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CBDC: Banking and Anonymity *

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Abstract

What is the optimal design of anonymity in a central bank digital currency (CBDC)? We examine this question in the context of bank lending by building a stylized model of anonymity in payment instruments. We specify the anonymity of payment instruments in two dimensions: The bank has no information about the entrepreneur's investment, and the bank has less control over the entrepreneur's profits. An instrument with higher anonymity may discourage the bank from lending, and thus, the entrepreneur strategically chooses payment instruments. Our analysis shows that introducing a CBDC with modest anonymity can improve welfare in one equilibrium, but can also destroy valuable information in bank lending, leading to inefficient lending in another equilibrium. Our results suggest that central banks should either make a CBDC highly anonymous or share CBDC data with banks to eliminate this bad equilibrium.

Key words: CBDC; Anonymity; Bank lending

JEL Codes: E42, E58, G28

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1 Introduction

The possibility of issuing a central bank digital currency (CBDC) hinges on its design. Unlike cash, central banks have a wide range of options in designing public money in the form of a CBDC, which has led to active discussions on the potential benefits and costs of issuing a CBDC over a number of dimensions. One of the most heated debates is the anonymity of CBDCs. Nations are concerned that using a CBDC may allow third parties to obtain personal or proprietary information. For example, ECB (2021) reports that the secrecy of information is the largest public concern in issuing the digital Euro. While the anonymity of CBDCs attracts end-users, the issue of how anonymity affects bank lending is not a trivial one. For example, lack of information is a classic source of inefficiency in a lender-borrower relationship. If issuing a CBDC with anonymity results in worsening such inefficiency, anonymity may not be desirable for bank lending. Based on such a conflict of desires, this paper asks: What is the optimal design of CBDC anonymity?

We address this question by modeling payment methods as signaling tools in bank lending such that an entrepreneur borrows from a bank to invest in a project. The entrepreneur privately learns the quality of her project and then chooses a payment method to receive the return of the investment. Payment methods have different degrees of anonymity, and we introduce anonymity in two dimensions: First, the bank finds it harder to identify the quality of the project; second, the bank has less control over the entrepreneur's use of profits, and thus, the bank can extract less surplus. Based on the chosen method, the bank makes inferences about the quality of the project in deciding whether to terminate the loan at an intermediate time. Additionally, the bank can audit the entrepreneur at a cost, which allows it to observe the quality of the project and control all the funds. Whether the entrepreneur uses an anonymous method or not depends on her strategic incentives: The entrepreneur may compromise on anonymity in choosing a payment method if doing so increases profits or convinces the bank not to terminate the loan or not to audit the entrepreneur.

We begin our analysis with two payment methods: a debit card (bank deposit) and cash. We assume that cash is fully anonymous and that the debit card is partially anonymous. In particular, using a debit card allows the bank to observe the quality of the project and to control a larger fraction of the entrepreneur's profit than cash. Our analysis shows that there exists a unique equilibrium where a good entrepreneur uses a debit card, while a bad entrepreneur uses cash. The good entrepreneur is discouraged from using cash due to the possibility of auditing and loan termination, which incentivizes her to reveal the quality of her project by using a debit card instead. The bad entrepreneur has no incentive to reveal the type, and she prefers using cash so that her profit is less controlled by the bank.

Next, we introduce a CBDC as a third payment method. We assume that the CBDC can be more anonymous than cash but less anonymous than a debit card, and we study how different degrees of anonymity in the CBDC affect equilibrium outcomes. We first establish that introducing a CBDC can improve welfare in some cases. However, there may also exist a pooling equilibrium where both good and bad entrepreneurs use the CBDC. In this case, the bank is unable to distinguish between good and bad entrepreneurs, leading to inefficient lending to bad entrepreneurs. This bad equilibrium exists when the degree of anonymity in the CBDC is not high enough for the bank to be able to control a substantial portion of the entrepreneur's funds such that the bank is willing to continue the investment without auditing the entrepreneur.

Finally, we show that the optimal design of anonymity in the CBDC may depend on how to eliminate the bad equilibrium. One solution is to increase the degree of anonymity in the CBDC in a way that the bank has less control over the entrepreneur's funds. However, this comes at the cost of reducing the bank's profits. Another solution is to introduce a data-sharing feature such that the bank can observe the entrepreneur's type when she uses a CBDC. For example, the bank may be allowed to access the CBDC account data to identify the quality of the project. This feature allows the bank to distinguish between good and bad entrepreneurs, even when both choose the CBDC, and prevents inefficient lending to bad entrepreneurs. However, implementing such a data-sharing feature may not be feasible in practice due to potential customer controversy or financial and technical challenges. In such a case, the first solution will be necessary to eliminate the bad equilibrium, resulting in a trade-off between efficiency and the multiplicity of equilibrium.

Related literature: Our paper adds to the growing literature on the value of information in payments, which has largely focused on consumer privacy in digital transactions (see Norberg, Horne, and Horne (2007), Athey, Catalini, and Tucker (2017) for privacy paradox; Kahn, McAndrews, and Roberds (2005) and Garratt and van Oordt (2021) for privacy externality; Parlour, Rajan, and Zhu (2022) and He, Huang, and Zhou (2022) for fintech competition and information spillover; Xiao (2021) for risk-sharing; also see Acquisti, Taylor, and Wagman (2016) for a recent survey). However, unlike these aforementioned studies, Ahnert, Hoffmann, and Monnet (2022) study anonymity in the context of firms, developing a model that demonstrates that while online platforms facilitate sales for the merchant, they also lead to a loss of privacy in the form of information rent. They show that a CBDC can improve welfare by maintaining both digital services and anonymity. Like Ahnert et al. (2022), we also examine anonymity in the context of firms, but we adopt a more general definition of anonymity and focus on the strategic interaction between a firm and a bank. Specifically, we allow firms to use payment methods as signaling tools and also allow banks to monitor and audit firms.

Our study sheds new light on the role of bank lending as a key aspect in designing the anonymity of a CBDC. The literature on the value of information in payments has often defined anonymity in terms of users' ability to keep their information private. For instance, Agur, Ari, and Dell'Ariccia (2022) build a model in which introducing a more anonymous CBDC may crowd out cash, while a less anonymous CBDC may compete with deposits, thereby trading off the value of a variety of payment instruments against the size of financial intermediation. Garratt and van Oordt (2021) and Garratt and Lee (2022) examine an environment in which firms can acquire information from consumers' payments, allowing them to price discriminate. They discuss how introducing an anonymous CBDC can improve welfare by preventing firms from acquiring this information. Our paper is the first to consider the design of anonymity in the context of bank lending.

Our study contributes to the classic literature on signaling the quality of investments in credit markets by introducing a new dimension: payment methods. Previous research has suggested various methods of signaling quality, such as the amount of own funds invested (Ross (1977) and Leland and Pyle (1977)), the use of collateral (Bester (1985)), and the size of the loan (Milde and Riley (1988)). Our study expands on this literature by exploring the use of payment methods as signaling tools in bank lending, and we examine the strategic interactions between firms and banks as firms choose payment methods to signal the quality of their investments.

The remainder of the paper is organized as follows. Section 2 outlines the baseline environment. Section 3 analyzes equilibrium without a CBDC. Section 4 introduces the CBDC and highlights the trade-off between efficiency and fragility. Section 5 discusses the optimal anonymity design. Section 6 extends the main results. Section 7 concludes.

2 Model

In this section, we describe a model of payment instruments and bank lending. We consider payment instruments as signaling tools and analyze the equilibrium without and with the central bank digital currency (CBDC) in the next two sections.

2.1 The environment

There are three periods, $t \in \{0, 1, 2\}$, and two risk-neutral agents: a monopolistic bank and an entrepreneur. The entrepreneur has access to a single, constant-returns-to-scale investment technology, called *project*, that requires 1 amount of funding in $t = 0$ and k amount of funding in $t = 1$. The bank has deep pockets, but the entrepreneur has no endowment. To invest in the project, the entrepreneur needs to borrow from the bank in periods 0 and 1.

The project can be of two types: a good type (G) or a bad type (B), with an ex-ante probability of $\theta \in (0, 1)$ of being good. The project yields returns in periods 1 and 2: It yields r in period 1 for both types and yields R_g and $R_b < R_g$ in period 2 for good and bad types, respectively.[1] The expected returns in period 2 are $M \equiv \theta R_g + (1 - \theta)R_b$. The good type has a positive net present value (NPV) and the bad type has a negative NPV in period 1: $R_b < k < R_g$. The entrepreneur privately observes the type of the project after the investment is made in period 0.

The entrepreneur then chooses a payment technology to obtain investment returns. We first consider that the entrepreneur can choose from two payment methods, which we call *Debit* and *Cash*. Debit represents the digital payment technology bank provides, which im-

[1] In what follows, we use "cash flow" and "return" interchangeably to express R and r and use "type" to describe both the entrepreneur and the project.

proves profitability.[2] Specifically, we assume that Debit increases the entrepreneur's revenues by $\Delta > 0$ in each period for every type. However, Debit, which is a product of the bank, allows the bank to identify the entrepreneur's type, while the bank cannot identify the type if the entrepreneur uses Cash.

The entrepreneur may divert returns, and the degree to which this is possible depends on payment technology being used. The entrepreneur can divert the entire returns if she uses Cash, while it is only possible for her to divert a fraction, denoted as $\lambda < 1$, of the returns if she uses Debit.[3] The entrepreneur gives the bank the non-divertible part of the funds as repayments in periods 1 and 2. This assumption captures the idea that with Debit, the bank can monitor or "control" the funds easily, which makes it harder for the entrepreneur to divert funds. When Cash is used, the bank has less or even little ability to prevent the entrepreneur from diverting funds.[4] To summarize the features of payment technologies, Debit increases returns, and Debit and Cash have different degrees of anonymity in two dimensions: First, the type of the project remains private. Second, the bank has less control over the entrepreneur's funds.

The bank may or may not continue the investment in period 1. To continue the investment, the bank has to provide $k > 0$ amounts of additional funding to the entrepreneur. This extra funding can be interpreted as a liquidity shock to the project, such as device maintenance or the entrepreneur's plan to expand its business into new markets or locations. If the

[2]The motivation for this specification is that the entrepreneur does not have to prepare changes, and also, the digital device would be more useful in bookkeeping. Using digital devices would reduce the risk of robbery as well. This specification is equivalent to assuming that using cash is costly.

[3]We can instead assume that the entrepreneur can divert only a fraction of the revenue with Cash as well. As long as Debit allows the entrepreneur to divert more than Cash, our results will remain qualitatively unchanged.

[4]For example, when the entrepreneur uses Debit, the funds are in the bank's vault, and the bank can confiscate them or decline transfer requests. The funds that are not divertible are often called *pledgeable* or *verifiable* income.

bank does not lend it, the bank does not have to pay this cost but cannot restore any of the original investment. We assume that a B-type entrepreneur project still has a negative NPV at $t = 1$ even when the entrepreneur uses Debit: $R_b + \Delta < 1$, and hence, the bank will not continue the investment whenever the entrepreneur is identified as a B-type entrepreneur.

In making the continuation decision, the bank has the option of *auditing* the entrepreneur, at a cost. The bank can choose to audit the entrepreneur anytime after the $t = 1$ repayment. By auditing, the bank can verify the entrepreneur's type and can seize all of the period-2 returns.[5] We assume that auditing incurs a cost of $c > \lambda(R_g + \Delta)$, which implies that the bank will not audit the entrepreneur if she uses Debit and the bank can identify her type.

Finally, we make three parametric assumptions. First, we assume that a B-type entrepreneur will prefer to use Cash over Debit to receive returns in period 1:

$$\lambda < \frac{r}{r + \Delta}. \tag{1}$$

The benefit of obtaining Δ is always smaller than the loss of divertible funds for a B-type entrepreneur. While this assumption simplifies our analysis, our conclusion about CBDCs do not rely on it. Second, we assume that a G-type entrepreneur will always prefer continuation to termination and that the bank will be willing to continue working with a G-type entrepreneur without auditing if they use Debit:

$$R_g + \Delta > \max\left\{ \left(\frac{1}{\lambda} - 1\right)(r + \Delta), \frac{k}{1 - \lambda} \right\}. \tag{2}$$

Lastly, we assume that the bank is willing to fund a project ex-ante when the G-type is

[5] Auditing in this model can be interpreted as a court intervention. This assumption can be relaxed in a way that the bank can only recover a fraction of the funds through auditing.

expected to use Debit:

$$(1-\lambda)\theta(r + R_g + 2\Delta) > 1 + \theta k. \tag{3}$$

This condition leads to a lower bound for θ, which is the probability of being a G-type entrepreneur. The funding problem at $t = 0$ is not important in our mechanism.

2.2 Timeline

The sequence of events is summarized in Figure 1. In period 0, the entrepreneur borrows from the bank and invests in her project. After the investment is made, she learns the type of her project and then chooses a payment technology. This choice becomes known to the bank immediately. In period 1, the project yields returns, and the entrepreneur makes a repayment to the bank, the amount of which depends on the chosen payment instrument. The bank then makes a decision about whether to audit the entrepreneur and a decision about whether to continue the investment. The period ends after these decisions are made. In period 2, the project yields returns again, and the entrepreneur makes a repayment.

$t = 0$	$t = 1$	$t = 2$ (if continued)
• Loan is made • Firm's type is revealed • Firm chooses a payment technology	• Repayments • Bank's auditing decision • Bank's continuation decision	• Repayments

Figure 1: Timeline of the events

2.3 Discussion

We would like to further discuss two of our assumptions. Firstly, we have assumed that the bank can identify the type of the entrepreneur when they use Debit. This is equivalent to assuming that the bank receives a signal about the type when the entrepreneur uses Debit, and the signal is perfect. A natural extension is to consider the case where the signal is imperfect. For example, if the project is of type-B, the bank will receive a bad signal b with probability one. If the project is of type-G, the bank will receive a good signal g with probability $\sigma < 1$ and a bad signal b with probability $1 - \sigma$. While this is an interesting extension, it does not change the equilibrium outcomes that we are interested in.

Secondly, we have assumed that the entrepreneur can divert a fraction λ of the revenues by using Debit. An alternative way to specify λ is as the probability that diversion is successful. If diversion is successful, the entrepreneur can divert the entire amount. If diversion is unsuccessful, the entrepreneur obtains nothing. This alternative specification will yield equivalent results as long as either (i) the bank's decision to audit the entrepreneur is not contingent on whether diversion is successful or not, or (ii) the entrepreneur is able to consume everything before the bank audits her.

3 Equilibrium without CBDC

We begin the equilibrium analysis in this section. Our focus is on how the entrepreneur's incentives in choosing a payment technology shape the outcome of bank lending. Specifically, we will study a signaling game in which the entrepreneur chooses a payment technology, and the bank updates its beliefs about the type based on the entrepreneur's choice. The entrepreneur's payoffs are determined by the bank's decisions about whether to continue the investment and whether to audit them. We define an equilibrium as follows:

Definition 1. The equilibrium of the signaling game consists of the entrepreneur's choice of payment technology in maximizing her payoff and the bank's belief, such that the belief is updated using Bayes' rule whenever possible and is consistent with the entrepreneur's choice. The bank decides whether or not to lend in $t = 0, 1$, audit, or continue to maximize its payoff, given the belief.

For the off-equilibrium beliefs, we assume that the bank believes that the entrepreneur is a bad-type if it observes any deviations from the path of the play. However, when the entrepreneur uses Debit, the bank will correctly learn the type.

3.1 Equilibrium analysis

There are four possible combinations of choices, as there are two payment technologies and two types of entrepreneurs. However, there is no equilibrium in which a B-type entrepreneur chooses Debit because her type will be observable to the bank and doing so is strictly dominated as $r > \lambda(r + \Delta)$. Therefore, we only need to examine two combinations of choices: (Debit, Cash) and (Cash, Cash), where the first element represents the G-type's choice and the second element represents the B-type's choice. After the entrepreneur makes her choice, the bank makes decisions about whether to audit her and whether to continue the investment. It is straightforward to show that if the bank decides to audit the entrepreneur, it will always do so before making a decision about continuation. Thus, we focus on the order of events where an audit decision is made before a lending decision.

We first find that the separating equilibrium (Debit, Cash) always exists. The G-type chooses Debit to increase returns by Δ and induce additional funding, although they have to give up a fraction $(1-\lambda)$ of returns. The B-type chooses Cash to enjoy the benefits of anonymity, giving up the opportunity to continue the investment until period 2. In such a case, the bank continues only with the G-type without auditing. As shown below, this equilibrium is the only equilibrium in this benchmark model:

Proposition 1. ***(Equilibrium).*** *There exists a unique equilibrium in which G-type chooses Debit and B-type chooses Cash, and the bank continues with G-type and does not audit her. The G-type repays* $(1-\lambda)r$ *at time 1 and* $(1-\lambda)(R_g+\Delta)$ *at time 2, while the B-type repays nothing.*

A pooling equilibrium (Cash, Cash) cannot exist because of the threat of auditing. Because Cash is fully anonymous, the bank cannot gain anything unless it chooses to audit the entrepreneur and continue the investment. If the bank chooses to audit the entrepreneur and continue the investment, the entrepreneur will not receive any returns. Anticipating this outcome, the G-type will always deviate to Debit.

It is worth emphasizing that in this separating equilibrium, the bank's payoff is the same as it would be in the full information allocation where the type is publicly known. This is because the bank is able to make informed decisions based on the entrepreneur's choice of payment technology.

3.2 Welfare criteria

Evaluating equilibrium in this framework is a nontrivial matter. In order to study how the introduction of a CBDC changes the equilibrium welfare, we introduce two welfare criteria. Throughout the paper, we conduct the welfare analysis using these two criteria. The first criterion is that we define the bank's payoff as welfare. This approach is equivalent to assigning all welfare weight to the bank. One way to think of this approach is that the value of a diverted unit of funds to the entrepreneur is substantially small, so diversion creates an efficiency loss.[6]

Criterion 1. The welfare is measured by the bank's payoff.

We define the constraint efficiency as the equilibrium outcome in the environment with full information. Suppose that the bank knows the entrepreneur's type regardless of the entrepreneur's action, and the bank's resulting payoff is then said to be constrained efficient. The unique separating equilibrium that we have shown above, therefore, achieves constrained efficiency.

The second criterion is that we define the ex-ante expected output, netting out funding costs, as welfare. This approach is equivalent to assigning equal welfare weights on the B-type, the G-type, and the bank. In this case, fund diversion plays a redistribution role between the two parties.

Criterion 2. The welfare is measured by the ex-ante total net output. The net output with full information is $M + 2\Delta - 1 - \theta$. The separating equilibrium achieves the constrained efficiency in this criterion as well.

4 Equilibrium with CBDC

We will now introduce a CBDC into the framework in a way that allows the firm to choose the CBDC as a payment technology as well. We assume that, like Debit, the digital component of CBDCs facilitates business and increases the entrepreneur's revenue by Δ in each period for

[6]See, for example, Holmstrom and Tirole (2011).

every type.[7] Unlike Debit, however, the bank cannot observe the entrepreneur's type when the entrepreneur uses the CBDC.[8] Lastly, if the entrepreneur uses the CBDC, we assume that the entrepreneur can divert a fraction $\eta \in [\lambda, 1]$ of the revenue, which captures the extent to which the bank can control the funds in the entrepreneur's CBDC account. When $\eta = 1$, CBDC is Cash-like: The bank cannot control any funds in the CBDC account. When $\eta = \lambda$, the CBDC is Debit-like: the bank can access the CBDC account and control the funds as if they are in the firm's deposit account. The intermediate case can be interpreted as a situation where the bank has access to the CBDC account but can control certain funds only. Given η as a parameter, we study equilibria in the signaling game by adding this CBDC into the entrepreneur's choice set. We later discuss the optimal level of η as the optimal CBDC design.

4.1 Types of equilibrium

We begin our analysis by narrowing down potential equilibrium outcomes. There are 3×3 combinations of payment choices for the entrepreneur, but only four of them are possible equilibrium outcomes. To see this, notice that there cannot be a separating equilibrium where the G-type chooses Cash. Cash allows the entrepreneur to divert all of the period-2 returns, which leaves nothing for the bank. Thus, the bank audits the entrepreneur or does not lend in period 1, depending on the magnitude of c. In either case, the G-type would prefer to deviate to Debit. Additionally, there cannot be an equilibrium where the B-type chooses Debit. Both Debit and the CBDC increase the entrepreneur's revenue, but the CBDC allows the B-type to divert more and hide her type. Thus, the B-type always prefers

[7] This assumption can be generalized by introducing different magnitudes of the digital technology benefits. However, the mechanisms and the qualitative results that we aim to present will remain unchanged.

[8] We relax this feature when we discuss the optimal design of CBDC anonymity in Section 5.2.

the CBDC over Debit. Finally, (Cash, Cash) cannot be an equilibrium, as shown in Section 3.

Lemma 1. *There can be 4 types of equilibrium outcomes: (Debit, Cash), (Debit, CBDC), (CBDC, Cash), and (CBDC, CBDC).*

We will examine different types of equilibria and categorize them into two groups. The first group consists of separating equilibria in which the G-type chooses Debit. We will demonstrate that these equilibria achieve constrained efficiency under both welfare criteria that we presented in the last section. In the second group, we will explore the existence of other equilibria. Our analysis will show that the welfare is lower in these equilibria under some criteria, and they may coexist with constrained-efficient separating equilibria.

4.2 Efficiency

We will begin by examining separating equilibria in which the G-type chooses Debit. Whether the B-type chooses CBDC or Cash depends on the parameter η. When comparing the CBDC to Cash, the B-type must weigh the trade-off between a lower fraction of diverted funds and the additional revenue of Δ. A small value of η makes the cost of using the CBDC higher, leading the B-type to strictly prefer Cash. As η increases, the cost of using the CBDC decreases, allowing the (Debit, CBDC) equilibrium to become viable. Our next proposition characterizes the threshold value of η and the two separating equilibria.

Proposition 2. ***(Separating 1)*** *Let $\widehat{\eta} \equiv \frac{r}{r+\Delta}$. When $\eta < \widehat{\eta}$, there exists a separating equilibrium with (Debit, Cash); when $\eta > \widehat{\eta}$, there exists a separating equilibrium with (Debit, CBDC); they achieve constrained efficiency. Moreover, the bank has higher payoff than without the CBDC when $\eta > \widehat{\eta}$.*

Note that the G-type does not choose the CBDC in these equilibria because doing so would drive the bank to terminate the lending, resulting in the loss of period-2 profits. When the G-type uses Debit, the bank will continue the investment without auditing her, and the G-type's payoff is the same as in the separating equilibrium without the CBDC. However, the B-type and the bank have higher payoffs in the (Debit, CBDC) equilibrium. Although the B-type cannot continue her business until period 2, she is still able to enjoy the additional profit of Δ in period 1. As the B-type diverts only a fraction η of the this additional profit, the introduction of the CBDC increases the payoffs of both the B-type and the bank in this equilibrium. The resulting allocation leads to higher welfare under both welfare criteria and is constrained-efficient, similar to the results presented in Section 3.

4.3 Fragility

The introduction of a CBDC may give rise to other equilibria in which the G-type chooses the CBDC. By using the CBDC instead of Debit, the G-type can divert more profits while the profits themselves remain unchanged. However, this action also increases the benefits for the bank when auditing the entrepreneur. Since auditing leaves no profit to the G-type in period 2, the G-type will choose the CBDC only if doing so does not result in the bank's auditing. Below, we will describe two cases where the G-type chooses the CBDC in equilibrium.

The first case is a substantially low level of η, at which the cost of auditing the G-type alone outweighs the benefit: $c > \eta(R_g + \Delta)$. The G-type is still able to divert a larger fraction of the revenue by using the CBDC rather than Debit. For the B-type, Cash is preferred because η is too small, making CBDC less attractive. Thus, the separating equilibria (Debit, Cash) and (CBDC, Cash) coexist when η is substantially small.[9]

[9] It is perhaps worth noting how the bank updates its beliefs in the two separating equilibria. In the

Proposition 3. ***(Fragility: separating 2)*** *Let* $\widetilde{\eta} \equiv \min\{\frac{c}{R_g+\Delta}, \frac{r}{r+R_b+2\Delta}, \frac{R_g+\Delta-k}{R_g+\Delta}\}$*. Then, when* $\eta < \widetilde{\eta}$*, there also exists a separating equilibrium with (CBDC, Cash), and the bank continues at time 1 without auditing. Moreover,* $\widetilde{\eta} < \hat{\eta}$*, and the bank's payoff in this equilibrium is strictly lower than in (Debit, Cash).*

Welfare in the (CBDC, Cash) equilibrium cannot be strictly better than the (Debit, Cash) equilibrium. The G-type diverts more funds, even though total revenue remains unchanged, resulting in a lower payoff for the bank. Therefore, under the first criterion, the welfare is lower in this (CBDC, Cash) equilibrium than (Debit, Cash). On the other hand, since the B-type chooses Cash in both cases, there is no change in welfare under the second criterion.

The second possible equilibrium is a pooling equilibrium where the bank is unable to distinguish the G-type from the B-type. In particular, both types use the CBDC, and the bank does not audit either type, continuing to lend to both. Our analysis shows that such a pooling equilibrium exists when the value of η falls within a specific range.

Proposition 4. ***(Fragility: pooling)*** *Let* $\bar{\eta} \equiv \min\{\frac{c-(1-\theta)(k-R_b)+(1-\eta-\theta)\Delta}{M+\Delta}, \frac{M+\Delta-k}{M+\Delta}\}$ *and* $\underline{\eta} \equiv \frac{r}{r+R_b+2\Delta}$*. Then, when* $\eta \in (\underline{\eta}, \bar{\eta})$*, there also exists the pooling equilibrium (CBDC, CBDC), and the bank continues with both the G-type and the B-type in period 1 without auditing. Moreover,* $\underline{\eta} \geq \widetilde{\eta}$*, and the welfare in this equilibrium is strictly lower than in the separating equilibrium (CBDC, Cash).*

That is, this equilibrium exists when the diversion ratio η is neither too high nor too low. The upper bound ensures that the bank does not audit and is willing to continue lending, while the lower bound ensures that the B-type prefers the CBDC over Cash. The anonymity

separating equilibrium with (Debit, Cash), if the G-type deviates to CBDC, the bank will believe the entrepreneur to be a B-type entrepreneur and will therefore not continue lending in period 1. In the separating equilibrium with (CBDC, Cash), deviating to Debit reveals the entrepreneur's type directly. This feature of Debit allows the two separating equilibria to coexist.

in this equilibrium allows the B-type to continue the investment until period 2, resulting in inefficiency under both welfare criteria.

4.4 Illustration of results

We illustrate the equilibrium conditions in Figure 2. The separating equilibrium where the G-type uses Debit always exists for any value of η. When $\eta \in [\lambda, \tilde{\eta}]$, the (CBDC, Cash) equilibrium co-exists, and when $\eta \in [\underline{\eta}, \bar{\eta}]$, the (CBDC, CBDC) equilibrium co-exists.

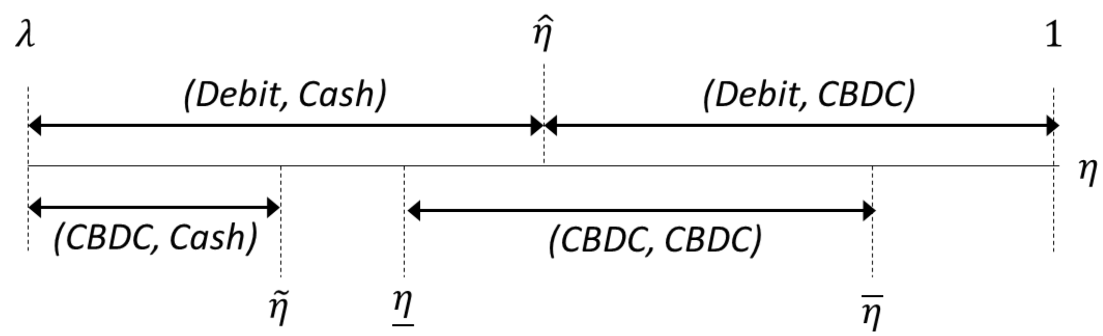

Figure 2: Types of equilibria

These thresholds always satisfy $\lambda < \tilde{\eta} < \underline{\eta} < \hat{\eta}$, while the inequality $\hat{\eta} < \bar{\eta}$ holds if and only if R_b or c are large or r is small. Figure 3 represents $\hat{\eta} < \bar{\eta}$ as the shaded region, illustrating that the region expands as c (y-axis) increases.[10]

[10]The parameter set used in this example is $(R_g, R_b, r, k) = (2, 0, 0.2, 1)$.

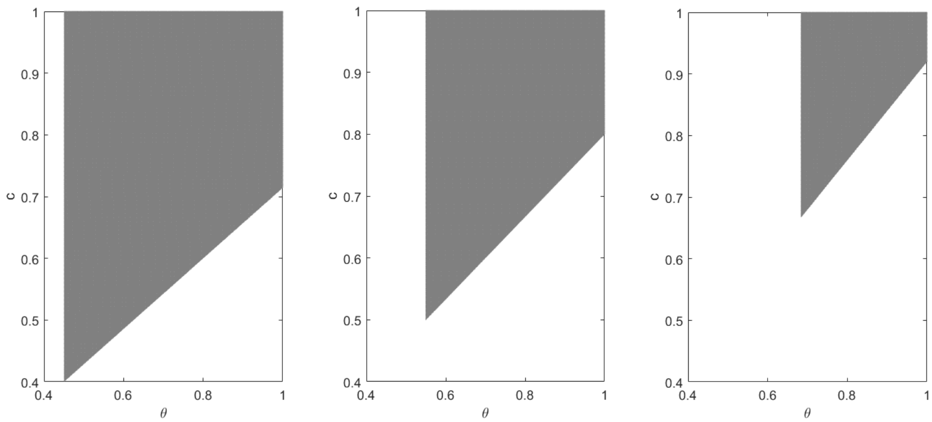

Figure 3: (a) $\Delta = 0.3$ (b) $\Delta = 0.4$ (c) $\Delta = 0.5$

Next, we illustrate the welfare comparison among those equilibria. In Figure 4, we plot the bank's payoff (the first welfare criterion) as a function of η. In the (Debit, Cash) equilibrium, the CBDC is not used, so the welfare is constant. At $\hat{\eta}$, there is a jump in the bank's payoff because the B-type starts using the CBDC, increasing total output and benefiting the bank as well.[11] When the CBDC is in circulation, as in the other three equilibria, the bank's payoff decreases as more funds are diverted away. In particular, when both types are using the CBDC, the bank's payoff decreases faster, resulting in a steeper line on the graph compared to the (Debit, CBDC) case.

[11] This jump depends on the tie-breaking mechanism employed here: We assume that at $\hat{\eta}$, when the B-type is indifferent between the CBDC and Cash, she prefers the CBDC. If the entrepreneur is allowed to use a mixed strategy, there will be a vertical line instead of a jump.

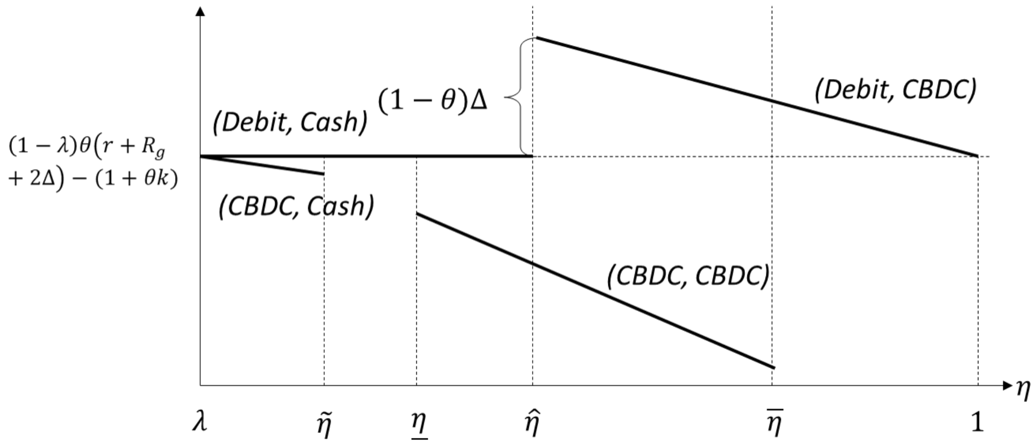

Figure 4: Bank's payoff (our first criterion of welfare)

In Figure 5, we depict the net output (the second welfare criterion) as a function of η. The welfare in each equilibrium is constant over η and is the same in both the (Debit, Cash) and (CBDC, Cash) equilibria. The pooling equilibrium (CBDC, CBDC) still has the lowest welfare because the bank funds the negative NPV project.

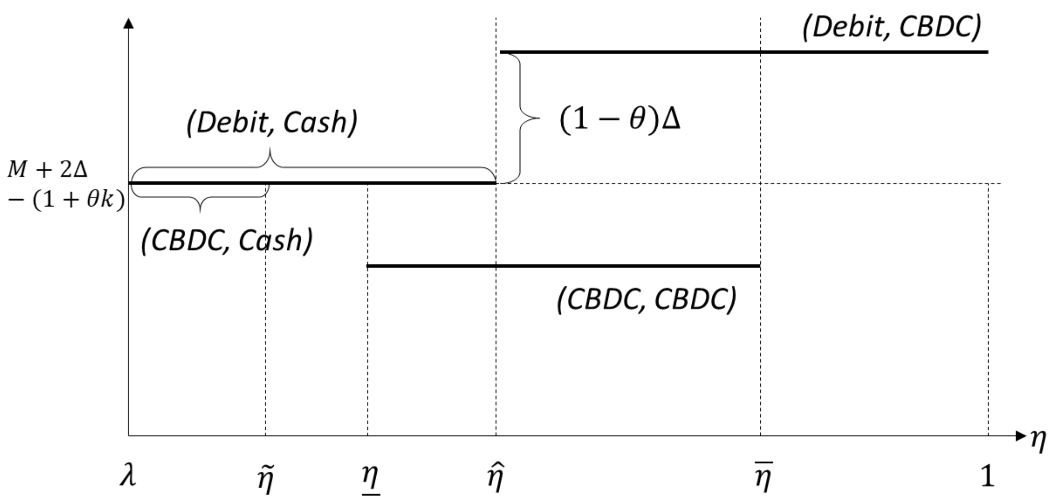

Figure 5: Net output (our second criterion of welfare)

These analyses highlight that the introduction of a CBDC can improve welfare when $\eta > \hat{\eta}$ but give rise to the bad equilibrium when $\eta \in [\underline{\eta}, \bar{\eta}]$. The most interesting case is, therefore, $\eta \in [\hat{\eta}, \bar{\eta}]$, which we will focus on in the rest of the paper.

5 Optimal design of CBDC anonymity

In this section, we consider the optimal design of anonymity for CBDCs. Our analysis has two parts. In the first part, we examine the case where the central bank can choose the value of η. That is, we design the CBDC along the fund control dimension of the anonymity, maintaining its informational anonymity. In the second case, we allow the central bank to also share information with the bank.

5.1 Optimal η

Suppose that the central bank sets the value of η before the economy begins. This choice creates a signaling game based on that level of η, and the central bank chooses η by anticipating equilibrium paths for each possible value of η. What value of η should the central bank choose?

Answering this question requires considering how to evaluate the existence of the bad equilibrium. We have shown that the CBDC improves welfare if $\eta \geq \hat{\eta}$, but the bad equilibrium coexists if $\eta \in [\hat{\eta}, \bar{\eta}]$. In this case, it is not clear how the central bank should evaluate the different equilibria.[12] We assume that the central bank maximizes welfare while eliminating bad equilibria.[13] The optimal value of η^* is then characterized by the following:

[12]When $\hat{\eta} > \bar{\eta}$, the bad equilibrium is not a concern: the central bank should choose $\hat{\eta}$ to maximize the bank's payoffs and any $\eta \geq \hat{\eta}$ to maximize the total output of the economy. Here, our focus is $\hat{\eta} \leq \bar{\eta}$.

[13]This approach is equivalent to the robust control approach in Hansen and Sargent (2001). Alternatively, we could introduce an extrinsic sunspot variable as an equilibrium selection mechanism, through which we

Proposition 5. ***(Optimal choice of*** η***)*** *Under the first criterion of welfare, the central bank should choose* $\eta^* = \bar{\eta}$*. Under the second criterion, the central banks should choose any* $\eta^* \in [\bar{\eta}, 1]$*.*

The optimal value of η relies on the result that the good equilibrium will be uniquely implemented when $\eta \geq \bar{\eta}$. On the one hand, increasing η changes the allocation: The bank's payoff is monotonically decreasing over η. If the central bank cares only about the bank's payoff (the first criterion of welfare), it should choose $\bar{\eta}$ and compromise some welfare loss in order to eliminate the bad equilibrium. On the other hand, the net output remains unchanged over $\eta \geq \hat{\eta}$. If the central bank cares only about the net output (the second criterion of welfare), any value of $\eta \geq \bar{\eta}$ will be optimal. In this case, it can eliminate the bad equilibrium without any cost.

It is perhaps worth emphasizing that this result does not rely on our assumption that $\eta \geq \lambda$. Suppose that the central bank can also choose $\eta < \lambda$. Such a situation can be interpreted as the central bank hiring a better machine learning or surveillance team than the bank reducing the agency cost. When $\eta < \lambda$, the CBDC becomes less attractive than Debit and the unique equilibrium (Debit, Cash) exists, just as in the benchmark. Therefore, the central bank will never choose $\eta < \lambda$.

5.2 Data-sharing

Another solution is to introduce the feature of data-sharing. Suppose that the bank is able to access the CBDC account data, which allows the bank to identify the entrepreneur's type in period 1. Through such data-sharing, the entrepreneur's type will be revealed when they

can assign the probability of each equilibrium being played. However, the mechanisms at play will remain unchanged.

choose the CBDC. The bank can now distinguish the G-type from the B-type even when both types choose the CBDC.

Whether the (CBDC, CBDC) equilibrium still exists for $\eta \geq \hat{\eta}$ depends on the G-type's incentives. When $\eta > \bar{\eta}$, the B-type is willing to choose the CBDC even though the bank will not continue with her. However, the G-type may deviate to Debit because a high η may incentivize the bank to audit the G-type. The bank audits the G-type if $\eta(R_g + \Delta) > c$. Therefore, when $\hat{\eta} > \frac{c}{R_g+\Delta}$, data-sharing eliminates the pooling equilibrium. When $\hat{\eta} \leq \frac{c}{R_g+\Delta}$, there is still an equilibrium with (CBDC, CBDC) where the bank continues with the G-type without auditing.

Proposition 6. ***(Data-sharing)*** *When auditing is not costly (c small), the data-sharing feature eliminates the (CBDC, CBDC) equilibrium.*

Although there can still exist a pooling equilibrium, this result has different implications under the two criteria of welfare. Recall that the multiple equilibria in interest are (Debit, CBDC) and (CBDC, CBDC). Now that the bank can distinguish the G-type from the B-type, there is no lending to the B-type in period 1. The resulting net output in both equilibria is the same, and thus, the pooling equilibrium is not a problem anymore. As a result, any value of $\eta \geq \hat{\eta}$ will be optimal under the second criterion of welfare. However, the distribution is not the same between the two equilibria. Since $\eta > \lambda$, the G-type can divert more funds and the bank has a lower payoff. Under the first criterion of welfare, the pooling equilibrium is still a problem, and the central bank should choose $\eta^* = \max\left\{\hat{\eta}, \frac{c}{R_g+\Delta}\right\}$. Therefore, the data-sharing feature still allows the central bank to choose a lower η in eliminating the pooling equilibrium than before, which improves the bank's payoffs.

5.3 Discussion

Although our analysis shows that sharing the CBDC account data eliminates the inefficiency and allows the economy to take full advantage of digital technologies, such action is controversial. First, it may be hard to obtain public support for such a feature.[14] Nations may oppose public authorities sharing information about individuals and firms with a particular private sector/company, such as banks. It would also be very costly to screen and decide which banks the central bank can credibly share the information with in a timely manner. Second, sharing confidential information requires both technical and financial challenges. For example, a US-based credit bureau announced a data breach in 2017, and the personal information of 147 million people was exposed.[15] These concerns undermine the feasibility of data-sharing, which questions to what extent the central bank is allowed to share the data. Our results imply that if the data-sharing is infeasible to implement, the central bank should choose $\bar{\eta}$ when $\hat{\eta} > \bar{\eta}$.

The implication of our results also relates to the discussion on who manages CBDC wallets. While central banks may operate CBDC wallets by themselves, it is also possible to allow banks to operate CBDC wallets. For example, a central bank may give licences to major banks to manage CBDC wallets. Then, there can be a bank that not only manages CBDC accounts but also lends to entrepreneurs. One question is whether this bank can use the information obtained through managing CBDC wallets for its business such as lending. Our result shows that doing so may improve welfare. However, some of the concerns expressed above still remain, and additionally, such operations can distort the competition among banks that are licensed to manage CBDC wallets and banks that are not licensed to do so.

[14] For example, a public survey conducted by ECB (2021) shows that privacy is considered the biggest concern of the digital Euro.

[15] See, for example, FTC (2022) for details.

6 Further discussions

Finally, we will discuss the key elements of our analysis and some extensions. We first examine the environment where the bank has commitment power, which provides an interesting implication for bundling financial services. Next, we will analyze the scenario in which Cash is not available, which may be useful for policymakers considering the adoption of digital currencies as the sole form of currency.

6.1 Commitment

One of the important elements in our analysis is the lack of commitment: The bank cannot pre-commit to a loan contract. If the bank has commitment power, the bank stipulates a loan contract such that the bank will not lend in period 1 if the entrepreneur chooses any payment instrument other than Debit. Then, the G-type will always choose Debit to continue the business until period 2. As a result, there will exist either (Debit, Cash) or (Debit, CBDC), depending on the value of η, as in Section 4.2. Notice that the B-type will still choose CBDC or Cash because it cannot continue anyway.

Proposition 7. ***(Commitment)*** *When the bank has commitment power, the bad equilibria do not exist.*

Such a loan contract can be interpreted as bundled services. When the bank offers loans, it may require the entrepreneur to open and use a bank account for business. Thus, the bank forces the entrepreneur to use Debit by bundling loans and payment instruments. However, enforcing the entrepreneur to actually use a particular payment method in business transactions may not be easy. Even if the entrepreneur opens a bank account, it can still use Cash or CBDC. Then, it will be ex-post inefficient for the bank not to continue the investment. We thus restrict the bankâs ability to commit so that the bank cannot make such a time-inconsistent action, which in turn, implies that the bank cannot effectively bundle the services.

6.2 Cashless economy

In an extreme case where a society becomes completely cashless, it is worth considering whether the central bank should continue to issue cash or not.[16] Our framework can be used to address this question.

Suppose that cash is removed from the entrepreneur's choice of payment instruments, and they must now choose between Debit or the CBDC. Under these circumstances, the (debit, cash) equilibrium will no longer exist, as cash is not an option. Instead, the (debit, CBDC) equilibrium will always exist for any value of η.

On the other hand, the (CBDC, CBDC) equilibrium is more likely to exist than before. In particular, the lower bound for this pooling equilibrium, $\underline{\eta}$, no longer exists, and the B-type will always choose the CBDC for any values of η. The upper bound for the pooling equilibrium remains unchanged. Therefore, when η is not too high, the pooling equilibrium will always co-exist, and our policy implications still apply in this case.

7 Conclusion

The possibility of introducing a CBDC has provoked a heated discussion on the value of information. While customer privacy has been highlighted, the availability of information is a classical problem in bank lending. For example, it is known that a lack of information

[16] It is reported that cash usage has been declining in some countries, such as Sweden.

can cause inefficient lending decisions. The discussion leads to the tension in designing the anonymity of CBDC: On the one hand, a customer may prefer to keep more information private. On the other hand, the bank may prefer to have more information to lend funds efficiently. The issue of how much information a CBDC should transmit is not trivial.

Our analysis shows how the anonymity design affects entrepreneur's strategic incentives in choosing a payment method, which in turn, shapes the equilibrium outcomes. We defined anonymity in two measurements. First, the bank cannot identify the entrepreneur's type from her payment method. The entrepreneur may then use a transparent payment method as a signaling tool. Second, the bank has less control over the entrepreneur's funds. The entrepreneur may then desire to choose a more anonymous payment method. The entrepreneur strategically chooses a payment method to induce investments from the bank while trying to avoid too much control from the bank.

Our results show that the equilibrium outcome is sensitive to the anonymity design. In order to motivate entrepreneurs to use a CBDC, some level of anonymity is necessary. There will then exist a good equilibrium where a CBDC improves welfare through associated digital services. There may, however, co-exist a bad equilibrium where the bank inefficiently lends to both good and bad entrepreneurs because the bank cannot distinguish a good type from a bad type. In a sense, the introduction of CBDC may reduce the information that is available to the bank.

The takeaway of this paper is that the anonymity of CBDCs should be designed to eliminate the equilibrium multiplicity: a CBDC should be very anonymous, or the bank should be able to access the CBDC data. Raising the degree of anonymity hurts the banking system and welfare depending on welfare criteria, and hence, the data-sharing is desirable in such a case. However, data-sharing faces a number of challenges in its implementation.

If data-sharing is not feasible to implement, the unique solution is to raise the degree of anonymity: The central bank has to give up some efficiency to eliminate the bad equilibrium.

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A Proofs for selected results

Proposition 1. Observing the pooling choices (Cash, Cash), the bank desires to audit if $c < \theta(R_g - k)$. Then, G-type will deviate to Debit because $\lambda(r+R+2\Delta) > r$. If $c \geq \theta(R_g - k)$, the bank neither audits nor continues, and G-type will deviate to Debit. □

Proposition 2. Given that the G-type chooses Debit, the CBDC dominates Cash for the B-type if $\eta(r + \Delta) > r$, which gives $\widehat{\eta}$; the G-type's incentive condition is satisfied because $\lambda(r+R_g+2\Delta) > r+\Delta > \max\{r, \eta(r+\Delta)\}$. The first inequality is guaranteed by assumption on $R_g+\Delta$; the bank's payoff in the (Debit, CBDC) equilibrium increases by $(1-\theta)(1-\eta)r$. □

Proposition 3. If $\eta > \frac{c}{R_g+\Delta}$, the bank will audit the G-type, and the G-type will deviate to Debit at time 0; if $\eta < \frac{c}{R_g+\Delta}$, the G-type will not deviate because $\eta > \lambda$; the B-type chooses Cash if $r > \eta(r + R_b + 2\Delta)$; lastly, the bank continues if $(1 - \eta)\theta(R_g + \Delta) > \theta k$ without auditing. □

Proposition 4. Note that there cannot be a pooling equilibrium when the bank audits and continues, because the G-type will deviate to Debit because $\lambda(r + R_g + 2\Delta) > r + \Delta > \max\{r, \eta(r + \Delta)\}$; when the bank does not audit, the G-type will not deviate to Debit because the bank continues lending and $\eta > \lambda$; the G-type will not deviate to Cash because $\eta(r+R_g+2\Delta) > \lambda(r+R_g+2\Delta) > r$; the B-type will not deviate to Cash when $\eta > \underline{\eta}$ (because $r < \eta(r+R_b+2\Delta)$); the B-type will not deviate to debit (obvious); $\eta < \bar{\eta}$ guarantees that the bank does not audit when continuing $((1-\eta)(M+\Delta) - k > \max\{\theta(R_g+\Delta-k) - c, 0\})$ □