Equilibrium Implications of Monetary Regime Change

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Abstract

We analyze monetary regime change due to retail CBDC or private cryptocurrencies. Allowing for general frictions we identify causes of non-neutrality related to payment preferences; fiscal instruments; technology; deposit complementarities; political frictions; and the mode of liquidity injection. Effects of cryptocurrencies are harder to offset than of CBDC. Our results imply that the value of central bank lender-of-last-resort guarantees for U.S. banks equals a quarter percent of GDP.

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1 Introduction

The monetary architecture in modern economies faces seismic shifts. Private cryptocurrencies make inroads into payment systems that have traditionally been dominated by public-private partnerships of monetary authorities and commercial banks built on national currencies. These partnerships are subject to change as well. With the advent of retail central bank digital currency (CBDC) or "reserves for all," financial intermediation and payments decouple and bank business models are put to the test.

How wide-ranging will the macroeconomic implications of this regime change be? An emerging literature, discussed below, offers first insights and points to important roles of policy and various elements in the economic environment. It leaves open, however, how these specific elements relate to each other and how fundamental they are.

The aim of this paper is to provide a general, unifying perspective on the ongoing regime change and to identify key elements that determine its macroeconomic implications. Since we are interested in general insights we embed the analysis in an abstract framework that nests a large set of models, including prominent ones in the literature. Rather than examining specific setups to obtain specific conclusions we pursue the opposite approach: We ask under what conditions regime change generally leaves the allocation and price system unaffected, and we use the answer to this question to identify fundamental factors that break the neutrality and make the change have material effects.

We begin the analysis by laying out an abstract monetary economy and its equilibrium. Our setup imposes very few restrictions and allows for complex frictions and very rich heterogeneity in all sectors of the economy. It accommodates various financial intermediaries, general sources of supply and demand for liquidity as well as arbitrary regulatory constraints or information limitations that can give rise to financial constraints or a "bank lending channel." We do not impose functional form assumptions on preferences, technology or other primitives. Consequently, the analysis sidesteps first-order conditions and instead emphasizes choice sets of economic agents and policy makers.

Within this general setup, we identify conditions under which a regime change is neutral. We define a regime change as an internally consistent change of balance sheet positions in the private and public sectors, potentially accompanied by transfers. And we define a regime change to be neutral if it does not alter the equilibrium allocation or price system. The conditions we find ensure that the regime change does not alter the effective choice sets of agents implying that except for balance sheet positions and transfers, the equilibrium does not change as well.

Following this abstract analysis, we interpret our general neutrality conditions in the CBDC context. We show that the wealth distribution and the private sector's liquidity holdings must not change if neutrality is to be guaranteed. Intuitively, and in line with Brunnermeier and Niepelt (2019), changes in the wealth distribution alter choice sets (and thus choices) and unchanged wealth levels at unchanged prices demand unchanged liquidity holdings. Fundamentally, neutrality thus requires constant marginal rates of substitution between different sources of liquidity, ruling out for example non-linear aggregation of "monies in the utility function." Depending on the payment characteristics of deposits and CBDC it may also require lump-sum transfers of zero market value.

We identify several additional fundamental neutrality conditions in the CBDC context. They relate to the marginal rate of transformation between different sources of liquidity; deposit-specific complementarities; the mode of CBDC injection; and state variables. Violations of either of the four conditions undermine the fundamental adjustment mechanism that renders a regime change neutral: They make it impossible to seamlessly channel CBDC funds to banks exposed to deposit outflows, and by preventing such flows they alter choice sets.

According to the first condition, the marginal rate of transformation between CBDC and deposits (or other sources of liquidity that CBDC replaces) must equal unity for a regime change to be neutral. Intuitively, when the aggregate resource requirements of CBDC and deposits differ neutrality must fail. We relate this restriction to models of CBDC and bank operating or balance sheet costs (Niepelt, 2020a, 2024; Piazzesi and Schneider, 2022) as well as of CBDC and the interbank market (Abad et al., 2023; Lamersdorf et al., 2023).

Second, neutrality may fail when deposits are "special" in the sense that they feature complementarities with other bank balance sheet positions that alternative bank funding sources do not feature. Such a situation could arise, for example, if deposit funding required less collateral than other sources of bank funding, for instance because the central bank provided unsecured lender-of-last-resort guarantees while insisting on collateral when lending to banks. We connect this point to a frequently made point in the policy debate.

In contrast, incentive constraints and associated collateral requirements in the banking sector do not *per se* undermine neutrality even if the central bank does not face them to the same extent, as in Williamson (2022).[1] After all, such frictions in the banking sector do not prevent the central bank from channelling CBDC funds back to the constrained institutions without allocative effects. Similarly, the empirical fact that deposit funding reduces financing costs and improves hedging (e.g., Whited et al., 2023) does not imply specialness since an appropriately structured central bank loan can replicate this.

Third, the mode of CBDC injection matters. Intuitively, CBDC injected by transfer, as in Keister and Sanches (2023) or Chiu et al. (2023), or by quantitative-easing type swaps of government bonds against CBDC, as in Kumhof and Noone (2021) or Barrdear and Kumhof (2022), increase the supply of liquidity on impact. To balance supply and demand the price of liquidity services thus must fall and this undermines the neutrality of a regime change with CBDC transfers. In contrast, injection by open market operations that maintain the supply of liquidity need not break equivalence.

A final potential source of non-neutrality is present when a regime change affects state variables that are irrelevant for a Ramsey government but relevant when policy is chosen sequentially or because of (other) political-economy frictions. Intuitively, policy makers without commitment re-optimize ex post, and they re-optimize differently after a regime change that alters political state variables. Similarly, fundamentally irrelevant state variables such as central bank balance sheet length may matter because of political frictions, for instance when they affect the salience of issues. We relate this source of non-neutrality to a general result in Gonzalez-Eiras and Niepelt (2015) and to discussions

[1] See also Böser and Gersbach (2020).

about political consequences of CBDC (Tucker, 2017; Cecchetti and Schoenholtz, 2018; Niepelt, 2021).[2]

In stark contrast to these fundamental sources of non-neutrality many other frictions need *not* undermine neutrality. We show, for example, that lack of competition in the banking sector, a two-tier monetary architecture with both reserves and bank money, or costs and benefits of maturity transformation are perfectly compatible with neutral regime change. In fact, a regime change may even be neutral when deposit and CBDC services generate resource costs (subject to the condition on the marginal rate of transformation discussed above) or if bank and central bank balance sheet length or central bank pass-through funding cause social costs.

These findings qualify frequent suggestions in the policy debate according to which a change of monetary architecture would have major (positive or negative) macroeconomic consequences. As our results show, it is very much in the hands of policy makers to choose whether CBDC has such wide ranging effects. And they make clear that the suggested implications of CBDC often derive from implicit assumptions about features in the economic environment that actually are orthogonal to CBDC.

Next, we turn our attention to private cryptocurrencies. We argue that the CBDC analysis applies largely unchanged with one important qualification: The incentives of a private cryptocurrency issuer introduce additional constraints on the set of implementable equilibria after a regime change. This makes it more difficult to offset the effects of a private cryptocurrency than of CBDC. A competitive stablecoin subject to no operating costs and no inherent liquidity benefits constitutes a very special case of a cryptocurrency that can satisfy the conditions for neutrality. We also discuss the introduction of bubbly "cryptocurrencies" (or bubbly CBDC) and argue that this changes the equilibrium allocation.

We also emphasize additional implications of our findings. First, we focus on the possibility of Pareto improving monetary regime change. When the neutrality conditions are satisfied, a Pareto improving intervention typically is feasible as long as the intervention enlarges the choice sets of policy makers. When the conditions are not satisfied then a Pareto improving regime change still is possible as long as CBDC or private cryptocurrencies require fewer resources or relax other equilibrium constraints. Second, we discuss how strongly the neutrality baseline relies on direct central bank refinancing of banks as opposed to bank funding from other market participants.

Finally, we exploit our neutrality conditions to gauge the value of central-bank lender-of-last-resort guarantees. We rely on the fact that the status quo can be mapped into a monetary architecture with CBDC and central bank funding of banks at favorable terms: Rather than issuing deposits (possibly exerting market power), partly investing them in reserves and operating a costly payment system banks could borrow from the central bank, which in turn issues CBDC; the effective choice set of banks would remain unaltered as long as the central bank posted a loan supply schedule commensurate to the deposit funding schedule under the status quo, controlling for operating costs, reserve holdings, and interest on reserves. We argue that the difference between safe, illiquid funding at

[2]See also Keister and Monnet (2022) and Niepelt (2020b) on the effect of regime change on information sets.

market rates and central bank funding at the "equivalent" loan rate in this alternative scenario determines the effective liquidity rent on bank deposits and thus, implicitly, the value of the central bank's lender-of-last-resort guarantee for banks. Relying on recent literature on liquidity premia we estimate this value for the U.S. to be on the order of a quarter percent of GDP.

Related Literature Our approach to establishing sufficient conditions for neutral regime change by comparing choice sets follows Gonzalez-Eiras and Niepelt (2015) and Brunnermeier and Niepelt (2019) as well as a classic literature on equivalence results including Modigliani and Miller (1958), Barro (1974), Wallace (1981), Bryant (1983), Chamley and Polemarchakis (1984) and Sargent (1987, 5.4). We show how the equivalence perspective can be applied in the context of monetary regime change, how it allows to identify potential sources of non-neutrality, and we use it to gauge the value of central-bank lender-of-last-resort guarantees for commercial banks.

The growing literature on the macroeconomic implications of CBDC and private cryptocurrencies contains many contributions in addition to the papers already cited. For example, in Andolfatto (2021) the introduction of CBDC leads noncompetitive banks to raise the deposit rate, with positive effects on financial inclusion although CBDC does not circulate in equilibrium.[3] Burlon et al. (2022) conduct a quantitative DSGE analysis in a model with CBDC that contains several of the sources of non-neutrality discussed above. Benigno et al. (2022) focus on the role of market participation in the international context.[4] Schilling et al. (2020) analyze conflicts between allocative efficiency, price stability, and financial stability that are present in monetary economies including a CBDC based system. Design options for CBDC are the focus of Kahn et al. (2018), Bindseil (2020), and Auer and Böhme (2020), among others. Garratt and van Oordt (2021) analyze the disciplining effect of CBDC on agents that exploit consumer information.

Our empirical analysis of the value of lender-of-last-resort guarantees connects to the recent literature on liquidity premia, Hanson et al. (2015), Nagel (2016), Kurlat (2019), Van den Heuvel (2022) and Bianchi and Bigio (2022).

Structure Section 2 lays out the economy and defines equilibrium, and Section 3 develops the general neutrality conditions. In Sections 4 and 5, respectively, we interpret the general conditions in the context of CBDC and private cryptocurrencies and we relate our findings to the literature. Section 6 discusses normative aspects and the role of central bank pass-through funding and Section 7 computes the value of lender-of-last-resort guarantees. Section 8 concludes.

2 The Model

Agents, Time and Risk We consider an economy with heterogeneous households, firms and banks as well as a consolidated government consisting of a central bank and

[3] For a qualification of this result, see Niepelt (2024).

[4] See also Ferrari Minesso et al. (2022).

a fiscal authority. We index private sector agents by i and denote their set by I. We allow for arbitrary dimensions of heterogeneity and do not impose symmetry assumptions. Preferences, technology and potentially other primitives may be subject to shocks. Time is discrete and indexed by t, histories up to and including t are indexed by ϵ^t.

Commodities and Assets We allow for arbitrary commodities and assets and we allow both to arbitrarily enter objectives and the determinants of choice sets.[5] Since this blurs the distinction between commodities and assets we refer to an *allocation* as a collection of both commodity and asset positions.

Individual Constraints and Objectives Each $i \in I$ as well as the government is subject to *individual constraints*. They include dynamic budget constraints[6] and no-Ponzi game conditions and they may also include technological constraints, borrowing limits, portfolio exclusion restrictions, links between the quantity of goods or assets and their price (when agents have market power), incentive constraints, regulatory constraints, etc. Each $i \in I$ also has an *objective*.

Formally, we let $\mathcal{C}^i$ denote the individual constraints faced by household, firm or bank i and we let $\mathcal{U}^i$ denote i's objective.[7] Both $\mathcal{C}^i$ and $\mathcal{U}^i$ take two arguments: First, i's choices, c^i. And second, factors beyond i's control, f^i. Such factors might include prices that i takes as given, demand functions for i's supplies when i has market power, production functions, external habits, etc. Agent i's *choice set* consists of the set of c^i such that (c^i, f^i) satisfies $\mathcal{C}^i$.

We denote the individual constraints of the government by $\mathcal{C}^g$ and the government's choices and factors by c^g and f^g, respectively; c^g constitutes the government policy, for instance its use of resources, quantity and/or price targets for government balance sheet positions, or tax functions. We denote by $\mathcal{C}$ the set of individual constraints of households, firms, banks and the government, and by $\mathcal{U}$ the set of objectives of households, firms and banks.

Aggregate Constraints In addition to the individual constraints $\mathcal{C}$ there are *aggregate constraints*, $\mathcal{A}$, such as market clearing conditions or other cross-agent relationships that connect choices and factors across individual constraints.[8] $\mathcal{A}$ takes two arguments: First, the union of the choices of households, firms, banks and the government, $c \equiv \cup_{i \in I} c^i \cup c^g$.

[5]For example, positions in means of payment may enter objectives (below: $\mathcal{U}$) when households and firms "like" liquidity as in Sidrauski (1967); they may enter constraints (below: $\mathcal{C}$) through "payment-in-advance" constraints as in Clower (1967); and they may enter cost functions when payments or balances require resources as in Baumol (1952) and Tobin (1956) or because bank operations require human resources and equipment.

[6]The dynamic budget constraint links an agent's beginning- and end-of-period balance sheet positions, the returns on these positions including capital gains and the net expenditures on commodities, all inclusive of taxes and transfers.

[7]$\mathcal{C}^i$ is a vector of inequalities of the form $\mathcal{C}^{i,s}(c^i, f^i) \leq 0, s = 1, 2, \ldots$; c^i and f^i are introduced below.

[8]$\mathcal{A}$ is a vector of inequalities of the form $\mathcal{A}^s(c, f) \leq 0, s = 1, 2, \ldots$; c and f are introduced below. Another example of an aggregate constraint is a technological externality.

And second, economy-wide factors, f, which are a subset of the union of factors in the individual constraints, $f \subseteq \cup_{i \in I} f^i \cup f^g$.

Equilibrium An *equilibrium* conditional on an initial state and a government policy is a feasible allocation and a price system consistent with $\mathcal{U}$ maximization on the part of private sector agents. Equivalently, an equilibrium consists of choices and factors, each of which may include elements of the allocation and the price system, such that the choices are feasible for the agents given the factors and optimal for the private sector agents.

Formally, an equilibrium conditional on an initial state and policy c^{g*} is a collection $(\{c^{i*}, f^{i*}\}_{i \in I}, f^{g*}, f^*)$, such that (c^{i*}, f^{i*}) satisfies $\mathcal{C}^i$ and c^{i*} maximizes $\mathcal{U}^i(\cdot, f^{i*})$ in i's choice set $\forall i \in I$; (c^{g*}, f^{g*}) satisfies $\mathcal{C}^g$; and (c^*, f^*) satisfies $\mathcal{A}$.

3 Neutral Regime Change

Starting from some "initial" equilibrium, indicated by "$*$," we consider a *regime change*, indicated by "Δ," which consists of changes in *transfers* as well as *affected balance sheet positions*. We are interested in sufficient conditions under which this regime change is consistent with a "new" equilibrium with the same price system and the same allocation except for the affected balance sheet positions. Other changes relative to the initial equilibrium are ruled out. In other words, we are interested in sufficient conditions for the *neutrality* of the regime change.

3.1 Conditions Related to $\mathcal{C}$

We start by focusing on neutrality conditions related to $\mathcal{C}$. There are two such conditions. First, in order to render the regime change feasible, it must respect the choice sets of all private sector agents and the government. And second, the regime change must not materially change the choice sets in the private sector.

To formalize these conditions let $c^{i*} + \Delta c^i$ and $f^{i*} + \Delta f^i$, respectively, denote the choices and factors in the program of household, firm or bank i that result when these objects maintain their equilibrium values except for the regime change; and proceed in parallel for the government. We have the following first condition:

Condition 1. For all $i \in I$, $(c^{i*} + \Delta c^i, f^{i*} + \Delta f^i)$ satisfies $\mathcal{C}^i$ and $\mathcal{U}^i(c^{i*}, f^{i*}) = \mathcal{U}^i(c^{i*} + \Delta c^i, f^{i*} + \Delta f^i)$. Moreover, $(c^{g*} + \Delta c^g, f^{g*} + \Delta f^g)$ satisfies $\mathcal{C}^g$.

Condition 1 states that if i faces the same environment as in the initial equilibrium except for the modified policy and affected balance sheet positions of other agents then it is feasible for i to choose $c^{i*} + \Delta c^i$; moreover, this choice yields the same payoff as in the initial equilibrium.[9] The condition also states that the government can choose $c^{g*} + \Delta c^g$ in the new environment. Condition 1 is violated, for example, if the regime change tightens or relaxes an agent's constraints or affects its objective.

[9] The condition that payoffs do not change can be relaxed. It can be dropped when there is a one-to-one relationship between c^i and $\tilde{c}^i$ in Condition 2 below.

While Condition 1 is necessary for the regime change to be implementable it is not sufficient (even abstracting from $\mathcal{A}$ for now). After all, there is no guarantee that i finds it optimal to actually choose $c^{i*}+\Delta c^i$ given $f^{i*}+\Delta f^i$. A sufficient condition to guarantee this is that the regime change materially preserves the choice sets of private sector agents:

Condition 2. For all $i \in I$ the following holds true: For each c^i such that (c^i, f^{i*}) satisfies $\mathcal{C}^i$ there exists a $\tilde{c}^i$ such that $(\tilde{c}^i, f^{i*}+\Delta f^i)$ satisfies $\mathcal{C}^i$ and $\mathcal{U}^i(c^i, f^{i*}) = \mathcal{U}^i(\tilde{c}^i, f^{i*}+\Delta f^i)$.

Condition 2 states that the modified transfers and affected balance sheet positions of other agents associated with the regime change do not reduce or enlarge choice sets as far as payoffs are concerned: Each payoff that a private sector agent could attain in the initial equilibrium remains attainable after the regime change.[10] Condition 2 is violated in similar circumstances as Condition 1. However, the scope for violations of Condition 2 is larger because the condition applies for arbitrary (feasible) choices, not only for choices consistent with the regime change.

If Condition 2 is satisfied then each possible choice in the initial equilibrium environment has a corresponding choice in the environment after the regime change which yields the same payoff. The preferred choice after the regime change (i.e., conditional on $f^{i*}+\Delta f^i$) then is given by the $\tilde{c}^i$ that corresponds to c^{i*}. Moreover, if Condition 1 is satisfied then this $\tilde{c}^i$ equals $c^{i*}+\Delta c^i$. In combination, the two conditions therefore imply that it is optimal for i to choose $c^{i*}+\Delta c^i$ given $f^{i*}+\Delta f^i$.

3.2 Conditions Related to $\mathcal{A}$

Next, we focus on conditions related to $\mathcal{A}$. Since aggregate constraints do not constrain the choice sets of private sector agents we do not need to impose a condition on $\mathcal{A}$ that parallels Condition 2 for $\mathcal{C}$. It suffices to impose a condition like Condition 1 to guarantee that the regime change is feasible at the aggregate level:

Condition 3. $(c^*+\Delta c, f^*+\Delta f)$ satisfies $\mathcal{A}$.

If the regime change satisfies market clearing conditions, i.e., if changes in affected balance sheet positions across agents match, then the regime change automatically satisfies the relevant restrictions in $\mathcal{A}$. Nevertheless, a regime change may violate $\mathcal{A}$, for example because the regime change has implications for commodity markets or because affected balance sheet positions generate externalities.[11]

3.3 Neutrality

In summary, we have the following result:

Theorem 1. Consider an initial equilibrium conditional on a state and policy. Under Conditions 1–3 a regime change is consistent with a new equilibrium with unchanged price system and allocation except for the affected balance sheet positions.

[10] This can be relaxed. For example, it suffices if the ranking of attainable payoffs is preserved.

[11] Such an externality could arise because of learning by doing when handling certain balance sheet positions if handling causes costs.

Proof. Consider a private sector agent $i \in I$. From Conditions 1 and 2 i can, and prefers to choose $c^{i*} + \Delta c^i$ given $f^{i*} + \Delta f^i$. Since this argument applies for all $i \in I$ the regime change is consistent with equilibrium as far as $\mathcal{C}$ is concerned. By Condition 3 it is also consistent with $\mathcal{A}$. □

4 CBDC

We now apply this abstract framework to a regime change that involves an expansion of retail central bank digital currency (CBDC). We check what properties such an expansion must have and by what measures it must be accompanied to satisfy Conditions 1–3 for neutrality. Subsequently, we connect the results to models of CBDC in the literature and we assess whether—or under what circumstances—these models imply neutrality or non-neutrality.

4.1 Regime Change

Without loss of generality we focus on a regime change in history ϵ^t and its immediate successor histories, $\{\epsilon^{t+1|t}\}$, that only involves one bank, $b \in I$.[12] We restrict the affected balance sheet positions to deposits, n; reserves, r; CBDC, m; a central bank loan to the bank, ℓ; and exposure to physical capital, e.g., bank loans to "main street," k.[13]

Formally, letting $J \subset I$ denote the set of households and firms, the regime change involves the following changes in affected balance sheet positions carried from history ϵ^t into period $t+1$:

$$\{\Delta n^i_{t+1}(\epsilon^t), \Delta m^i_{t+1}(\epsilon^t), \Delta k^i_{t+1}(\epsilon^t)\}_{i\in J}, \quad \Delta n^b_{t+1}(\epsilon^t), \Delta \ell^b_{t+1}(\epsilon^t), \Delta r^b_{t+1}(\epsilon^t),$$
$$\Delta m^g_{t+1}(\epsilon^t), \Delta r^g_{t+1}(\epsilon^t), \Delta \ell^g_{t+1}(\epsilon^t), \Delta k^g_{t+1}(\epsilon^t).$$

The first set of changes concerns households and firms whose holdings of deposits, CBDC, and capital may change. The second set concerns the bank's deposit and loan liabilities as well as its reserve holdings. The final set concerns the government's CBDC and reserve liabilities along with its loan and capital holdings. In addition, the regime change involves changes in transfers to households, firms, the bank and the government, respectively, in history ϵ^t and its immediate successor histories:

$$\{\Delta\tau^i_t(\epsilon^t), \{\Delta\tau^i_{t+1}(\epsilon^{t+1|t})\}\}_{i\in J\cup b}, \quad \Delta\tau^g_t(\epsilon^t), \ \{\Delta\tau^g_{t+1}(\epsilon^{t+1|t})\}.$$

Note that a regime change does *not* include changes in bank capital holdings, i.e., we require the change in monetary architecture to be associated with unaltered investment financing by banks. Implicitly, we therefore impose restrictions (that could be embedded either in $\mathcal{C}$ or $\mathcal{A}$ constraints) according to which it is crucial that banks rather than

[12] The extension to regime change in multiple histories or involving many banks is immediate.

[13] The central bank loan to banks, ℓ, may be interpreted broadly: The central bank could extend a loan to a third party as long as this third party extends a loan of the same size and subject to the same terms to the bank.

households, firms or the central bank extend credit to main street. In other words, our analysis is robust to arbitrary forms of a "bank lending channel" (Bernanke and Blinder, 1988).

We impose from the outset that the regime change satisfies asset market clearing (encoded in $\mathcal{A}$). That is, the change in the bank's deposit liabilities equals the total change in households' and firms' deposit holdings, $\Delta n^b_{t+1} = \sum_{i \in J} \Delta n^i_{t+1}$; ditto for CBDC, $\Delta m^g_{t+1} = \sum_{i \in J} \Delta m^i_{t+1}$; the total position of households, firms and the government in capital remains constant, $\Delta k^g_{t+1} = -\sum_{i \in J} \Delta k^i_{t+1}$; and reserve as well as loan changes in the balance sheets of the bank and the central bank match, $\Delta r^g_{t+1} = \Delta r^b_{t+1}$ and $\Delta \ell^g_{t+1} = \Delta \ell^b_{t+1}$.[14] Moreover, transfer changes must sum to zero in each history.

4.2 Implications of Conditions 1 and 2

To satisfy Condition 1 the transfers must be adapted to the changes in the affected balance sheet positions to satisfy the agents' budget constraints at dates t and $t+1$. Denoting equilibrium gross rates of return for a generic asset x by $R^{x*}_{t+1}(\epsilon^{t+1|t})$ this entails for households or firms and for the bank, respectively,

$$\begin{aligned}
\sum_{x=n,m,k} \Delta x^i_{t+1} &= \Delta \tau^i_t \quad \forall i \in J, && (1)\\
\sum_{x=n,m,k} R^{x*}_{t+1} \Delta x^i_{t+1} &= -\Delta \tau^i_{t+1} \quad \forall i \in J, \forall \epsilon^{t+1}|\epsilon^t, && (2)\\
\Delta r^b_{t+1} &= \sum_{x=\ell,n} \Delta x^b_{t+1} + \Delta \tau^b_t, && (3)\\
R^{r*}_{t+1} \Delta r^b_{t+1} &= \sum_{x=\ell,n} R^{x*}_{t+1} \Delta x^b_{t+1} - \Delta \tau^b_{t+1} \quad \forall \epsilon^{t+1}|\epsilon^t. && (4)
\end{aligned}$$

Equations (1)–(4) and the fact that transfers add to zero in each history imply that the government budget constraints are satisfied as well.[15]

To satisfy Condition 2 the regime change must not alter choice sets and thus, in particular, wealth. Letting $\mathrm{sdf}^*_{t+1}(\epsilon^{t+1|t})$ denote the equilibrium stochastic discount factor between ϵ^t and $\epsilon^{t+1|t}$ this implies $\Delta \tau^i_t + \mathbb{E}_t[\mathrm{sdf}^*_{t+1} \Delta \tau^i_{t+1}] = 0$ for all $i \in J \cup b$. This has implications for liquidity. To see this, subtract the SDF-weighted Equation (2) from Equation (1) and take expectations to find

$$\sum_{x=n,m,k} \Delta x^i_{t+1} \left(1 - \mathbb{E}_t[\mathrm{sdf}^*_{t+1} R^{x*}_{t+1}]\right) = \Delta \tau^i_t + \mathbb{E}_t[\mathrm{sdf}^*_{t+1} \Delta \tau^i_{t+1}] \quad \forall i \in J \qquad (5)$$

[14] We suppress histories when there is no danger of confusion.

[15] Combining (1)–(4) yields

$$\begin{aligned}
\sum_{x=\ell,k} \Delta x^g_{t+1} &= \sum_{x=r,m} \Delta x^g_{t+1} + \Delta \tau^g_t,\\
\sum_{x=\ell,k} R^{x*}_{t+1} \Delta x^g_{t+1} &= \sum_{x=r,m} R^{x*}_{t+1} \Delta x^g_{t+1} - \Delta \tau^g_{t+1}.
\end{aligned}$$

and parallel conditions for the bank and the government. Because the wealth effect of the regime change must equal zero the left-hand side of Equation (5) must equal zero as well. If the affected balance sheet positions pay the equilibrium required rate of return such that $\mathbb{E}_t[\text{sdf}^*_{t+1} R^{x*}_{t+1}] = 1$ then this always holds true independently of $\{\Delta x^i_{t+1}\}_{x=n,m,k}$. But if the positions carry liquidity or convenience premia because they affect $\mathcal{U}$ or enter $\mathcal{C}$ through channels other than budget constraints then the changes in the affected positions must satisfy cross restrictions such that the total liquidity or convenience value—whose change is reflected on the left-hand side of equation (5)—remains unaltered (Brunnermeier and Niepelt, 2019).

When the affected balance sheet positions affect $\mathcal{U}$ or enter $\mathcal{C}$ through channels other than budget constraints, a further restriction arises: The regime change must not modify these effects or channels in ways that materially alter choice sets. When the affected balance sheet positions enter additively, weighted by liquidity premia, as they do in equation (5) then this restriction is directly satisfied as long as transfers have no wealth effects. We illustrate this case in the following example. Subsequently, we present another example to demonstrate that non-linear specifications can also be consistent with Conditions 1 and 2.

Example 1 (Household)**.** Household i has "money in the utility function" preferences (Sidrauski, 1967). The liquidity services of deposits and CBDC are a weighted sum of the household's holdings of the two balance sheet positions, $n_{t+1} + \lambda m_{t+1}, \lambda > 0$. In equilibrium, deposits and CBDC therefore enjoy a liquidity premium and the CBDC premium relative to deposits equals λ.[16]

The regime change enters the household's budget constraint at date t as $\Delta k^i_{t+1} + \Delta n^i_{t+1} + \Delta m^i_{t+1} - \Delta\tau^i_t$ and at date $t+1$ as $R^{k*}_{t+1}\Delta k^i_{t+1} + R^{n*}_{t+1}\Delta n^i_{t+1} + R^{m*}_{t+1}\Delta m^i_{t+1} + \Delta\tau^i_{t+1}$. To have no effect on the objective function it must be the case that $\Delta n^i_{t+1} + \lambda\Delta m^i_{t+1} = 0$. To insulate the budget constraints at date t and $t+1$ from the regime change we must then have $\Delta k^i_{t+1} = (\lambda^{-1} - 1)\Delta n^i_{t+1} + \Delta\tau^i_t$ and $R^{k*}_{t+1}\{(\lambda^{-1} - 1)\Delta n^i_{t+1} + \Delta\tau^i_t\} + (R^{n*}_{t+1} - R^{m*}_{t+1}/\lambda)\Delta n^i_{t+1} = -\Delta\tau^i_{t+1}$, which also implies that the regime change is wealth neutral.[17] We conclude that the restrictions

$$\left.\begin{array}{l} \Delta m^i_{t+1} = -\lambda^{-1}\Delta n^i_{t+1}, \quad \Delta k^i_{t+1} = (\lambda^{-1} - 1)\Delta n^i_{t+1} + \Delta\tau^i_t \\ \Delta\tau^i_{t+1} = -R^{k*}_{t+1}\Delta\tau^i_t - \{(\lambda^{-1} - 1)R^{k*}_{t+1} + R^{n*}_{t+1} - R^{m*}_{t+1}/\lambda\}\Delta n^i_{t+1} \end{array}\right\} \tag{6}$$

guarantee that the regime change satisfies Condition 1 for household i. This is intuitive. The first restriction ensures that the household's liquidity holdings remain unchanged. The second guarantees budget balance at time t even if the market value of deposits and CBDC changes; this is achieved by altering transfers and/or the household's capital exposure. The final restriction ensures that transfer changes have no wealth effect and it neutralizes the effect of the household's modified portfolio on the budget constraint in period $t+1$.

[16] The household's Euler equations imply $\lambda(1 - \mathbb{E}_t[\text{sdf}^*_{t+1} R^{n*}_{t+1}]) = 1 - \mathbb{E}_t[\text{sdf}^*_{t+1} R^{m*}_{t+1}]$.

[17] We have $\Delta\tau^i_t + \mathbb{E}_t[\text{sdf}^*_{t+1}\Delta\tau^i_{t+1}] = \Delta\tau^i_t - \{(\lambda^{-1}-1)\Delta n^i_{t+1} + \Delta\tau^i_t\} - \mathbb{E}_t[\text{sdf}^*_{t+1}(R^{n*}_{t+1} - R^{m*}_{t+1}/\lambda)]\Delta n^i_{t+1} = 0$ since $\mathbb{E}_t[\text{sdf}^*_{t+1} R^{m*}_{t+1}] = 1 - \lambda(1 - \mathbb{E}_t[\text{sdf}^*_{t+1} R^{n*}_{t+1}])$.

The restrictions in (6) also guarantee that Condition 2 is satisfied for household i. This follows from the fact that the factors determining the household's choice set are unchanged once the household has neutralized the effect of the transfer change—as it can do as we just saw. Starting from that position the household finds itself in exactly the same situation as in the initial equilibrium.

Note, finally, that the type of monetary friction (here: money in the utility function) is not important for the argument.

Example 2 (Bank)**.** Bank b holds reserves (and claims on capital) and collects funds from depositors and the central bank. The bank faces a deposit funding schedule that may be less than perfectly elastic, due to market power. Deposit operations (e.g., payments) generate a unit cost α at the time of issuance. At date t the regime change thus enters the bank's budget constraint as $\Delta r^b_{t+1} + (\alpha - 1)\Delta n^b_{t+1} - \Delta \ell^b_{t+1} - \Delta \tau^b_t$. Deposit operating costs are a function of the reserves-to-deposits ratio; this is captured by another constraint in $\mathcal{C}^b$, namely $\alpha = \bar{\alpha}(\zeta)$ with $\bar{\alpha}' < 0$ and $\zeta \equiv r^b_{t+1}/n^b_{t+1}$. The equilibrium reserves-to-deposits ratio, ζ^*, minimizes the costs of deposit operations, $\zeta^* = \arg\min_\zeta n_{t+1}(\mathbb{E}_t[\text{sdf}^*_{t+1}\{(R^{k*}_{t+1} - R^{r*}_{t+1})\zeta + \bar{\alpha}(\zeta)R^{f*}_{t+1}\}])$. Accordingly, the bank invests the share $1-\zeta^*$ of its deposit funding in capital.

The loan funding schedule posted by the central bank is such that the gross interest payments of the bank on deposit and loan liabilities are given by

$$h\left(n^b_{t+1} + \frac{\ell^b_{t+1}}{1-\zeta^*}\right) + \beta \ell^b_{t+1},$$

where $h(x) \equiv x \cdot R^n_{t+1}(x)$[18] and β denotes an additional unit cost of loan funding. At date $t+1$ the regime change thus enters the bank's budget constraint as

$$R^{r*}_{t+1}\Delta r^b_{t+1} - \Delta h\left(n^b_{t+1} + \frac{\ell^b_{t+1}}{1-\zeta^*}\right) - \beta \Delta \ell^b_{t+1} + \Delta \tau^b_{t+1}.$$

A regime change satisfying $\Delta \ell^b_{t+1} = -(1-\zeta^*)\Delta n^b_{t+1}$ and $\Delta r^b_{t+1} = \zeta^* \Delta n^b_{t+1}$ leaves both $\bar{\alpha}$ and h unaffected. To also have no net effect on the date-t budget constraint the regime change must satisfy $\bar{\alpha}(\zeta^*)\Delta n^b_{t+1} = \Delta \tau^b_t$, and to also balance the date-$t+1$ budget constraint it must satisfy

$$\Delta n^b_{t+1}\{\beta(1-\zeta^*) - \bar{\alpha}(\zeta^*)R^{k*}_{t+1} + \zeta^* R^{r*}_{t+1}\} = -R^{k*}_{t+1}\Delta \tau^b_t - \Delta \tau^b_{t+1}.$$

The absence of wealth effects requires the SDF weighted expectation of the term on the right-hand side to equal zero. Accordingly, β must satisfy[19]

$$\beta(1-\zeta^*)/R^{f*}_{t+1} = \bar{\alpha}(\zeta^*) - \zeta^* R^{r*}_{t+1}/R^{f*}_{t+1}.$$

[18] That is, the gross interest rate on deposits depends on the amount of deposits plus the scaled loan. The gross interest rate on the loan exceeds the deposit rate by the same scaling factor.

[19] We assume that the interest rate on reserves is risk-free. Otherwise the term multiplying ζ^* on the right-hand side of the equation is given by $\mathbb{E}_t[\text{sdf}^*_{t+1}R^{r*}_{t+1}]$.

We conclude that a regime change subject to the restrictions

$$\left.\begin{aligned} &\Delta\ell^b_{t+1} = -(1-\zeta^*)\Delta n^b_{t+1}, \quad \Delta r^b_{t+1} = \zeta^* \Delta n^b_{t+1} \\ &\Delta\tau^b_t = \bar{\alpha}(\zeta^*)\Delta n^b_{t+1} \\ &\Delta\tau^b_{t+1} = -\bar{\alpha}(\zeta^*) R^{f*}_{t+1}\Delta n^b_{t+1} \\ &\beta = (\bar{\alpha}(\zeta^*) R^{f*}_{t+1} - \zeta^* R^{r*}_{t+1})/(1-\zeta^*) \end{aligned}\right\} \tag{7}$$

satisfies Condition 1 for the bank. Such a regime change also satisfies Condition 2 for the bank[20] because, as for the household in Example 1, the bank finds itself in exactly the same situation as in the initial equilibrium.

4.3 Implications of Condition 3

By construction the regime change is consistent with asset market clearing for all affected balance sheet positions. Even if the change does not interfere with other asset markets it may not be consistent with other aggregate consistency requirements such as commodity market clearing. The following example illustrates potential implications for commodity market clearing.

Example 3 (Resources)**.** Monetary balance sheet positions generate resource costs because payment operations require resources. These costs occur in the form of the same commodity. Deposits carry unit resource costs $\nu + \omega(r^b_{t+1}/n^b_{t+1})$ where ω is a decreasing function of the reserves-to-deposits ratio and the costs are born by the bank; CBDC and reserves carry unit costs μ and ρ, respectively, born by the central bank; and a central bank loan carries unit costs o, also born by the central bank.

A regime change that leaves the reserves-to-deposits ratio constant at ζ^* enters the commodity market clearing constraint in $\mathcal{A}$ as

$$(\nu + \omega(\zeta^*))\Delta n^b_{t+1} + \rho\Delta r^g_{t+1} + o\Delta\ell^g_{t+1} + \mu\Delta m^g_{t+1}.$$

Subject to the cross-position restrictions (7) in Example 2 as well as market clearing for reserves and loans this reduces to

$$\{(\nu + \omega(\zeta^*)) + \rho\zeta^* - o(1-\zeta^*)\}\Delta n^b_{t+1} + \mu\Delta m^g_{t+1}. \tag{8}$$

For the regime change to be neutral this expression must equal zero because the commodity allocation cannot remain unaltered otherwise.

4.4 Models in the Literature

We now connect the previous results to models in the literature.

[20] Unless the balance sheet changes directly affect the bank's objectives.

4.4.1 Market Power and Bank Lending Channel: Neutrality

Consider an environment with household and firm sectors as described in Example 1. Deposit and CBDC positions appear in the budget constraints of households and firms and in their objectives. Only those households and firms that are indifferent between deposits and CBDC engage in the swap between the two payment instruments.[21]

The bank operates as described in Example 2 except that we let $\alpha = 0$ for now. The bank exerts market power in the deposit market and thus faces an imperfectly elastic deposit funding schedule, which reflects households' and firms' liquidity demand.[22] When the bank loses deposit funding because households and firms switch to CBDC the central bank refinances the bank through a loan (Brunnermeier and Niepelt, 2019). Refinancing is less than one-to-one, however, because the bank reduces reserve holdings proportionally to deposit funding (it keeps the reserves-to-deposits ratio constant at value ζ^*, which is optimal at given prices). That is, the central bank loan only refinances the share $1 - \zeta^*$ of the deposit outflow.[23]

The choice set of the bank is preserved if the central bank posts a loan funding schedule that renders the supply function of deposits and loans after the intervention commensurate to the functions in the initial equilibrium. From the perspective of the bank it makes no difference in this case whether it collects deposits at gross interest rate R^{n*}_{t+1} while investing a share ζ^* in reserves at gross interest rate R^{r*}_{t+1}, or whether it receives a smaller (share $1-\zeta^*$) central bank loan at gross interest rate $R^{n*}_{t+1}/(1-\zeta^*)+\beta$ subject to the restriction on β in Condition (7) (with $\alpha = 0$). Managing payments or balance sheet positions does not require resources.[24]

A regime change in this environment is neutral when it satisfies the restrictions derived in Examples 1–2, Conditions (6)–(7) (with $\alpha = 0$). That is, neutrality is guaranteed if funding schedules and transfers adjust appropriately to accommodate the balance sheet changes. The central bank must issue CBDC, redeem reserves and lend to banks in the right proportions,[25]

$$\Delta m^g_{t+1} = -\lambda^{-1}\Delta n^b_{t+1}, \quad \Delta r^b_{t+1} = \zeta^* \Delta n^b_{t+1}, \quad \Delta \ell^b_{t+1} = -(1-\zeta^*)\Delta n^b_{t+1},$$

and it must make the bank indifferent between deposit and central bank funding by posting a commensurate loan funding schedule with

$$R^{\ell *}_{t+1} = \frac{R^{n*}_{t+1} - \zeta^* R^{r*}_{t+1}}{1-\zeta^*}.$$

Moreover, from Conditions (6) and (7), capital exposures as well as transfers must adjust

[21] Other households and firms face short-selling constraints that support the initial equilibrium.

[22] Introducing market power in lending markets would not materially affect the analysis.

[23] Mechanically, this may occur as follows: For each dollar the household converts from deposits into CBDC by transferring funds from the bank to the central bank, the latter debits the bank's reserves account by ζ^* and acquires a claim against the bank equal to $1 - \zeta^*$.

[24] Except for this latter feature the environment closely resembles the setting in Niepelt (2024).

[25] Nonnegativity constraints imply that the reduction of deposits must not be too large.

to satisfy budget constraints while preserving wealth:[26]

$$\begin{aligned}
&\Delta k^i_{t+1} = \Delta\tau^i_t + (\lambda^{-1}-1)\Delta n^i_{t+1},\\
&\Delta\tau^i_{t+1} = -R^{k*}_{t+1}\Delta\tau^i_t - \{(\lambda^{-1}-1)R^{k*}_{t+1} + R^{n*}_{t+1} - R^{m*}_{t+1}/\lambda\}\Delta n^i_{t+1},\\
&\Delta\tau^b_t = 0,\\
&\Delta\tau^b_{t+1} = 0.
\end{aligned}$$

These equations make clear that feasible regime changes form an equivalence class with multiple elements. Even if deposits and CBDC are not swapped ($\Delta n^i_{t+1} = 0$) capital exposures can be reshuffled between households and firms on the one side and the government on the other as long as this is accommodated by transfers.[27] Alternatively, even if date-t transfers remain unchanged, deposits and CBDC can be swapped. When $\lambda \neq 1$ this requires adjustments in the capital exposure of households, firms and the government. In general, it also requires adjustments in date-$t+1$ transfers to neutralize the effect of modified portfolio returns. Finally, a regime change may occur even if capital exposures remain unaltered. This requires $\Delta\tau^i_t = -(\lambda^{-1}-1)\Delta n^i_{t+1}$ and $\Delta\tau^i_{t+1} = -\{R^{n*}_{t+1} - R^{m*}_{t+1}/\lambda\}\Delta n^i_{t+1}$ and changes in government transfers in the opposite direction. A general regime change combines changes in capital exposures, transfers as well as deposit-CBDC swaps.[28] Bank transfers, however, are never affected because we have imposed that their capital exposures do not change.

In conclusion, bank capital holdings can be insulated from the consequences of the regime change and more generally, neutrality can be guaranteed even if banks have market power.[29] If the introduction of CBDC changes the equilibrium allocation then this reflects the government's choice.

4.4.2 Non-Linear Liquidity Benefits: Non-Neutrality

Consider next the environment of Subsection 4.4.1 except that the objectives of households and firms (or restrictions on their choice sets) aggregate the liquidity services of CBDC and deposits in a non-linear fashion. This may reflect, for example, that the liquidity services of deposits relative to CBDC vary with the quantities of these means of payment. (The plausibility of this assumption appears disputable but this is of no concern here because the assumption is made for illustrative purposes.)

[26] The changes reported in the text also imply changes for the government,

$$\begin{aligned}
&\Delta k^g_{t+1} = -\sum_{i\in J}\Delta\tau^i_t - (\lambda^{-1}-1)\Delta n^b_{t+1},\\
&\Delta\tau^g_{t+1} = R^{k*}_{t+1}\sum_{i\in J}\Delta\tau^i_t + \{(\lambda^{-1}-1)R^{k*}_{t+1} + R^{n*}_{t+1} - R^{m*}_{t+1}/\lambda\}\Delta n^b_{t+1}.
\end{aligned}$$

[27] That is, households and firms may transfer capital to the government (or vice versa) and receive it back, inclusive of its return, in the following period.

[28] The transfers given in the equations may be netted.

[29] Neutrality may still fail if CBDC changes the asset span. If the initial equilibrium already features CBDC then the asset span does not change.

Brunnermeier and Niepelt (2019) show that non-linear liquidity aggregation generally undermines neutrality. Since a deposit-CBDC swap changes the relative valuation of the two means of payment by the household or firm involved in it, the swap—and thus the regime change—cannot occur without price changes.

4.4.3 Unequal Resource Costs of Liquidity Provision: Non-Neutrality

Consider next the environment of Subsection 4.4.1 except that managing payments or balance sheet positions requires resources, as in Example 3. This closely resembles the setting analyzed in Niepelt (2024). Banks bear unit resource costs $\nu + \omega(r_{t+1}/n_{t+1})$ when issuing deposits such that $\bar{\alpha}(\zeta^*)$ in Example 2 equals $\nu + \omega(\zeta^*)$. The central bank bears unit resource costs μ, ρ and o for CBDC, reserves and loans, respectively.

Neutrality now requires a parametric restriction to be satisfied: The unit resource cost of providing liquidity to non-banks either with deposits or with CBDC must be the same, taking into account that deposit operations require reserve operations and CBDC issuance requires pass-through funding from the central bank to preserve bank choice sets. Formally, Condition (8) combined with the constant liquidity requirement $\Delta n^i_{t+1} = -\lambda \Delta m^i_{t+1}$ implied by (6) and market clearing implies

$$\nu + \omega(\zeta^*) + \rho\zeta^* - o(1 - \zeta^*) = \frac{\mu}{\lambda}.$$

If this equality is violated a neutral regime change is impossible.[30]

The resource costs also modify the loan funding schedule and "equivalent" loan rate, which now is given (from Condition (7)) by

$$R^{\ell *}_{t+1} = \frac{R^{n*}_{t+1} + (\nu + \omega(\zeta^*))R^{f*}_{t+1} - \zeta^* R^{r*}_{t+1}}{1 - \zeta^*}.$$

Intuitively, the loan rate is higher than in the environment of Subsection 4.4.1 because deposits generate resource costs for the bank, unlike a central bank loan. Preserving bank choice sets thus requires higher loan interest rates.

Finally, from Condition (7), resource costs alter the bank transfers compared with the situation in Subsection 4.4.1. Guaranteeing neutrality now requires[31]

$$\Delta\tau^b_t = (\nu + \omega(\zeta^*))\Delta n^b_{t+1},$$
$$\Delta\tau^b_{t+1} = -(\nu + \omega(\zeta^*))R^{f*}_{t+1}\Delta n^b_{t+1}.$$

[30] A special case where the condition is satisfied arises when public and private payment operations in a narrow banking system generate commensurate costs, $\mu/\lambda = \nu + \rho$, liquidity transformation is costless, $\omega(\zeta^*) = (1 - \zeta^*)\rho$, and loans do not generate costs, $o = 0$.

[31] From Condition (6), household and firm capital exposures and transfers are unaffected. We have

$$\Delta k^g_{t+1} = -\sum_{i \in J} \Delta\tau^i_t - (\lambda^{-1} - 1)\Delta n^b_{t+1},$$
$$\Delta\tau^g_{t+1} = R^{k*}_{t+1}\sum_{i \in J} \Delta\tau^i_t + \{(\lambda^{-1} - 1)R^{k*}_{t+1} + R^{n*}_{t+1} - R^{m*}_{t+1}/\lambda + (\nu + \omega(\zeta^*))R^{f*}_{t+1}\}\Delta n^b_{t+1}.$$

Unlike in Subsection 4.4.1 changes in bank deposit liabilities need to be accommodated by transfer changes because deposits generate immediate costs for the bank, unlike a loan. Transfer changes must be compensated in the following period to eliminate wealth effects.

In conclusion, even in the presence of resource costs of payment operations or balance sheet positions it remains possible to sterilize the effects of CBDC-deposit swaps as far as the choice sets of private sector agents are concerned. However, such resource costs will undermine neutrality from a resource point of view unless they happen to satisfy the restriction given earlier. This implies that the introduction of CBDC is beneficial if and only if it delivers liquidity at lower resource costs than deposits.

Piazzesi and Schneider (2022) assume that asset rather than liability positions of banks and the central bank generate resource costs. This can break neutrality for very related reasons. They also assume that banks but not the central bank can offer contingent, on-demand liquidity via credit lines, which requires fewer asset backing than noncontingent CBDC.

A resource costs channel can also operate in models of CBDC and frictional interbank markets. When CBDC induces banks to change their exposure to the interbank market and this exposure creates real costs then the regime change cannot be neutral, even if the banks end up bearing unchanged costs of finance.[32]

Niepelt (2024) argues that there are indirect social costs of bank based payment systems, in addition to the direct costs captured by ν, ρ, o and ω. He emphasizes indirect costs that arise because government measures to correct frictions in the banking sector (lack of competition in deposit markets, externalities from reserve holdings) require regulation or Pigouvian subsidies, which in turn impose deadweight losses, e.g., due to tax distortions. He also discusses indirect costs created by too-big-to-fail banks or as a consequence of financial crises. All these indirect costs modify the cost-benefit comparison of deposit- and CBDC-based payment systems in favor of the latter.

4.4.4 CBDC Injection by Transfer: Non-Neutrality

Consider next the environment of Subsection 4.4.1 except that CBDC is injected by transfer rather than issued in exchange for a central bank claim against the bank. This captures the key assumption in Keister and Sanches (2023); other differences between the two environments are not important for the argument.[33]

The introduction of CBDC or expansion of its supply in this modified environment is not neutral. To see this most transparently suppose that the non-bank sector is homogeneous such that the CBDC injection by transfer does not affect the wealth distribution among households nor their wealth. (Households are homogeneous residual claimants to the government.) If prices remained unchanged banks would issue the same quantity of deposits as in the initial equilibrium. But with unchanged wealth households would continue to demand the same liquidity services as in the initial equilibrium such that

[32] For models of interbank markets and CBDC (albeit not necessarily socially costly interbank access) see Abad et al. (2023) and Lamersdorf et al. (2023).

[33] See also Chiu et al. (2023) who analyze an environment that combines features of the models in Keister and Sanches (2023) and Subsection 4.4.1.

supply and demand would differ. We conclude that the injection by transfer cannot leave the allocation and price system unaltered.[34] Wealth effects due to heterogeneity clearly undermine neutrality further.

4.4.5 CBDC Injection by Government-Bond Purchases: Non-Neutrality

Consider next the environment of Subsection 4.4.1 except that CBDC is exclusively exchanged against government bonds. This removes funding pressure from banks because they cannot come in a situation in which they must transfer deposit balances to the central bank and seek alternative sources of funding (Kumhof and Noone, 2021; Barrdear and Kumhof, 2022). Instead, the effect of an increase in CBDC is akin to quantitative easing: The consolidated government's balance sheet remains unchanged bar for a swap of outstanding government debt for CBDC.

Such an intervention is not neutral for the same reasons that quantitative easing is not neutral—it changes the total supply of liquidity. To see this most clearly note that the intervention can be represented as the combination of two sub-interventions. First, a swap of deposits for CBDC in combination with a central bank loan, in line with the neutral interventions considered so far. And second, a swap of government bonds held by households or firms for the loan, which effectively leads households or firms to re-acquire deposits. This second sub-intervention generally is not neutral.

4.4.6 Specialness of Deposits: Non-Neutrality

Consider next the environment of Subsection 4.4.1 except that deposits affect the choice sets of banks not only as a source of funding or an argument of the cost function ω but also through other channels, and that central bank loans do not have these additional effects. Such specialness could arise, for example, if deposits induced more monitoring than central bank loans, which is unlikely given that banks are mainly monitored by the central bank and bank supervisors. It could also arise as a consequence of collateral scarcity, as in Williamson (2022) or Böser and Gersbach (2020), as long as banks needed to post less collateral for deposit funding than for central bank loans.[35]

Synergies between deposits and bank assets such as in Kashyap et al. (2002) or Hanson et al. (2015) do not cause specialness as long as the synergies are also present with a central bank loan.[36] Whited et al. (2023) analyze three channels through which deposit-CBDC substitution could affect bank lending, but none of these channels operates when the

[34] This is confirmed by Keister and Sanches (2023). They show that the real effects of CBDC issuance in their framework disappear when CBDC is not transferred to households but revenues from CBDC issuance are lent to banks.

[35] An unsecured central bank loan after the regime change is the mirror image of unsecured implicit lender-of-last-resort guarantees backing deposits in the initial equilibrium. If those implicit guarantees were secured then the "equivalent" loan would be secured as well. The conditions for neutrality thus point to a potential inconsistency of central bank policies. Collateral requirements may reflect concerns about central bank net worth and independence; see the following discussion on politico-economic considerations.

[36] Pulley and Humphrey (1993) offer an empirical assessment of such synergies, as do Egan et al. (2022).

central bank refinances the bank through an equivalent loan.[37] While the evidence in favor of deposit specialness thus is not strong the theoretical case is clear: If deposits are special, Conditions 1–2 are no longer guaranteed and the issuance of CBDC generally changes the allocation.

4.4.7 Sequential Policy Choice: Neutrality Depending on State Variables

Consider finally the environment of Subsection 4.4.1 except that policy is determined sequentially by the government (or voters).[38] In addition to the conditions discussed so far this introduces the equilibrium requirement that policy must be ex-post incentive compatible, i.e., continuation policy choices must be ex-post optimal. The appropriate notion of, and conditions for neutrality then transcend Conditions 1–3. Two "policy regimes"—sets of admissible policy choices over time—are "politico-economically equivalent" if they give rise to equilibrium policy sequences conditional on which Conditions 1–3 are satisfied (Gonzalez-Eiras and Niepelt, 2015). Politico-economic equivalence of policy regimes is guaranteed when the effective choice sets of political decision makers evolve in parallel across the two regimes. This requires, in particular, that the respective state variables in the two policy regimes evolve in parallel.

The introduction of CBDC affects the policy regime by introducing new admissible policy instruments, namely CBDC, central bank loans and possibly government exposure to capital; these instruments constitute state variables once issued or acquired but as we have seen, access to transfers allows policy makers to neutralize return differences ex post. When transfers and affected balance sheet positions do not enter the objectives of political decision makers the regime change thus does not affect effective choice sets, and politico-economic equivalence is guaranteed as long as Conditions 1–3 are satisfied.

Politico-economic equivalence could fail even if Conditions 1–3 are satisfied if, e.g., the government's modified balance sheet positions change government information sets. For example, if the government does not observe deposit balances of households but does observe CBDC balances this might provide information relevant for other policy dimensions and might thus differentially affect ex-post incentives across policy regimes. Or, central bank loans might alter voters' understanding of liquidity rents in the banking sector and this might undermine the political support for "too cheap" central bank financing in the regime with CBDC, again undermining the neutrality of the regime change in politico-economic equilibrium. As another example, the treasury could subject the central bank to more intense fiscal pressure once the introduction of CBDC lengthens the central bank balance sheet and makes seignorage a more salient source of government funding.[39]

[37] Whited et al. (2023) describe three consequences of deposit-CBDC substitution for bank lending: (i) Higher costs of funding in the form of wholesale funding. (ii) Weaker hedging benefits for banks from short-duration wholesale funding as opposed to sticky, effectively long-duration deposits. (iii) Consequently, lower bank profits and tighter bank capital requirements. None of these consequences is material when the central bank refinances the bank subject to terms that replicate those of deposit funding.

[38] We presume that some objectives of political decision makers are given.

[39] A rigorous analysis of these examples would require a framework with heterogeneous households and/or strategic fiscal and monetary authorities with conflicting interests, as well as some frictions that render transparency relevant. See Tucker (2017), Cecchetti and Schoenholtz (2018) or Niepelt (2021) for

Independently of political frictions neutrality could be undermined if the information sets of political decision makers evolve differently after a regime change.[40]

5 Private Cryptocurrency

We turn next to private cryptocurrencies and their equilibrium implications. One key difference to the CBDC case analyzed before lies in the fact that a cryptocurrency issuer is a private entity—unlike the government that issues CBDC. We discuss below how preserving the choice sets of agents in the financial sector thus becomes more challenging and imposes stricter restrictions. We also discuss the role of bubbly crypto assets.

5.1 Regime Change

To focus on the cryptocurrency case we abstract from CBDC. But to ease the comparison with the analysis in Section 4 we maintain the notation in that section and simply modify the interpretation of variables indexed by "g." Rather than referring to balance sheet positions or transfers of/to the consolidated government such variables now denote balance sheet positions or transfers of/to the government *and the cryptocurrency issuer*. For example, $\Delta\tau_t^g$ denotes the change of transfer to the government *cum* cryptocurrency issuer and Δm_{t+1}^g denotes the change in the quantity of cryptocurrency (because we abstract from CBDC). With this modified interpretation all market clearing restrictions remain unchanged.

5.2 Profit Motive

The modified interpretation of the model variables suggests a two-step approach for our analysis. In the first step we treat the private cryptocurrency as if it were a form of publicly issued money. Our analysis of Section 4 applies in this case without change. In the second step we ask what additional neutrality requirements have to be satisfied as a consequence of the fact that the private cryptocurrency is not CBDC and its issuer not part of the government.

Focusing on this second step immediately makes clear that the profit motive (or related objectives) of the cryptocurrency issuer introduces additional and rather strong restrictions beyond Conditions 1–3. As the discussion in Section 4 has shown the allocation and price system do not change after CBDC issuance if CBDC carries the appropriate interest rate and the central bank lends the appropriate quantity of funds to banks at equivalent terms. This will generally not be the case with a cryptocurrency issuer that has no interest to supply funds below market rates. We conclude that a regime change that involves a cryptocurrency generally violates the restrictions that guarantee neutrality.

discussions of potential political implications of CBDC.

[40] This could open the possibility for Pareto improvements, or achieve the opposite. See, e.g., Keister and Monnet (2022) and Niepelt (2020b).

Neutrality is easier to guarantee, however, when the issuer is competitive and bears no operating costs and if its instruments are backed by deposits from which they derive their liquidity benefits. Under such circumstances the cryptocurrency is just a veil without significance for the allocation and the price system and Conditions 1–3 are satisfied. By contrast a stablecoin may change the allocation or the price system when its issuer is non-competitive, bears operating costs or when the stablecoin's liquidity benefits are inherent rather than derived.

5.3 Bubbly "Cryptocurrency"

Some "cryptocurrencies" may provide very limited or even no liquidity services. Lacking real dividends these instruments are sometimes characterized as bubbles—speculative stores of value—with minor added liquidity benefits, or even as pure bubbles. We show next that the characterization of cryptocurrencies as bubbles with added liquidity benefits is dubious and discuss thereafter the case of pure bubbles.

Consider a cryptocurrency that provides liquidity services at each date and in each history, i.e., it always contributes to the objective of some household or firm or relaxes a $\mathcal{C}$ constraint beyond the budget constraint. Let $p_t(\epsilon^t)$ denote the price of the cryptocurrency at the beginning of period t, history ϵ^t, expressed in terms of the numeraire. Let $\underline{\chi} > 0$ denote the minimum liquidity contribution of one unit of real balances of the cryptocurrency across histories. Since the price must weakly exceed the fundamental value this implies $p_t \geq \underline{\chi} \sum_{s \geq 0} \mathbb{E}_t[\text{sdf}^*_{t+1} \cdots \text{sdf}^*_{t+s} p_{t+s}]$. Following Tirole (1985) and to establish a contradiction suppose that the price also contains a bubble component, $b_t(\epsilon^t)$ in history ϵ^t say. The bubble must pay the required rate of return, $b_t = \mathbb{E}_t[\text{sdf}^*_{t+1} b_{t+1}]$. Moreover, the price must weakly exceed the bubble component, $\mathbb{E}_t[\text{sdf}^*_{t+1} \cdots \text{sdf}^*_{t+s} p_{t+s}] \geq \mathbb{E}_t[\text{sdf}^*_{t+1} \cdots \text{sdf}^*_{t+s} b_{t+s}]$. This implies that $p_t \geq \underline{\chi} \sum_{s \geq 0} \mathbb{E}_t[\text{sdf}^*_{t+1} \cdots \text{sdf}^*_{t+s} b_{t+s}] \geq \underline{\chi} \sum_{s \geq 0} b_t$, which is unbounded unless $b_t = 0$. In conclusion the cryptocurrency cannot at the same time provide liquidity services and feature a price bubble. Either it provides liquidity services—the case analyzed so far—or its price reflects a bubble.

Consider, then, the case of a cryptocurrency whose price reflects a bubble but which does not provide liquidity services.[41] As far as budget constraints of households or firms are concerned the bubbly nature of such an instrument does not matter.[42] However, the replacement of a liquid instrument by a bubble does have effects on $\mathcal{U}$ and/or $\mathcal{C}$ (beyond budget constraints), and Conditions 1 and 2 for households and firms thus may be violated. Moreover, the introduction of the bubble also violates Conditions 1 and 2 for the issuer. Holding prices constant the bubble increases the issuer's net worth and thereby enlarges its choice set. Even if this gain in net worth is taxed away, somebody else's (e.g., the government's) wealth position changes. Neutrality fails and the introduction of the bubble changes the equilibrium allocation and prices.

[41] The same argument applies to a "CBDC bubble" if the government rather than a private sector entity issued a bubble.

[42] Only the asset return matters, not the composition between dividends and capital gains.

6 Discussion

6.1 Pareto Improving Regime Change

If the conditions for a neutral regime change are satisfied then it is possible to introduce/expand CBDC or a private cryptocurrency without changes in the commodity allocation. A strict Pareto improvement is possible in this case if policy was suboptimal in the initial equilibrium or if the introduction of CBDC or private cryptocurrencies introduces new options for policy makers beyond the option to simply replicate the initial equilibrium.

Even if the conditions for a neutral regime change are not satisfied normative statements may be possible. In particular, the introduction of CBDC or a private cryptocurrency still allows for a Pareto improvement in this case as long as the regime change reduces resource requirements or relaxes other equilibrium conditions without tightening further ones.

If neutrality conditions only are violated because of the injection method chosen by policy makers or because of political economy frictions then responsibility for the lack of Pareto improvements solely lies with policy makers. If the conditions are met but policy makers choose balance sheet positions or transfers that do not exploit their potential then the same holds true.

6.2 Indirect Refinancing of Banks

Our argument for a neutral monetary regime change rests on the assumption that the central bank directly refinances banks when depositors convert funds into CBDC. From a balance sheet perspective such refinancing need not be direct. For example, the central bank could alternatively invest newly gained CBDC funds with some third entity that in turn invests with banks. While this perspective is correct as far as accounting relationships are concerned it abstracts from incentive compatibility: Whether the third entity would *want* to source funds from the central bank and invest at banks is not guaranteed. The situation therefore parallels the case with a private cryptocurrency. Adding private entities to the set of agents that need to behave in certain ways to guarantee neutrality tightens the neutrality restrictions.

7 Value of Lender-of-Last-Resort Guarantees

The results of Section 4 allow to assess by how much banks' ability to issue deposits reduces their financing costs. Equivalently, they permit to quantify the value of factual or perceived lender-of-last-resort guarantees by the central bank to stand ready to exchange deposits against central bank money.

Among other factors (discussed below) the reduction in financing costs reflects the product of deposits outstanding, n^{b*}_{t+1}, and the liquidity premium on deposits, $\chi^{n*}_{t+1} \equiv 1 - R^{n*}_{t+1}/R^{f*}_{t+1}$. Figure 1 plots bounds for this product over the period 1973–2023 that are constructed from different data sources including FRED, Hanson et al. (2015), Nagel

(2016), Kurlat (2019), Van den Heuvel (2022) and Bianchi and Bigio (2022). Appendix A contains a detailed description. Figure 1 shows that banks collected total deposit liquidity premia between -0.3 and 2.6 percent of annualized GDP; the mean of the premium equalled roughly 0.7 percent.

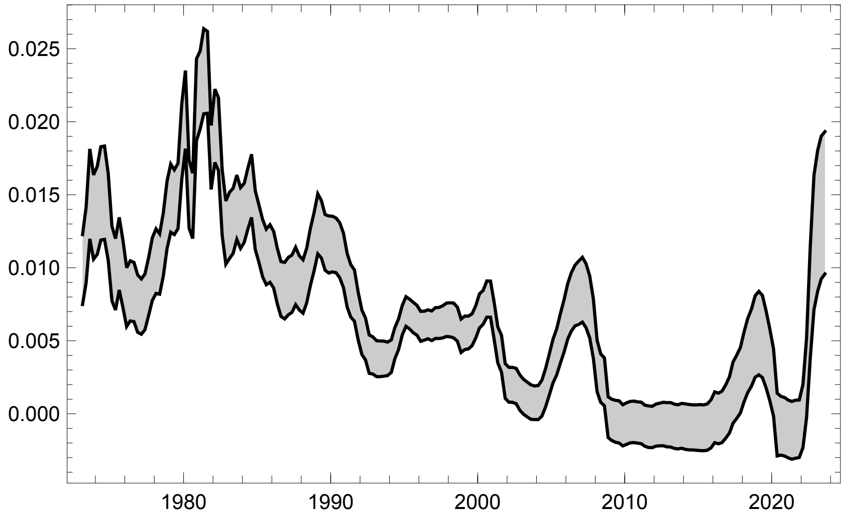

Figure 1: Bounds for deposit-to-GDP ratio times deposit spread, annualized.

To collect this premium banks incur costs beyond interest paid to depositors, namely costs of managing customer payments as well as opportunity costs of reserve holdings. That is, the net benefit that banks reap from money creation equals the total deposit liquidity premium displayed in Figure 1 net of the payment operating and opportunity costs. Recall that the latter costs affect the equivalent loan rate $R^{\ell*}_{t+1}$ given in Subsection 4.4.3 and that the funding costs of a bank whose deposits net of associated reserve holdings are fully replaced by a central bank loan of size $\ell^{b*}_{t+1} = n^{b*}_{t+1}(1-\zeta^*)$ are equal to $\ell^{b*}_{t+1}R^{\ell*}_{t+1}/R^{f*}_{t+1}$ in present value. Compared with the funding costs at non-liquid market rates, $\ell^{b*}_{t+1}R^{f*}_{t+1}/R^{f*}_{t+1}$, the central bank loan at the equivalent rate thus reduces bank funding costs by

$$n^{b*}_{t+1}(1-\zeta^*)\frac{R^{f*}_{t+1}-R^{\ell*}_{t+1}}{R^{f*}_{t+1}}. \tag{9}$$

Our objective is to evaluate this expression.

Recall also that under the general assumptions of Subsection 4.4.3 (and in the absence of CBDC, private cryptocurrencies or a central bank loan) a bank maximizes

$$n^b_{t+1}\left\{-\bar{\alpha}(\zeta)+\mathbb{E}_t\left[\mathrm{sdf}^*_{t+1}\left((R^{k*}_{t+1}-R^n_{t+1}(n^b_{t+1}))+\zeta(R^{r*}_{t+1}-R^{k*}_{t+1})\right)\right]\right\}.$$

Letting $\chi^{r*}_{t+1}\equiv 1-R^{r*}_{t+1}/R^{f*}_{t+1}$ denote the liquidity premium on reserves the bank's ζ and n^b_{t+1} choices, respectively, satisfy

$$\begin{aligned}\chi^{r*}_{t+1} &= -\bar{\alpha}'(\zeta^*),\\ \bar{\alpha}(\zeta^*)-\zeta^*\bar{\alpha}'(\zeta^*) &= \mathbb{E}_t[\mathrm{sdf}^*_{t+1}(R^{k*}_{t+1}-R^{n*}_{t+1})]-\mathbb{E}_t[\mathrm{sdf}^*_{t+1}]n^{b*}_{t+1}\frac{\partial R^{n*}_{t+1}}{\partial n^b_{t+1}}.\end{aligned}$$

That is, the liquidity premium on reserves equals the marginal reduction in operating costs and the deposit choice reduces to $\bar{\alpha}(\zeta^*) - \zeta^* \bar{\alpha}'(\zeta^*) = \chi^{n*}_{t+1} - \eta R^{n*}_{t+1}/R^{f*}_{t+1}$, where η denotes the elasticity of the deposit rate with respect to n^b_{t+1}.

Suppose that households' liquidity demand is approximately isoelastic, $(n^b_{t+1})^{-\psi} \propto \chi^n_{t+1}$; this is the case, for example, when households have CES preferences over consumption and liquidity services with elasticity of substitution $\psi^{-1} > 1$ (e.g., Niepelt, 2024). Elasticity η then satisfies $\eta R^{n*}_{t+1}/R^{f*}_{t+1} = \psi \chi^{n*}_{t+1}$ such that the second bank optimality condition simplifies to $\chi^{n*}_{t+1}(1 - \psi) = \bar{\alpha}(\zeta^*) - \zeta^* \bar{\alpha}'(\zeta^*)$; the equivalent central bank loan rate reduces to

$$R^{\ell*}_{t+1} = \frac{R^{n*}_{t+1}}{1 - \zeta^*} + \frac{\bar{\alpha}(\zeta^*) R^{f*}_{t+1} - \zeta^* R^{r*}_{t+1}}{1 - \zeta^*} = R^{f*}_{t+1} - \frac{\psi}{1 - \zeta^*}(R^{f*}_{t+1} - R^{n*}_{t+1});$$

and, most importantly, the funding cost reduction (9) collapses to $\psi n^{b*}_{t+1} \chi^{n*}_{t+1}$. We conclude that the funding cost reduction equals the total deposit liquidity premium times the inverse of the elasticity of substitution. Niepelt (2024) follows Pasqualini (2021) who argues that consistent with findings in Drechsler et al. (2017) or Wang et al. (2020) the markdown in U.S. deposit markets equals 1.5, corresponding to $\psi = 1/3$. Under this assumption and using the total deposit liquidity premium illustrated in Figure 1 the value of the Fed's lender-of-last-resort guarantees for U.S. banks amounts to roughly a quarter percent of U.S. GDP.

8 Conclusion

The conditions for monetary regime change to be neutral are stringent. But in the case of CBDC they are much less stringent than suggested by policy makers who envision dramatic consequences for financial stability, credit, investment and growth. As our examples have shown central banks can go a long way to insulate banks and the asset side of their balance sheets from the consequences of CBDC. And as long as the total social costs of liquidity provision *via* deposits and CBDC are similar governments are in a position to keep the consequences of CBDC manageable not only for banks but also for society at large.

As far as private cryptocurrencies are concerned the verdict is more cautious. The conditions for neutrality are substantially more stringent unless the issuer is competitive and bears no operating costs and the currency is backed by deposits from which they derive their liquidity benefits. The cryptocurrency is just a veil in this case and its introduction without macroeconomic significance.

Whether societies and central banks would *want* to insulate banks and the macroeconomy from the consequences of CBDC or private cryptocurrencies is a different question. Central banks could choose to raise banks' funding costs—according to our estimate by roughly a quarter percent of GDP on average—and they might also choose to change the allocation. Indeed, if the total social costs of CBDC or private cryptocurrencies are favorable compared with deposits such that a regime change is necessarily non-neutral then regime change is welfare improving unless policy makers introduce new frictions in the process.

Our analysis does not speak to "microeconomic" implications of CBDC or private cryptocurrencies that would be reflected in differential effects on parameters of our setup. It also does not speak to secondary implications of CBDC that are sometimes mentioned in the policy debate. For example, since the presence of cash gives rise to an effective lower bound on nominal interest rates, which may be binding when prices are rigid, CBDC could empower monetary policy if it were associated with an abolition of cash (Bordo and Levin, 2017).[43] Or, CBDC could enhance the speed and accuracy of government transfer payments if its introduction were associated with an improvement of address and death records.

[43] See, however, Buiter (2009).

A Data

All data is measured at the quarterly frequency or aggregated from weekly or monthly data.

Figure 2 illustrates alternative measures of the deposit-to-GDP ratio (annualized). We measure GDP based on the FRED series `GDP` (Gross Domestic Product, Billions of Dollars, Quarterly, Seasonally Adjusted Annual Rate). The solid line depicts the (normalized) FRED series `DPSACBW027SBOG` (Deposits, All Commercial Banks, Billions of U.S. Dollars, Quarterly, Seasonally Adjusted); we refer to this series as "long (FRED)." The dashed line depicts the (normalized) sum of the discontinued FRED series `TCDSL` (Total Checkable Deposits, Billions of Dollars, Quarterly, Seasonally Adjusted) and `SAVINGSL` (Savings Deposits: Total, Billions of Dollars, Quarterly, Seasonally Adjusted); we refer to this series as "short (FRED)." The dotted line depicts the series used in Nagel (2016) and also by Bianchi and Bigio (2022);[44] we refer to this series as "short (Nagel)."

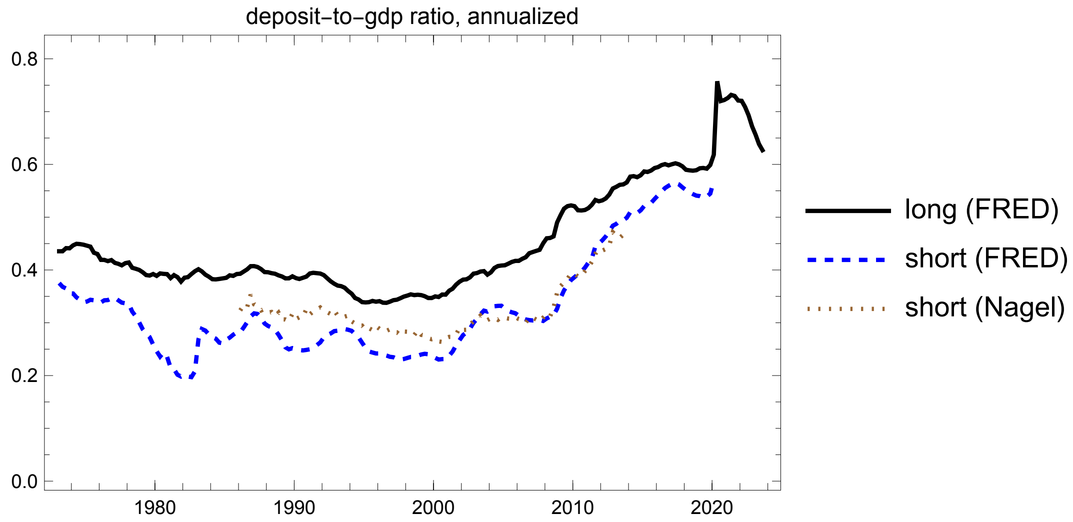

Figure 2: Measures of the deposit-to-GDP ratio.

Figures 3 and 4 illustrate alternative measures of annual gross interest rates that we use to construct measures of deposit liquidity premia. The solid line in Figure 3 depicts the FRED series `TB3MS` (3-Month Treasury Bill Secondary Market Rate, Discount Basis, Quarterly). The dashed line depicts the safe, illiquid benchmark rate used by Kurlat (2019), and the dotted and dot-dashed lines, respectively, depict the rates on savings and checking accounts constructed by Kurlat (2019).[45] The solid line in Figure 4 again depicts the FRED series `TB3MS`. The dashed and dotted lines, respectively, depict the benchmark and deposit rates used by Nagel (2016).[46]

[44] See `https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/KHNXYJ&version=1.1`, file `AggregateDataAndFigures.xlsx`; it represents the (normalized) sum of `savdep`, `timedepl100k` and `transdep`

[45] We thank Pablo Kurlat for providing the data for the benchmark rate and the two spreads.

[46] See file `AggregateDataAndFigures.xlsx`, series `Deposit rate` and `Fed funds rate`.

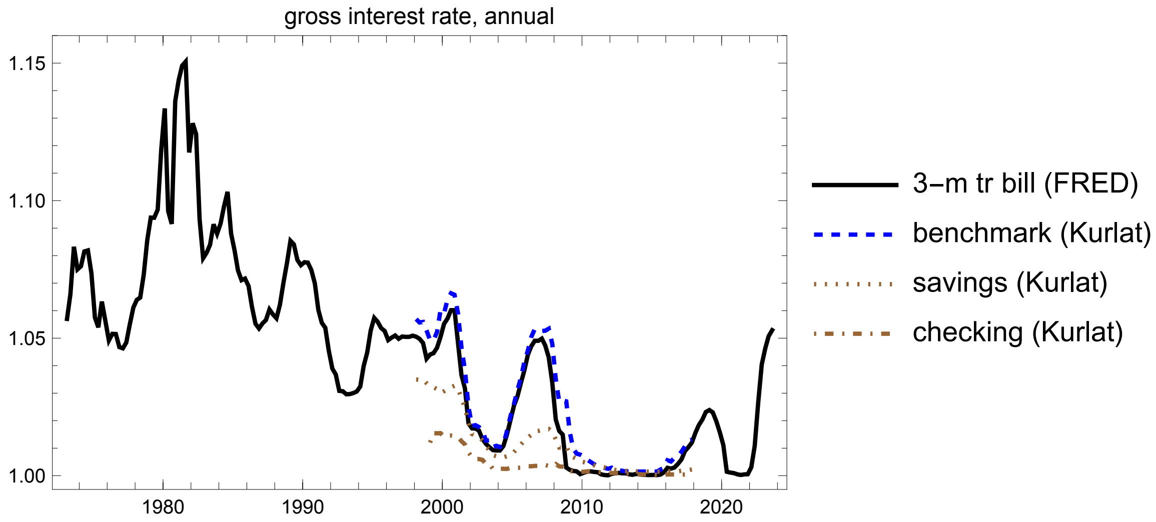

Figure 3: Measures of gross interest rates.

Figure 5 illustrates alternative measures of the annual deposit liquidity premium. The solid line depicts the premium resulting from the Kurlat (2019) data where we construct the deposit rate as a weighted average of the rates on savings and checking accounts, using the components of "short (FRED)" as weights. The dashed line depicts the premium that results from the Nagel (2016) data. For comparison, the figure also depicts the average premia estimated by Hanson et al. (2015, p. 453) and Van den Heuvel (2022, p. 34); these averages are represented by the (dash-)dotted lines whose lengths indicate the respective sample periods.

Figure 6 illustrates alternative measures of the object of interest, the product of the annual deposit liquidity premium and the annualized deposit-to-GDP ratio. The solid line depicts the product computed based on the Kurlat liquidity premium and the "short (FRED)" deposit-to-GDP ratio. The dashed line depicts the product computed based on the Nagel liquidity premium and the "short (Nagel)" deposit-to-GDP ratio. The averages of these two series lie between 0.3 and 0.4 percent.

Since the latter two series are short and heavily influenced by the post-financial crisis period of very low interest rates we use the information from our other, longer series to extrapolate values of the object of interest. In particular, we regress both "short (FRED)" and "short (Nagel)" on "long (FRED)" and a constant, and we regress the deposit liquidity premium according to the Kurlat and Nagel data on `TB3MS` and a constant. Figures 7–10 report for each of the four cases the actual (short) data series and the (longer) predicted series. Evidently, the simple specifications capture most of the relevant variation in the measured data.

The bounds reported in Figure 1 in the main text reflect the products of the predicted series in Figures 7 and 9 on the one hand and Figures 8 and 10 on the other.

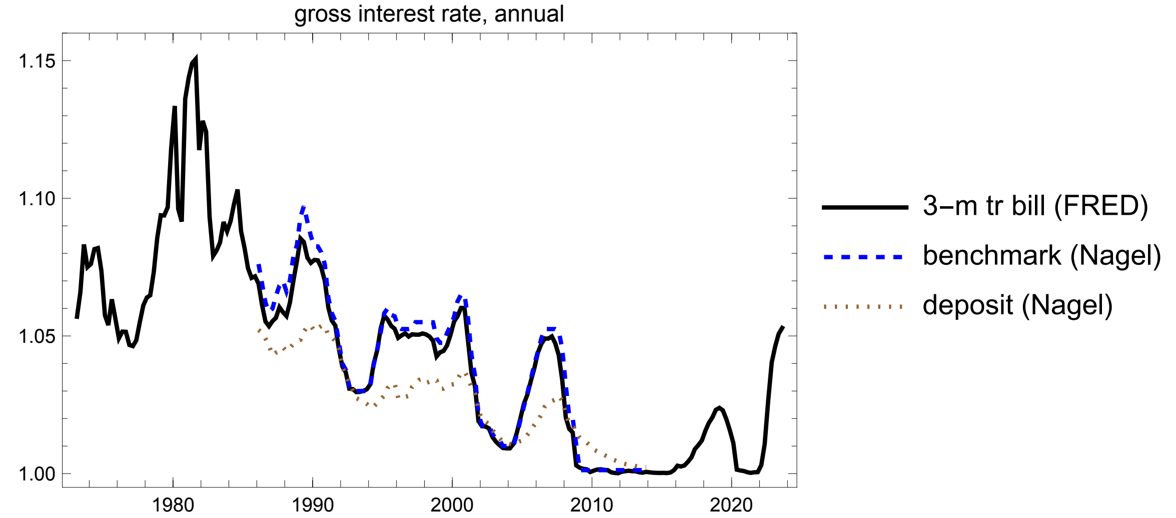

Figure 4: Measures of gross interest rates.

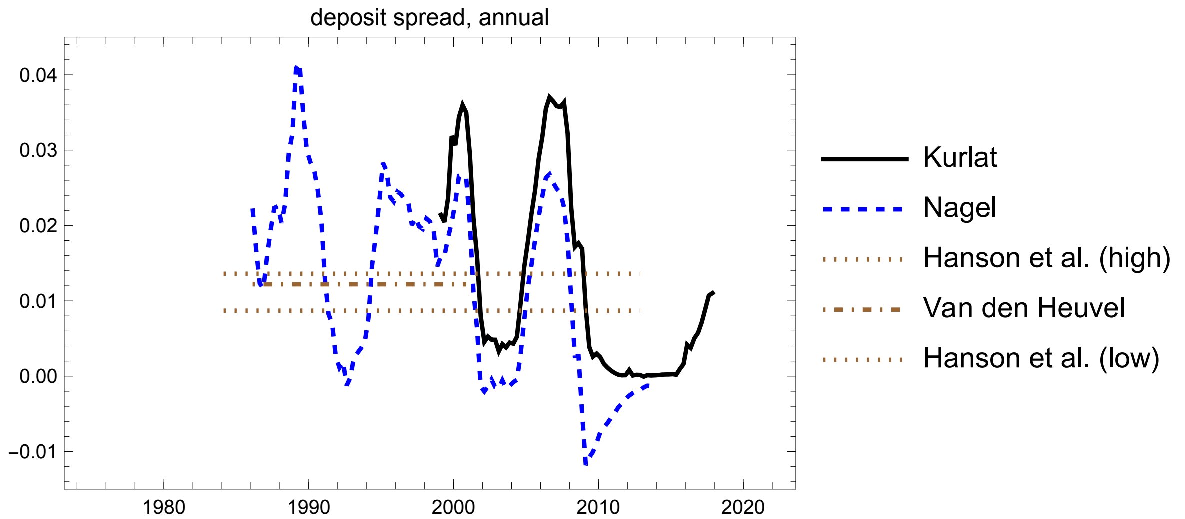

Figure 5: Measures of the deposit spread.

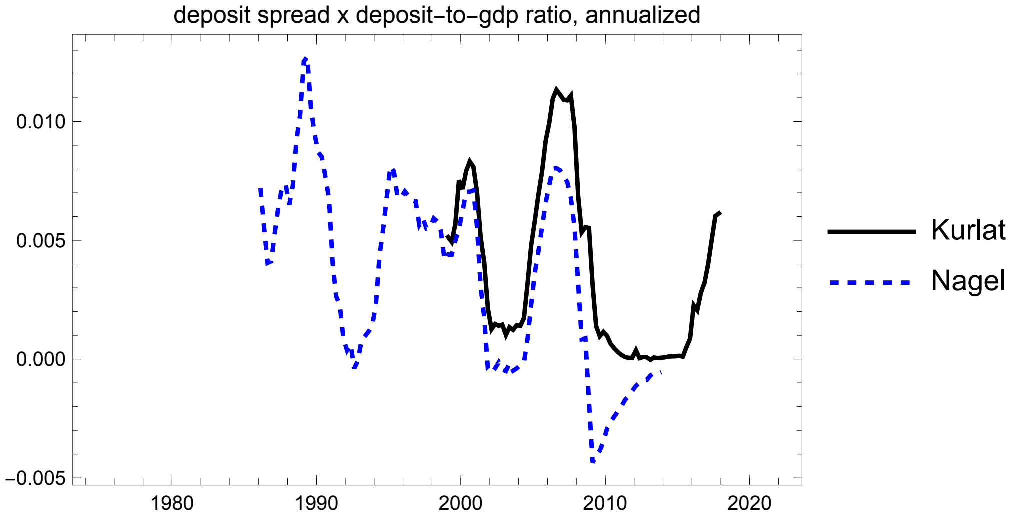

Figure 6: Measures of the deposit spread times the deposit-to-GDP ratio.

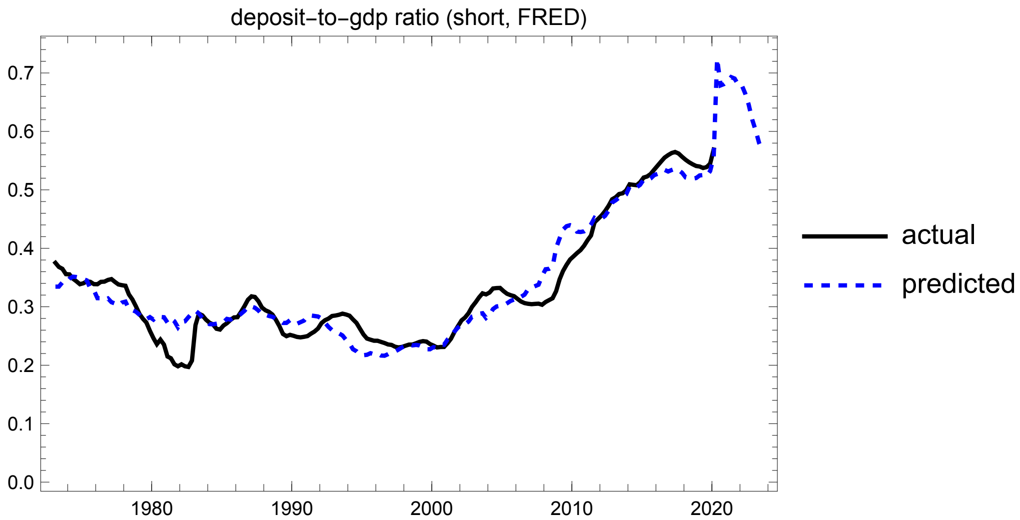

Figure 7: Actual and predicted deposit-to-GDP ratio (short, FRED).

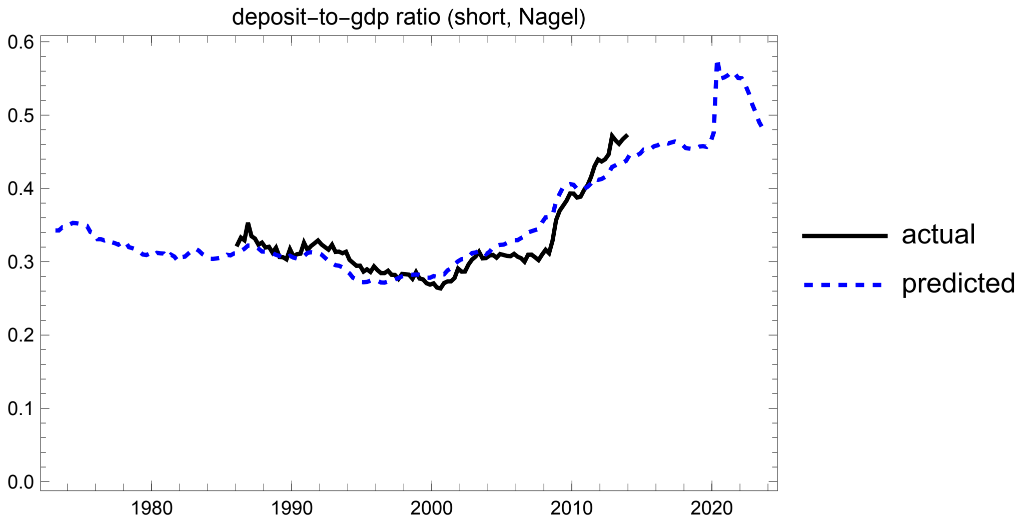

Figure 8: Actual and predicted deposit-to-GDP ratio (short, Nagel).

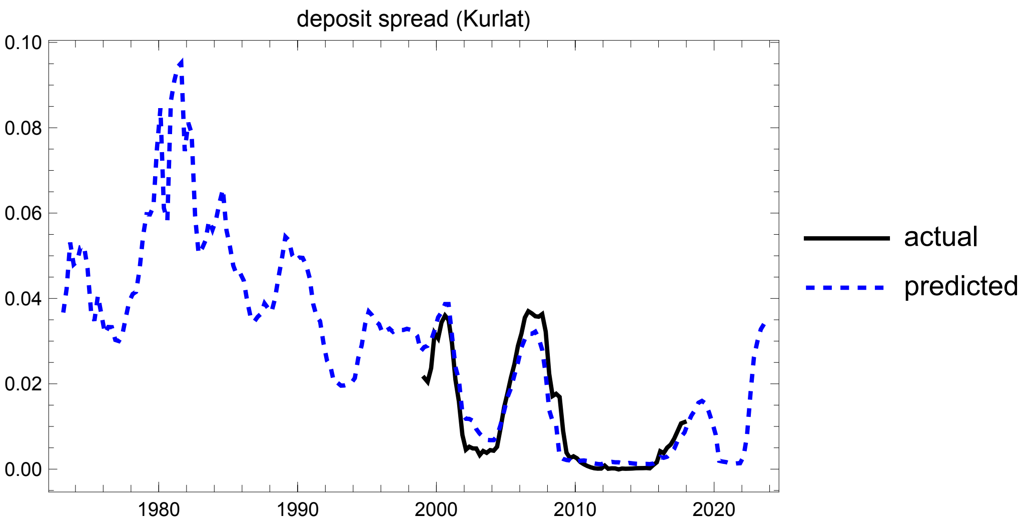

Figure 9: Actual and predicted deposit spread (Kurlat).

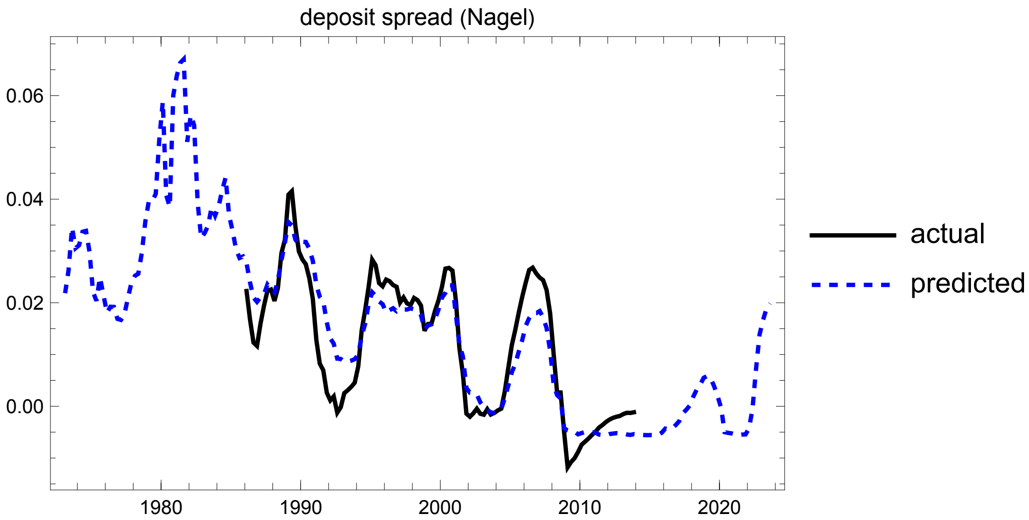

Figure 10: Actual and predicted deposit spread (Nagel).

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