Money as Safe Assets: Design of CBDCs

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Abstract

We present a tokenized money model of Central Bank Digital Currency (CBDC) where it serves both as a payment instrument and a safe asset. In the model, CBDC derives its value from its status as a legal means of payment. To overcome limited commitment frictions, productive agents borrow against a collateral portfolio composed of risky and safe assets. More safe assets lower the information sensitivity of the collateral portfolio, mitigate information frictions, and increase the pledgeability of risky assets, thereby acting as a collateral multiplier that enhances collateralizable funding for productive investments. This multiplier role boosts the value of CBDC, enabling it to be exchanged for more consumption, which further increases its value, forming a feedback loop. CBDC complements existing safe assets like reserves (accessible solely to banks) and sovereign bonds (which lack payment instrument functionality), thereby breaking the potential "doom loop" between sovereign bonds and banking crises and averting disruptions caused by "dash for cash" phenomena.

Keywords: CBDC, Digital Payment, Means of Payment, Medium of Exchange, Safe Asset, Collateral Multiplier, Tokenization, Digital Money, Adverse Selection

JEL classification: G10, G01

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1 Introduction

A Central Bank Digital Currency (CBDC) is virtual money backed and issued by a central bank. As money and payments have become more digital, central banks have realized that they need to provide a public option. According to the count by the Atlantic Council CBDC tracker conducted in March 2024, 134 countries and currency unions, representing 98% of global GDP, are exploring a CBDC.[1]

The development of CBDCs is not a trivial undertaking due to the significant costs and risks involved, including technological infrastructure costs, cybersecurity risks, and potential disruptions to the existing financial and monetary systems.[2] Furthermore, considering that numerous efficient private solutions for digital payments already exist, it is essential to question whether CBDCs offer any new features and to examine how these features might affect the real economy and the conduct of monetary and financial policy.

In this paper, we construct a model of the securities market and the consumption goods market to study these concerns. In the model, CBDCs serve not only as means of payment in the consumption goods market but also as safe collateral assets in the securities market, a role often overlooked in current academic debates. Combining CBDCs with risky assets reduces the information friction and the extent of adverse selection in the economy. Conventional fiat money cannot perform this function due to technology constraints on its storage, clearing, and settlement. Based on this model, we outline the unique economic mechanisms through which CBDCs affect the value of money, asset prices, investment, and consumption levels in the economy.

The modeling approach is to combine the canonical monetarist model proposed by Lagos and Wright (2005) with an asset-backed securities market dedicated to project financing as in Ozdenoren, Yuan, and Zhang (2021). That is, in the model, there are a **securities market** where the productive agents decide how

[1]Source: https://www.atlanticcouncil.org/cbdctracker/

[2]Serious concerns have been raised that CBDCs could lead to financial disintermediation, wherein depositors withdraw funds from private banks and transfer them to the central bank's CBDC accounts. This could potentially destabilize the banking sector and disrupt traditional lending and monetary transmission mechanisms. However, proponents argue that CBDCs could promote financial inclusion by providing access to banking services for underserved populations. Additionally, it has been argued that the introduction of CBDCs could stimulate innovation in the financial sector, enhancing its competitiveness and efficiency(Chiu et al. (2019)). Furthermore, there are important implications for the conduct of monetary policies when CBDCs are introduced. An interest-bearing CBDC could provide central banks with additional flexibility, particularly in times of low interest rates, by potentially mitigating the zero lower bound constraint. CBDC issuance could also generate additional seigniorage income for central banks. It is important to evaluate these concerns and potential benefits and understand the tradeoff formally. An inquiry conducted by Riksbank, presented in March 2023, concludes that there is currently insufficient social demand for the issuance of an e-krona, although it does not rule out the possibility of a future launch (source: https://www.riksbank.se/en-gb/payments--cash/e-krona/)

to raise financing via issuing debt backed by a risky asset and fiat money, a **consumption goods market** where agents choose how much to consume by exchanging fiat money for consumption goods, and **asset markets** where agents purchase fiat money and the risky asset. The risky asset pays a risky dividend or interest per period. The holders of the risky asset are better informed about this risky component than all other agents in the economy. This means that the securities market is subject to information frictions. By contrast, the consumption goods market is free from any frictions. Fiat money is valued since it generates a "dividend" or a convenience yield derived from being a payment instrument in the consumption goods market.

In our model, CBDCs function as a means of payment in the consumption goods market, motivated by their legal tender status. Consequently, CBDCs can be regarded as safe assets in the securities market since they must be accepted by sellers of consumption goods, generating a safe convenience yield, akin to a safe interest rate, for CBDC holders. These two characteristics are essential features of all central bank-issued money and are not unique to CBDCs. What makes CBDCs different is that they are tokens. Therefore, it is economically feasible to pledge CBDCs as safe collateral assets.

To understand how tokenization facilitates the use of CBDCs as safe assets, we highlight three key aspects in which it would transform transactions involving CBDCs. First, tokenization significantly reduces custody and service costs by providing secure storage and transactions of CBDCs, eliminating the need for trusted third parties. Second, tokenization enables atomic swaps for settlement, a feature currently used in some financial transactions to eliminate settlement risks but not widely in monetary transactions. In atomic swaps, the transfer of assets is conditional: the transfer of one asset occurs only if the transfer of another asset also occurs. This accelerates settlements and further removes the need for intermediaries. Third, the use of code in tokenization allows for programmability, facilitating the creation of financial contracts such as derivative securities backed by CBDCs.[3] These technological advantages offered by tokenization mean that fiat money like CBDCs no longer needs to be locked in costly safe storage offered by trusted custodians (such as a bank deposit account) and used solely for consumption payments. They can also be used as safe collateral in financial transactions.

In the model setup, we capture the programmability feature of CBDCs by allowing agents to trade financial contracts backed by CBDCs in the securities market. Consequently, in our framework, CBDCs are not merely payment instruments essential to the consumption goods market but also serve as safe assets in

[3]These assets can be bundled with messages necessary for transactions such as information needed for AML/CFT or CFM compliance.

the financial market, similar to traditional safe assets such as government bonds or reserves.

Next, we examine the crucial role of safe assets in the securities market using this model setup. In our model, and as commonly observed in reality, risky assets in the securities market are subject to information frictions, which limit their pledgeability when used as collateral to raise financing for productive agents. Safe assets, such as CBDCs, due to their broad accessibility, can be used to form a collateral portfolio with risky assets. The information sensitivity of the combined portfolio is reduced, thereby enhancing the collateralizability and pledgeability of risky assets. In essence, CBDCs act as collateral multipliers, increasing the amount of security sales for productive projects and thus boosting investment levels in the economy.

Our analysis also reveals a complex effect of CBDC introduction on the risky collateral asset price. As mentioned earlier, the dividend component of the risky asset is subject to information frictions. CBDCs, as a safe asset, mitigate this information friction and increase the pledgeability of the risky asset's dividend. This enhancement means that more funding (backed by the dividend flow of the risky asset) can be raised, making the risky asset a more valuable collateral, resulting in a high asset price. That is, the introduction of CBDCs has a complementary effect on the risky asset price. However, a countervailing effect also exists. In the dynamic equilibrium of our model, the collateral asset price itself can be self-fulfilling: a higher asset price lowers adverse selection and allows borrowers to raise greater funding, which makes the asset more valuable. Combining CBDCs with the risky asset lowers the adverse selection, weakens this self-fulfilling loop. Put differently, CBDCs can act as substitutes for the risky asset price. Therefore, the net effect of a CBDC introduction on the risky asset price can be modest. When only a fraction of CBDCs can be used as safe collateral, we find that as this fraction increases, consumption, investment, face value of debt, and asset price level all become higher, but the magnitude of increase in the asset price is the smallest.

The model generates other interesting comparative static results as well. We find that debt face value, real balance of money, risky asset price, consumption and investment are all decreasing in λ, the fraction of low quality collateral asset in the economy. This decrease is less for real balance of money and consumption. When compared with the regime without CBDCs, the debt face value and investment level are less sensitive to the information friction parameter, λ. We also examine the effect of monetary policy under the CBDC regime. We find that debt face value, real balance of money, risky asset price, consumption and investment are all decreasing in inflation. However, this decrease is less for risky asset price and investment level. Moreover, investment decreases less than consumption when inflation increases. This is because investment uses both risky assets and CBDCs as collateral and risky asset prices do not decrease as much with a higher inflation rate.

Discussions. We now discuss the economic relevance of our model assumptions on the use of CBDCs as safe assets and the empirical and policy implications of our findings. In our model, we emphasize only CBDCs are used as safe assets. It is important to point out that fiat money such as physical cash is also used as safe asset in the non-digitalized economy but this function is only accessible to those with access to trusted third party (such as banks) and at a significant cost. Cash collaterals are often used to secure international trade transactions. An extreme example is given by Kotidis, MacDonald, and Malliaropulos (2023). They show that cash collaterals had to be posted for importers for foreign goods when Greek bank guarantees were not accepted by their foreign correspondent banks during the 2015 banking crisis in Greece. Papoutsi et al. (2024) have shown that among the universe of corporate loans issued by all euro-area-resident banks and their non-euro-area branches in 2019, a significant portion is backed by cash or cash-equivalent assets with a haircut about 30-40%.[4] Ozdenoren, Yuan, and Zhang (2021) reported that Apple Inc. took out $5.2 billion of repo borrowing (shown in its 2020 10-K filing support) backed by cash-like collateral and stated its purpose was to meet its working capital need during the Covid-19 pandemic. While it is feasible to use physical cash as collateral, as we have observed in these examples, this option is only available to players who have access to the trusted third party in the banking or financial systems and often in desperate situations, due to the fact that cash is difficult to store, ease to abscond with, untraceable and comes with a high custody cost. Consequently, the paper cash is too costly to be used as collateral.

We want to emphasize that tokenization makes central bank money much easier and more accessible to be used as an asset and especially as a collateral, and making its safe asset role much more economically relevant. That is, CBDCs is an ideal class of safe collaterals because they are not only widely available, less costly to pledge, but also offer more flexibility to write payment and financial contracts due to programmability embedded in tokenization. Additionally, CBDCs have the design option to be traceable, increasing the recovery rate of CBDCs as pledgeable collateral. [5] Moreover, we have already observed that tokenization has enabled the tight integration of financial and payment contracts on tokenized assets and facilitated financial innovations in the blockchain ecosystem, such as Decentralized Finance (DeFi) lending protocols.[6]

[4]One of the main motivations for corporations to use cash collaterals (to back working capital borrowings) instead of spending them is to lower the adverse selection in the funding market by maintaining a strong balance sheet as shown in Ozdenoren, Yuan, and Zhang (2023).

[5]In addition, this option also enables borrowers to establish credit history based on past evidence of cash collateral-backed borrowings, making it more attractive as collateral. While we do not model the impact of this use in this paper, we use it as motivation for utilizing CBDCs as collateral.

[6]Although our paper draws parallels between the use of CBDCs as collateral and the utilization of cryptocurrencies in DeFi

Moreover, CBDCs possess qualities that distinguish them from traditional safe assets like reserves and sovereign bonds. Unlike reserves, which are typically exclusive to banks and serve as settlement balances between financial institutions, CBDCs are accessible to everyone. This accessibility makes CBDCs a more inclusive form of safe assets, available to both banks and non-banks alike. CBDCs combine the characteristics of a payment instrument and a safe asset. While reserves are primarily used for interbank settlements and sovereign bonds are held by non-bank investors, CBDCs serve both functions.

Functioning as safe assets and as highly liquid payment instruments, CBDCs might avoid the "dash for cash" phenomenon such as those occurred in March 2020. The "dash for cash" refers to a scenario where market participants urgently seek cash or cash-equivalent assets to satisfy margin calls or other liquidity demands. During periods of heightened market volatility or uncertainty, such as the onset of the COVID-19 pandemic in March 2020, investors initially flew to "quality' by buying sovereign bonds and driving up prices. However, due to immediate needs for cash, they subsequently rapidly sell off sovereign bonds for cash/central bank money. Unlike sovereign bonds, CBDCs could fulfill payment obligations, such as margin calls, without facing delays or counterparty risks associated with traditional settlement systems.

Furthermore, by providing an alternative safe asset accessible to all participants, CBDCs have the potential to reduce the reliance on sovereign bonds within the financial sector. This is particularly significant in mitigating the risks associated with the "doom loop" between sovereign and financial sector insolvency (which for example, is a key driver for the European sovereign debt crisis in 2009-2010). During times of financial stress, the interconnectedness between sovereign debt and financial institutions can exacerbate instability. CBDCs offer a diversification option, potentially breaking this cycle by providing a safe asset with broader accessibility.

Overall, we offer a novel and unified framework for understanding the potential role of central bank money as safe assets, within the financial market, leveraging their unique characteristics to promote efficient and secure financial transactions. The arrival of CBDCs makes this integration of monetary and financial transactions economically more relevant, indicating that financial and monetary policy making are closely intertwined in this digital economy.

lending protocols (See, among other, the modeling of DeFi lending mechanism in Chiu et al. (2023)), it emphasizes a crucial distinction: while cryptocurrencies in DeFi protocols may not always be safe assets, CBDCs are explicitly treated as safe within our model. Similarly, even though most private payment instruments (such as bank deposits) are secure and efficient, and potentially tokenizable, the crucial difference with CBDC is that CBDCs are safe and provide a backstop to consumption goods market and therefore can lower the adverse selection in securities market, especially during the time of distress.

Using this framework, beyond the scope of this paper, one can examine the impact on the banking sector as well as central bank's seigniorage. Risky assets in our model can be interpreted as uninsured tokenized bank deposits. In this case, the introduction of CBDCs would lower the information friction embedded in these deposits and help banks to obtain more rather than crowding out funding. Our model also implies that the introduction of CBDCs will improve central bank seignorage income since CBDCs are more valuable than tokenized private moneys. We draw comparison between the prolific use of private digital payment instruments in the current environment and the free banking era. During the free banking era, central banks earned little seigniorage income as private banknotes served as the predominant means of exchange. Introducing CBDCs can be seen as akin to establishing a "digital" central bank in a modern "free digital banking era," where the central bank can regain control over currency issuance and potentially increase seigniorage income.

2 Literature Review

The demand for CBDCs as a potential digital payment instrument have been studied via survey and structural modeling approaches in the existing literature. As an alternative to traditional payment instruments (cash, credit/debit cards, bank deposit), CBDCs, as a safe payment instrument and a backstop to the private payment systems, potentially commands a large market share depending on design features (Bijlsma et al. 2021, Huynh, Nicholls, and Shcherbakov 2022, Li 2023). Additionally, several papers study the optimal monetary policy and CBDC design choices (such as Brunnermeier and Niepelt 2019, Davoodalhosseini (2022), Agur, Ari, and Dell'Ariccia (2022), Ahnert, Hoffmann, and Monnet (2024)) and the associated macroeconomic impacts (Barrdear and Kumhof (2022), Burlon, Munoz, and Smets (2023), Paul, Ulate, and Wu (2024)).

The impact of CBDCs on the economy is often considered via how it affects the banking system and the conduct of monetary policy. There is a growing literature on how CBDCs could affect bank deposits and thus financial intermediation (e.g., Andolfatto 2021, Chiu et al. 2019, Garratt, Yu, and Zhu 2022, Fernandez-Villaverde et al. 2021, Keister and Sanches 2022, Williamson (2022), Niepelt (2023), Whited, Wu, and Xiao (2022), Abad, Nuno, and Thomas (2024) Ahnert et al. (2023), Paul, Ulate, and Wu (2024)) by studying the competition pressure on bank deposit on bank lending behavior and possibilities of bank runs. Our paper is the first to study the unique role of CBDCs as safe assets in stimulating financial transactions in the economy.

By studying CBDCs as collateral, our paper is also related to the broader literature on safe assets. Safe assets are often considered as assets that preserve or appreciate in value during adverse systemic events (Caballero and Farhi (2017), Caballero, Farhi, and Gourinchas (2017), and Brunnermeier and Haddad (In Preparation)). Our paper, like Ozdenoren, Yuan, and Zhang (2023) who study safe asset holding in banks' balance sheet in a static setting, characterizes another feature of safe assets: which is free of information frictions. This is similar to the definition of safe assets as information-insensitive securities in Dang, Gorton, and Holmstrom (2013).

The mechanism of creating a pooling portfolio of safe and risky asset for information reasons is also present in Gorton and Ordonez (2013) and Gorton and Ordoñez (2020). The underlying economic rationale is different because the information friction in our model is asymmetric information which leads to adverse selection. They model instead incentives to acquire information in an environment of symmetric ignorance.

Chiu et al. 2023 also study payment instruments such as cryptocurrencies that can be used as collaterals for borrowing funds in a Decentralized Finance (DeFi) lending protocol. In their model, cryptocurrencies are risky and exposed to adverse selection. Consequently, DeFi lending is fragile due to self-fulfilling beliefs. CBDCs in our paper, on the contrary, are safe assets which help to lower the adverse selection in the lending market.

Our model combines the canonical monetarist model proposed by Lagos and Wright (2005) with a market-based financial intermediation system model in Ozdenoren, Yuan, and Zhang (2021). The lending modeled in Ozdenoren, Yuan, and Zhang (2021) is not bank or credit-based, but asset-backed. These asset values are determined in the decentralized capital market rather than trusted third parties such as banks or credit agencies. Therefore, the framework proposed by Ozdenoren, Yuan, and Zhang (2021) lends itself naturally to modeling financial infrastructure in a tokenized economy. There is also a long monetarist literature including but unlimited to Kiyotaki and Wright (1989), Kiyotaki and Moore (1997), Lester, Postlewaite, and Wright (2012), and Lagos, Rocheteau, and Wright (2017).

3 The Model

The economy is set in discrete time and lasts forever. We index time by $t = 1, 2, \ldots$. There are two types of agents. We refer to the first type as active agents. These agents purchase consumption goods with fiat money and raise capital for productive projects in securities markets by issuing asset-backed securities. We refer to the second type as passive agents. Passive agents are sellers in the consumption goods market and

buyers or investors in the securities markets. These agents live for only one period and make zero profit.

Risky collateral asset A risky asset yields a random payoff in each period t which we denote $s_t \in [\underline{s}, \bar{s}]$, where $0 \leq \underline{s} < \bar{s}$. The payoff, s_t, captures both cash payoff that the asset generates, such as dividend or interest rate payment, and other benefits that accrue from the asset such as rental income. We assume that s_t i.i.d. over time and is distributed according to probability distribution F_{Q_t} where $Q_t \in \{L, H\}$ denotes the quality of the asset. Q_t is a signal that the active agent observes. It is i.i.d. over time and $Q_t = L$ with probability $\lambda \in (0, 1)$. We assume that F_H dominates F_L in terms of hazard rate:

$$\frac{f_H(\delta)}{\widetilde{F}_H(\delta)} < \frac{f_L(\delta)}{\widetilde{F}_L(\delta)}.$$

There are A units of the risky collateral asset available in the economy.

Fiat money There are two types fiat money: conventional and tokenized money. We refer to tokenized money also as CBDCs. Active agents and sellers use fiat money to exchange goods in the consumption goods market. Traditional fiat money cannot be used as collateral but CBDCs can be used as a second type of collateral. The supply of money in period t is given by M_t. We assume that money supply grows at a constant rate and denote the growth rate $\mu = \frac{M_{t+1}}{M_t} > 1$.

We study two cases of collateral usage: when only the risky asset is available as collateral and when the fiat money is tokenized and both the risky asset and the tokenized money are available as collateral. The first case serves as a benchmark for us to study the impact of introducing CBDCs to this economy.

Time Each time period is divided into four sub-periods. In sub-period 1, agents trade securities in a financial market. We refer to the financial market as securities market or Market-S. In subperiod 3, the agents trade consumption goods. We refer to this market as Market-C. Agents discount future utility with per-period discount factor $0 < \beta < 1$. Hence, there is no discounting between sub-periods. In sub-periods 2 and 4, agents settle payments from the previous subperiod and trade fiat money and risky collateral assets with numeraire goods in competitive asset markets. We refer to these asset markets as AM-1 and AM-2, respectively.

Asset markets In both asset markets, agents can produce and consume a numeraire good. The marginal utility of consuming the numeraire goods and the marginal cost of producing the goods are both normalized

to one. The numeraire good is perishable. We denote the net utility from the numeraire good by n, i.e., for an agent this is the utility from numeraire good consumed minus the disutility from producing it.

As will become clear, agents' ability to produce the numeraire good allows buyers to balance their budgets in the asset markets. We denote the price of the fiat money in asset market $j \in \{1, 2\}$ in period t (that takes place in sub-period j) by ϕ_{jt}^m and the risky asset by ϕ_{jt}^a.

Securities market In the first subperiod, a productive opportunity arises. To benefit from this opportunity, an active agent needs to sell a promise/security in exchange for intermediate goods, which can be labor, capital, foreign currency, or any other productive inputs. The marginal cost for the buyer of this security or promise, that is, the marginal cost of unit of intermediate goods, is normalized to 1. The active agent can realize constant marginal benefit $z > 1$ per unit of funding. We assume that there is two-sided limited commitment problem between the buyers and sellers of the security. Buyers of the security are not able to commit to provide the intermediate good, if they are paid upfront by fiat money. At the same time, active agents are not able to fulfill their promises. As a result, a promised payment must be enforced by collateral assets which can be a pool of the risky collateral asset and, when available, tokenized money. The buyer of the security provides the intermediate good and the seller of the security receives the collateral back once the promise is fulfilled.

We refer to the active agent's continuation value from entering the securities market at time t with $\hat{m}$ units of fiat money and $\hat{a}$ units of traditional collateral by $V_t^1(\hat{m}, \hat{a})$.

Consumption goods market In the third subperiod, active agents purchase consumption goods from sellers. Sellers produce consumption goods at unit marginal cost. Active agents who are buyers of consumption goods must pay with fiat money. [7]In contrast with the securities market, the consumption goods market operates as a spot market where exchange is simultaneous. Seller provides the good and receives the cash from the buyer at the same time.

An active agent's utility from consuming c units of the consumption good (specialized or general) is $u(c)$. The utility function u is positive, twice differentiable, increasing and concave, i.e. $u(c) > 0$ for $c > 0$, $-\infty < u''(c) < 0 < u'(c)$ for $c > 0$. To guarantee there is positive consumption in equilibrium, we further

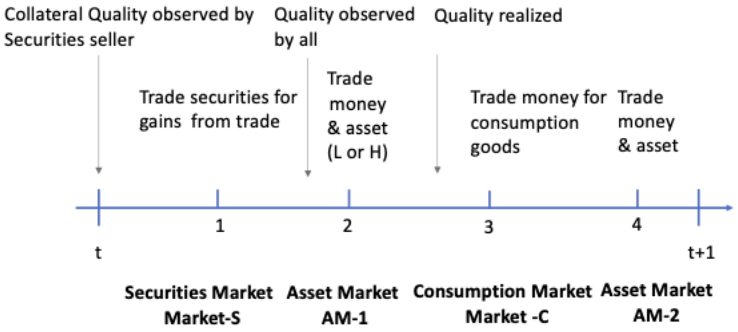
[7]Unlike sellers of securities, sellers of the consumption goods lacks the technology to recognize payoff from collateral assets. Recently, there is emergence of "buy now and pay later" payment technology (e.g. Klarna in Sweden). However, it is not wide spread.

assume that utility is increasing sufficiently rapidly near zero consumption so that $u'(0^+) > 1 + \frac{1-\beta}{\beta\gamma}$ and $\lim_{c\to\infty}[u'(c) + cu''(c)] = 0$. We refer to an active agent's continuation value from entering the consumption good market at time t with $\hat{m}$ units of fiat money and $\hat{a}$ units of traditional collateral by $V_t^2(\hat{m}, \hat{a})$.

Information environment Active agents observe a private noisy signal about the payoff of the risky asset in that period in subperiod 1, and in particular, this information is not observed by their counterparties in the securities market. Hence, there is asymmetric information between the buyers and sellers of the securities in subperiod 1 about the quality of the risky collateral. After subperiod 1, this private information becomes common knowledge and information is symmetric across all agents.

Timeline Figure 3.1 summarizes the event timeline of this economy within each time period.

Figure 3.1: Timeline



4 Fiat Money

We first solve for the active agents' optimization problem in each market taking the asset prices and debt contract terms as given.

4.1 Active Agents' Problem in AM-2

[8] In AM-2, the active agent decides how much money and risky asset to bring to the securities market in the next period given her endowment of the money and risky asset. She can produce/consume the numeraire good to balance her budget. Hence, her optimization problem in asset market 2 can be expressed as:

$$W_t^2(\hat{m}, \hat{a}) = \max_{n, \tilde{m}, \tilde{a}} -n + \beta V_{t+1}^1(\tilde{m}, \tilde{a})$$

subject to

$$\phi_{2t}^m \tilde{m} + \phi_{2t}^a \tilde{a} \leq \phi_{2t}^m \hat{m} + \phi_{2t}^a \hat{a} + n$$

Substituting for n,

$$\begin{aligned} W_t^2(\hat{m}, \hat{a}) &= \phi_{2t}^m \hat{m} + \phi_{2t}^a \hat{a} + \left[\max_{\tilde{m}, \tilde{a}} -\phi_{2t}^m \tilde{m} - \phi_{2t}^a \tilde{a} + \beta V_{t+1}^1(\tilde{m}, \tilde{a}) \right] \\ &= \phi_{2t}^m \hat{m} + \phi_{2t}^a \hat{a} + W_t^2(0, 0) \end{aligned}$$

Taking the first order condition and using market clearing where M_t and A_t are the supply of fiat money and risky collateral, we obtain the following equations for the risky asset and money prices in AM-2:

$$\phi_{2t}^m = \beta \frac{\partial}{\partial \hat{m}} V_{t+1}^1 (M_t, A_t) \tag{4.1}$$

$$\phi_{2t}^a = \beta \frac{\partial}{\partial \hat{a}} V_{t+1}^1 (M_t, A_t) \tag{4.2}$$

4.2 Active Agent's Problem in Market-C

We assume that the active agent makes the seller a take it or leave it offer of $\hat{m} - \tilde{m} \geq 0$ units of the fiat money in exchange for c units of the consumption good. Hence, if the seller accepts the offer, the buyer retains $\tilde{m} \geq 0$ units of money, with which she enters AM-2 and rebalances her portfolio of money and risky asset holdings. The seller enters AM-2 with $\hat{m} - \tilde{m}$ units of money, which he sells at price ϕ_{2t}^m and obtains $\phi_{2t}^m (\hat{m} - \tilde{m})$ units of the numeraire good. If the seller refuses the offer, he obtains reservation value of zero. Hence, we can write the active agent's value function as:

$$V_t^2(\hat{m}, \hat{a}) = \max_{c, \tilde{m} \geq 0} u(c) + W_t^2(\tilde{m}, \hat{a})$$

[8] Recall that AM-2 takes place in the fourth subperiod of period t and precedes Market I that takes place in the first subperiod of period $t+1$. By assumption agents discount the payoff that they obtain in time $t+1$ Market I when they compute their continuation values in time t AM-2.

subject to

$$c \leq \phi_{2t}^m \left(\hat{m} - \tilde{m}\right).$$

The above constraint can be viewed as either the budget constraint for the active agent or the participation constraint of the seller of consumption goods. Since the constraint must be satisfied with equality we can substitute for c and write the active agent's value function as:

$$V_t^2(\hat{m}, \hat{a}) = \max_{\tilde{m} \geq 0} u\left[\phi_{2t}^m \left(\hat{m} - \tilde{m}\right)\right] + \phi_{2t}^m \tilde{m} + \phi_{2t}^a \hat{a} + W_t^2(0,0).$$

The first order condition for the active agent's optimization problem is:

$$-\phi_{2t}^m u'\left[\phi_{2t}^m(\hat{m} - \tilde{m})\right] + \phi_{2t}^m \leq 0$$

or

$$u'\left[\phi_{2t}^m(\hat{m} - \tilde{m})\right] \geq 1 \tag{4.3}$$

with equality if $\tilde{m} > 0$.

4.3 Active Agent's Problem in AM-1

The active agent's optimization problem in asset market 1 can be expressed as:

$$W_t^1(\hat{m}, \hat{a}) = \max_{n, \tilde{m}, \tilde{a}} -n + V_t^2(\tilde{m}, \tilde{a})$$

subject to

$$\phi_{1t}^m \tilde{m} + \phi_{1t}^a \tilde{a} \leq \phi_{1t}^m \hat{m} + \phi_{1t}^a \hat{a} + n$$

Substituting for n,

$$\begin{aligned} W_t^1(\hat{m}, \hat{a}) &= \phi_{1t}^m \hat{m} + \phi_{1t}^a \hat{a} + \left[\max_{\tilde{m}, \tilde{a}} -\phi_{1t}^m \tilde{m} - \phi_{1t}^a \tilde{a} + V_t^2(\tilde{m}, \tilde{a})\right] \\ &= \phi_{1t}^m \hat{m} + \phi_{1t}^a \hat{a} + W_t^1(0,0) \end{aligned}$$

Taking the first order condition and using market clearing where M_t and A_t are the supply of fiat money and the risky collateral, we obtain:

$$\phi_{1t}^m = \frac{\partial}{\partial \hat{m}} V_t^2\left(M_t, A_t\right) \tag{4.4}$$

$$\phi_{1t}^a = \frac{\partial}{\partial \hat{a}} V_t^2\left(M_t, A_t\right) \tag{4.5}$$

4.4 Market-S with Traditional Fiat Money

Suppose an active agent enters Market-S with $\hat{a}$ units of the collateral asset and issues a debt claim with face value D_t, backed by the collateral asset price and its dividend. She learns the collateral quality and decides how many units of the security to sell given the collateral type. Since the security is backed by the collateral she can sell at most $\hat{a}$ units of the security. We assume that she makes the required payment y_t^1 per unit of security and retains $\hat{a}$ units of the collateral in AM-1 next sub-period. This assumption is innocuous since the asset trades at price ϕ_{1t}^a in Market-S (and there is no discounting between sub-periods). The contract terms are chosen before the owners receive private info about the period dividend payoff to maximize the surplus of trading securities. Formally, the debt claim promises to pay at the end of the Market-S:

$$y_t(\tilde{s}_t, \phi_{1t}^a) = \min(\tilde{s}_t + \phi_{1t}^a, D_t). \tag{4.6}$$

and the value of the borrower from holding $\hat{a}$ units of the risky collateral in Market-S is given by:

$$\begin{aligned} V_t^1(\hat{m}, \hat{a}) = \lambda \max_{0 \le \tilde{a}_L \le \hat{a}} E_L\left[\tilde{a}_L\left(zp_t - y_t\right)\right] + (1-\lambda) \max_{0 \le \tilde{a}_H \le \hat{a}} E_H\left[\tilde{a}_H\left(zp_t - y_t\right)\right] \\ + \phi_{1t}^m \hat{m} + \left(\lambda E_L s_t + (1-\lambda) E_H s_t\right)\hat{a} + \phi_{1t}^a \hat{a} + W_t^1(0,0) \end{aligned} \tag{4.7}$$

The social surplus from trade is maximized when the terms of debt security enables a pooling equilibrium. The price of the security is determined by the break even condition for the sellers. In the pooling equilibrium, the price of the debt security is

$$p_t = \lambda E_L\left[\min(s_t + \phi_{1t}^a, D_t)\right] + (1-\lambda) E_H\left[\min(s_t + \phi_{1t}^a, D_t)\right] \tag{4.8}$$

and $\tilde{a}_L = \tilde{a}_H = \hat{a}$. Hence, the value function in a pooling equilibrium is

$$\begin{aligned} V_t^1(\hat{m}, \hat{a}) = (z-1)\hat{a}\left[\lambda E_L\left[\min(s_t + \phi_{1t}^a, D_t)\right] + (1-\lambda) E_H\left[\min(s_t + \phi_{1t}^a, D_t)\right]\right] \\ + \phi_{1t}^m \hat{m} + \left(\lambda E_L s_t + (1-\lambda) E_H s_t\right)\hat{a} + \phi_{1t}^a \hat{a} + W_t^1(0,0) \end{aligned}$$

The debt is traded in the pooling equilibrium if and only if

$$\begin{aligned} zp_t &= z\left\{\lambda E_L\left[\min(D, s + \phi_{1t}^a)\right] + (1-\lambda) E_H\left[\min(D, s + \phi_{1t}^a)\right]\right\} \\ &\ge E_H\left[\min(D, s + \phi_{1t}^a)\right] \end{aligned}$$

Or

$$\frac{E_L\left[\min(D, s+\phi_{1t}^a)\right]}{E_H\left[\min(D, s+\phi_{1t}^a)\right]} \geq \zeta = 1 - \frac{z-1}{\lambda z}. \tag{4.9}$$

After we describe the active economic agent's optimization problem in each sub-period, we are ready to define the equilibrium concept and solve for it

4.5 Equilibrium Concept

Suppose the money supply $\{M_t\}_{t=0}^{\infty}$, the asset supply A and the growth rate of money supply $\mu = \frac{M_{t+1}}{M_t}$ are given. A stationary monetary equilibrium is asset prices ϕ_1^a, ϕ_2^a, money prices ϕ_1^m, ϕ_2^m and debt threshold D such that:

1. Money and asset prices satisfy Euler equations given in (4.1), (4.2), (4.4) and (4.5).
2. Real money balances are given by $Z_1 = \phi_{1t}^m M_t$, $Z_2 = \phi_{2t}^m M_t$ where $Z_1 > 0$ and $Z_2 > 0$.
3. Debt threshold satisfies (4.9).

We first solve the benchmark case where money is traditional fiat money and cannot be used as collateral. We then solve for the case where CBDC replaces traditional fiat money and can be used as collateral.

4.6 Equilibrium with Traditional Fiat Money: Benchmark

There are two cases to consider.

Case 1: $u'(\phi_{2t}^m \hat{m}) < 1$. This is the case when the active agent has brought too much fiat assets to the goods market. Denote c^* to be such that $u'(c^*) = 1$

$$V_t^2(\hat{m}, \hat{a}) = \phi_{2t}^m \hat{m} + (u(c^*) - c^*) + \phi_{2t}^a \hat{a} + W_t^2(0,0)$$

Case 2: $u'(\phi_{2t}^m \hat{m}) \geq 1$. This is the case when the active agent spends all the fiat assets that she has brought to purchase consumption goods.

$$V_t^2(\hat{m}, \hat{a}) = u(\phi_{2t}^m \hat{m}) + \phi_{2t}^a \hat{a} + W_t^2(0,0)$$

We can now use the expressions for $V_t^2(\hat{m}, \hat{a})$ to solve for ϕ_{1t}^m, ϕ_{1t}^a and $W_t^1(\hat{m}, \hat{a})$. Recall that there are two cases.

Case 1: $u'(\phi_{2t}^m \hat{m}) < 1$. In this case,

$$V_t^2(\hat{m}, \hat{a}) = \phi_{2t}^m \hat{m} + (u(c^*) - c^*) + \phi_{2t}^a \hat{a} + W_t^2(0,0)$$

$$\frac{\partial}{\partial \hat{m}} V_t^2(\hat{m}, \hat{a}) = \phi_{2t}^m$$

$$\frac{\partial}{\partial \hat{a}} V_t^2(\hat{m}, \hat{a}) = \phi_{2t}^a$$

From (4.4) and (4.5) we obtain

$$\phi_{1t}^m = \phi_{2t}^m,$$

$$\phi_{1t}^a = \phi_{2t}^a$$

Case 2: $u'(\phi_{2t}^m \hat{m}) \geq 1$. In this case,

$$V_t^2(\hat{m}, \hat{a}) = u(\phi_{2t}^m \hat{m}) + \phi_{2t}^a \hat{a} + W_t^2(0,0)$$

$$\frac{\partial}{\partial \hat{m}} V_t^2(\hat{m}, \hat{a}) = \phi_{2t}^m u'(\phi_{2t}^m \hat{m})$$

From (4.4) and (4.5) we obtain

$$\phi_{1t}^m = \phi_{2t}^m u'\left(\phi_{2t}^m M_t\right),$$

$$\phi_{1t}^a = \phi_{2t}^a$$

We focus on a steady state equilibrium. Given the asset endowment $a_t = A$, the growth rate of money supply $\mu = \frac{m_{t+1}}{m_t}$, a stationary monetary equilibrium is δ, ϕ_1^a, ϕ_2^a, and real money balances $Z_1 = \phi_{1t}^m m_t$, $Z_2 = \phi_{2t}^m m_t$.

Recall from previous discussion that there are two cases. We show that case 1 ($u'(\phi_{2t}^m m_t) < 1$) is inconsistent with a stationary equilibrium. To see this note that in case 1, $\phi_{1t}^m = \phi_{2t}^m$ and $\phi_{1t}^a = \phi_{2t}^a$. From (4.1) we get

$$\phi_{2t}^m = \beta \frac{\partial}{\partial m} V^1\left(M_t, A_t\right) = \beta \phi_{1t+1}^m$$

or

$$Z_2 = \frac{\beta}{\mu} Z_1.$$

Since $\mu > \beta$, $Z_1 = Z_2 = 0$. But this is inconsistent since Case 1 requires $u'(Z_2) = u'(0) < 1$ but by assumption $u'(0) > 1$.

In case 2, $u'(\phi_{2t}^m m_t) \geq 1$. From (4.1) and (4.4) we get

$$Z_2 = \frac{\beta}{\mu} Z_1$$

and

$$Z_1 = Z_2 u'(Z_2).$$

Combining we obtain:

$$1 = \frac{\beta}{\mu} u'(Z_2)$$

Now the collateral asset price.

$$\phi_{2t}^a = \beta \frac{\partial}{\partial a} V^1(M_t, A_t)$$

$$\begin{aligned}\phi_1^a = \phi_2^a &= \beta \frac{\partial}{\partial a} V^1(M_t, A_t) \\ &= \beta\phi_1^a + \beta(z-1)\left[\lambda E_L\left[\min(D, s_t + \phi_1^a)\right] + (1-\lambda)E_H\left[\min(D, s_t + \phi_1^a)\right]\right] \\ &+ \beta\left(\lambda E_L s_t + (1-\lambda) E_H s_t\right)\end{aligned}$$

Let $\delta = D - \phi_1^a$. The stationary collateral asset price is then

$$\phi_1^a = \beta z\phi_1^a + \beta\left(\lambda E_L s_t + (1-\lambda) E_H s_t\right) + \beta(z-1)\left[\lambda \int_0^\delta \widetilde{F}_L(s)ds + (1-\lambda)\int_0^\delta \widetilde{F}_H(s)ds\right]$$

Let

$$\Lambda(\delta) = (z-1)\left[\lambda \int_0^\delta \widetilde{F}_L(s)ds + (1-\lambda)\int_0^\delta \widetilde{F}_H(s)ds\right]$$

$$\phi_1^a = \beta z\phi_1^a + \beta\left(\lambda E_L s_t + (1-\lambda) E_H s_t\right) + \beta\Lambda(\delta)$$

$$\phi_1^a = \frac{\beta\Lambda(\delta) + \beta\left(\lambda E_L s_t + (1-\lambda) E_H s_t\right)}{1 - \beta z}$$

Moreover, the debt is traded in the pooling equilibrium if and only if

$$(1-\zeta)\phi_1^a = \zeta \int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds$$

where $\widetilde{F}_Q(s) = 1 - F_Q(s)$.

The following proposition summarizes the discussion and shows that a stationary equilibrium exists.

Proposition 1. *There exists at least one stationary equilibrium. In a stationary equilibrium prices and the security design are given by:*

$$Z_2 = \frac{\beta}{\mu} Z_1$$
$$Z_1 = Z_2 u'(Z_2)$$

and

$$\begin{aligned}\phi_2^a = \phi_1^a &= \frac{\beta\left[\lambda\left(z\int_0^\delta \widetilde{F}_L(s)ds + \int_\delta^1 \widetilde{F}_L(s)ds\right) + (1-\lambda)\left(z\int_0^\delta \widetilde{F}_H(s)ds + \int_\delta^1 \widetilde{F}_H(s)ds\right)\right]}{1-\beta z} \\ &= \frac{\zeta\int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds}{(1-\zeta)}.\end{aligned}$$

4.7 Equilibrium with Tokenized CBDC

In sub-periods 2 to 4 the active agent's problem is the same with or without tokenized CBDC. However, existence of tokenized money affects the analysis of the securities market in subperiod 1 which we study next.

With tokenized money, at the end of securities market the debt claim promises to pay:

$$y_D(s) = \min(\tilde{s} + \phi_1^a + \gamma\phi_1^m, D) \tag{4.10}$$

where γ is the amount of tokenized money pledged per unit of collateral asset. Note that, information sensitivity ratio of the debt securities backed this portfolio of risky and CBDC assets is larger than the case where the debt is backed by the risky asset only as show below:

$$\frac{E_L\left[\min(D, s+\phi_{1t}^a+\gamma\phi_1^m)\right]}{E_H\left[\min(D, s+\phi_{1t}^a+\gamma\phi_1^m)\right]} \geq \frac{E_L\left[\min(D, s+\phi_{1t}^a)\right]}{E_H\left[\min(D, s+\phi_{1t}^a)\right]},$$

which means that adverse selection is lower when CBDC is included in the collateral portfolio.

In a pooling equilibrium, the value of the borrower from holding $\hat{m}$ units of tokenized money and $\hat{a}$ units of the risky collateral is given by

$$\begin{aligned}V_t^1(\hat{m},\hat{a}) = \lambda \max_{0\leq\tilde{a}\leq\hat{a}} E_L\left[\tilde{a}_L\left(zp_t - y_t^L\right)\right] + (1-\lambda)\max_{0\leq\tilde{a}\leq\hat{a}} E\left[\tilde{a}_H\left(zp_t - y_t^H\right)\right] \\ + \phi_{1t}^m\hat{m} + \left(\lambda E_L s_t + (1-\lambda)E_H s_t\right)\hat{a} + \phi_{1t}^a\hat{a} + W_t^1(0,0)\end{aligned} \tag{4.11}$$

where the pooling security price is

$$p_t = \lambda E_L\left[\min(D, s_t + \phi_{1t}^a + \frac{\hat{m}}{\hat{a}}\phi_{1t}^m)\right] + (1-\lambda)E_H\left[\min(D, s_t + \phi_{1t}^a + \frac{\hat{m}}{\hat{a}}\phi_{1t}^m)\right] \tag{4.12}$$

Letting $\delta = D - \phi_1^a - \frac{\hat{m}}{\hat{a}}\phi_{1t}^m$, we rewrite the value function as:

$$\begin{aligned} V_t^1(\hat{m}, \hat{a}) = (z-1)\left[\hat{a}\phi_1^a + \hat{m}\phi_{1t}^m + \hat{a}\left[\lambda E_L \min(\delta, s_t) + (1-\lambda)E_H \min(\delta, s_t)\right]\right] \\ + \phi_{1t}^m\hat{m} + \left(\lambda E_L s_t + (1-\lambda)\, E_H s_t\right)\hat{a} + \phi_{1t}^a\hat{a} + W_t^1(0,0) \end{aligned}$$

The debt is traded in the pooling equilibrium if and only if

$$(1-\zeta)(\phi_{1t}^m\hat{m} + \phi_{1t}^a\hat{a}) = \hat{a}(\zeta\int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds) \tag{4.13}$$

The next proposition shows that in an economy with CBDC, if the pooling condition is binding, increasing the supply of money increases the face value of the debt security and increasing the supply of risky asset decreases it.

Proposition 2. *Suppose $\hat{m} > 0$ and (4.13) is binding. Then*

$$\frac{\partial\delta}{\partial\hat{m}} = \frac{(1-\zeta)\phi_{1t}^m}{\hat{a}(\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta))} > 0$$

and

$$\frac{\partial\delta}{\partial\hat{a}} = \frac{(1-\zeta)\phi_{1t}^a - \left[\zeta\int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds\right]}{\hat{a}(\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta))} < 0.$$

Proof. The expressions follow from the implicit function theorem. Denominator must be positive. Otherwise, δ can be increased without violating (4.13). Numerator of $\partial\delta/\partial\hat{a}$ must be negative because (4.13) is binding and $\hat{m} > 0$. □

Marginal value of CBDC in the securities market is given by:

$$\begin{aligned} \frac{\partial V_t^1}{\partial\hat{m}}(\hat{m}, \hat{a}) &= z\phi_{1t}^m + (z-1)\hat{a}\left[\lambda\widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta))\right]\frac{\partial\delta}{\partial\hat{m}} \\ &= \phi_{1t}^m\left(z + W\left(\delta\right)\right) \end{aligned}$$

where

$$W\left(\delta\right) = (z-1)(1-\zeta)\frac{\lambda\widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta))}{\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta)}.$$

Marginal value of the risky asset in the securities market is given by:

$$\frac{\partial V_t^1}{\partial \hat{a}}(\hat{m},\hat{a}) = z\phi_{1t}^a + (z-1)\left[\lambda E_L \min(\delta, s_t) + (1-\lambda)E_H \min(\delta, s_t)\right] + \left(\lambda E_L s_t + (1-\lambda) E_H s_t\right)$$
$$+ (z-1)\hat{a}\left[\lambda \widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta)\right]\frac{\partial \delta}{\partial a}$$

which can be expressed as:

$$\frac{\partial V_t^1}{\partial \hat{a}}(\hat{m},\hat{a}) = \phi_{1t}^a\left(z + W\left(\delta\right)\right) + \lambda E_L s_t + (1-\lambda) E_H s_t + \Lambda\left(\delta\right) + \Psi\left(\delta\right)$$

$$\frac{\partial V_t^1}{\partial \hat{a}}(\hat{m},\hat{a}) = \left[\phi_{1t}^a z + \lambda E_L s_t + (1-\lambda) E_H s_t + \Lambda\left(\delta\right)\right] + \left[\phi_{1t}^a W\left(\delta\right) + \Psi\left(\delta\right)\right]$$

where

$$\Psi\left(\delta\right) = -\frac{(z-1)\left[\lambda \widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta)\right]\left[\zeta \int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds\right]}{\zeta \widetilde{F}_H(\delta) - \widetilde{F}_L(\delta)}.$$

Using (4.1) and (4.2) we obtain:

$$\phi_{2t}^m = \beta \phi_{1t+1}^m\left(z + W\left(\delta\right)\right)$$

$$\phi_{2t}^a = \beta \phi_{1t+1}^a\left(z + W\left(\delta\right)\right) + \beta\left(\lambda E_L s_t + (1-\lambda) E_H s_t + \Lambda\left(\delta\right) + \Psi\left(\delta\right)\right)$$

and

$$\Lambda\left(\delta\right) + \Psi\left(\delta\right) = \frac{z-1}{z}\frac{\widetilde{F}_H(\delta)\int_0^\delta \widetilde{F}_L(s)ds - \widetilde{F}_L(\delta)\int_0^\delta \widetilde{F}_H(s)ds}{\zeta \widetilde{F}_H(\delta) - \widetilde{F}_L(\delta)}.$$

As in the fiat money case we can show that the active agent will never bring too much money since money is costly. Hence we are in the case where $u'(\phi_{2t}^m m_t) \geq 1$. From (4.1) and (4.4) we get

$$Z_2 = \frac{\beta}{\mu} Z_1\left(z + W\left(\delta\right)\right)$$

and

$$Z_1 = Z_2 u'\left(Z_2\right).$$

We summarize the equilibrium conditions in the next proposition.

Proposition 3. *There exists at least one stationary equilibrium. In steady state Z_1, Z_2, ϕ_1^a, ϕ_2^a and δ are given by:*

$$\frac{\mu}{\beta} = u'\left(Z_2\right)\left(z + W\left(\delta\right)\right)$$

$$Z_1 = Z_2 u'(Z_2),$$

$$\phi_2^a = \beta\phi_2^a (z + W(\delta)) + \beta(\lambda E_L s_t + (1-\lambda) E_H s_t + \Lambda(\delta) + \Psi(\delta))$$

$$\phi_1^a = \phi_2^a$$

$$(1-\zeta)(Z_1 + \phi_1^a A) \geq A(\zeta \int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds)$$

4.7.1 Two Point Distribution

Suppose that the high quality asset pays one dividend with probability π_H and the low quality asset pays the dividend with probability π_L, $0 < \pi_L < \pi_H < 1$. Note $\widetilde{F}_Q(s) = \pi_Q$ for $s < 1$. Let $u(x) = \frac{x^{1-\gamma}}{1-\gamma}$ where $\gamma > 0$.

Equilibrium with only fiat money:

$$Z_2^{fiat} = \left(\frac{\beta}{\mu}\right)^{\frac{1}{\gamma}}$$

$$Z_1^{fiat} = \left(\frac{\beta}{\mu}\right)^{\frac{1}{\gamma}-1}$$

$$\phi_2^a = \frac{\beta\left[\lambda((z-1)\delta+1)\pi_L + (1-\lambda)\left(z\int_0^\delta \widetilde{F}_H(s)ds + \int_\delta^1 \widetilde{F}_H(s)ds\right)\right]}{1-\beta z}$$

$$\phi_2^a = \frac{\zeta\int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds}{(1-\zeta)}.$$

$$\phi^{fiat} = \frac{\beta(\zeta\pi_H - \pi_L)[\lambda\pi_L + (1-\lambda)\pi_H]}{(1-\beta z)(\zeta\pi_H - \pi_L) - \beta(z-1)(1-\zeta)[\lambda\pi_L + (1-\lambda)\pi_H]}$$

$$\delta^{fiat} = \frac{\beta(1-\zeta)[\lambda\pi_L + (1-\lambda)\pi_H]}{(1-\beta z)(\zeta\pi_H - \pi_L) - \beta(z-1)(1-\zeta)[\lambda\pi_L + (1-\lambda)\pi_H]}$$

Equilibrium with CBDC:

$$W(\delta) = (z-1)(1-\zeta)\frac{\lambda\pi_L + (1-\lambda)\pi_H}{\zeta\pi_H - \pi_L}$$

$$z + W(\delta) = z + (z-1)(1-\zeta)\frac{\lambda\pi_L + (1-\lambda)\pi_H}{\zeta\pi_H - \pi_L}.$$

$$\phi_2^a = \beta\phi_2^a (z + W(\delta)) + \beta(\lambda E_L s_t + (1-\lambda) E_H s_t + \Lambda(\delta) + \Psi(\delta))$$

$$\Lambda(\delta) + \Psi(\delta) = \frac{z-1}{z}\frac{\widetilde{F}_H(\delta)\int_0^\delta \widetilde{F}_L(s)ds - \widetilde{F}_L(\delta)\int_0^\delta \widetilde{F}_H(s)ds}{\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta)}.$$

$$\phi_2^a = \beta\phi_2^a\left(z + (z-1)(1-\zeta)\frac{\lambda\pi_L + (1-\lambda)\pi_H}{\zeta\pi_H - \pi_L}\right) + \beta\left(\lambda\pi_L + (1-\lambda)\,\pi_H\right)$$

$$\phi_2^a = \delta^{fiat}\frac{(\zeta\pi_H - \pi_L)}{(1-\zeta)}$$

$$Z_2^{CBDC} = \left(\frac{\beta}{\mu}\right)^{\frac{1}{\gamma}}\left[z + (z-1)(1-\zeta)\frac{\lambda\pi_L + (1-\lambda)\pi_H}{\zeta\pi_H - \pi_L}\right]^{\frac{1}{\gamma}}$$

$$Z_1^{CBDC} = \left(\frac{\beta}{\mu}\right)^{\frac{1}{\gamma}-1}\left[z + (z-1)(1-\zeta)\frac{\lambda\pi_L + (1-\lambda)\pi_H}{\zeta\pi_H - \pi_L}\right]^{\frac{1}{\gamma}-1}$$

$$\phi_2^{CBDC} = \frac{\beta\left(\lambda\pi_L + (1-\lambda)\pi_H\right)}{1 - \beta\left(z + W\left(\delta\right)\right)}$$

$$\phi_2^{CBDC} = \frac{\beta\left(\lambda\pi_L + (1-\lambda)\pi_H\right)}{1 - \beta\left(z + (z-1)(1-\zeta)\frac{\lambda\pi_L + (1-\lambda)\pi_H}{\zeta\pi_H - \pi_L}\right)}$$

$$\phi_2^{CBDC} = \frac{\beta\left(\zeta\pi_H - \pi_L\right)\left[\lambda\pi_L + (1-\lambda)\pi_H\right]}{\left(\zeta\pi_H - \pi_L\right)(1-\beta z) - \beta(z-1)(1-\zeta)\left(\lambda\pi_L + (1-\lambda)\pi_H\right)}$$

$$\delta^{CBDC} = \frac{(1-\zeta)}{(\zeta\pi_H - \pi_L)}\left[Z_1^{CBDC} + \phi_2^{CBDC}\right]$$

That is, $\phi^{fiat} = \phi^{CBDC}$, $Z_1^{CBDC} > Z_1^{fiat}$, $Z_2^{CBDC} > Z_2^{fiat}$ and $\delta^{CBDC} > \delta^{fiat}$.

4.7.2 Only a fraction of money is collatrailizable

Suppose only a fraction α of CBDC can be collateralized. Security face value is

$$y_D(s) = \min(\tilde{s}, \delta) + \phi_1^a + \frac{\alpha\hat{m}}{\hat{a}}\phi_1^m$$

where $\delta = D - \phi_1^a - \frac{\alpha\hat{m}}{\hat{a}}\phi_{1t}^m$. Pooling security price is

$$p_t = \phi_1^a + \frac{\alpha\hat{m}}{\hat{a}}\phi_{1t}^m + \lambda E_L\left[\min(\delta, s_t)\right] + (1-\lambda)E_H\left[\min(\delta, s_t)\right]$$

Value function in the investment market is:

$$\begin{aligned} V_t^1(\hat{m}, \hat{a}) = {} & (z-1)\left[\hat{a}\phi_1^a + \alpha\hat{m}\phi_{1t}^m\right] + (z-1)\hat{a}\left[\lambda E_L\min(\delta, s_t) + (1-\lambda)E_H\min(\delta, s_t)\right] \\ & + \phi_{1t}^m\hat{m} + \left(\lambda E_L s_t + (1-\lambda)\,E_H s_t\right)\hat{a} + \phi_{1t}^a\hat{a} + W_t^1(0,0) \end{aligned} \tag{4.14}$$

The debt is traded in the pooling equilibrium if and only if

$$(1-\zeta)(\phi_{1t}^m\alpha\hat{m} + \phi_{1t}^a\hat{a}) = \hat{a}(\zeta\int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds) \tag{4.15}$$

Using IFT we obtain:

$$\frac{\partial \delta}{\partial \hat{m}} = \frac{(1-\zeta)\alpha\phi_{1t}^{m}}{\hat{a}(\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta))} > 0$$

and

$$\frac{\partial \delta}{\partial \hat{a}} = \frac{(1-\zeta)\phi_{1t}^{a} - \left[\zeta \int_0^{\delta} \widetilde{F}_H(s)ds - \int_0^{\delta} \widetilde{F}_L(s)ds\right]}{\hat{a}(\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta))}.$$

Let

$$W(\alpha, \delta) = 1 + \alpha(z-1)\left[1 + (1-\zeta)\frac{\lambda\widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta))}{\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta)}\right].$$

Envelope theorem gives:

$$\begin{aligned}\frac{\partial V_t^1}{\partial \hat{m}}(\hat{m}, \hat{a}) &= \left[(z-1)\alpha + 1\right]\phi_{1t}^{m} + (z-1)\hat{a}\left[\lambda\widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta))\right]\frac{\partial \delta}{\partial \hat{m}} \\ &= \phi_{1t}^{m} W(\alpha, \delta)\end{aligned}$$

$$\begin{aligned}\frac{\partial V_t^1}{\partial \hat{a}}(\hat{m}, \hat{a}) &= z\phi_{1t}^{a} + (z-1)\left[\lambda E_L \min(\delta, s_t) + (1-\lambda)E_H \min(\delta, s_t)\right] + (\lambda E_L s_t + (1-\lambda)E_H s_t) \\ &\quad + (z-1)\hat{a}\left[\lambda\widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta)\right]\frac{\partial \delta}{\partial a}\end{aligned}$$

$$\begin{aligned}\frac{\partial V_t^1}{\partial \hat{a}}(\hat{m}, \hat{a}) &= z\phi_{1t}^{a} + (z-1)\left[\lambda E_L \min(\delta, s_t) + (1-\lambda)E_H \min(\delta, s_t)\right] + (\lambda E_L s_t + (1-\lambda)E_H s_t) \\ &\quad + (z-1)\left[\lambda\widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta)\right]\frac{(1-\zeta)\phi_{1t}^{a} - \left[\zeta \int_0^{\delta} \widetilde{F}_H(s)ds - \int_0^{\delta} \widetilde{F}_L(s)ds\right]}{\zeta\widetilde{F}_H(\delta) - \widetilde{F}_L(\delta)}\end{aligned}$$

$$\frac{\partial V_t^1}{\partial \hat{a}}(\hat{m}, \hat{a}) = \phi_{1t}^{a} W(1, \delta) + \Lambda(\delta)$$

Hence:

$$\phi_{2t}^{m} = \beta\phi_{1t+1}^{m} W(\alpha, \delta)$$

$$\phi_{2}^{a} = \beta\phi_{2}^{a} W(1, \delta) + \beta\Lambda(\delta)$$

Equilibrium is given by:

$$1 = \frac{\beta}{\mu}u'(Z_2)\, W(\alpha, \delta)$$

$$Z_1 = Z_2 u'(Z_2).$$

$$\phi_{2}^{a} = \beta\phi_{2}^{a} W(1, \delta) + \beta\Lambda(\delta)$$

$$\phi_{1}^{a} = \phi_{2}^{a}$$

$$(1-\zeta)(\alpha Z_1 + \phi_1^a A) \geq A(\zeta \int_0^{\delta} \widetilde{F}_H(s)ds - \int_0^{\delta} \widetilde{F}_L(s)ds)$$

4.8 Comparison of the equilibria with fiat money and CBDC

Next, we compare the equilibrium with tokenized money with the baseline where regular money cannot be used collateral.

Risky asset price with regular physical money is:

$$\begin{aligned}\phi_2^a = \beta z \phi_2^a + \beta(z-1)\left[\lambda \int_0^\delta \widetilde{F}_L(s)ds + (1-\lambda)\int_0^\delta \widetilde{F}_H(s)ds\right] \\ + \beta\left(\lambda E_L s_t + (1-\lambda) E_H s_t\right)\end{aligned}$$

Risky asset price with tokenized money is:

$$\begin{aligned}\phi_2^a = \beta z \phi_2^a + \beta(z-1)\left[\lambda \int_0^\delta \widetilde{F}_L(s)ds + (1-\lambda)\int_0^\delta \widetilde{F}_H(s)ds\right] \\ + \beta\left(\lambda E_L s_t + (1-\lambda) E_H s_t\right) \\ + \beta(z-1)\hat{a}\left[\lambda \widetilde{F}_L(\delta) + (1-\lambda)\widetilde{F}_H(\delta)\right]\frac{\partial \delta}{\partial a}\end{aligned}$$

where

$$\frac{\partial \delta}{\partial \hat{a}} = \frac{(1-\zeta)\phi_2^a - \left[\zeta \int_0^\delta \widetilde{F}_H(s)ds - \int_0^\delta \widetilde{F}_L(s)ds\right]}{\hat{a}(\zeta \widetilde{F}_H(\delta) - \widetilde{F}_L(\delta))}$$

Suppose without tokenized money, incentive compatibility constraint is violated. Then $\frac{\partial \delta}{\partial a} < 0$. For a given δ risky asset price will be lower. However, with tokenized money δ is higher. If $\zeta \widetilde{F}_H(\delta) - \widetilde{F}_L(\delta)$ is small optimal δ then this effect may dominate and risky asset price may be lower with tokenized money.

First, we show that when $u'(x) + u''(x)\, x > 0$, (which implies roughly that asset demand in the model increases with the asset's own rate of return; that is, substitution effects dominate income effects,) the asset price in the regime with CBDCs is not less than the asset price in the regime without CBDC.

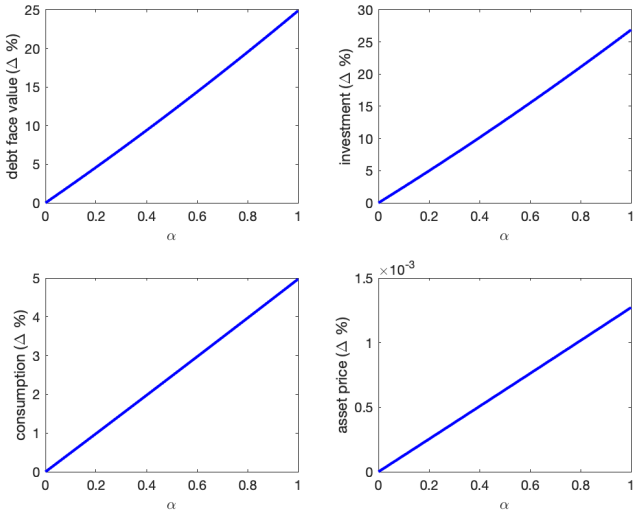
Proposition 4. *The asset price in the equilibrium with CBDCs is less sensitive to information friction than the asset price in the equilibrium without CBDCs. That is,* $\frac{\partial \phi_2^a}{\partial \lambda}|_{\text{CBDCs}} \leq \frac{\partial \phi_2^a}{\partial \lambda}$

To summarize, fiat money derives its value purely as payment instrument while CBDC derives its value from being a payment instrument and a safe collateral. CBDC also increases collateralizability or pledgeability of the risky asset (i.e. D) by lowering the adverse selection consequently increase risky asset price but there is a countervailing effect because CBDC reduces the self-fulfilling feedback of asset price. Since CBDC is more valuable, money now sustains higher consumption/investment with the same money growth, which means a higher seignorage income for central banks.

5 Numerical Examples

In this section, we present numerical examples to examine the effect of CBDCs. In these numerical examples, the equilibrium qualities with CBDCs are graphed in blue and without CBDCs are graphed in red. First, we present an example where only a fraction, denoted by α, of CBDCs is allowed to be pledged as collateral. Figure 5.1 shows that debt face value, investment, consumption, real money balance, and asset prices all increase with this fraction. The percentage increase is much larger for debt face value and investment but very modest for the asset price.

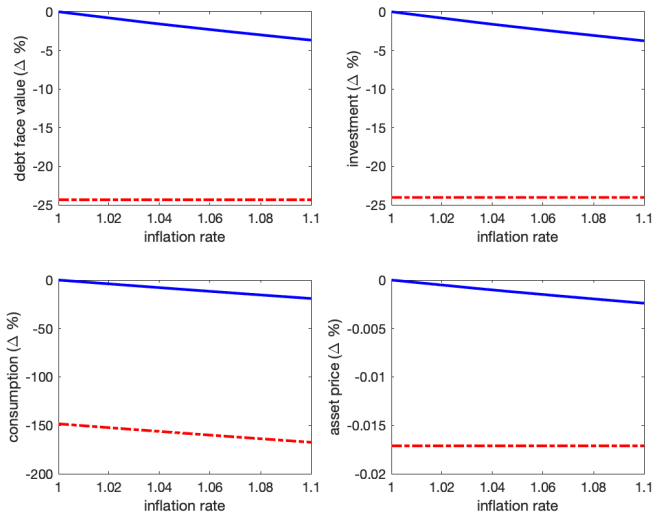
Figure 5.1: Fraction of CBDCs (α) Used as Safe Collateral



The blue line is the CBDC case and the red line is without CBDC. Parameter values:
$z = 1.05, \lambda = 0.9, \beta = 0.9, U(c) = \left(C^{1-\gamma} - 1\right)/(1-\gamma), Q = \{H, L\}, s \sim Exp(l)$, $E_H(s) = 1, E_L(s) = 0.1$,
$l_H = 1, l_L = 10, \mu = 1$

Second, we examine how inflation (μ) affects the equilibrium quantities. The results are shown in Figure 5.2. We find that debt face value, real balance of money, risky asset price, consumption and investment are all decreasing in inflation. However, we find that risky asset price decreases less than real balance of money because risky asset acts as collateral and is used only in securities market instead of consumption market. Investment decreases less than consumption as inflation increases. This is because investment uses both risky asset and CBDC as collateral and risky asset price does not decrease much as inflation rises.

Figure 5.2: Impact of Monetary Policy



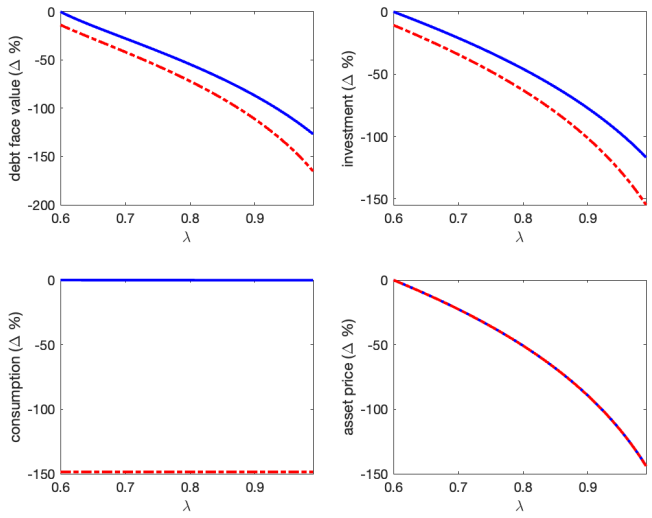
The blue line is the CBDC case and the red line is without CBDC. Parameter values:
$z = 1.05, \lambda = 0.9, \beta = 0.9, U(c) = \left(C^{1-\gamma} - 1\right)/(1-\gamma), Q = \{H, L\}, s \sim Exp(l)$, $E_H(s) = 1, E_L(s) = 0.1$, $l_H = 1, l_L = 10$

Third, we examine how the fraction of low type λ, a proxy for information friction, affects debt face value, investment, consumption, real money balance, and asset prices. The results are shown in Figure 5.3. We find that debt face value, real balance of money, risky asset price, consumption and investment are all decreasing in λ . However, we find that, as λ increases, risky asset price decreases more than real balance of money, and investment decreases more than consumption. This is because investment uses both risky asset and CBDC as collateral. Additionally, comparing the equilibrium quantities across the regime with CBDC (graphed in blue lines) and the regime without CBDC (graphed in red lines), we observe that the debt face value and investment are less sensitive to adverse selection in the regime with CBDC than in the regime without CBDC, indicating that CBDC mitigates information friction in the economy.

6 Conclusion

In this paper, we have constructed a model where money serves both as a payment instrument for consumption goods and as safe asset which can be used as collateral to raise funding in the financial market. We use it to examine the potential impact of CBDCs on financial market and real economy since CBDCs, as

Figure 5.3: Impact of Adverse Selection



The blue line is the CBDC case and the red line is without CBDC. Parameter values:
$z = 1.05, \beta = 0.9, U(c) = \left(C^{1-\gamma} - 1\right) / (1-\gamma), Q = \{H, L\}, s \sim Exp(l),\ E_H(s) = 1, E_L(s) = 0.1,\ l_H = 1, l_L = 10, \mu = 1$

tokenized money, are highly collateralizable. We find CBDCs lower adverse selection in the economy, act as collateral multiplier by increasing the pledgeability of risky assets, increase asset prices, promote more investment, economic activities and consumption.

The higher valuation of CBDCs and the safety aspect of CBDCs will also imply that CBDCs should be preferred over private digital solutions, potentially leading to a larger central bank's seigniorage income. In fact, CBDCs can be seen as akin to establishing a "digital" central bank in a modern "free digital banking era," where the central bank can regain control over currency issuance and potentially increase seigniorage income.

The model has implications for uninsured bank deposits. When tokenized, uninsured bank deposit can be regarded as the semi-safe or risky assets in our model. Combined with CBDCs, their information frictions are lower, pledgeability is higher which means bank funding is greater. This indicates that CBDCs do not necessarily crowd out bank financing but require bank deposits tokenized.

Motivated by the fact that assets under the (capital-)market-based financial intermediation have surpassed those under traditional banks (characterized by the originate-and hold business models) by the end of 2018, Ozdenoren, Yuan, and Zhang (2021) have established a theoretical framework to analyze the impact

of such (capital-)market-based financial system on the asset price, investment, output, and the fragility of the economy. However, these market-based financial system is still based on the monetary foundation that is heavily relied on bank notes to intermediate cash flows.

In a policy speech, He (2023) proposed that CBDC represents a new monetary foundation for the digital economy, while the tokenization of assets is being actively explored worldwide as a catalyst for innovating monetary and financial services. Adrian and Griffoli (2023) from the IMF envisioned an exchange platform for both cross-border and domestic CBDC transactions. Our paper supports these propositions and provides a detailed economic mechanism that utilizes CBDCs to construct a unique financial infrastructure. Our paper shows that tokenized CBDC is compatible with the evolving capital-market-based financial system in the current economy and models their unique interactions.

In practice, central banks face numerous practical tradeoffs when designing their CBDC offerings, including privacy concerns and potential disruption to the banking sector during the transition to the digital era. This paper emphasizes that the safe asset feature of CBDCs can significantly enhance the efficiency of the monetary and financial systems, advocating that programmability and contractibility of tokenized money should be incorporated into CBDC design, even if not initially utilized.

China's central bank exemplifies this pragmatic approach with the launch of its digital currency, termed 'Digital Currency Electronic Payment' (DC/EP) or 'Digital RMB.' To minimize economic disruption, the DC/EP functions as digital cash with an upper limit on account balances, issued through commercial bank accounts or special wallets. It is built with blockchain and cryptography, featuring programmability, yet operates on a centralized database. There are various types of E-CNY wallets cater to personal or corporate use cases, offering different levels of privacy or anonymity with a range of account balance caps.

In conclusion, our analysis of CBDC with built-in programmability and contractibility functionality indicates that as a safe asset for the economy, it facilitates the integration of monetary and financial systems, establishing the monetary groundwork for constructing the next generation of financial infrastructure in the digital era.

References

Abad, Jorge, Galo Nuno, and Carlos Thomas (2024). "Cbdc and the Operational Framework of Monetary Policy". In: *SSRN Electronic Journal*. DOI: 10.2139/ssrn.4703300.

Adrian, Tobias and Tommaso Mancini Griffoli (2023). *The Rise of Payment and Contracting Platforms*. Fintech Note 005. IMF. URL: https://www.imf.org/en/Publications/fintech-notes/Issues/2023/06/16/The-Rise-of-Payment-and-Contracting-Platforms-534794?utm_source=coinspaidmedia&utm_medium=referral&utm_campaign=imf-proposes-concept-platforms-tokenized-assets.

Agur, Itai, Anil Ari, and Giovanni Dell'Ariccia (2022). "Designing central bank digital currencies". In: *Journal of Monetary Economics* 125, pp. 62–79. ISSN: 0304-3932. DOI: https://doi.org/10.1016/j.jmoneco.2021.05.002. URL: https://www.sciencedirect.com/science/article/pii/S0304393221000520.

Ahnert, Toni, Peter Hoffmann, and Cyril Monnet (2024). *Payments and privacy in the digital economy*. Working Papers. ECB.

Ahnert, Toni et al. (2023). *Central Bank Digital Currency and Financial Stability*. Working Papers. ECB.

Andolfatto, David (2021). "Assessing the Impact of Central Bank Digital Currency on Private Banks". In: *The Economic Journal* 131.634, pp. 525–540.

Barrdear, John and Michael Kumhof (2022). "The macroeconomics of central bank digital currencies". In: *Journal of Economic Dynamics and Control* 142. The Economics of Digital Currencies, p. 104148. ISSN: 0165-1889. DOI: https://doi.org/10.1016/j.jedc.2021.104148. URL: https://www.sciencedirect.com/science/article/pii/S016518892100083X.

Bijlsma, Michiel et al. (2021). "What triggers consumer adoption of Central Bank Digital Currency?" In: *SSRN Electronic Journal*. DOI: 10.2139/ssrn.3839477.

Brunnermeier, Markus K. and Valentin Haddad (In Preparation). "Safe Assets". In:

Brunnermeier, Markus K. and Dirk Niepelt (2019). "On the equivalence of private and public money". In: *Journal of Monetary Economics* 106, pp. 27–41. ISSN: 0304-3932. DOI: https://doi.org/10.1016/j.jmoneco.2019.07.004. URL: https://www.sciencedirect.com/science/article/pii/S0304393219301229.

Burlon, Lorenzo, Manuel A. Munoz, and Frank Smets (2023). "The Optimal Quantity of CBDC in a Bank-Based Economy". In: *American Economic Journal: Macroeconomics* forthcoming.

Caballero, Ricardo and Emmanuel Farhi (2017). "The Safety Trap". In: *The Review of Economic Studies* 85.1, pp. 223–274. ISSN: 0034-6527. DOI: 10.1093/restud/rdx013. eprint: https://academic.oup.com/restud/article-pdf/85/1/223/23033558/rdx013.pdf. URL: https://doi.org/10.1093/restud/rdx013.

Caballero, Ricardo J., Emmanuel Farhi, and Pierre-Olivier Gourinchas (2017). "The Safe Assets Shortage Conundrum". In: *Journal of Economic Perspectives* 31.3, pp. 29–46. DOI: 10.1257/jep.31.3.29. URL: https://www.aeaweb.org/articles?id=10.1257/jep.31.3.29.

Chiu, Jonathan et al. (2019). *Central Bank Digital Currency and Banking*. 2019 Meeting Papers 862. Society for Economic Dynamics. URL: https://ideas.repec.org/p/red/sed019/862.html.

Chiu, Jonathan et al. (2023). *On the Fragility of DeFi Lending*. Staff Working Papers 23-14. Bank of Canada. URL: https://ideas.repec.org/p/bca/bocawp/23-14.html.

Dang, Tri Vi, Gary Gorton, and Bengt Holmstrom (2013). "The information sensitivity of a security". In: *Working paper*.

Davoodalhosseini, Seyed Mohammadreza (2022). "Central bank digital currency and monetary policy". In: *Journal of Economic Dynamics and Control* 142. The Economics of Digital Currencies, p. 104150. ISSN: 0165-1889. DOI: https://doi.org/10.1016/j.jedc.2021.104150. URL: https://www.sciencedirect.com/science/article/pii/S0165188921000853.

Fernandez-Villaverde, Jesus et al. (2021). "Central Bank Digital Currency: Central Banking For All?" In: *Review of Economic Dynamics* 41, pp. 225–242. DOI: 10.1016/j.red.2020.12.004.

Garratt, Rodney J, Jiaheng Yu, and Haoxiang Zhu (2022). *The Case for Convenience: How CBDC Design Choices Impact Monetary Policy Pass-Through*. BIS Working Papers 1046. Bank for International Settlements. URL: https://ideas.repec.org/p/bis/biswps/1046.html.

Gorton, Gary and Guillermo Ordoñez (2020). "Fighting Crises with Secrecy". In: *American Economic Journal: Macroeconomics* 12.4, pp. 218–45. DOI: 10.1257/mac.20190169. URL: https://www.aeaweb.org/articles?id=10.1257/mac.20190169.

Gorton, Gary B. and Guillermo Ordonez (2013). *The Supply and Demand for Safe Assets*. NBER Working Papers 18732. National Bureau of Economic Research, Inc. URL: https://ideas.repec.org/p/nbr/nberwo/18732.html.

He, Dong (2023). *CBDC: The Monetary Foundation for Digitalized Capital Markets*.

Huynh, Kim, Gradon Nicholls, and Oleksandr Shcherbakov (2022). *Equilibrium in Two-Sided Markets for Payments: Consumer Awareness and the Welfare Cost of the Interchange Fee*. Staff Working Papers 22-15. Bank of Canada. URL: https://ideas.repec.org/p/bca/bocawp/22-15.html.

Keister, Todd and Daniel Sanches (2022). "Should Central Banks Issue Digital Currency?" In: *The Review of Economic Studies* 90.1, pp. 404–431. ISSN: 0034-6527. DOI: 10.1093/restud/rdac017. eprint: https:

//academic.oup.com/restud/article-pdf/90/1/404/48523295/rdac017.pdf. URL: https://doi.org/10.1093/restud/rdac017.

Kiyotaki, Nobuhiro and John Moore (1997). "Credit cycles". In: *Journal of Political Economy* 105.2, pp. 211–248.

Kiyotaki, Nobuhiro and Randall Wright (1989). "On Money as a Medium of Exchange". In: *Journal of Political Economy* 97.4, pp. 927–954. ISSN: 00223808, 1537534X. URL: http://www.jstor.org/stable/1832197 (visited on 03/24/2024).

Kotidis, Antonis, Margaux MacDonald, and Dimitris Malliaropulos (2023). *Guaranteeing Trade in a Severe Crisis: Cash Collateral over Bank Guarantees*. Staff Working Papers. IMF.

Lagos, Ricardo, Guillaume Rocheteau, and Randall Wright (2017). "Liquidity: A New Monetarist Perspective". In: *Journal of Economic Literature* 55.2, pp. 371–440. DOI: 10.1257/jel.20141195. URL: https://www.aeaweb.org/articles?id=10.1257/jel.20141195.

Lagos, Ricardo and Randall Wright (2005). "A unified framework for monetary theory and policy analysis". In: *Journal of Political Economy* 113.3, pp. 463–484.

Lester, Benjamin, Andrew Postlewaite, and Randall Wright (2012). "Information, liquidity, asset prices, and monetary policy". In: *Review of Economic Studies* 79.3, pp. 1209–1238.

Li, Jiaqi (2023). "Predicting the demand for central bank digital currency: A structural analysis with survey data". In: *Journal of Monetary Economics* 134, pp. 73–85. ISSN: 0304-3932. DOI: https://doi.org/10.1016/j.jmoneco.2022.11.007. URL: https://www.sciencedirect.com/science/article/pii/S0304393222001398.

Niepelt, Dirk (2023). *Money and Banking with Reserves and CBDC*. Discussion Papers. CEPR.

Ozdenoren, Emre, Kathy Yuan, and Shengxing Zhang (2021). *Dynamic Asset-Backed Security Design*. London School of Economics.

— (2023). *Safe Assets as Balance Sheet Multiplierss*. Working Paper. LSE.

Papoutsi, Melina et al. (2024). *Collateralized Corporate Loan Markups*. Working Paper. LSE.

Paul, Pascal, Mauricio Ulate, and Jing Cynthia Wu (2024). *A Macroeconomic Model of Central Bank Digital Currency*. Working Papers 11. Federal Reserve Bank of San Francisco.

Whited, Toni, Yufeng Wu, and Kairong Xiao (2022). "Central Bank Digital Currency and Banks". In: *SSRN Electronic Journal*. DOI: 10.2139/ssrn.4112644.

Williamson, Stephen (2022). "Central Bank Digital Currency: Welfare and Policy Implications". In: *Journal of Political Economy* 130.11, pp. 2829–2861. DOI: 10.1086/720457.