Tokenized Finance and The Perimeter of Central Banking*

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Abstract

Programmable 24x7 ledgers will increase the efficiency of financial markets. Adoption will be gradual due to the network scale economies of legacy platforms for trade, payment, and settlement. A crucial missing element of large-scale tokenized finance is safe cash settlement. Stablecoins and tokenized commercial bank deposits are unsuitable for multi-trillion-dollar core-market infrastructure applications such as financing government securities and exchange clearinghouse payments. Central banks are therefore reconsidering the formats and perimeters of their payment systems and deposit accounts. I outline the state of play and suggest some options for supporting the development of tokenized financial markets while maintaining the current perimeter of central banking and preserving financial stability. Alternative designs are analyzed from the perspective of financial stability, costs of payment-system fragmentation, and the sizes of central-bank balance sheets. Without a high degree of interoperability between traditional and novel large-value payment-and-settlement systems, fragmentation will delay the growth of tokenized finance even if central banks accommodate the increased demand for settlement balances.

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1 Introduction

Programmable 24x7 ledgers will increase the efficiency of financial markets. Adoption will be gradual because of the network scale economies of legacy payment and settlement systems. Today, tokenized finance is a "drop in the bucket." For example, of over $32 trillion in U.S. Treasuries outstanding, a mere $15 billion—less than 0.05%—are held in tokenized form.[1] All other tokenized "real-world assets" combined total only around $15 billion.[2] As for securities financing, likely to become the most important application of tokenized finance, of the over $6 trillion per day of Treasury repos, around 5% are currently tokenized but virtually all of that "on-chain" activity is between affiliates of the same firm.[3] Despite the tiny fraction of financial market activity now done "on chain," many central banks, securities regulators, finance ministries, dealers, commercial banks, and securities depositories are gearing up for a potentially large migration toward tokenized finance.

A crucial hurdle to large-scale tokenized finance is safe cash settlement. Stablecoins and tokenized commercial bank deposits are unsuitable for multi-trillion-dollar core-market infrastructure applications such as clearinghouse margin payments and financing government securities. Central banks are therefore reconsidering the formats and perimeters of their payment systems and deposit accounts. I outline the state of play and suggest some options for supporting the development of tokenized financial markets while maintaining the current perimeter of central banking and preserving financial stability. Alternative designs are analyzed from the perspective of financial stability, costs of payment-system fragmentation, and the sizes of central-bank balance sheets. Without a high degree of interoperability between traditional and novel large-value payment-and-settlement systems, fragmentation will delay the growth of tokenized finance even if central banks accommodate the increased demand for settlement balances.

Today, the majority of payments in core financial markets involve transfers of central-bank deposits between the clearing banks of the payer and receiver. Tokenized financial-market payments now rely mainly on stablecoins or, increasingly, tokenized commercial bank deposits. These payment arrangements are not sufficiently safe for applications at the core of the financial system involving multi-trillion-dollar volumes. Until the largest central banks support 24x7 programmable payments, tokenized finance cannot reach its natural efficient scale without impairing financial stability. Internationally agreed principles[4] state that cash settlement for systemic financial market infrastructure should be in central-bank deposits or an effective close substitute. The underlying tenet is that the soundness of the cash underlying core financial markets

1. Lin, Prasad, Rabetti, and Zhang (2026).
2. See a16zcrypto.
3. For total market repo volumes, see Cenicola, Friedrichs, Olson, and Mann (2026) and Cenicola, Heilbron, Mann, and Paddrik (2026). The intra-affiliate repos that now constitute virtually all repos of tokenized Treasuries are described by Galper (2026) and Broadridge (2026).
4. See Committee on Payments and Market Infrastructures and Board of the International Organization of Securities Commissions (2022).

should not come into question under stress. The alternative is to risk a sudden stop at which large financial market participants refuse to trade over concerns about settlement risk. While retail payments can depend on a medium of exchange that is normally accepted at par value, systemic financial-market infrastructure should rely for settlement on the literal unit of account, which only central banks can provide.

Central banks are generally reluctant to offer full interest-paying deposit accounts to financial market participants other than banks and, in a few cases, systemic financial market infrastructure. Retail central bank digital currencies are unlikely to pay interest or support wallets that are sufficiently large for financial-market applications. As a working hypothesis, I assume that central banks will not extend the perimeter of central banking to support tokenized finance. Widening the perimeter of master accounts at the central bank would force central banks to enlarge their balance sheets and supervisory resources. In most financial systems, wholesale central-bank deposits will likely continue to be held exclusively by banks and a selection of financial market infrastructure such as clearinghouses. Taking this as a starting point, one can envision the following approaches to cash settlement in tokenized financial markets:

1. Provision of central-bank deposits to banks on programmable 24x7 ledgers, either exclusively or in parallel with conventional ledgers.

2. Synchronization of the movement of central bank deposits on conventional large-value payment systems with the movement of tokenized assets on programmable ledgers, along with extended operating hours for conventional payment systems.

3. Omnibus-account narrow banks that provide 24x7 deposit services to banks on platforms that are suitable for tokenized-finance applications.

4. Stablecoins backed by government-quality assets that price to par on a daily basis. Suitable backing assets could include new forms of government securities that are issued at par on a daily basis (Duffie and Wilson, 2025) or money-market funds that invest exclusively in overnight repos backed by Treasury securities.

While all four of these approaches maintain the current perimeter of central banking, the last is not grounded in central-bank money and is dominated by the other approaches from a financial-stability perspective once tokenized finance reaches a large scale. The first three approaches are antithetical to the values and premises of the decentralized-finance (DeFi) movement, which envisions unrestricted equal access to decentralized settlement ledgers and an absence of reliance on trusted third parties such as central banks (Makarov and Schoar, 2022; McNulty and Milne, 2026). I will outline factors that make decentralized permissionless approaches unlikely for wholesale financial applications, at least for many years.

Much of the current impetus for tokenized finance is the attractiveness of 24x7 capabilities for trade, payment, and settlement. If central banks and private firms continue to expand the operating hours of their conventional infrastructure, this initial impetus for tokenized finance might therefore diminish, delaying the network scale economies needed for liftoff. This could likewise delay the deeper structural benefits of programmability. Smart contracts will be used not only "on the back end" to make payments, mobilize collateral, and settle transactions. Smart contracts will also create powerful new ways to combine transactions involving multiple parties, assets, and platforms.[5] Eventually, smart contracts will be used to *identify suitable counterparties and negotiate efficient deal terms in networks of market participants* (Duffie and Wang, 2026). It's hard to imagine that financial market behavior will not be fundamentally transformed by tokenization.

Section 2 discusses the implications of tokenization for the perimeter of central banking and reviews recent work by central banks on alternative approaches to the cash settlement layer for tokenized financial markets. Section 3 explains the essential efficiency-driving features of tokenized finance, including how programmable ledgers can be used for atomic settlement of financial transactions. This section also outlines some of the most important applications and most challenging hurdles to adoption. Section 4 models the cost of fragmentation across traditional and novel payment systems, including impacts on the size of a central bank's balance sheet and on the funding costs of financial market participants, both of which rise with delays in shifting settlement balances between payment systems. Even a small amount of fragmentation could lead to significantly higher funding costs, which will be borne only if the tokenized financial ledgers are highly interoperable with conventional systems or offer substantial new profit opportunities. The model also implies that the network scale economies of conventional systems will impede the migration of trade to more efficient novel systems. Section 5 concludes with some suggested next steps for central banks to consider.

2 Maintaining the perimeter of central banking

As a general principle, non-bank financial market participants do not hold central-bank money. For example, an asset manager typically funds a large purchase of government bonds from its prime-brokerage margin account or from its commercial-bank deposit account. But the settlement of the transaction relies on a transfer of central bank deposits from the buyer's clearing bank to the seller's clearing bank, as depicted in Figure 1, which shows a payment by a customer of bank 2 to a customer of bank 3 that involves a transfer of central-bank deposits from bank 2 to bank 3. While a non-bank buyer may be able to *direct* this movement of reserve balances, it does not *own* the reserve balances. At the retail level, this approach is mirrored in instant payment systems like TIPS, FedNow, RTP, and Pix. In on-chain wholesale financial markets,

5. See Townsend (2020), Lee (2026), and Bank for International Settlements and Institute of International Finance (2026).

non-bank market participants could likewise deploy smart contracts that cause transfers of tokenized central bank deposits between banks without actually owning central-bank money. This is explained in Section 3.

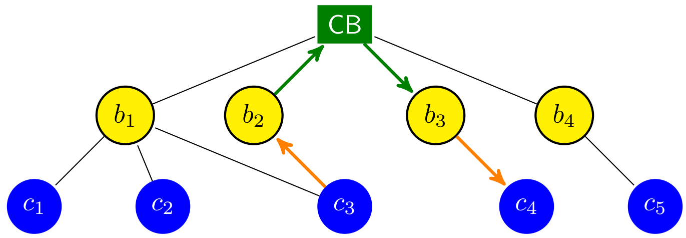

Figure 1: The perimeter of central banking includes banks but, with rare exceptions, does not allow non-banks to hold central-bank deposits. In this schematic, "CB" is the central bank; b_1, b_2, b_3, and b_4 are banks; and $c_1, \ldots, c_5$ are customers of the banks. Account relationships are shown with thin black lines. A real-time payment from c_3 to c_4 is processed by the illustrated sequence of debits and credits of commercial-bank and central-bank deposits. The orange arrows show funds moving on the balance sheets of banks, from c_3 to b_2 and from b_3 to c_4. The green arrows show a transfer of central-bank deposits from b_2 to b_3.

Figure 2 shows the extension of this approach to settings in which a narrow bank holding an omnibus account at the central bank provides sub-accounts to banks for the primary purpose of real-time payments. For tokenized cash settlement of financial trades, the narrow bank could provide its deposits on a programmable ledger. Figure 3 shows how a bank can create additional narrow-bank deposits with a liquidity management transfer from its central-bank deposit account to its narrow-bank account. The reverse transfer is also available. The sizes of central bank balance sheets and the funding costs of market participants are reduced by systems that allow frequent liquidity management transfers, ideally 24x7. These effects are modeled in Section 4.

The perimeter of central banking is preserved by the approach depicted in Figure 2, in that only banks are permitted to hold central-bank or narrow-bank deposits. This approach can be extended to systemtically important financial market infrastructure such as clearinghouses that transfer margin and settlement payments between the clearing banks of market participants. The efficiency of the narrow-bank approach can be impaired, however, by latencies in the conversion of funds between central-bank accounts and narrow-bank accounts, especially to the extent that narrow-bank deposits are not remunerated with interest at the central-bank deposit rate, as explained in Section 4. This problem is mitigated by 24x7 payment systems that allow narrow-bank deposits to be quickly exchanged with reserves. In the United States this is already feasible (FedNow Service, 2023). Some central banks may prefer the simpler two-tiered scheme shown in Figure 1, at the cost of building and maintaining their own 24x7 programmable deposit ledgers.

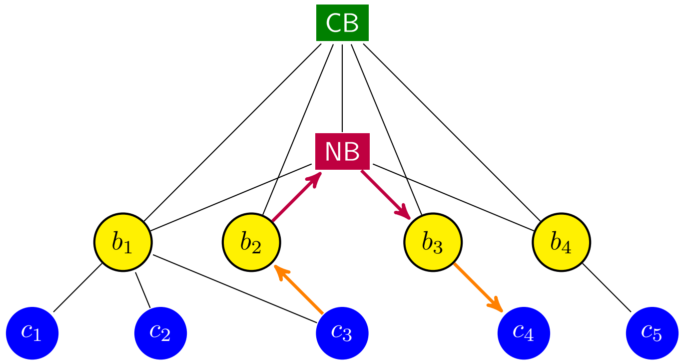

Figure 2: A payment by c_3 to c_4 can be processed by a sequence of debits and credits of commercial-bank and narrow-bank deposits. The orange arrows show funds moving on the balance sheets of banks, from c_3 to b_2 and from b_3 to c_4. The purple arrows show a transfer of narrow-bank deposits from b_2 to b_3.

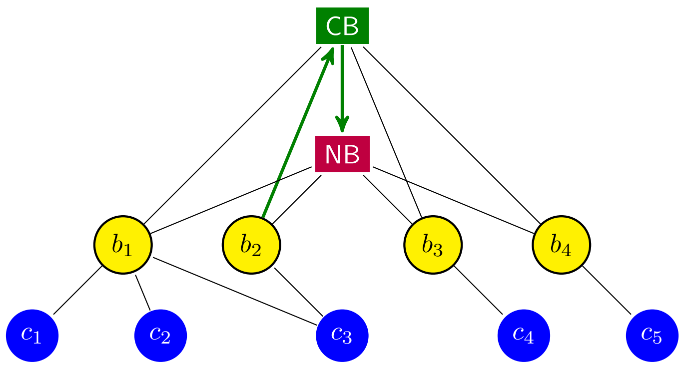

Figure 3: Bank b_2 recharges its narrow-bank deposit account with a liquidity management transfer from its central deposit account.

There has been progress with each of the four approaches:

1. Tokenized reserves. Under this approach, a central bank develops a 24x7 programmable ledger for its settlement balances.[6] Non-bank market participants can cause tokenized reserve balances to move between their clearing banks, as depicted in Figure 1. The Swiss National Bank is a front-runner on this path. The SNB has been providing tokenized reserves on the SIX Digital Exchange (SDX) since the end of 2023 and in June 2025 extended this Helvetia pilot to at least mid-2027 (Swiss National Bank, 2025b, 2025a). SNB's Project Helvetia piloted this approach for trade of tokenized SNB Bills.[7] In June 2024, the SNB also became the first central bank to conduct a live monetary policy operation in a production environment on a regulated programmable ledger when it issued digital SNB Bills settled in tokenized reserves.[8]

The Bank of Canada's Project Samara conducted an experiment in which a tokenized bond was issued

6. See Kunaratskul, Lannquist, and others (2025) and Bank of Canada, Swiss National Bank, European Central Bank, Bank of England, Bank of Japan, Board of Governors Federal Reserve System, Sveriges Riksbank, Bank for International Settlements (2025).

7. See Swiss National Bank (2025b, 2025a) and Gerosa, Gloede, and others (2024).

8. See Swiss National Bank (2025b, 2025a) and Gerosa, Gloede, and others (2024).

and settled using Bank of Canada wholesale digital money.[9] Banque de France introduced a DL3S solution, by which central-bank money is issued in tokenized form as "Exploratory Cash Tokens" on a distributed ledger.[10] The Eurosystem has two Projects, Pontes and Appia, that explore how to deploy tokenized reserves (European Central Bank, 2025a, 2026e, 2026a).

The Bank of England is testing whether central bank money can be transacted safely on an external programmable ledger (Bank of England, 2025c). The U.S. Federal Reserve System has done some experimentation in Projects Cedar and Pine but has not announced a plan to pilot tokenized reserves.[11] The Bank of Japan is experimenting with the use of tokenized central bank money for applications to domestic interbank markets, including securities settlement (Ueda, 2026). Many central banks are participating in Project Agorá, which envisions cross-border payments involving chains of payments in tokenized commercial-bank and central-bank deposits.[12]

In September 2026 the Bank of Korea will begin testing its Digital Currency System (DCS) for transferring tokenized reserves among nine commercial banks. Customers of these banks will then be able to pay each other with tokenized commercial bank deposits in the manner depicted in Figure 1.[13]

2. Synchronization. This approach keeps reserves on the central bank's conventional centralized ledger system and links transfers of reserves via existing real-time gross settlement (RTGS) payment systems with transfers of tokenized assets on an external ledger through a technical bridge or some other form of synchronization mechanism.[14]

The Eurosystem has explored this approach in Project Pontes, which will link DLT platforms and TARGET Services in central bank money (European Central Bank, 2025a, 2026a). Germany's Trigger Solution and Italy's TIPS Hash-Link are prototypes of this model.[15] The Bank of England is developing synchronization capabilities.[16] The Swiss National Bank has expanded Project Helvetia to include an RTGS link

9. See Arora, Faruqui, and others (2026) and Bank of Canada (2026) Project Samara was a limited real-world experiment using permissioned distributed cash and bond ledgers (Arora, Faruqui, and others, 2026). Export Development Canada issued a tokenized bond, while the cash leg used wholesale central bank digital money (W-CAD).

10. See Banque de France (2024a, 2024b).

11. See Federal Reserve Bank of New York (2025), Bank for International Settlements Innovation Hub (2025), and Federal Reserve Bank of New York (2023).

12. See Bank for International Settlements and Institute of International Finance (2026).

13. As explained by Nickell (2026), "When a customer of Bank A pays a merchant whose account is at Bank B, three steps execute as a single atomic transaction via smart contract: the sending bank's deposit tokens are burned; an equivalent amount of wholesale central bank digital currency transfers between the two banks on the DCS; and the receiving bank reissues deposit tokens to the merchant. This is called the burn-and-issue mechanism. If any one of the three steps fails, the entire transaction is voided — there is no partial settlement, no settlement risk, no gap between delivery and payment."

14. See Bank of England (2026), Bank of Canada, Swiss National Bank, European Central Bank, Bank of England, Bank of Japan, Board of Governors Federal Reserve System, Sveriges Riksbank, Bank for International Settlements (2025), and Bank of England (2025b).

15. See Deutsche Bundesbank (2021), Banca d'Italia (2023), European Central Bank (2025b), and Bank of Canada, Swiss National Bank, European Central Bank, Bank of England, Bank of Japan, Board of Governors Federal Reserve System, Sveriges Riksbank, Bank for International Settlements (2025).

16. See Bank of England (2025a, 2025b, 2026).

through the SIC system for BX Digital.[17] The central banks of Canada, Japan, the U.S. and Sweden are exploring this approach with basic research-and-development sandboxes.[18]

Before synchronization can support 24x7 financial markets, a conventional large-value payment system would need to extend its operating hours to 24x7. Table 1 shows the current operating hours of a selection of large-value payment systems, none of which yet support 24x7 payment services.

3. Omnibus-account narrow banks. By this approach, a private payment system operator holds pooled participant funds in an omnibus central-bank account and provides tokenized deposits to particpating banks on a programmable ledger.[19]

For example, the Bank of England supports the Sterling Fnality Payment System (Bank of England, 2025b; Fnality International, 2024). Fnality has indicated that discussions with U.S. regulators are under way (Fnality International, 2026). I presume for the purposes of this paper that Fnality would provide accounts only to firms that already have master accounts at the Fed.

In the United States, this approach could alternatively exploit an existing private-sector instant payment system like RTP, which is operated by The Clearing House, an agent for a consortium of large banks. RTP has an omnibus master account at the Federal Reserve that is remunerated at the normal rate of interest paid to master-account holders on their reserve balances (IOR).[20] RTP currently provides 24x7 payment services to approximately 1260 participating banks and their customers.[21] Payments are made to and from banks' pre-funded RTP sub-accounts. A bank's RTP deposits and its Federal Reserve deposits are convertible for most of the time that Fedwire is closed, with liquidity management transfers (LMTs) that use the 24x7 payment infrastructure created for FedNow.[22] Although LMTs and RTP payments are currently limited to $10 million each, this limit can be changed and multiple transfers are feasible.[23] For tokenized financial-market cash settlement, RTP could provide deposit services on a programmable ledger, just as Fnality is proposing to do.

17. See Swiss National Bank (2025a, 2025b).
18. See Arora, Faruqui, and others (2026), Ueda (2026), Board of Governors of the Federal Reserve System (2026), Federal Reserve Bank of New York (2025), and Sveriges Riksbank (2026).
19. See Bank of England, 2021; Bank of Canada, Swiss National Bank, European Central Bank, Bank of England, Bank of Japan, Board of Governors Federal Reserve System, Sveriges Riksbank, Bank for International Settlements, 2025; Kunaratskul, Lannquist, and others, 2025.
20. See Board of Governors of the Federal Reserve System (2023).
21. See RTP Network.
22. See FedNow Service (2023).
23. See The Clearing House (2024).

Table 1: Operating hours of selected large-value payment systems.

Payment system	Business-day hours	Weekend hours
BOJ-NET	08:30–21:00 JST, Monday–Friday.	Closed on weekends.
CHAPS	06:00–18:00 UK time, Monday–Friday.	Closed on weekends.
CHIPS	21:00 ET on the preceding calendar day to 18:00 ET on the banking day.	Saturday closed; opens Sunday at 21:00 ET for the next Monday banking day, if Monday is a banking day.
Fedwire Funds Service	21:00 ET on the preceding calendar day to 19:00 ET on the funds-transfer business day.	Saturday closed; opens Sunday at 21:00 ET for the next Monday funds-transfer business day, if Monday is a business day.
Fedwire Securities Service	Securities business day begins at 08:00 ET; securities transfer messages begin processing at 08:30 ET. Secondary market transfer cut-off is 15:15 ET, with reversals and repo balance adjustments until 15:30 ET; reposition against payment is available until 16:30 ET, and final/free-of-payment cut-offs are at 19:00 ET.	Closed on weekends.
T2	Current T2 RTGS payment settlement runs from 02:30–18:00 CET/CEST on TARGET business days; customer payment cut-off is 17:00 and interbank/RTGS settlement ends at 18:00.	Currently closed for RTGS payments from Friday 18:00 to Monday 02:30. The Eurosystem has announced a roadmap to introduce a one-to-two-hour weekend/TARGET-holiday settlement window for liquidity transfers.
T2S	TARGET business day starts at 18:45 CET/CEST; start-of-day runs 18:45–20:00, night-time settlement 20:00–23:30, and real-time settlement 23:30–18:00. Standard same-day DvP cut-off is 16:00; end-of-day processing is 18:00–18:45.	No regular weekend settlement; runs after Friday evening change of business day until Saturday 02:30; mandatory maintenance from Saturday 02:30 to Monday 02:30.

Sources: BOJ-NET hours are from Bank of Japan (Bank of Japan, 2014, p. 1); CHAPS hours are from Bank of England (Bank of England, 2018, p. 18); CHIPS hours are from The Clearing House (The Clearing House Payments Company L.L.C., 2025, pp. 51–52); Fedwire Funds hours are from the Board of Governors of the Federal Reserve System (Board of Governors of the Federal Reserve System, 2025, pp. 2, 4); Fedwire Securities hours are from Federal Reserve Financial Services (Federal Reserve Financial Services, 2025, p. 2); general TARGET/T2/T2S schedules are from the ECB TARGET operating schedule (European Central Bank, 2026b, pp. 1–2); current T2 RTGS payment hours and the roadmap for extending T2 operating hours, including its relevance for Pontes, are from the ECB report on the public consultation outcome (European Central Bank, 2026d, pp. 5, 18, 23–24) and the related ECB MIP News announcement (European Central Bank, 2026c); T2S detailed settlement phases and the 16:00 DvP cut-off are from the ECB Information Guide for TARGET participants, Part 4 – T2S Cash (European Central Bank, 2023, p. 10).

Notes: Times are local to each system. For T2 and T2S, times refer to CET/CEST. Sunday evening opening for CHIPS and Fedwire refers to the next Monday business day, not to a separate Sunday business day. For CHIPS, during the overnight window it is open for payment messages for the next banking day, but each participant must fund its opening position before it can send or receive CHIPS payment orders, and that funding must be completed by 9:00am ET. For T2, the table reports current RTGS payment hours and separately notes the Eurosystem's announced roadmap for extending T2 operating hours. The planned weekend/TARGET-holiday settlement window is for liquidity transfers, not a current full weekend RTGS payment window.

4. Stablecoins built for wholesale finance. The cash leg of wholesale financial market trades could be conducted in purpose-built stablecoins backed by safe assets that re-price daily at par market value. At this point, stablecoins meeting this high standard do not exist. A suitable backing asset could be a new form of floating-rate government security that is auctioned at par on a daily basis (Duffie and Wilson, 2025). Another approach is to back such a stablecoin with a money market mutual fund that invests exclusively in overnight Treasury repos.

Yet another alternative is a stablecoin backed 100% by central-bank money. For example, the SNB has investigated how private tokenized money could be backed one-for-one by sight deposits at the SNB (Maechler and Moser, 2023). It can be argued that this approach effectively expands the perimeter of central bank money by allowing non-banks to hold claims — albeit indirect — to central bank money. This concern is mitigated to the extent that the stablecoin issuer's deposits at the central bank are not remunerated with interest, but in that case the prospects for adoption are reduced by heightened private-sector funding costs, as modeled in Section 4.

Stablecoins suitable for wholesale finance would need to pay interest at – or close to – wholesale money market rates. Failing that, funding costs would be unacceptably high.[24] Interest payments on payment stablecoins are not legally permitted in almost all developed-market economies. New laws might be needed for special-purpose stablecoins suitable for many large-scale financial applications.[25] Interest-paying tokenized money market mutual funds (MMFs) have not been adapted for payment applications but, if sufficiently safe and liquid, are suitable for certain large-scale financial applications such as margin collateral.[26]

Because stablecoins are claims on private issuers rather than the unit of account, official-sector analysis treats this approach with caution.[27] The Bank for International Settlements (2025) argues that stablecoins perform poorly with respect to the singleness of money, supply elasticity, and integrity. Researchers at the Federal Reserve note that tokenized MMFs have familiar private-money vulnerabilities such as liquidity transformation, threshold effects, and contagion (Anadu, McCabe, and others, 2026). Duffie and Wilson (2025) emphasize the importance of holding stablecoin backing assets in perfectly safe assets, on-chain, allowing 24x7 convertibility. While the extra-safe stablecoins envisioned under this approach mitigate

24. If the time between commitment of funds to a trade and trade settlement is negligible, and if stablecoins are instantaneously fungible with interest-bearing instruments, it would be economically feasible to use zero-interest stablecoins to conduct settlement. However, extremely short settlement lags are unlikely to be feasible for a range of important applications. Counterparties are likely to require some time to commit funds and assets to a smart contract for atomic settlement.

25. Presumably, wholesale stablecoins that pay interest would be prohibited from retail applications, so would presumably need to be issued on permissioned ledgers with limited access.

26. Securities Industry and Financial Markets Association (2026) summarizes the assets and properties of tokenized U.S. registered money market mutual funds.

27. See Financial Stability Board (2024), Bank for International Settlements and Committee on Payments and Market Infrastructures (2024), Kunaratskul, Lannquist, and others (2025), Kim, Ruprecht, and others (2026), Azar, Carapella, and others (2025), Bank of Canada, Swiss National Bank, European Central Bank, Bank of England, Bank of Japan, Board of Governors Federal Reserve System, Sveriges Riksbank, Bank for International Settlements (2025), and Financial Stability Board (2024).

financial-stabilty concerns relative to the use of existing stablecoins, this approach is inferior to tokenized central-bank deposits as a settlement medium for wholesale finance.

3 Why tokenize financial markets?

While there is no general agreement on the definition of "tokenized" finance, its essence is the ability to transfer assets programmably, that is, to treat an asset as a record whose control is managed by a software platform on which multiple parties can negotiate and settle transactions based on many types of contingencies, such as the completion of other transactions.[28] Critical to this is the ability for parties to conduct smart contracts. Long before the advent of decentralized finance or blockchains, Szabo (1996) described a smart contract as "a set of promises, specified in digital form, including protocols within which the parties perform their promises." The remainder of this section explains the growing popularity of tokenized financed and why, relative to most conventional approaches, financial services can be more effectively provided by applying smart contracts. I also cover some of the key challenges to a large-scale migration to tokenized finance and some of the related risks to financial stability.

Figure 4 illustrates how a smart contract can be used to make a payment with tokenized commercial bank deposits. Firm B pays Firm A with a message to a programmable ledger that triggers a smart contract, freezing $10 million of the tokenized deposits held by Firm B at Bank B. The smart contract then burns (destroys) these deposits and creates a $10 million deposit in Bank A. Finally, the smart contract releases the newly created $10 million deposit into the account (wallet) of Firm A. This approach, now under development by The Clearing House and by SWIFT,[29] relies on the net settlement of all such payments between banks using central-bank reserves. Large-value payment systems operated by central banks are not yet available 24x7, as indicated in Table 1. When done on a large scale, deferred net settlement represents systemic risk. Many central banks introduced real time gross settlement systems after the failure of Bank Herstatt in 1974 in order to reduce this form of systemic risk (Heckinger, Marshall, and others, 2009).

In the near term, the greatest impact of tokenized wholesale finance is the ability to conduct payments and finance securities with flexible timing, quickly, and around the clock. Applications include intraday or overnight repurchase agreements, the payment of margins to and from exchange clearinghouses, and international corporate treasury transactions. Updating legacy bank-railed payment systems for 24x7 operation is complicated and costly, especially in cross-border correspondent-banking settings. Banks are instead developing ways to let their customers make payments around the clock and across borders with stablecoins

28. See, for example, Cook (2026) and Duffie and Wang (2026).

29. See "Major Financial Institutions Unveil Bank-Led On-Chain Money Initiative," Press release, The Clearing House, June 5, 2026; and Swift to Add Blockchain-based Ledger, Press release, SWIFT, September 29, 2025.

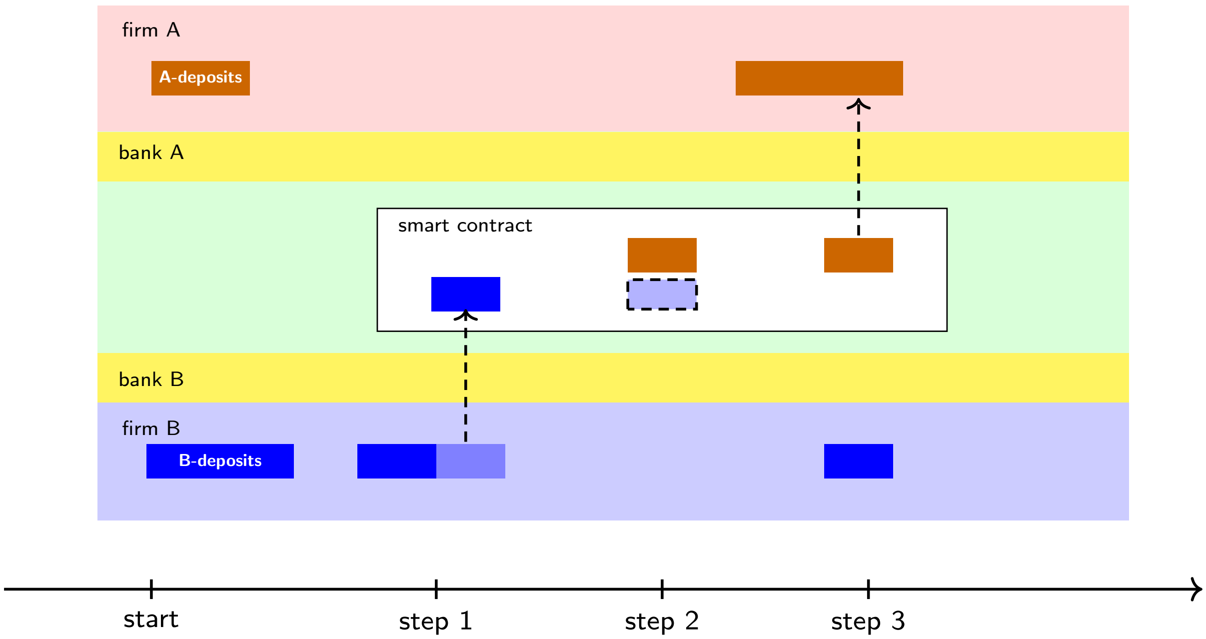

Figure 4: A payment of tokenized deposits. At Step 1, a smart contract freezes some amount of deposits of Bank B committed by firm B, shown in blue. At Step 2, the committed B-deposits of firm B are "burned" and an equal quantity of Bank-A deposits (shown in amber) are created. At Step 3, the newly created A-deposits are transferred by the smart contract into the account (wallet) of firm at bank A. This approach is now in development for global banks by The Clearing House and by Swift.

and tokenized deposits. These applications make relatively light use of programmability.

While this is happening, the financial industry is also gearing up to eventually transform the trade and settlement of financial-market transactions with programmable ledgers. In July 2026, the world's largest securities depository, the Depository Trust and Clearing Corporation, announced that it "successfully converted assets held at The Depository Trust Company (DTC) into tokens that were then used in real production trades."[30] In this pilot, the tokenized assets that were traded or financed in repurchase agreements included popular exchange-traded index funds, SPDR S&P 500 and QQQ, and U.S. Treasury securities. These transactions were conducted on two different permissioned programmable ledgers, Canton and DTCC's own HyperBesu, depending on the choices of the investors involved in each transaction.[31] In the same July 2026 pilot, J.P. Morgan posted tokenized assets to satisfy margin requirements with CME's clearinghouse.

In October 2026, DTCC will offer investors holding securities at DTCC the option to have them held in tokenized form, under a regulatory exemption provided by the Securities and Exchange Commission. DTCC earlier indicated its intent to eventually make available tokenized versions of all of the securities that it custodies, currently totaling $114 trillion. Also in July 2026, BNY, which handles trillions of dollars of Treasury repo transactions every day, announced its plan to introduce tokenized Treasuries on its private blockchain by the end of 2026, with an aim to support 24x7 settlement for both conventional and tokenized

30. See DTCC (2026) and Ge Huang (2026).
31. Egilsson (2026).

Treasuries in 2027.[32]

Tokenized finance can be conducted on both centralized and distributed asset ledgers, whether public, private, permissioned, or permissionless, although there is disagreement among technology specialists over the relative advantages of various forms of ledger management. The biggest source of contention here is the wisdom of reliance on trusted authorities to validate the truth of the ledger.[33] Although the choice of ledger management technology is not the focus of this paper, it plays important roles in regulatory compliance, privacy, security, and transaction throughput. For example, fully decentralized permissionless ledgers rely on more computationally intensive validation schemes and can take a substantial amount of resources to secure.[34] A ledger's ability to support compliance with payment regulations and control the privacy of transactions is also crucial for large corporations and official-sector entities.[35]

In all existing tokenized-finance applications, cryptography is used to securely control and transfer assets, subject to conditions defined by the state of the ledger. For example, the ledger can include a smart contract that accepts an instruction by a buyer to freeze access to a designated amount of the buyer's cash settlement asset until a seller similarly commits another asset in exchange, in which case their smart contract transfers their respective assets to each other. Atomic (all or none) settlement has been available for decades in the U.S. Treasury market through Fedwire Securities, which processes the messaged payment of reserves from the buyer to seller if and only if the seller of securities also messages the transfer of securities. This is feasible without cryptographic smart contracts because the Federal Reserve operates the ledgers for both Treasury securities and reserve balances.[36]

Figure 5 illustrates the use of a smart contract for the atomic (all-or-none) settlement of a bond trade on a programmable ledger. The same process is used to settle the opening or closing leg of a repurchase agreement. The trade terms may have been agreed on a separate platform or on the same platform supporting the programmable ledger on which the buyer and seller have their cash and asset wallets. The agreed terms of trade are entered into a smart contract. The seller then cryptographically commits the agreed quantity of bonds to the smart contract. The buyer likewise commits the agreed cash settlement amount to the smart

32. See Lee (2026). BNY (2026) explains that "BNY's Intraday Repo facilitates the allocation and return of eligible collateral for intraday settlement (versus payment). This tool provides market participants with the ability to source liquidity for precise periods of time without having to borrow for a full 24-hour period, while allowing lenders to generate additional income on idle cash." J.P. Morgan (2023) writes that "Managing intraday cashflows is an essential part of a financial institution's liquidity management program. Traditional intraday financing solutions, such as intraday credit facilities and overnight repo agreements, can be costly and prone to operational friction. Digital Financing is a revolutionary alternative that streamlines intraday financing, reduces borrowing costs and optimizes capital deployment."

33. See, for example, Egilsson (2026) and McNulty and Milne (2026).

34. See Budish (2025) and Eidan, Frost, Kansal, Lewrick, Lim, and Rybarczyk (2026).

35. See Duffie, Olowookere, and Veneris (2025) and Kunaratskul, Lannquist, Reslow, and Zhang (2025).

36. The seller's clearing bank submits a transfer message to Fedwire Securities that specifies the security, the quantity, and the required payment amount. Fedwire Securities then automatically checks that the seller actually holds the specified securities in its book-entry account. If so, Fedwire Securities instantly executes two actions at the exact same moment: (1) debit the securities account of the seller's clearing bank and credit the securities account of the buyer's clearing bank, and (2) debit the master funds account of the clearing bank of the buyer and credit the master funds account of the seller's clearing bank. These two transfers are irrevocable and unconditional upon completion. See Federal Reserve Board (2014).

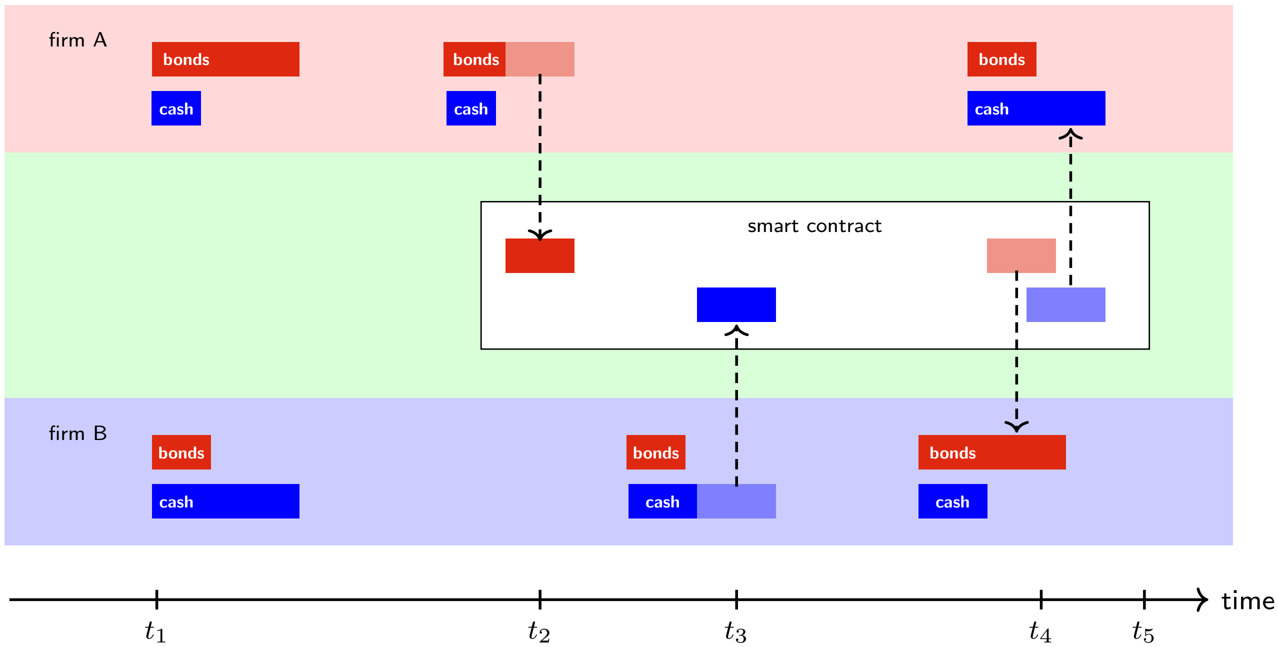

Figure 5: A programmable ledger supports delivery versus payment with the atomic settlement of a bond trade. At time t_1, Firms A and B hold some initial quantities of bonds and cash in their wallets on the ledger, indicated in red and blue respectively. They negotiate terms — not necessarily using ledger software — by which A will sell bonds to B. At time t_2, Firm A cryptographically irrevocably commits the agreed quantity of bonds to a smart contract. At time t_3, Firm B likewise irrevocably commits the agreed amount of cash to the smart contract. At time t_4, which may be immediately after t_3, the smart contract transfers the committed cash to Investor A and the committed bonds to Investor B. If, by time t_5, one or both of the investors had failed to commit the proposed asset to the smart contract, the smart contract would then have returned any committed assets to the original holder.

contract. Neither of these commitments is revocable until the expiration of the smart contract. Once both parties have completed this step, the smart contract completes the settlement by transferring the cash to the seller's wallet and the bonds to the buyer's wallet.

If one of the investors does not commit its asset to the smart contract by the expiration time stipulated in the deal terms recorded in the smart contract, the smart contract releases any asset that it holds to its original owner. This avoids the need for a trust firm or clearinghouse to guarantee settlement.[37] The terms of a smart contract could require the asset seller to make an initial commitment of cash to the smart contract that is forfeited in the event of delivery failure. Delivery failures provide a useful degree of optionality, especially to dealers economizing on balance-sheet space who can take advantage of the ability to sell an asset before having located the asset. Unregulated and uncontrolled delivery failures can, however, propagate and destabilize financial markets.

37. The U.S. Treasury triparty repo market has the unusual property that the assets and cash positions of the collateral providers and cash investors are all in accounts at the same bank, BNY. This allows cash to be moved from the buyer's deposit account to the seller's deposit account at the same bank, and assets from seller's custody account to the buyer's custody account at the same bank. The bank acts as a trusted agent that ensures delivery-versus-payment (DvP), achieving the same effect of atomic settlement. This allows efficiencies comparable to those of tokenized finance, provided that these operations are available 24x7 using efficient software. There remains the concern that financial stability rests crucially on the continued existence of a single private-sector bank.

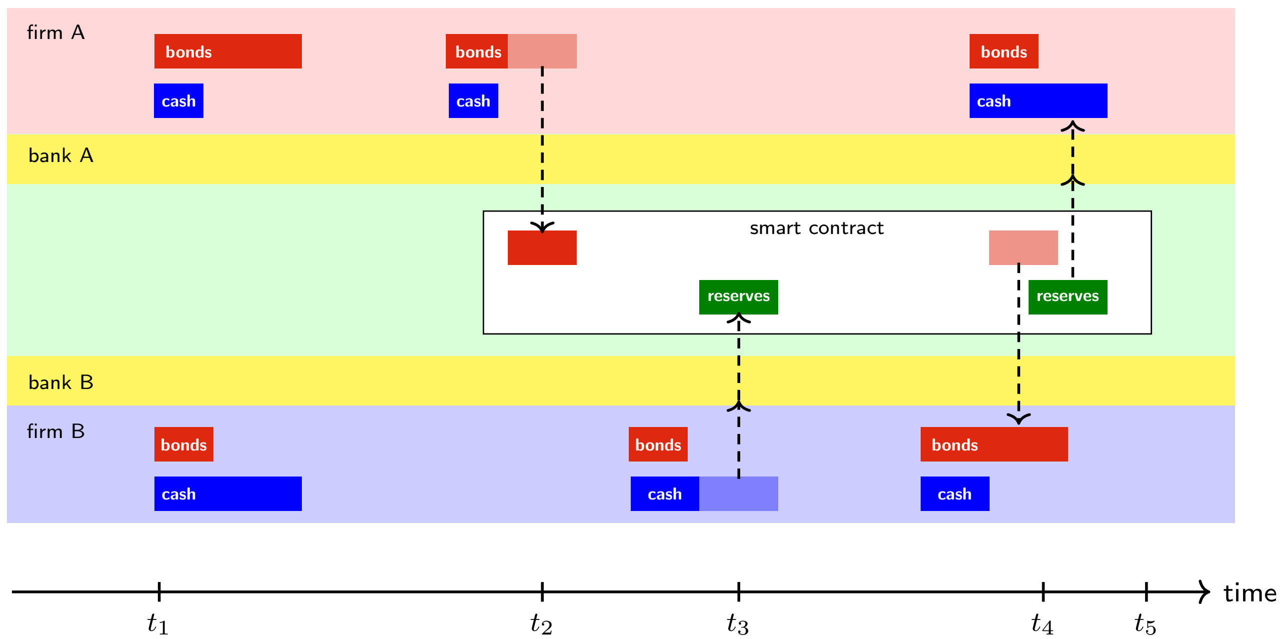

Figure 6: A programmable ledger supports delivery versus payment with the atomic settlement of a bond trade, involving transfers of both commercial bank deposits (blue) and central-bank deposits (green). As in Figure 5, at time t_2, Firm A cryptographically and irrevocably commits the agreed quantity of bonds to a smart contract. At time t_3, Firm B likewise irrevocably commits the agreed amount of cash to the smart contract with a message that debits its deposit account at bank A (in blue) and instructs bank A to commit the same amount of tokenized reserves (in green) to the smart contract. At time t_4, which may be immediately after t_3, the smart contract transfers the committed tokenized reserves to the clearing bank of Firm A and the same amount into the deposit account of Firm A. The committed bonds are transferred to Firm B. If, by time t_5, one or both of the investors had failed to commit the proposed asset to the smart contract, the smart contract would then have returned any committed assets to the original holder.

The ability to conduct faster trade settlement on programmable ledgers will not cause settlement delays to disappear because that would force counterparties to have their assets and cash in advance of trading, thus conceding significant netting efficiencies. Settlement lags will be optimized based on funding costs and netting efficiency (McLaughlin, 2023). For trades involving delayed settlement, atomic settlement does not avoid the risk of default losses caused by changes in market values between the times of agreement to trade and the time at which the smart contract terminates. Central counterparties (CCPs) will therefore remain critical in tokenized financial markets. The advantages of a CCP naturally apply to "$T + 1$" settlement of securities trades, derivatives contracts, and the closing legs of repurchase agreements.

The trade depicted in Figure 5 is settled entirely with a form of cash, such as stablecoins, held in the wallets of the buyer and seller. As I have explained, however, this is generally unsatisfactory for systemically important financial market infrastructure. Figure 6 shows how this trade could alternatively be settled with tokenized reserves held by the clearing banks of the buyer and seller. In this case, the bond buyer instructs its clearing bank to debit the buyer's commercial bank account and to commit the required amount of tokenized reserves to the smart contract. The smart contract completes the settlement with a transfer of tokenized reserves to the seller's clearing bank, which in turn credits the seller's commercial bank account. This can be "straight-through" settlement, in that the respective clearing banks may have authorized their customers to conduct all of the cash transfers, subject to ongoing checks on the sufficiency of funds in their trading accounts.

If the central bank does not provide reserves to banks in a tokenized form, the programmable settlement illustrated in Figure 6 could instead use tokenized narrow-bank deposits.

Although 24x7 operation is not an inherent property of programmable settlement, it comes naturally with distributed ledger technology (DLT) given the "always-on" reliance on many nodes that constantly update their copies of the same ledger.

In the near term, the most important advantage of 24x7 programmable financial ledgers is improved collateral mobility, especially cash collateral for conducting around-the-clock repos and derivatives margin payments (Nasdaq, 2026). Intraday funding flexibility allows large financial firms to meet their funding needs with less capital and lower financing costs.[38] Other motives include reduced operating costs through streamlined settlement with fewer delivery failures, reduced need for third-party infrastructure, more effective trade reconciliation and process monitoring, the ability to compose multiple transactions programmably, and reduced counterparty risk through increased settlement finality.[39]

The Woolard (2026) report to the UK Chancellor summarized these types of benefits as follows:

"Tokenisation can improve collateral mobility, capital efficiency, and risk management by making assets easier to identify, move, substitute, and reuse across venues and workflows. This reduces trapped collateral, excess buffers, failed trades, and friction in collateralised funding and treasury activity. Faster settlement and greater transparency over asset location and ownership can also reduce operational, counterparty, and liquidity risk. Capital freed up from more efficient collateral and treasury functions can be redeployed into higher-value activity. The projected 1–2% improvement in collateral efficiency would generate hundreds of millions of pounds of annual economic value for an average wholesale bank and contribute up to 4% uplift in return on equity.

These near-term benefits of tokenization, although large, are mundane in comparison with the deeper structural benefits of programmability. Tokenization will engender a wide variety of entirely new types of financial transactions. Smart contracts will be used not only "on the back end" to make payments, mobilize collateral, and settle transactions. "Composability" will create powerful new ways to combine multiple types of transactions, which may involve multiple parties, assets, and platforms (Townsend, 2020; Lee, 2026). For example, Project Agorà envisions modular combinations of smart contracts as a revolutionary new way to conduct correspondent banking.[40] Eventually, smart contracts will be used to *find suitable counterparties*

38. See Galper (2026), Depository Trust and Clearing Corporation (2026), Treasury Borrowing Advisory Committee (2026), and J.P. Morgan (2023).

39. For more detailed descriptions of these and other advantages of tokenized finance, see Cook (2026), Financial Stability Board (2024), Reserve Bank of Australia and Digital Finance Cooperative Research Centre (2026), Kunaratskul, Lannquist, Reslow, and Zhang (2025), and Central Bank of Ireland (2026), among many other sources. On the role of financial market infrastructure in a tokenized financial market, see Cabedo, Mancini-Griffoli, Schär, and Zhang (2026).

40. See Bank for International Settlements and Institute of International Finance (2026).

and negotiate efficient deal terms, atomically, among multiple market participants (Duffie and Wang, 2026). It's hard to imagine that financial market behavior will not ultimately be transformed by programmability.

The advantages of tokenized finance are to be weighed against the potential costs of fragmentation between and among conventional and tokenized systems, as modeled in the next section. Some of the other cost factors described in Nasdaq's survey include the cost of onboarding to new systems, additional network charges, the cost of making internal system changes that allow 24x7 processes, additional staffing costs for running 24x7, and various other potential costs of fragmentation across systems such as lost netting and fungibility. Initially, at least, the network scale benefits of legacy systems, combined with these tokenization costs, may significantly delay the migration of wholesale finance onto tokenized platforms.

Tokenized finance could also add risks to financial stability.[41] Among these risks, Danmarks Nationalbank (2025) warns that

> *"Errors in smart contracts can pose a systemic risk. Tight integration of smart contracts can create dependencies where errors in one contract can quickly spread to others via automated processes. In systemically important infrastructures, such contagion effects can have far reaching consequences, especially if adequate mechanisms are not in place to control the use of smart contracts. Smart contract failures can occur not only unintentionally but also as a result of targeted attacks by malicious entities, emphasizing the need for a thorough assessment of cyber risks and the potential systemic impact of technology."*

4 Fragmentation, funding costs, and the demand for reserves

Fragmentation of payment activity across multiple payment-and-settlement systems increases the total amount of settlement balances that central banks must supply in order maintain market interest rates at targeted levels with ample reserves and to meet other monetary policy objectives (Duffie, 2026). Nevertheless, even if the central bank expands its balance sheet so as to fully accommodate the added demand for settlement balances caused by fragmentation, the cost of "pre-funding" a greater aggregate amount of settlement balances to multiple payment systems raises funding costs for financial market participants. Even with ample reserves, the fragmentation cost to market participants of funding more cash leads to welfare losses. Market participants will forgo some of the socially beneficial trades that require cash payments, given the wedge known as funding value adjustments (Andersen, Duffie, and Song, 2019). Unlike the theory underlying the Friedman Rule (Berentsen, Camera, and Waller, 2005), the central bank cannot eliminate this social cost by providing ample reserves and paying the risk-free rate on reserves. This cost of fragmentation is reduced to the extent that payment systems are more interoperable, that is, more frequently accessible to each other at low frictional cost.

41. See Adrian (2026), Central Bank of Ireland (2026), Financial Stability Board (2024), Kunaratskul, Lannquist, and others (2025), Cook (2026), Lee (2026), and World Economic Forum (2025).

For example, suppose the risk-free rate is $r = 4\%$. A firm's marginal cost of funds is $F = 5\%$, representing a spread of 1% caused by the firm's credit risk and the illiquidity of its issuances. To raise 100 in risk-free settlement balances that pay $100(1 + r)$, the firm borrows 100 with a payback of $100(1 + F)$. The firm's net funding cost is $100(F - r)$. The firm is willing to raise this cash only if the funds can be used for sufficiently profitable trading opportunities. The funding spread $F - r$ is a therefore a wedge causing some gains from trade to be lost. In the financial industry, the funding cost for a trade is labeled a "funding value adjustment" (FVA). Dealer trading desks are charged FVAs to the extent that their trades require cash. This inhibits the least profitable trades.[42]

The same principles apply to the cost of funding non-cash assets to different platforms that are not fully interoperable. In 2025, Accenture (2025) found 72 different digital asset platforms with varying degrees of interoperability. Proliferation and fragmentation continues, although emerging technologies are likely to improve interoperability.[43] Financial market participants will not migrate toward tokenized finance given the incremental funding costs caused by fragmentation unless these costs are reduced by improved interoperability and eventually offset by the combined benefits of shorter settlement cycles, technology-based cost reductions, the ability to trade 24x7, the ability to program trades and settlements with many types of contingencies, and access benefits associated with novel payment systems.

This section models how the optimal stock of settlement balances that a firm commits to a given system trades off the profitability of trades in that system against the cost of funding the initial stock of reserves. Fragmentation is costly because it requires more settlement balances to handle the same aggregate volume of trades.[44]

First, consider one of the two payment systems, which is separated from the other system until some time $T > 0$. Settlement balances can be moved from one system to the other at time zero but not again until time T. Funding costs shrink as T approaches zero. We first solve a firm's optimal policy for accepting cash-draining deal opportunities, and then show how the firm splits its initial total balances across the two systems. In equilibrium, all firms choose the same initial "cash" settlement balance $b > 0$ in the system under analysis. At Poisson times with intensity λ, the firm encounters a deal opportunity with a random counterparty in the same system. If accepted, the deal requires the payment of one unit of cash to the counterparty. If the firm has at least one unit of cash and the value of the deal is higher than the opportunity value of a unit of cash, the firm accepts the deal. Conversely, the same firm receives cash from randomly-matched counterparties facing the same situation, whenever these counterparties are likewise able and willing to enter the associated

42. The underlying economic friction is debt overhang. For example, a firm that increases its stock of settlement balances supports the firm's creditors at the expense of its equity shareholders. See Andersen, Duffie, and Song (2019).

43. See Accenture (2025) and World Economic Forum (2025).

44. This model is from research in progress with Sam Wycherley. Illustrative calculations were computed by Tony Liu.

deals. All of the Poisson processes and deal profits are independent.

At time T, a final cash balance of x is worth $(1 + rT)x$, where r is the rate of interest paid on balances held at time T. (The model can alternatively be solved with interest paid continually on balances held during the interval from 0 to T.) To maintain tractability, I model a continuum of firms of total mass 1.[45]

I first solve for the value $U(x, t)$ to an arbitrary firm of having x units of cash in this payment system at some time $t < T$. Optimally, the firm will accept any deal that pays it a unit of cash, but will only accept a deal requiring it to pay a unit of cash at time t if $x > 0$ and if the deal value exceeds the value $\pi(x, t) = U(x, t) - U(x - 1, t)$ of giving up a unit of cash. Every deal's value is assumed to be exponentially distributed with parameter ξ, so the conditional probability that the deal is accepted by the firm is $e^{-\xi\pi(x,t)}$. The conditional expected value of an accepted deal is $\pi(x, t) + 1/\xi$, the mean of the exponentially distributed value conditional on exceeding $\pi(x, t)$.

At any time, the cross-sectional distribution $\mu(t)$ of balances among firms at some future time t plays a role in determining the current value of balances to a given firm because $\mu(t)$ determines the likelihood of receiving cash from a potential future counterparty at time t, whose willingness to accept a deal depends on the counterparty's own cash balances. The probability that a randomly matched counterparty at time t accepts a deal that pays cash to the given firm is

$$\theta_t = \sum_{x=1}^{\infty} \mu(x, t) e^{-\xi\pi(x,t)}.$$

The cross-sectional distribution $\mu(t)$ of balances at time t is equal to the unconditional probability distribution of any firm's balances at time t (Duffie, Qiao, and Sun, 2025). The Kolmogorov forward equation (KFE) determining the evolution of μ is therefore

$$\frac{\partial \mu(x,t)}{\partial t} = \lambda\theta_t\mu(x-1,t) + \lambda e^{-\xi\pi(x+1,t)}\mu(x+1,t) - (\lambda\theta_t + \lambda e^{-\xi\pi(x,t)})\mu(x,t), \quad x > 0, \tag{1}$$

and

$$\frac{\partial \mu(0,t)}{\partial t} = \lambda e^{-\xi\pi(1,t)}\mu(1,t) - \lambda\theta_t\mu(0,t). \tag{2}$$

The initial condition is $\mu(b, 0) = 1$ and $\mu(x, 0) = 0$ for $x \neq b$.

The optimal rate of mean increase of $U(x, t)$ associated with accepting deals is

$$\sup_{\bar{\pi}} \Big\{ \lambda e^{-\xi\bar{\pi}} \Big(\bar{\pi} + \frac{1}{\xi} + U(x-1,t) - U(x,t) \Big) \Big\} = \frac{\lambda}{\xi} e^{-\xi(U(x,t) - U(x-1,t))}, \tag{3}$$

45. The probability space and agent space satisfy the measurability conditions of Duffie, Qiao, and Sun (2025), which allow an application of the exact law of large numbers for continuous-time random matching.

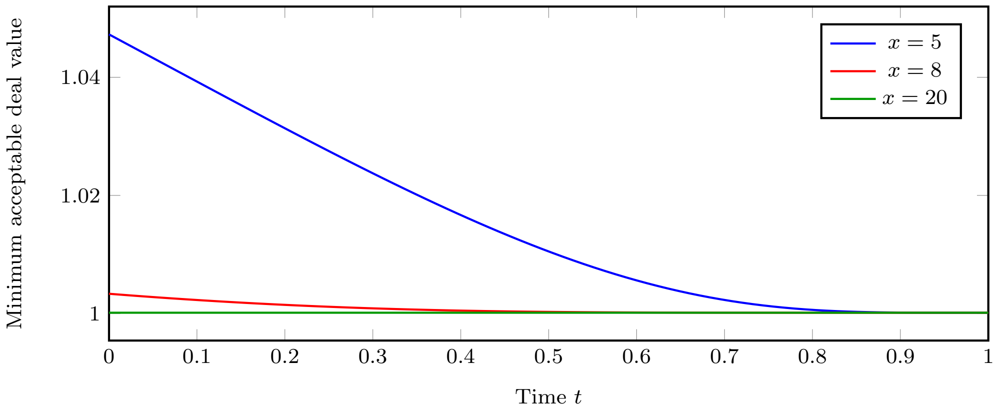

Figure 7: The minimum acceptable deal value $\pi(x,t) = U(x,t) - U(x-1,t)$ for various levels of time t and current holding x of settlement balances. At low levels of x, the firm is more discriminating about acceptable deals. Parameters: interest rate $r = 0.05$, time until replenishment of funds $T = 1$, initial settlement balances $b = 10$, mean deal value $\xi^{-1} = 1$, and mean frequency of deal opportunities $\lambda = 100$. The probability of an acceptable deal, $e^{-\xi\pi(x,t)}$, is approximately 0.37 for $\pi(x,t) \simeq 1$.

using the fact that the optimum is achieved at $\pi(x,t) = U(x,t) - U(x-1,t)$. Figure 7 shows how the minimum acceptable deal value $\pi(x,t)$ decreases with the current balance x and time t. The Hamilton-Jacobi-Bellman (HJB) equation for U thus reduces to the backward differential equation[46]

$$-\frac{\partial U(x,t)}{\partial t} = \frac{\lambda}{\xi} e^{-\xi(U(x,t)-U(x-1,t))} + \lambda\theta_t(U(x+1,t) - U(x,t)), \qquad x > 0, \tag{4}$$

with

$$-\frac{\partial U(0,t)}{\partial t} = \lambda\theta_t(U(1,t) - U(0,t)). \tag{5}$$

The boundary condition is

$$U(x,T) = (1 + rT)x, \qquad x \geq 0. \tag{6}$$

The Appendix shows how the KFE-HJB system of ordinary differential equations is solved. The Appendix also includes a generalization of this model in which the firms are banks that not only conduct deals for themselves but also act as counterparties and clearing banks for their own customers' deals. This gives rise to additional demands for cash balances.

Fragmentation raises the demand for reserves and consequently increases market interest rates unless the central bank accommodates by increasing the supply of settlement balances to meet the higher demand. Because $U(x,0)$ is concave in x, a firm's demand for initial balances in this system is

$$B(\lambda, \xi, r, F, T) = \max\{b \geq 0 : U(b,0) - U(b-1,0) \geq 1 + FT\}, \tag{7}$$

46. A martingale verification argument shows that there is a unique symmetric Markov equilibrium in which the solution of the HJB equation is the unique optimal expected value in this payment system of holding x in balances at time t.

where $F \geq r$ is the firm's external cost of funds per unit of time.[47] A higher funding spread $F - r$ decreases the demand for balances. Reducing the rate r of interest remuneration on the settlement cash used by a payment system has approximately the same impact on funding costs as increasing the funding spread $F - r$. Unless the external cost of funding F is close to zero, this implies that a non-interest-bearing settlement asset like a conventional stablecoin would be prohibitively expensive unless the settlement time T is close to zero.

The demand $B(\lambda, \xi, r, F, T)$ for settlement balances in a given system is increasing in λ, increasing in mean deal value $1/\xi$, decreasing in the funding cost F, increasing in the rate r paid on settlement balances, and increasing in the amount T of time before balances can be replenished. The mean rate of profit,

$$W(\lambda, \xi, r, F, T) = \frac{1}{T}\left[U(B(\lambda, \xi, r, F, T), 0) - B(\lambda, \xi, r, F, T)(1 + FT)\right] \tag{8}$$

is decreasing in T. Shorter intraday settlement cycles have been an impetus for the development of tokenized finance.[48]

To isolate the pure impact of fragmentation, I hold constant the aggregate frequency and profitability of deal opportunities across the two systems, as well as the refunding settlement time T and suppose that the total mean frequency Λ of deal opportunities is split between two systems at λ and $\Lambda - \lambda$. The total demand for settlement balances across the two systems,

$$D(\lambda, \Lambda, \xi, r, F, T) = B(\lambda, \xi, r, F, T) + B(\Lambda - \lambda, \xi, r, F, T) \tag{9}$$

is increasing in λ on the interval $[0, \Lambda/2]$. An illustrative example is shown in Figure 8.

In order to maintain ample reserves, a central bank would accommodate this demand by increasing the supply of settlement balances rather than allowing fragmentation-induced scarcity of settlement balances to cause an increase in interest rates. In that case, each firm's net funding cost, $(F - r)D(\lambda, \Lambda, \xi, r, F, T)$, rises with fragmentation in proportion to the total demand for settlement balances shown in Figure 8. For example, for these illustrative parameters, shifting 10% of trade from the legacy system to a novel system increases the total demand for reserves and funding costs by roughly 30%, with dollar magnitudes that depend on the refunding time T.

However, this cost of fragmentation can potentially be dominated by the benefits of interoperability between payment systems! Net funding cost *benefits* can be achieved by adding a novel payment system

47. This condition characterizes optimality because $U(b, 0)$ is concave in b.
48. See Treasury Borrowing Advisory Committee (2026), Galper (2026), Depository Trust and Clearing Corporation (2026), and J.P. Morgan (2023).

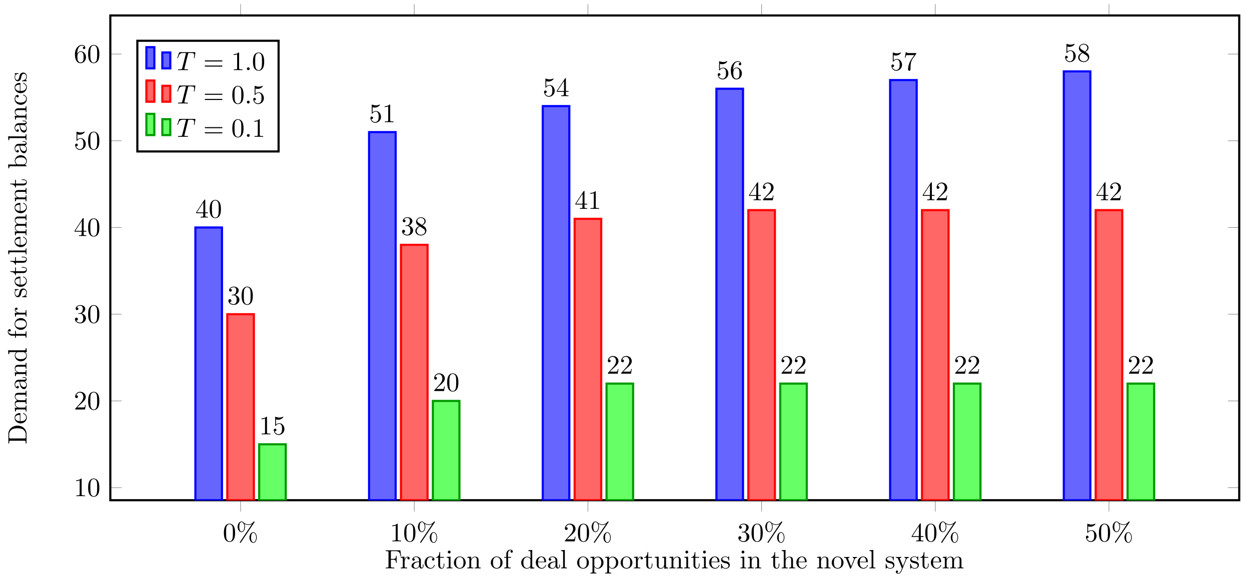

Figure 8: The figure shows how splitting a fixed total mean rate of deal opportunities across two systems increases the demand for settlement balances, which also depends on the amount T of time until cash can be replenished. At Poisson event times with total intensity Λ, a firm is presented with the opportunity to pay one unit of cash settlement balances to another firm in exchange for a deal with a value that is exponentially distributed with mean one. Deals arrive with mean frequency λ in System A and with mean frequency $\Lambda - \lambda$ in System B. A firm accepts a deal in a given system only if the outcome of the deal value exceeds the value of giving up one unit of cash settlement balances in that system. At time zero, each firm optimally splits its total initial quantity of settlement balances between the two systems, given the split of the other firms. With $\lambda = 0$, firms optimally put the entire quantity of their settlement balances in System B. As λ increases and firms demand more cash in System A, fragmentation increases the total quantity of settlement balances demanded by each firm, shown on the vertical axis. The parameters are $\Lambda = 100, \xi = 1, r = 0.05/360$, and $F = 0.06/360$.

with shorter intraday funding cycles *if* funds obtained in the novel system can be moved intraday between the two systems at the end of each funding cycle, or even more frequently.[49] To show this using the same model, suppose that the legacy system has a one-day funding settlement ($T = 1$) and the novel system allows for funding ten times a day ($T' = 0.1$). Relax the assumption that funds cannot move to the legacy system from the novel system until T. Instead, suppose funds can move between the systems at the end of the shorter funding period T' of the novel system. Without the novel system, Figure 8 shows a total demand for balances of 40 per firm. With the novel system and the ability to make inter-system transfers at the shorter funding settlement T' of the novel system, the legacy system can rely on funding from the novel system, reducing the effective length of a funding cycle in *both* systems to 0.10. The total demand for balances drops from 40 to 22 or less per firm, depending on the degree of fragmentation. This 45% reduction in the demand for cash settlement balances likewise generates a 45% reduction in funding costs in this example, despite the impact of fragmentation. This simple example is not calibrated to market data and leaves out many other considerations. Among the funding-cost benefits achieved through intraday funding with tokenized repos is

49. Again, see Galper (2026), Treasury Borrowing Advisory Committee (2026), and Depository Trust and Clearing Corporation (2026).

a reduced cost for meeting regulatory liquidity constraints, as achieved through intra-affiliate repos arranged by Broadridge.[50]

If fragmentation adds to net funding costs, participants will not participate in this adverse outcome unless there is another market friction that can be reduced by shifting some financial activity to a novel payment system. For example, suppose certain types of deal opportunities are uniquely available in payment system A, while other types of deal opportunities are uniquely available in payment system B. To model this tradeoff, we could suppose that increasing λ' does not come at the expense of a fully offsetting reduction in λ. This could happen with tokenization because of a potential widening of market access or increased trading hours. Moreover, the deal profitability parameters ξ and ξ' could differ across the two systems. This could happen with tokenization because of a reduction in technical settlement costs, for example through atomic settlement and more generally through programmability of trading and settlement and increased flexibility in settlement timing. To address new and profitable trade opportunities, a tokenized financial market may therefore be profitably introduced despite the fragmentation costs generated by a distinct settlement system.

Another issue is whether exploiting the technology benefits of a novel payment-settlement system will be significantly delayed by the network scale economies of the legacy system. Individual market participants may not migrate some of their trading to a novel system if most potential counterparties remain in the legacy system. In our model, scaling the mass of participants that are active in a given system by some constant ϕ is equivalent to scaling the mean deal-opportunity frequency λ to $\phi\lambda$. If profitability depends heavily on the ability to find suitable counterparties, the network scale effect dominates and make it extremely difficult to reach scale in a novel segmented financial market.

In order to model the impact of fragmentation on incentives related to trade clearing costs, suppose a fraction $\gamma < 1$ of firms have the specialized ability to move their trade from System A to a novel System B that has the advantage of a shorter refunding time $T' < T$. A clearing bank clears the trade of a customer trading firm by conducting the cash settlement with the counterparty's clearing bank, using a form of settlement cash that is specialized to the system. (I assume for simplicity that the counterparties to a trade have different clearing banks.) This fragmentation of trade across systems increases the funding costs of clearing banks, so increases the average clearing fees charged to their customers. In aggregate, the two systems have a total mean trade frequency of λ per clearing bank. If some fraction γ of firms shift to System B, the total mean rate of trades in System B per clearing bank is $\gamma\lambda$, leaving $(1-\gamma)\lambda$ per clearing bank in System A.

For illustrative parameters, Figure 9 compares the breakeven clearing fees in the legacy system with

50. See Galper (2026), Treasury Borrowing Advisory Committee (2026), J.P. Morgan (2023), and Depository Trust and Clearing Corporation (2026).

those of a novel system with less participation but shorter funding cycles.[51] As shown, at least from the perspective of clearing costs, migration of trade to a novel system is not discouraged provided that the novel system has a sufficiently short funding cycle relative to the legacy system and provided that there is at least some critical mass of other joiners.

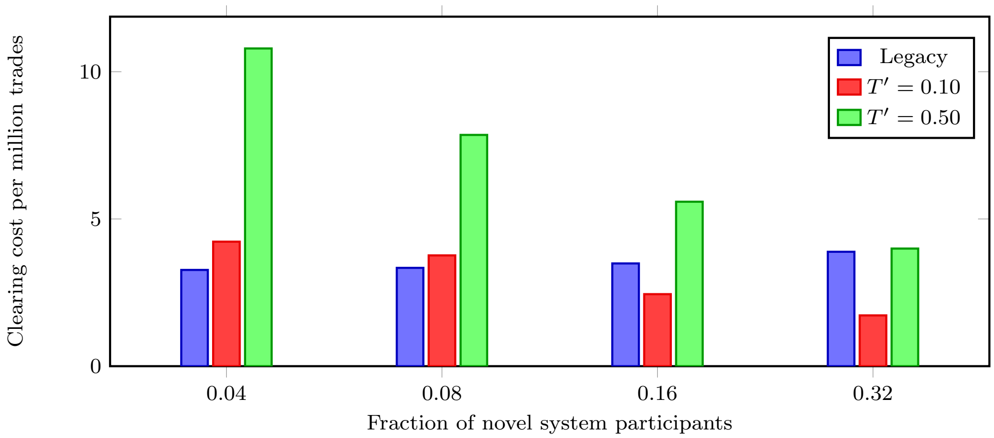

Figure 9: Competitive break-even clearing costs in the legacy and novel systems, in dollars per $1 million payment. The legacy and novel funding times are $T = 1$ and $T' = 0.1$, in days. The other model parameters are $\lambda = 100$, $r = 0.05/360$, $F = 0.06/360$. The illustrative cost calculations are reasonable when viewing the unit of payment to be $100 million. The associated mean payment volume per day for each clearing bank would then be $10 billion.

5 Conclusion

In addition to its potential role as a provider to market participants of tokenized reserves as a settlement medium, the central bank is itself a potential *user* of tokenized cash and securities when implementing its monetary policy with market operations.[52] This raises the question of whether a central bank or finance ministry should also introduce a programmable ledger for government securities (perhaps among other digital assets). How should that asset ledger be designed and governed, potentially in coordination with the private sector? Should this be the same ledger on which tokenized reserves are provided? These questions are complex and beyond the scope of this paper, but are to be considered at the point of introduction of

51. A clearing bank receives a fee of ψ per customer trade. Each trade requires a payment of one unit of settlement balances. At a mean trade frequency of λ, the value $V(x,t)$ to a clearing bank of having x in settlement balances at time t thus solves the HJB equation

$$0 = V_t(x,t) + \lambda\psi + \frac{\lambda}{2}(V(x+1,t) - V(x,t)) + \frac{\lambda}{2}(V(x-1,t) - V(x,t)), \quad x \geq 0.$$

Assuming overdrafts are charged fees on a running basis at the interest rate r,

$$0 = V_t(x,t) - rx + \lambda\psi + \frac{\lambda}{2}(V(x+1,t) - V(x,t)) + \frac{\lambda}{2}(V(x-1,t) - V(x,t)), \quad x < 0.$$

The boundary condition is $V(x,T) = x(1+rT)$. The clearing bank funds the optimal initial amount of balances at a funding cost of F. For a system with participation by some fraction γ of customers, the mean deal frequency per clearing bank is $\gamma\lambda$ rather than λ.

52. See Reserve Bank of Australia and Digital Finance Cooperative Research Centre (2026) and Kunaratskul, Lannquist, and others (2025) for full discussions of this topic.

tokenized reserves.[53] Given the design complexities and the quickly evolving underlying technologies, some central banks and finance ministries will likely delegate tokenization almost entirely to the private sector, at least for the next decade or two. Narrow payment-services banks, securities depositories, clearinghouses, exchanges, securities dealers, and large banks can probably manage the early stages of development of tokenized finance reasonably well. This does not rule out market failures associated with network scale economies that favor incumbent systems. Some central banks may choose to play a more active role by providing market infrastructure, just as with the development of public-sector RTGS payment systems and liquidity savings mechanisms, or closely coordinating with financial market utilities such as CLS Group.

While the regulation of tokenized finance should be based on "same activity — same rules," smart contracting will likely introduce entirely new types of activities to be regulated.

If financial firms are active on both traditional and novel systems for payment and settlement and if those systems are not highly interoperable, funding costs could rise significantly. These fragmentation costs should not be ascribed to tokenization itself, but rather to splitting liquidity across *any* systems that are not highly interoperable. Central banks should mitigate the costs of fragmentation by supplying additional reserves, so that a scarcity of settlement balances is not an impediment to trade and does not interfere with market interest rates and monetary policy implementation. Fragmentation may nevertheless increase private-market funding costs. Market participants will only choose to shoulder fragmentation and switching costs if these costs are dominated by the benefits of tokenization. Ideally, major payment-and-settlement systems will become highly interoperable. Rather than add a tokenized payment system side by side with a conventional payment system, some central banks may eventually upgrade their legacy payment systems to allow a greater degree of programmability. The most obvious alternative is to delegate tokenization of settlement balances to a private-sector utility, which is the narrow-bank approach depicted in Figure 2.

Much of the current impetus for tokenized finance is simply based on the attractiveness to some firms of 24x7 capabilities for trade, payment, and settlement. If central banks and private firms continue to expand the operating hours of their conventional infrastructure, the impetus for tokenized finance could therefore diminish, delaying the critical-mass network scale economies needed for liftoff and thus delaying the richer structural benefits associated with programmability. Already, however, some large central banks, commercial banks, dealers, and infrastructure providers are gearing up for a significant migration toward tokenized finance.

53. Kunaratskul, Lannquist, Reslow, and Zhang (2025) provide an excellent overview of these issues.

Appendix

A Algorithm used to solve the fragmentation model

The model was solved with the following algorithm.

1. Initialize some guess U^0 for U.
2. Let $k = 0$.
3. Solve the forward equation for μ^{k+1}, treating U as though equal to U^k. This is an ordinary differential equation. The Euler method is effective for a small time step like $T/100$.
4. Solve the HJB equation for U^{k+1}, treating μ as though equal to μ^{k+1}. Again, one could solve this using the Euler method with a time step like $T/100$.
5. If the sup-norm of $U^{k+1} - U^k$ is smaller than a pre-set error bound ϵ, stop. Otherwise, replace k with $k+1$ and return to Step 3.

Although the state space for a bank's balances is the set of non-negative integers, we truncate at a high level of balances, such as $\bar{x} = b + c\lambda T$, for a constant c, say 2. The KFE and HJB equations need to be approximated at $\bar{x}$. For this, one can ignore the terms in the KFE and HJB that involve incoming payments.

B Extended fragmentation model

I fix a probability space and a nonatomic measure space $(J, \mathcal{J}, \iota)$ of symmetric firms,[54] with $\iota(J) = 1$. Each firm j has total reserve balances $R \in \mathbb{N}$ at time 0, and participates in two payment systems, A and B.

Each firm j chooses initial balance $X^{ij}(0) \in \mathbb{N}$ to hold as cash in its system i deposit account, with $X^{Aj}(0) + X^{Bj}(0) = R$. Firms must, at all times, hold nonnegative balances in each system. Balances in system i earn an interest rate r_i, accrued linearly and paid at the end of the trading session.

Over the course of the trading session, which takes place over the time interval $[0, T]$, customers in system $i \in \{A, B\}$ approach each firm with opportunities to trade assets for cash. Customers use firms for two purposes: broker-dealer services, and banking services. Without loss of generality, we assume each customer banks with a different firm to their broker-dealer.[55] We model a customer arrival to firm j as a match between firm j and the bank (firm $k \neq j$) of the customer. The Poisson arrival intensity at which customers conduct trades with firm j in system i is λ_i.

With probability p_i, an arriving potential trade is a purchase, that is, the purchase of an asset by firm j from one of its clients in system i. This requires that firm j transfers a unit of system-i cash to one of the other firms. With complementary probability, the trade is a sale, that is, the sale of an asset by firm j to one of its customers in system i. In this case, the customer's bank k transfers a unit of system-i cash to firm j.

Each potential trade has a profitability π drawn from the exponential distribution F_i with rate parameter $\xi_i > 0$. For each potential trade arriving to firm j, the firm chooses whether to accept or reject the trade. Trades are settled immediately. A firm making a purchase in system i must have cash-on-hand in that system in order to pay for the transaction. We conjecture and verify that the optimal policy for the firm in system i is to accept all purchases and sales with profitability above some thresholds $\pi^-_{ij}(x,t)$ and $\pi^+_{ij}(x,t)$ respectively, where x denotes the firm's current balance in system i. Let $\pi^{i\pm}(x,t)$ denote the corresponding policies adopted by other firms. We let $V(x_A, x_B, t)$ denote the maximal value that firm j can expect to obtain when it holds cash balances x_A and x_B in systems A and B respectively at time t.

54. See Duffie, Qiao, and Sun (2025) for measurability conditions on the product space of states and agents that justify the existence of the continuous-time random-matching results applied here.

55. For each firm j, a profitable trade with a customer who also banks with that firm is always worth accepting because it involves no transfer of reserve balances.

We conjecture that in symmetric equilibrium, each firm's value function $V : \mathbb{N}^2 \times [0,T] \to \mathbb{R}$ takes the form $V(x_A, x_B, t) = V^A(x_A, t) + V^B(x_B, t)$, for some functions $V^i : \times[0,T] \to \mathbb{R}$. Conjecturing that each $V^i(x_i, t)$ is increasing in cash balances x_i for all $t < T$, note that it is optimal for a firm to accept all sales in either system, since our choice of profitability distribution implies that all arriving sales are profitable, and any sale increases firm j's cash balance in that system. We therefore conjecture that $\pi_{ij}^+ = \pi^{i+} = 0$.

Let $\mu^i(x,t)$ denote the fraction of firms that have cash balance x in system i at time t. When a bank has zero balances, its customers are unable to propose purchases to other firms. We define

$$\theta_i^+(t) = \sum_{x=1}^{\infty} \mu^i(x,t)(1 - F_i(\pi^{i-}(x,t))).$$

The cash balance of firm j in system i depends on the settlement of four different kinds of transaction:

(i) With intensity $p_i\lambda_i(1 - F_i(\pi_{ij}^-(x,t)))$, the firm accepts a purchase from a customer in system i, with $\pi_{ij}^-(0,t) = \infty$. Let N^{ij-} denote the counting process corresponding to the number of purchases in system i accepted by the firm.

(ii) With intensity $(1-p_i)\lambda_i(1 - \mu^i(0,t))$, the firm accepts a sale from a customer in system i. Let N^{ij+} denote the counting process corresponding to the number of sales in system i accepted by the firm.

(iii) With intensity $p_i\lambda_i\theta_i^+(t)$, firm j receives a unit payment from some other firm k, due to a sale of an asset to firm k made by a customer who banks with firm j. Let M^{ij+} denote the counting process for the number of in-payments to firm j associated with such sales.

(iv) With intensity $(1-p_i)\lambda_i 1_{X^{ij}(t)>0}$, firm j makes a unit payment to some other firm k, due to a purchase of an asset from firm k by a customer who banks with firm j. Let M^{ij-} denote the counting process for the number of out-payments by firm j associated with such sales.

In system i, the cash balance of firm j is the process X^{ij} given by

$$X^{ij}(t) = X^{ij}(0) + N_t^{ij+} + M_t^{ij+} - N_t^{ij-} - M_t^{ij-},$$

which is bounded below by 0. The cumulative income process Y^{ij} of firm j in system i satisfies

$$\mathrm{d}Y_t^{ij} = r_i X_t^{ij}\,\mathrm{d}t + \pi_i^-\,\mathrm{d}N_t^{ij-} + \pi_i^+\,\mathrm{d}N_t^{ij+},$$

where π_i^- is an independent random variable with the distribution $F_i(\cdot \mid \pi_i^- > \pi_{ij}^-(X_t^{ij}, t))$ and π_i^+ is an *iid* random variable with distribution F_i. Because F_i is the exponential distribution with rate parameter ξ_i, we have

$$\mathbb{E}[\pi_i^- \mid \pi_i^- > \pi_{ij}^-(X_t^{ij}, t)] = \pi_{ij}^-(X_t^{ij}, t) + \frac{1}{\xi_i},$$

while $\mathbb{E}[\pi_i^+] = \frac{1}{\xi_i}$. Firm j maximizes $\mathbb{E}[Y_T^A + Y_T^B + X_T^A + X_T^B]$ subject to $X_t^{ij} \geq 0$ for $i = A, B$ and all $t \in [0,T]$, and $X_0^{Aj} + X_0^{Bj} = R$.

Recall we conjecture that $V(x_A, x_B, t) = V^A(x_A, t) + V^B(x_B, t)$. Each V^i solves an HJB equation. For $x_i > 0$, this yields

$$\begin{aligned}
0 = V_t^i(x_i,t) + r_i x_i &+ \sup_{\pi}\Big\{p_i\lambda_i e^{-\xi_i\pi}\Big(\pi + \frac{1}{\xi_i} + V^i(x_i-1,t) - V^i(x_i,t)\Big)\Big\} \\
&+ (1-p_i)\lambda_i(1-\mu^i(0,t))\Big(\frac{1}{\xi_i} + V^i(x_i+1,t) - V^i(x_i,t)\Big) \\
&+ p_i\lambda_i\theta_i^+(t)\Big(V^i(x_i+1,t) - V^i(x_i,t)\Big) \\
&+ (1-p_i)\lambda_i\Big(V^i(x_i-1,t) - V^i(x_i,t)\Big),
\end{aligned}$$

Here, the final four terms are those associated with cash inflows and outflows due to trading. Solving the first-order condition associated with the first of these four terms, the optimal policy turns out to be

$$\pi_{ij}^{-}(x_i, t) = V^i(x_i, t) - V^i(x_i - 1, t).$$

Substituting this into the HJB equation, we obtain,

$$\begin{aligned} 0 = V_t^i(x_i, t) + r_i x_i + \frac{p_i \lambda_i}{\xi_i} e^{-\xi_i (V^i(x_i,t) - V^i(x_i - 1, t))} \\ + (1 - p_i)\lambda_i (1 - \mu^i(0, t)) \Big(\frac{1}{\xi_i} + V^i(x_i + 1, t) - V^i(x_i, t) \Big) \\ + p_i \lambda_i \theta_i^{+}(t) \Big(V^i(x_i + 1, t) - V^i(x_i, t) \Big) \\ + (1 - p_i)\lambda_i \Big(V^i(x_i - 1, t) - V^i(x_i, t) \Big), \end{aligned}$$

At $x_i = 0$, the terms associated with payment outflows drop out, and we have

$$\begin{aligned} 0 = V_t^i(0, t) + (1 - p_i)\lambda_i (1 - \mu^i(0, t)) \Big(\frac{1}{\xi_i} + V^i(1, t) - V^i(0, t) \Big) \\ + p_i \lambda_i \theta_i^{+}(t) \Big(V^i(1, t) - V^i(0, t) \Big). \end{aligned}$$

Finally, we have terminal condition $V^i(x_i, T) = x_i$ for all $x_i \geq 0$.

The distribution $\mu^i(x, t)$ of i-cash balances across firms enters firms' HJB equation, both directly and through $\theta_i^{+}(t)$. For $x > 0$, we have Kolmogorov forward equation,

$$\mu_t^i(x, t) = \upsilon(t)\mu^i(x - 1, t) + \delta(x, t)\mu^i(x + 1, t) - (\upsilon(t) + \delta(x, t))\mu^i(x, t),$$

where

$$\begin{aligned} \upsilon(t) = (1 - p_i)\lambda_i (1 - \mu^i(0, t)) + p_i \lambda_i \theta_i^{+}(t), \\ \delta(x, t) = p_i \lambda_i e^{-\xi_i (\tilde{V}^i(x,t) - \tilde{V}^i(x - 1, t))} + (1 - p_i)\lambda_i, \end{aligned}$$

and where $\tilde{V}^i$ is the value function of an arbitrary firm. Likewise, for $x = 0$, we have the Kolmogorov forward equation

$$\mu_t^i(x, t) = \delta(1, t)\mu^i(1, t) - \upsilon(t)\mu^i(0, t).$$

Finally, in a pure-strategy symmetric equilibrium,

$$\mu^i(x, 0) = 1\{x = x_i^*\},$$

where x_i^* is the initial balance each firm optimally chooses to hold in system i in equilibrium.

Substituting for the optimal policy in the definition of θ_i^{+},

$$\theta_i^{+}(t) = \sum_{x=1}^{\infty} e^{-\xi_i (\tilde{V}^i(x,t) - \tilde{V}^i(x - 1, t))} \mu^i(x, t).$$

It remains to determine optimal initial balances, (x_A^*, x_B^*), subject to the constraint $x_A^* + x_B^* = R$. Taking as given the initial distribution μ^A and μ^B, the optimal A-balance for firm j solves

$$\sup_{0 \leq x_A \leq R} V^A(x_A, 0) + V^B(R - x_A, 0).$$

References

Accenture. 2025. Liquidity Without Borders Why Cross-Chain Interoperability Is Essential in an Increasingly Multi-Chain Financial Ser vices Landscape. Report in collaboration with Chainlink, May.

Adrian, Tobias. 2026. Tokenized Finance. IMF Note no. 2026/001, International Monetary Fund, April.

Anadu, Kenechukwu, Patrick McCabe, JP Perez-Sangimino, and Nathan Swem. 2026. A Framework for Understanding the Vulnerabilities of New Money-Like Products. Finance and Economics Discussion Series 2026-002, Board of Governors of the Federal Reserve System, January.

Andersen, Leif, Darrell Duffie, and Yang Song. 2019. "Funding Value Adjustments." *Journal of Finance* 74:145–192.

Arora, Rakesh, Umar Faruqui, Scott Hendry, Dinesh Shah, André Usche, Mark Byrne, Caroline Cook, Kevin Fraites, Wally Forsyth, Alex Caridia, Chris Meston, Teresa Venturino, Devon Read, Chadrick Buffel, Anne Boulanger, Sylvie Lacombe, and Marsha Loraas. 2026. Project Samara Research Paper. Bank of Canada Staff Analytical Paper no. 2026-8, March.

Azar, Pablo, Francesca Carapella, JP Perez-Sangimino, Nathan Swem, and Alexandros P. Vardoulakis. 2025. The Financial Stability Implications of Tokenized Investment Funds. Federal Reserve Bank of New York *Liberty Street Economics*.

Banca d'Italia. 2023. TIPS Hash-Link: Service Description. European Central Bank, December.

Bank for International Settlements. 2025. Annual Economic Report 2025. Bank for International Settlements, June.

Bank for International Settlements and Committee on Payments and Market Infrastructures. 2024. Tokenisation in the Context of Money and Other Assets: Concepts and Implications for Central Banks. BIS/CPMI Report to the G20, Bank for International Settlements, October.

Bank for International Settlements and Institute of International Finance. 2026. Project Agorá: A Shared Programmable Platform for Wholesale Cross-Border Payments. Bank for International Settlements, May.

Bank for International Settlements Innovation Hub. 2025. Project Pine: Central Bank Open Market Operations with Smart Contracts. Bank for International Settlements Innovation Hub, May.

Bank of Canada. 2026. Bank of Canada, Export Development Canada, RBC and TD Successfully Complete Bond Issuance Experiment Using Distributed Ledger Technology. Bank of Canada News Release, March.

Bank of Canada, Swiss National Bank, European Central Bank, Bank of England, Bank of Japan, Board of Governors Federal Reserve System, Sveriges Riksbank, Bank for International Settlements. 2025. Wholesale central bank money in the context of technological innovation. Bank for International Settlements, September.

Bank of England. 2018. The Bank of England's Real-Time Gross Settlement Service: Service Description. Bank of England, December.

———. 2021. Bank of England Publishes Policy for Omnibus Accounts in RTGS. Bank of England News Release, April.

———. 2025a. Synchronisation. Bank of England, October.

———. 2025b. Real-Time Gross Settlement (RTGS) System and CHAPS Annual Report 2024/25. Bank of England, August.

———. 2025c. DLT Innovation Challenge. Bank of England, October.

———. 2026. Synchronisation Lab. Bank of England, February.

Bank of Japan. 2014. The Extension of the Operating Hours of the New BOJ-NET and the Planned Starting Date. Accessed May 12, 2026, May.

Banque de France. 2024a. Wholesale Central Bank Digital Currency. Banque de France.

———. 2024b. The Banque de France Has Successfully Carried Out Two Market Transactions in Tokenised Assets. Banque de France Press Release, December.

Berentsen, Aleksander, Gabriele Camera, and Christopher Waller. 2005. "The Distribution of Money Balances and the Nonneutrality of The Distribution of Money Balances and the Nonneutrality of Money." *International Economic Review* 46:465–487.

BNY. 2026. Global Collateral Intraday Repo. BNY Fact Sheet.

Board of Governors of the Federal Reserve System. 2023. Order Concerning the Payment of Interest on RTP Joint Account Balances. Board of Governors of the Federal Reserve System, June.

———. 2025. Board Memo: Expansion of Fedwire Funds Service and National Settlement Service Operating Hours. Board of Governors of the Federal Reserve System, October.

———. 2026. Central Bank Digital Currency (CBDC). Board of Governors of the Federal Reserve System, February.

Broadridge. 2026. Broadridge's Distributed Ledger Repo Achieves 268% Year Over Year Growth in April. Press release, May 4.

Budish, Eric. 2025. "Trust at Scale: The Economic Limits of Cryptocurrencies and Blockchains." *The Quarterly Journal of Economics* 140:1–62.

Cabedo, Yaiza, Tommaso Mancini-Griffoli, Fabian Schär, and Nicolas Zhang. 2026. The Evolution of Financial Market Infrastructures in a Tokenized Economy: Exploring Blockchain Implementation Options for Issuance, Central Clearing, Settlement, and Reporting. International Monetary Fund Working Paper WP/26/136, July.

Cenicola, Ashlyn, Melanie Friedrichs, Luke M. Olson, and Robert Mann. 2026. Who Participates in Repo? OFR Brief Series, Office of Financial Research, March.

Cenicola, Ashlyn, John Heilbron, Robert Mann, and Mark Paddrik. 2026. How Will Central Clearing Impact the Repo Market? The OFR Blog, Office of Financial Research, January.

Central Bank of Ireland. 2026. Discussion Paper 12: DLT and Tokenisation in Financial Services. Central Bank of Ireland, March.

Committee on Payments and Market Infrastructures and Board of the International Organization of Securities Commissions. 2022. Application of the Principles for Financial Market Infrastructures to Stablecoin Arrangements. Bank for International Settlements and IOSCO, July.

Cook, Lisa. 2026. Perspectives on Tokenization and Implications for the Financial System. Federal Reserve Board of Governors, Speech, May.

Danmarks Nationalbank. 2025. New Technology and Settlement in Central Bank Money Between Banks. Danmarks Nationalbank Analysis no. 14, June.

Depository Trust and Clearing Corporation. 2026. Collateral Infrastructure for Tokenized Capital Markets Just-in-Time Mobility, Capital Efficiency and Market Resilience. DTCC.

Deutsche Bundesbank. 2021. DLT-Based Securities Settlement in Central Bank Money Successfully Tested. Deutsche Bundesbank Press Release, March.

DTCC. 2026. DTCC Turns Tokenization into Reality: U.S. Trades Successfully Processed Using DTC-Tokenized Assets. Press release, The Depository Trust and Clearing Corporation, July 15.

Duffie, Darrell. 2026. The Payment System Puts a Floor on the Fed's Balance Sheet. *Brookings Papers on Economic Activity*, Spring.

Duffie, Darrell, Odunayo Olowookere, and Andreas Veneris. 2025. The Stablecoin Balancing Act. *Finance and Development*, International Monetary Fund, September.

Duffie, Darrell, Lei Qiao, and Yeneng Sun. 2025. "Continuous-Time Random Matching." *Annals of Applied Probability* 35:1755–1790.

Duffie, Darrell, and Chaojun Wang. 2026. Smart Contracting in Network Markets. Graduate School of Business, Stanford Unversity, June.

Duffie, Darrell, and Donald Wilson. 2025. The Case for a New Floating Rate Treasury Note. Brookings Institution, December.

Egilsson, Jon. 2026. Ethereum Vs. Canton: Two Different Paths To Institutional Blockchain. *Forbes*, March 10.

Eidan, Daniel, Jon Frost, Rudraksh Kansal, Ulf Lewrick, Sang Hyuk Lim, and Tomasz Rybarczyk. 2026. Blockchain consensus mechanisms and fragmentation. BIS Bulletin 126, July.

European Central Bank. 2023. Information Guide for TARGET Participants, Part 4 – T2S Cash. European Central Bank.

———. 2025a. ECB Commits to Distributed Ledger Technology Settlement Plans with Dual-Track Strategy. European Central Bank Press Release, July.

———. 2025b. The Eurosystem's Exploratory Work on New Technologies for Wholesale Central Bank Money Settlement: Annex II – Comprehensive Overview of Trials and Experiments. European Central Bank, June.

———. 2026a. Pontes. European Central Bank.

———. 2026b. TARGET Systems Operating Schedule – Euro. European Central Bank.

———. 2026c. Eurosystem Moves Toward Extending T2 Operating Hours. MIP News, European Central Bank, May 28.

———. 2026d. Outcome of the Public Consultation on the Extension of T2 Operating Hours. European Central Bank, May.

———. 2026e. Eurosystem Unveils Appia Roadmap for Europe's Tokenised Finance. European Central Bank Press Release, March.

Federal Reserve Bank of New York. 2023. Project Cedar: Improving Cross-Border Payments With Distributed Ledger Technology. New York Innovation Center, Federal Reserve Bank of New York, May.

———. 2025. Project Pine: Central Bank Open Market Operations with Smart Contracts. Federal Reserve Bank of New York, May.

Federal Reserve Board. 2014. Fedwire Securities Services. Federal Reserve Board, July.

Federal Reserve Financial Services. 2025. Fedwire Securities Service. Federal Reserve Financial Services.

FedNow Service. 2023. Guide to Liquidity Management Transfers.

Financial Stability Board. 2024. The Financial Stability Implications of Tokenisation. Financial Stability Board, October.

Fnality International. 2024. Sterling Fnality Payment System Receives Settlement Finality Designation. Fnality International Press Release, December.

———. 2026. Dollar Payment System. Fnality International.

Galper, Josh. 2026. Bank balance sheet benefits from intraday Distributed Ledger Repo. Finadium.

Ge Huang, Vicky. 2026. JPMorgan, Blackrock, and Goldman to Tokenize Stocks, Treasuries. *Wall Street Journal*, July 15.

Gerosa, Rebecca, Oliver Gloede, and Philipp Müller. 2024. Piloting Monetary Policy Implementation on a DLT-Based Infrastructure – Issuance of Digital SNB Bills. Swiss National Bank Economic Note no. 04/2024, November.

Heckinger, Richard, David Marshall, and Robert Steigerwald. 2009. Financial Market Utilities and the Challenge of Just-in-time Liquidity. Chicago Fed Letter Number 268a, November.

J.P. Morgan. 2023. Revolutionizing intraday financing with a blockchain-based solution. Press Release, Kinexys by J.P. Morgan.

Kim, Kyungmin, Romina Ruprecht, and Mary-Frances Styczynski. 2026. Payment Stablecoins and Cross Border Payments: Benefits and Implications for Monetary Policy Implementation. FEDS Notes, Board of Governors of the Federal Reserve System, March.

Kunaratskul, Tansaya, Ashley Lannquist, André Reslow, and Nicolas Xuan-Yi Zhang. 2025. Central Bank Exploration of Tokenized Reserves. International Monetary Fund, November.

Lee, Michael Junho. 2026. Composable Finance. Federal Reserve Bank of New York Staff Report 1177, January.

Lin, Chen, Eswar Prasad, Daniel Rabetti, and Che Zhang. 2026. Digital Safe Havens: The Economics of Tokenized Treasuries. NBER Working Paper No. 35412, July.

Maechler, Andréa M., and Thomas Moser. 2023. Swiss Payments Vision – An Ecosystem for Future-Proof Payments. Speech, Swiss National Bank Money Market Event, March.

Makarov, Igor, and Antoinette Schoar. 2022. "Cryptocurrencies and Decentralized Finance (DeFi)." *Brookings Papers on Economic Activity,* 141–196.

McLaughlin, Dennis. 2023. "The trade-off between shorter settlement times and multilateral netting benefits in deferred net settlement." *Journal of Financial Market Infrastructure* 11:1–17.

McNulty, David, and Alistair Milne. 2026. Direct holding and control of financial assets: An alternative to tokenization. Policy Note, SUERF The European Money and Finance Forum, August.

Nasdaq. 2026. Making the Case for Tokenized Collateral. Nasdaq.

Nickell, Philip. 2026. South Korea Moves Digital Won Into Real Government Funds as US Blocks CBDC. *TechTimes*, July 20.

Reserve Bank of Australia and Digital Finance Cooperative Research Centre. 2026. Project Acacia: Final Report. Reserve Bank of Australia, May.

Securities Industry and Financial Markets Association. 2026. Digital Assets Research Brief. SIFMA, May.

Sveriges Riksbank. 2026. Tokenisation of Money and Assets. Payments Report 2026, Sveriges Riksbank, March.

Swiss National Bank. 2025a. Swiss National Bank Extends and Expands Project Helvetia. Swiss National Bank Press Release, June.

———. 2025b. Project Helvetia. Swiss National Bank.

Szabo, Nick. 1996. *Smart Contracts: Building Blocks for Digital Markets.* Technical report. Phonetic Sciences Amsterdam.

The Clearing House. 2024. Higher $10 Million RTP® Network Transaction Limit Empowers New Uses. The Clearing House, December.

The Clearing House Payments Company L.L.C. 2025. CHIPS Rules and Administrative Procedures. The Clearing House, effective April 21.

Townsend, Robert M. 2020. *Distributed Ledgers: Design and Regulation of Financial Infrastructure and Payment Systems.* The MIT Press.

Treasury Borrowing Advisory Committee. 2026. Intraday Repo. Treasury Borrowing Advisory Committee Chargebook, August.

Ueda, Kazuo. 2026. The New Financial Ecosystem and the Role of Central Banks. Remarks at FIN/SUM 2026, Bank of Japan, March.

Woolard, Chris. 2026. Wholesale Digital Markets Champion: First report. HM Treasury, July.

World Economic Forum. 2025. Asset Tokenization in Financial Markets: The Next Generation of Value Exchange. World Economic Forum Insight Report, May.