailed proof of Lemma 3

In this appendix, we provide a detailed proof for Lemma 3. The first order conditions of bank 1 wrt q_1 and c_1 are respectively:

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

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

$$\underbrace{\left.\frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1}\right|_{q_i=q,c_i=c} - \frac{\partial T\left(q,c\right)}{\partial q}}_{=\left.\frac{\partial \Pi_1(q_1,q_2,c_1,c_2)}{\partial q_1}\right|_{q_i=q,c_i=c}} = 0; \underbrace{\left.\frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial c_1}\right|_{q_i=q,c_i=c} - \frac{\partial T\left(q,c\right)}{\partial c}}_{=\left.\frac{\partial \Pi_1(q_1,q_2,c_1,c_2)}{\partial c_1}\right|_{q_i=q,c_i=c}} = 0 \tag{E.1}$$

where

$$\left.\frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1}\right|_{q_i=q,c_i=c} = \left(\begin{array}{c} \int_0^{\frac{1}{2}} -\frac{R^4(1-q(1-z))z\left((1-qz)\left(1+2\sqrt{\frac{q(1-2z)}{1-qz}}\right)+q(1-2z)\right)}{32c^2\sqrt{\frac{q(1-2z)}{1-qz}}(1-qz)}dz \\ +\frac{(2-q)R^2\left((2-q)R^2-16cf\right)}{128c^2}\left(-\frac{1}{4q}\right) \end{array}\right);$$

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

We prove the lemma with two steps: first, we show that the system of equations (E.1) has a unique solution; second, we prove that the solution is indeed an equilibrium.

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

$$-\left.\frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1}\right|_{q_i=q,c_i=c} = -\frac{\partial T\left(q,c\right)}{\partial q} \tag{E.2}$$

for a given $c \in [\underline{c}, \overline{c}]$. The left hand side (LHS) of Equation (E.2) 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 (E.2) are positive.

Equation (E.2) is equivalent to

$$-q\frac{\partial\int_0^{\tilde{x}}D(z)\pi_1(z)dz}{\partial q_1}\bigg|_{q_i=q,c_i=c}=-q\frac{\partial T(q,c)}{\partial q} \tag{E.3}$$

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

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

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

for all $c\in[\underline{c},\overline{c}]$. Since $\partial T(q,c)/\partial q=0$ when $q\geq\overline{q}$ and $\lim_{q\to 0}-q\partial T(q,c)/\partial q$ is large enough, there must exist a $q\in(0,\overline{q})$ that solves Equation (E.3) for any $c\in[\underline{c},\overline{c}]$. We denote the largest solution as $q(c)$ and let $q_{\max}\equiv\max_{c\in[\underline{c},\overline{c}]}q(c)$. The assumption $\lim_{q\to 0}-q\partial T(q,c)/\partial q$ is large ensures that $q_{\max}$ must belong to the open interval $(0,\overline{q})$.

Next we need to show that $q(c)$ is the unique solution to Equation (E.3) when $-q\frac{\partial^2T(q,c)/\partial q^2}{\partial T(q,c)/\partial q}$ is large enough for $q<\overline{q}$. Note that $q(c)$ must be the unique solution if $-q\partial T(q,c)/\partial q$ increases faster than $-q\partial\int_0^{\tilde{x}}D(z)\pi_1(z)dz/\partial q_1\Big|_{q_i=q,c_i=c}$ as q decreases in the interval $(0,q(c)]$, which means:

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

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

$$-1-q\frac{\partial^2T(q,c)/\partial q^2}{\partial T(q,c)/\partial q}>\frac{\partial\left(q\frac{\partial\int_0^{\tilde{x}}D(z)\pi_1(z)dz}{\partial q_1}\Big|_{q_i=q,c_i=c}\right)/\partial q}{-\partial T(q,c)/\partial q} \tag{E.4}$$

for $q\in(0,q(c)]$. The assumption that $-q\frac{\partial^2T(q,c)/\partial q^2}{\partial T(q,c)/\partial q}$ is large enough for $q<\overline{q}$ means the LHS of Inequality (E.4) is large enough for $q\in(0,q(c)]$. This means Inequality (E.4) will hold if the RHS of (E.4) is smaller than $+\infty$ for $q\in(0,q(c)]$. Since $-\partial T(q,c)/\partial q>0$

must hold for $q \leq q_{\max} < \overline{q}$, we need only show that

$$\partial \left(q \frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1} \bigg|_{q_i=q, c_i=c} \right) / \partial q < +\infty \tag{E.5}$$

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

$$q \frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1} \bigg|_{q_i=q, c_i=c}$$

$$= \left(\begin{array}{c} \underbrace{-\int_0^{\frac{1}{2}} q \frac{R^4 (1-q(1-z)) z \left((1-qz) \left(1 + 2\sqrt{\frac{q(1-2z)}{1-qz}} \right) + q(1-2z) \right)}{32c^2 \sqrt{\frac{q(1-2z)}{1-qz}} (1-qz)} dz}_{\text{denoted by } RHS_1^q} \\ \underbrace{-\frac{1}{4} \frac{(2-q) R^2 ((2-q) R^2 - 16cf)}{128c^2}}_{\text{denoted by } RHS_2^q} \end{array} \right).$$

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

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

we must have $\lim_{q \to 0} \frac{\partial RHS_1^q}{\partial q} < 0 < +\infty$. Therefore, Inequality (E.5) indeed holds. As a consequence, $q(c)$ is the unique solution to Equation (E.3) when $-q \frac{\partial^2 T(q,c)/\partial q^2}{\partial T(q,c)/\partial q}$ is large enough for $q < \overline{q}$. Meanwhile, by implicit function theorem and Inequality (E.4), we can show that $\max_{c \in [\underline{c}, \overline{c}]} \partial q(c) / \partial c$ is finite.

To show that the system of equations (E.1) has a solution, next we need to show that there exists a unique $c \in (\underline{c}, \overline{c})$ that solves

$$-c \frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial c_1} \bigg|_{q_i=q(c), c_i=c} = -c \frac{\partial T(q,c)}{\partial c} \bigg|_{q=q(c)} \tag{E.6}$$

given that q is equal to $q(c)$. The LHS of Equation (E.6) must be positive and finite on the close interval $[\underline{c}, \overline{c}]$. Since $\frac{\partial T(q,c)}{\partial c} = 0$ for $c \geq \overline{c}$ and $-c \partial T(q,c) / \partial c$ is large enough when $c = \underline{c}$, there must at least exist a $c \in (\underline{c}, \overline{c})$ that solves Equation (E.6). We denote the largest solution to (E.6) as $c^* \in (\underline{c}, \overline{c})$. 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:

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

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

$$-1-c\frac{\partial^2 T\left(q\left(c\right),c\right)/\partial c^2}{\partial T\left(q\left(c\right),c\right)/\partial c}-c\frac{\frac{\partial^2 T(q(c),c)}{\partial q\partial c}\frac{\partial q(c)}{\partial c}}{\partial T\left(q\left(c\right),c\right)/\partial c}>\frac{\partial\left(c\frac{\partial\int_0^{\tilde{x}}D(z)\pi_1(z)dz}{\partial c_1}\Big|_{q_i=q(c),c_i=c}\right)/\partial c}{-\partial T\left(q\left(c\right),c\right)/\partial c} \quad \text{(E.7)}$$

Since $\max_{c\in[\underline{c},\overline{c}]}\partial q\left(c\right)/\partial c$ 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 $c\in[\underline{c},\overline{c}]$ because it is a continuous function of c on the close interval $[\underline{c},\overline{c}]$. Meanwhile, the assumption that $-c\frac{\partial^2 T(q,c)/\partial c^2}{\partial T(q,c)/\partial c}$ is large enough for $c\in[\underline{c},\overline{c}]$ ensures that the LHS of Inequality (E.7) is large enough for $\underline{c}\leq c\leq c^*$; this means Inequality (E.7) indeed holds if $-c\frac{\partial^2 T(q,c)/\partial c^2}{\partial T(q,c)/\partial c}$ is large enough for $c\in[\underline{c},\overline{c}]$. Therefore, c^* is the unique solution to Equation (E.6). Overall, there exists a unique solution $\{c^*, q^*\equiv q\left(c^*\right)\}\in(\underline{c},\overline{c})\times(0,\overline{q})$ that solves the system of equations (E.1). This means in a symmetric equilibrium we must have $q_i=q^*\in(0,\overline{q})$ and $c_i=c^*\in(\underline{c},\overline{c})$.

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

$$\underbrace{-q_1\frac{\partial\int_0^{\tilde{x}}D(z)\pi_1(z)dz}{\partial q_1}\Bigg|_{q_2=q^*,\ c_2=c^*}}_{\text{denoted by } MBq_1}=-q_1\frac{\partial T\left(q_1,c_1\right)}{\partial q_1}\ \text{and} \quad \text{(E.8)}$$

$$\underbrace{-c_1\frac{\partial\int_0^{\tilde{x}}D(z)\pi_1(z)dz}{\partial c_1}\Bigg|_{q_2=q^*,\ c_2=c^*}}_{\text{denoted by } MBc_1}=-c_1\frac{\partial T\left(q_1,c_1\right)}{\partial c_1} \quad \text{(E.9)}$$

where

$$MBq_1 = -q_1 \left(\begin{array}{l} \int_0^{\tilde{x}} \frac{R^4(1-q_2(1-z))z\left(c_1+c_1q_2(-1+z)+2c_2(-1+q_1z)\left(1+\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}}\right)\right)}{32c_1(c_2)^2(1-q_1z)\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}}}dz \\ +\frac{(q_1(-1+q_2)-q_2)R^2\left(8c_2q_1f+8c_1q_2f+(-q_1+(-1+q_1)q_2)R^2\right)}{32(c_2q_1+c_1q_2)^2}\frac{-c_2(c_2+c_1(-1+q_2))}{(c_2q_1+c_1q_2)^2} \end{array} \right);$$

$$MBc_1 = -c_1 \left(\begin{array}{l} \int_0^{\tilde{x}} \frac{R^4(1-q_2(1-z))\left(c_1+c_1q_2(-1+z)+2c_2(-1+q_1z)\left(1+\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}}\right)\right)}{32(c_1)^2(c_2)^2\sqrt{1-\frac{c_1(1-q_2(1-z))}{c_2(1-q_1z)}}}dz \\ +\frac{(q_1(-1+q_2)-q_2)R^2\left(8c_2q_1f+8c_1q_2f+(-q_1+(-1+q_1)q_2)R^2\right)}{32(c_2q_1+c_1q_2)^2}\frac{-c_2(q_2-q_1(-1+q_2))}{(c_2q_1+c_1q_2)^2} \end{array} \right).$$

For a given $c \in [\underline{c}, \overline{c}]$, we can find that $MBq_1 > 0$ and $\lim_{q_1 \to 0} MBq_1 = 0$ hold, which implies

$$-\partial MBq_1/\partial q_1 = \partial \left(q_1 \frac{\partial \int_0^{\tilde{x}} D(z)\pi_1(z)dz}{\partial q_1}\Bigg|_{q_2=q^*,\ c_2=c^*} \right) / \partial q_1 < +\infty$$

for $q_1 \in (0, \overline{q}]$. Therefore, following the way in which we show the existence and uniqueness of the solution to (E.1), we can also show that the solution to equations (E.8) and (E.9) exists and is unique if $\lim_{q \to 0} -q\partial T(q,c)/\partial q$ 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 $q \in (0, \overline{q})$ (resp. $c \in [\underline{c}, \overline{c})$); 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.