EUROPEAN CENTRAL BANK

EUROSYSTEM

Working Paper Series

Charles-Enguerrand Coste,
George Pantelopoulos

Central bank money as a catalyst for fungibility: the case of stablecoins

No 3111

Abstract

To ensure that means of payments are readily interchangeable at face value – i.e. fungible – for retail payments, three elements are required: (1) settlement finality; (2) interoperability; and (3) seamless convertibility of the means of payment into the "ultimate" or quasi-ultimate means of payment. This paper argues that stablecoins issued by different issuers on different blockchains can be fungible to the same extent as commercial bank deposits from different banks provided that (i) payment and settlement technologies are interoperable, (ii) payments are transacted on ledgers that offer settlement finality, and (iii) that central bank money acts as the anchor to the monetary system (assuming that the central bank money is itself underscored by a homogenous unit of account). On this basis, this paper asserts that tokenised funds and off-chain collateralised stablecoins are fungible means of payments under some conditions, and that on-chain collateralised stablecoins can be prima facie classified as fungible means of payments, so long as the identical preconditions associated with accomplishing means of payment fungibility for tokenised funds/off-chain collateralised stablecoins can be fulfilled, and on the premise that the on-chain collateral can be readily converted into higher level money. Finally, it is determined that algorithmic stablecoins are not fungible means of payments.

Key Words: stablecoin, electronic money token, fungibility, central bank

JEL classification: B26; E42

Non-Technical Summary

Since 2014, stablecoins have evolved from a niche innovation to a significant component of the digital asset landscape, with total issuance reaching approximately USD 250 billion as of end-June 2025 (equivalent to just over 1% of USD M2 money).[2]

The terminology surrounding stablecoins has developed rapidly but often lacks precision. The term "stablecoin" remains a broad label for various crypto-assets that aim to maintain a stable value relative to a specific asset or pool of assets. However, this goal-oriented definition focused on intended price stability tends to obscure critical distinctions in design and function. Key attributes such as the token's use case, asset-backing model, convertibility mechanism, settlement finality, and interoperability are essential to assessing a token's ability to support the singleness of money.

This paper argues that stablecoins can only function as fungible means of payments – i.e. be readily interchangeable at face value with other forms of money – if three core conditions are met:

- Interoperability with dominant payment and settlement technologies;
- Settlement finality on the ledger on which the stablecoin is issued; and
- Seamless convertibility into central bank money or quasi-ultimate means of payments

Some stablecoins, such as e-money tokens issued by regulated e-money institutions, may offer the required level of convertibility, and on the proviso they also meet the conditions of settlement finality and interoperability, can be considered fungible to the same extent as traditional e-money issued by e-money institutions.

To this end, this paper argues that tokenised funds and off-chain collateralised stablecoins backed by high quality assets can meet the above criteria when supported by robust governance and regulatory frameworks. On-chain collateralised stablecoins can also be considered fungible under the same conditions, provided that their collateral can be readily and reliably converted into higher-tier money. In contrast, algorithmic stablecoins do not meet these requirements and therefore cannot be regarded as fungible means of payments.

[2] Fred Saint-Louis USD M2 money series
Stablewatch.io stablecoin money supply

1. Introduction

Fungibility is an overriding precondition for payment and settlement, which infers that means of payments[3] issued by different entities underpinned by the same unit of account (e.g. EUR, AUD, USD etc.) are more or less indistinguishable as they can be mutually interchanged at face value (see e.g. Brunnermeier and Niepelt, 2019; Brunnermeier and Landau, 2022; Garratt and Shin, 2023).

Fungibility can be considered from two perspectives: from a "narrow" perspective in that means of payments are tradeable at par, which maintains the so-called "singleness of money" (Garratt and Shin, 2023); or from a "wider" perspective, that in addition to means of payments being tradeable at par, incorporates some other factors. Unlike much of the literature (in which the narrow perspective is generally adopted), **this paper investigates fungibility from the wider perspective.** This is because while say two stocks of commercial bank money issued in two different jurisdictions (i.e. underscored by different units of account) may be tradeable at par – since the exchange rate between two currencies may be 1:1 – this does not automatically imply that the two stocks of commercial bank money are mutually interchangeable at face value.[4]

Further still, **fungibility in means of payments can be broken down into three predominant types** (assuming at par interchangeability and a homogenous unit of account):

- (1) A means of payment from a single issuer is fungible with another means of payment of the <u>same type</u> from the <u>same issuer</u> (e.g. bank deposits from the same bank).
- (2) A means of payment from a single issuer is fungible with another means of payment of the <u>same type</u> from a <u>different issuer</u> (e.g. bank deposits from two banks).
- (3) A means of payment from a single issuer is fungible with another means of payment of a <u>different type</u> from a <u>different issuer</u> (e.g. bank deposits from one bank vs e-money from an EMI/Fintech; bank deposits vs banknotes).

Depending on whether the means of payment is predicated on account or token-based technologies, **three elements must generally be fulfilled so that means of payments are fungible for retail payments,** namely **(1) settlement finality; (2) interoperability;** and **(3) seamless convertibility** of the means of payment into the "ultimate" or quasi-ultimate means of payment (unless the means of payment is itself the quasi-ultimate means of payment).

The applicability of the three aforementioned elements to safeguard means of payment fungibility is predicated on the basis of whether the **process to bring about shifts of value is intermediated or not – i.e. disintermediated.** In other words, one can segregate the applicability of the elements on the basis of whether the means of payment is either account or token-based.[5] Means of payments and payment systems based on cryptographic proofs however (i) represent a major change to the

[3] Means of payments can be thought of as the medium that permits value to be transferred from one entity to another, whereas payments can be framed as the overall process by which value is shifted between entities through a means of payment. Means of payments exist as claims toward either a central bank (central bank money) or a commercial bank (commercial bank money, with a promise of convertibility into central bank money), or indeed toward an e-money institution/Fintech (with a promise of convertibility into commercial bank money, which can be in turn converted into central bank money).

[4] For instance, if the exchange rate between EUR and AUD were to be 1:1, two stocks of bank deposits (say 100 AUD and 100 EUR) would not be considered as mutually interchangeable at face value (i.e. fungible) even though they are tradeable at par, as they are underpinned by differing units of account.

[5] In the case of account-based means of payments, all three elements apply, whereas in the context of token-based means of payments (i.e. banknotes), only settlement finality and interoperability apply, given that banknotes are by definition the quasi-ultimate settlement asset.

traditional intermediation/disintermediation discourse in the sense that the settlement process **is decentralised**[6] **rather than being intermediated/disintermediated**; and (ii) unlike both account and token-based means of payments, in the case of "unbacked" crypto-assets and some stablecoins (e.g. algorithmic), **the means of payment does not exist as a claim on a counterparty.**

How then do stablecoins fit within the realms of the above discussion? That is to say, if it is believed that stablecoins have the potential to serve as a means of payment, **do they currently/can they fulfill the three elements of fully fungible means of payments** in the sense that:

1. The consensus mechanism underpinning the blockchain achieves settlement finality;
2. The various blockchain ecosystems where stablecoins are issued are interoperable between themselves, and with "traditional" payment systems;
3. Stablecoins as means of payments are readily convertible into the quasi-ultimate settlement asset: i.e. central bank money.

This paper argues that for **stablecoins issued by different issuers on different blockchains to be considered fungible** (to the same extent as commercial bank deposits from different banks), interoperability and settlement finality are prerequisites,[7] **but true fungibility is only achieved if central bank money acts as the anchor to the monetary system** (assuming that the central bank money is itself underscored by a homogenous unit of account).[8] It is envisaged that by exploring means of payment fungibility in the context of stablecoins, the paper will also contribute to the literature with regard to the determinants of means of payment fungibility in a more general sense.

To achieve its objectives, this paper proceeds as follows. Section 2 outlines the elements which typically ensure fungibility in means of payments, provides a survey of historical means of payment fungibility, and reflects on some general lessons to safeguard means of payment fungibility. Section 3 then explores the role of central bank money in enabling means of payment fungibility, with section 4 providing a taxonomy of stablecoins (as well as reflecting on some terminological issues with stablecoins). Sections 5, 6 and 7 investigate whether the elements that constitute fungibility are fulfilled in the context of stablecoins, namely settlement finality, interoperability and convertibility (respectively). Section 8 concludes, and a determination as to whether stablecoins issued by different issuers on different blockchains are fungible is disseminated.

2. Fungibility in means of payments: some historical lessons

As purported by Holmstrom (2015), fungibility implies that counterparties "ask no questions" with regard to the face value of the means of payment when making payments, and infers that means of

[6] It is often alleged that "decentralisation" implies that settlement is "peer-to-peer"; i.e. no third-party sits between the payer/payee. This is however a misnomer as during the course of settlement, a third-party (e.g. a "miner") sits between the payer and payee. In other words, settlement in the crypto-verse is not "peer-to-peer". In fact, settlement is only peer-to-peer (or disintermediated) whereby the means of payment resides in the form of banknotes.

[7] This is setting aside that the term "stablecoin" is to some extent redundant/problematic (see e.g. Bindseil, Coste and Pantelopoulos, 2025). See also section 4.

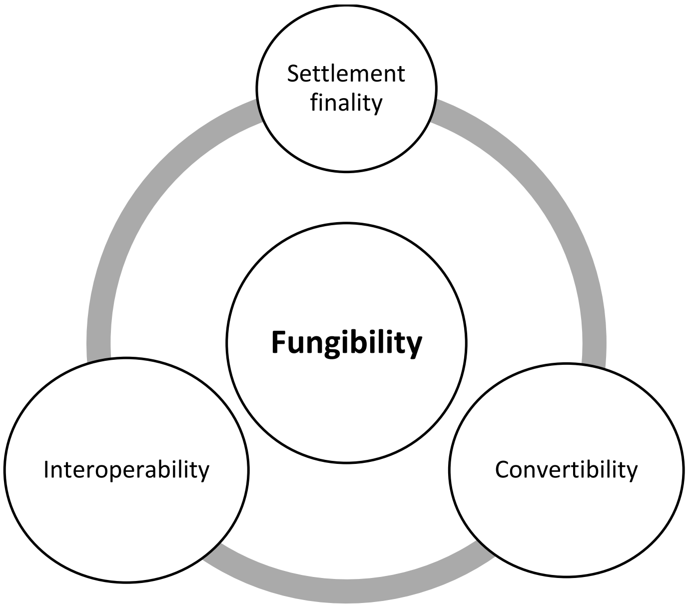
[8] If two stablecoins issued by different issuers on different blockchains were to offer convertibility into central bank money buttressed by two different units of account (e.g. say euros and AUD), then by default the two stablecoins would not be fungible (analogous to how two stocks of commercial bank money issued by two different banks in two different jurisdictions would not be fungible, even if they were to be tradeable at par, as alluded to above).

payments which circulate in a particular jurisdiction allows the jurisdiction to function as an “optimal currency area” as means of payments are mutually interchangeable at face value (Mundell, 1961). Historically speaking, accomplishing fungibility has however not been a straightforward task (see e.g. Gorton, 2017 for a similar discussion or Quinn and Roberds, 2024, 196). To survey the notion of fungibility in a little more detail, we begin by disseminating the general elements that together constitute means of payment fungibility (section 2.1) and examine how achieving fungibility was problematic in historical means of payments (section 2.2). This is then followed by some lessons that can be learnt to ensure that means of payments are fungible (section 2.3).

2.1 Elements in means of payment fungibility

As alluded to earlier in the introduction, at a high-level, **three elements must generally be fulfilled if means of payment fungibility is to be achieved,**[9] as shown in Figure 1 below.

Figure 1: Elements for means of payment fungibility



Settlement finality

As defined by the Principles of Financial Market Infrastructures (see CPSS-IOSCO, 2012, 64; see also Geva, 2003; Nabilou, 2022), settlement finality can be described as “…the irrevocable and unconditional transfer of an asset or financial instrument, or the discharge of an obligation by the FMI or its participants in accordance with the terms of the underlying contract.”

Settlement finality means that after a trade is completed, there should be no remaining financial obligations between the payer and the payee. If there are, then settlement isn't truly final because one party might still have the right to force the other to do something to meet an obligation (Kahn and Roberds, 2007) – i.e. obligations are not fully discharged. Such “weaker” forms of settlement finality may appear if for instance following settlement, the payer may incur a contingent liability vis-à-vis the

[9] Sections 5, 6 and 7 will respectively unpack each element at a somewhat deeper level and in the context of stablecoins.

payee, like in the case where the payer pays through endorsing a bill of exchange (see below).[10] This is why Kahn and Roberds (2007, 961) note that “the higher degree of finality, the more money-like the character of a debt transfer”.

Settlement finality is crucial during insolvency proceedings when a party involved in the payment process defaults. If the rules around settlement finality are unclear, it complicates determining what creditors are owed. For instance, if a party receives goods and subsequently goes into liquidation, the seller's compensation depends on whether any attempted payment for these goods was final. If the payment was final and irrevocable, the seller receives the full value (x=1). However, if the payment was not final, it may be reversed or contested during the insolvency process, leaving the seller potentially uncompensated. This is why reaching settlement finality quickly is vital for sellers to minimize their risk of not being paid. It is to be noted that while many payment systems[11] ensure that transactions are final once processed, **absolute perfection in finality, where no transaction could ever be questioned or reversed under any extreme implausible circumstances, is not achievable.**

Interoperability

According to the online glossary of the BIS, interoperability is the:

> *“…technical or legal compatibility that enables a system or mechanism to be used in conjunction with other systems or mechanisms. Interoperability allows participants in different systems to conduct, clear, and settle payments or financial transactions across systems without participating in multiple systems.”*

Put differently, interoperability refers to the ability of payment and settlement technologies that support means of payments to interact effectively so that value can be shifted between accounts, otherwise means of payments can circulate as independent “silos”. In the realm of token-based (or similar – i.e. paper-based/commodity money) means of payments, interoperability resides in the context of means of payment homogeneity (e.g. one 5 euro banknote is exactly the same as another 5 euro banknote; two 5 euro banknotes are equal to one 10 euro banknote; one precious metal coin is the same as another precious metal coin etc.).

Convertibility

The inference that means of payments can be readily converted into the “ultimate” (or quasi-ultimate) means of payment implies that the “cross-exchange rate” between two means of payments is equal to unity; they are tradeable at par.[12] To illustrate, suppose that two means of payments (MoP A and MoP B) are each convertible into the ultimate settlement medium (USM) at par. As both MoP A and MoP B

---

[10] Also, idiosyncrasies in the creditworthiness of contingent debtors implies that the degree to which settlement finality may be weak can differ. See section 2.2 below for an explanation.

[11] Payment systems can be split real-time gross settlement (RTGS) systems that achieve instant settlement as and when payment instructions are received and deferred net settlement (DNS) systems that collect payment instructions over a specific period (often throughout the day) which are netted to determine the overall credit or debit position of each participating institution. DNS systems are often used because they can reduce the liquidity needs of participants and can be more efficient for environments where high volumes of transactions can be netted against each other. However, they carry higher credit settlement risk compared to RTGS systems, where transactions are settled individually in real time and with immediate finality.

[12] Aside from enabling the cross-exchange rate to equate to par, convertibility into central bank money is a mechanism to “bridge” heterogeneities between means of payments – see Pantelopoulos (2025b) for a discussion.

are tradeable at par vis-à-vis USM, the cross-exchange rate between MoP A and MoP B is equal to unity. This can be shown more formally in the following way:

$$\textbf{USM/MoP A} \div \textbf{USM/MoP B} = \textbf{MoP B/MoP A} = \textbf{1}$$

$$\boldsymbol{\beta \div \mu = \beta/\mu = 1}$$

- **β** is the number of MoP A units required to purchase 1 unit of USM (i.e. USM/MoP A)
- **μ** is the number of MoP B units required to purchase 1 unit of USM (i.e. USM/MoP B)
- **β/μ** is the bilateral cross-exchange rate, which equates to the number of units of MoP A required to purchase 1 unit of MoP B (i.e. MoP B/MoP A)
- Alternatively, **μ/β** equals the number of MoP B units required to purchase 1 unit of MoP A (i.e. MoP A/MoP B)

2.2 Fungibility in historical means of payments

In this section, we will delve into a brief discussion as to why historical means of payments were in many cases not fully fungible, namely by examining **(i) precious metal coins; (ii) endorsed bills of exchange; (iii) early private bank deposits; and (iv) early private banknotes**.[13]

Precious metal coins

For centuries, economic activity presided on the basis of precious metal coins as the means of payment to overcome the problem of the double coincidence of wants – i.e. barter. Settlement in precious metal coins is "ultimate" settlement, as the transaction is closed without leaving any residual financial positions either (i) between the payer and payee, or (ii) between the payee and some other counterparty.

Commodity money does however suffer from several major drawbacks as a means of payment. *First*, specie is inconvenient as a medium of exchange due to costs in its storage and transportation. *Second*, as a finite commodity, settlement with specie can become very costly (Dean, 1884, 25; Einzig, 1962, 61-63). *Third*, there remains the issue of heterogeneity of coins and debasement (and therefore adverse selection – i.e. Gresham's law, where "bad" money drives out the "good" – Kindleberger, 1984, 21). For example, Cipolla (1963) cites several examples of debasement amid the 9th and 16th centuries in England, France and Italy. Reasons for debasement were wide ranging; from deliberate debasement – or "clipping", where with a pair of shears, individuals would remove a small part of say gold or silver from the coin for private profit – to debasement caused by "wear and tear", otherwise known as "sweating" (Allen, 2016, 43).

Coin heterogeneity (and thus adverse selection) created the precondition for **weakened fungibility as precious metal coins were not entirely interoperable**. As noted by Quinn and Roberds (2024, 59-60), "[b]ullion was thus a store of value, but it was not a universally traded, 'no questions asked' asset. Information mattered. To trade in bullion required knowledge of an ingot's weight and fineness, the current market price, and how to adjust for variation in fineness from the market standard."

[13] The segregating factor between paper-based and token-based means of payments is that following the payment and settlement process in the latter case, the payee only holds a claim on a counterparty that differs in identity to that of the original debtor (i.e. the payer). By contrast with paper-based means of payments, the payee following the payment and settlement process holds a claim on a new debtor, and also a contingent claim on the original debtor.

To circumvent the lack of interoperability, traders often sought the services of "middlemen" known as moneychangers to inspect precious metals for signs of clipping or sweating (Mueller, 1997, Chapter 1). In other words, though settlement in specie was in theory based on peer-to-peer (P2P) transfer, heterogeneity in coins resulted in intermediation to safeguard fungibility. Intermediation in the form of moneychangers was however cumbersome, as at least in principle, every coin was required to be inspected for any imperfections etc. Intermediation also creates inefficiencies as the payment and settlement process becomes somewhat cumbersome (for instance, once a payment is triggered by the payer handing over specie, settlement may not transpire if the middleman is not satisfied with regard to the quality of the coin(s) etc.).

Endorsed bills of exchange

Notwithstanding ambiguities regarding their origin (see e.g. Usher, 1914; Read, 1926), a bill of exchange is an order by one entity (the drawer) which instructs another entity (the payer or the drawee) to pay a third party (the payee) at a given date in the future. To explain how endorsed bills of exchange constituted paper-based means of payments,[14] suppose that an individual trader (e.g. Trader A) wishes to purchase a stock of goods from another trader (e.g. Trader B), but must travel to some faraway location so as to purchase the goods. Through non-deposit taking banks (i.e. merchant banks), Trader A at time T hands over a stock of say gold coins to Bank A, which draws a bill of exchange on Bank B (the drawee, or payer) – that is signed by a representative of Bank B ("accepted") – and is given to Trader A (the payee). Trader A then travels to where Bank B (and Trader B) is located and presents the bill, upon which they are informed to return at T+90. On settlement date, Trader A returns to Bank B, and is paid-out. Using their newly acquired stock of specie, Trader A purchases a stock of goods from Trader B after the two meet at a local market.

Let us now suppose that Trader A does not want to wait the 90 days however to receive their gold coins, as they wish to immediately purchase some goods from Trader B. Trader A can then "endorse" the bill of exchange (by adding their signature to the bill) and give it to Trader B as payment for the goods. Through such a process, the endorsed bill of exchange has morphed into a paper-based means of payment. However, Trader B as the payee continues to hold a contingent claim on Trader A, as should Bank B not pay-out on the date specified on the bill (i.e. at T+90), Trader B can approach Trader A for payment. There also exists a second method for Trader A to gain early access to their gold coin through the bill of exchange being "discounted", meaning that Bank B immediately pays out Trader A, but charges a fee to do so (i.e. Bank B pays-out an amount of specie to Trader A that is less than what is specified on the bill).

From a fungibility perspective, **the problems with early paper-based means of payments like endorsed bills of exchange were five-fold.** *First*, bills of exchange were not necessarily interoperable as a consequence of the plethora of standards (e.g. legal) and types of bills that existed in various settlement places (see e.g. Kruse, 1782; Moshenskyi, 2008, 97; Kohn, 1999a). *Second*, endorsed bills of exchange remained susceptible to adverse selection problems and hence Gresham's Law, as if say after depositing a stock of specie with Bank A Trader A comes to recognise that the creditworthiness of Bank B is questionable, Trader A may not be able to convert their claim into the ultimate asset, being precious metal coins. An incentive is therefore founded for Trader A to offload the note through endorsement as quickly as possible, in the hope that the new holder of the note will then also offload the note through endorsement etc. In the event where the final holder of the note is then not paid-

[14] If endorsed, promissory notes were also able to be used as paper-based means of payments. See e.g. Pantelopoulos (2025a, chapter 2) for a discussion.

out by Bank B, the chain of endorsements is so lengthy that Trader A will not be required to fulfil any contingent liability. It is for such reasons that in many cases, potential acceptors of endorsed bills would employ intermediaries to examine the credit quality of those who had previously endorsed the bill (Jobst and Kernbauer, 2016, 60). *Third*, endorsed bills of exchange exhibited probabilistic (i.e. non-deterministic) settlement finality as the payer following endorsement continued to incur a contingent liability vis-à-vis the payee. And since contingent debtors theoretically exhibited various grades of creditworthiness, the degree of settlement finality differed with each endorsed bill.[15] *Fourth*, bills of exchange that theoretically represented the same value could potentially be discounted at various rates, depending on who was discounting the bill and how the entity interpreted the credit quality of the debtor that would eventually settle the liability as a result of the bill being discounted (in the context of our provided example, Bank A) (see e.g. Moshenskyi, 2008, 165-166; Clapham, 1944, 123, 299).[16] It is also reasonable to presume – analogous to privately issued banknotes (see below) – that the rate at which discount rates varied increased the further away bills circulated from the location at which they were originally drawn. *Fifth*, owing to heterogeneity in precious metal coins, it was not guaranteed that the final holder of an endorsed bill would receive specie of homogenous/high-quality when finally presenting the bill so that they could be paid-out.

Early private bank deposits

Deposit-taking banks came into being around the 12th century in Venice and Genoa through merchant banks expanding their operations (Kohn, 1999b, 1999c). To buttress their creditworthiness, early commercial bank money was convertible into specie, which required banks to hold adequate stocks of precious metals as a buffer. On the presumption that the specie held by say one bank was of high quality (in terms of homogeneity etc.), the promise of convertibility also inferred that all of the bank's IOUs were (all else equal) able to be interchanged at the same value. There were distinct efficiency gains with early forms of deposit banking (particularly if both the payer and payee generally held deposits in the same bank). In a large number of cases, both the payer and payee were also physically present at the bank to effectuate a transfer of deposits, which meant that interoperability issues did not apply, settlement finality was instant and left no residual financial positions between the payer and payee.

Nonetheless, **traders were highly conscious of counterparty credit risks.** With no readily accessible LOLR, bank runs (through end-users converting their claims into specie) and failures were frequent (Kohn, 1999b; see also Dunbar, 1892). To mitigate the threat of financial instability, local legislators imposed a raft of regulations. Typically, these ranged from the imposition of liquidity buffers (in the form of reserve ratios) to capital requirements where assets could be seized in the event of failure (Roberds and Velde, 2016). In the face of protracted runs however, banks were forced to suspend convertibility. This was generally done by banks prohibiting the withdrawal of deposits into specie whilst at the same time allowing traders to continue to execute payments in-bank. **The abandonment of convertibility thereby jeopardised the fungibility of commercial bank money,** as given the absence of an anchor, the cross-exchange rate between two stocks of commercial bank money may not have

[15] This is because should the final endorser – the contingent debtor – in the chain not pay-out if the merchant bank were to not pay-out, the previous contingent debtor in the chain would be liable to fulfill the claim. And as one endorsed bill may have more creditworthy contingent debtors than another endorsed bill, the latter bill exhibits a weaker form of settlement finality than the former, since the contingent claim is more likely to be fulfilled in the first case.

[16] It can be implied that the larger the discount rate, the higher the perception that Bank B considers its potential counterparty credit risk vis-à-vis Bank A to be.

equated to unity. In other instances, the authorities simply banned deposit banking altogether, and led to the return of precious metal coins as the settlement medium (Kohn, 1999b). The instability of private deposit banks led to the advent of **state-sponsored public deposit banks (i.e. central banks)**, in which the state provided an explicit guarantee that the public deposit bank would not be susceptible to any insolvency risk.[17]

Privately issued banknotes

In the United States, privately issued banknotes were widely issued prior to the Civil War – otherwise known as the "free banking era" (Hsu, 2022). Every bank printed their own notes, and all were of different sizes/colours/materials. Yet despite their heterogeneity, all purported to represent the same value. Gorton and Zhang (2023, 944-945), quoting Sumner (1896), describe how middlemen/intermediaries attempted to overcome the heterogeneity of private banknotes (and thus to minimise their lack of interoperability and hence overcome the problem of adverse selection and Gresham's Law):[18]

> *"It is difficult for the modern student to realize that there were hundreds of banks whose notes circulated in any given community. The "bank notes" were bits of paper recognizable as a species by shape, color, size and engraved work. Any piece of paper which had these appearances came with the prestige of money; the only thing in the shape of money to which the people were accustomed. The person to whom one of them was offered, if unskilled in trade and banking, had little choice but to take it. A merchant turned to his "Detector." He scrutinized the worn and dirty scrap for two or three minutes, regarding it as more probably "good" if it was worn and dirty than if it was clean, because those features were proof of long and successful circulation. He turned it up to the light and looked through it, because it was the custom of the banks to file the notes on slender pins which made holes through them. If there were many such holes the note had been often in bank and its genuineness was ratified. All the delay and trouble of these operations were so much deduction from the character of the notes as current cash. A community forced to do its business in that way had no money. It was deprived of the advantages of money."*

In-part against a backdrop of heterogeneity issues, banknotes in the United States differed in value by as much as 25 percent owing to large discrepancies in discount rates when banknotes – like endorsed bills of exchange – circulated far away from their original jurisdiction of issue (Gorton and Zhang, 2023). This then led to debates as to whether the US Government should take over the issuance of notes (see Greenberg, 2020, chapter 6).

2.3 Lessons to safeguard fungibility in means of payments

On the basis of the above (albeit brief) survey, historic means of payments were problematic in that in many instances they were unable to accomplish full fungibility as they did not fulfill – where applicable – the elements that constitute means of payment fungibility.

Table 1 below summarises whether each fungibility element was attained in strong/weak manner with respect to settlement finality/interoperability/convertibility.

---

[17] Reviews of early central banking can be found in Usher (1943), De Roover (1948), Roberds and Velde (2014, 2016), Ugolini (2017) and Bindseil (2019).

[18] Greenberg (2020, 108) also highlights that given their crucial role, intermediaries gained and then exploited their monopoly power for their own benefit.

Table 1: Summary of problems in early means of payments with regard to accomplishing fungibility

	Settlement finality	Interoperability	Convertibility
Precious metal coins	**Strong**. Since settlement was based on P2P transfer (on the presumption that coins were homogenous), settlement finality was instant and deterministic and did not leave any open financial positions between the payer and payee.	**Weak.** Issues in heterogeneity of coins.	**N/A**. Precious metals were the ultimate settlement asset, so convertibility does not apply.
Endorsed bills of exchange	**Weak.** Payments with endorsed bills left residual financial positions in the books of both the payer and payee through contingent claims/liabilities (i.e. probabilistic settlement finality). Also, as each contingent debtor in theory differed in terms of their creditworthiness, there were large disparities in the degree of weakness with respect to the completeness of settlement finality.	**Weak.** Interoperability issues largely resided on the fact there existed a plethora of types of bills, and as a consequence, a litany of regulations and frameworks were applied to each type of bill.	**Weak.** Question marks with regard to the credit quality of contingent debtors (e.g. endorsees) and final debtors (e.g. merchant banks). Furthermore, heterogeneity of precious metal coins created problems in the sense that the final holder of the endorsed bill would not necessarily receive high-quality specie.
Early private bank deposits	**Strong.** If payments were completed between the payer and payee by both parties being physically present at the same bank, then settlement finality was instantaneous and deterministic, and did not leave residual financial positions between the payer and payee.	**Strong.** On the precondition that both the payer and payee held deposits at the same bank (and that both parties were physically present at the bank), any interoperability issues were automatically overcome.	**Weak.** Haphazard credit quality led to bank runs through end-users attempting to convert deposits into specie, that, on the presumption that convertibility was banned, jeopardised the fungibility of commercial bank money.
Early private banknotes	**Strong.** Settlement based on P2P transfer, and no residual financial positions were left between the payer and payee following settlement; i.e. settlement finality was deterministic.	**Weak.** Issues in heterogeneity of notes.	**Weak.** Analogous to early bank deposits, counterparty credit risks imply that should end-users en-masse attempted to convert their notes into other assets (e.g. specie), fungibility would be jeopardised.

What then are some of the general lessons that can be learnt to ensure means of payments are fungible?

- *First*, construct an architecture so that the issuer of the ultimate (or quasi-ultimate) means of payment is free of any credit and liquidity risks, and that the means of payment is itself homogenous and scalable. This averts adverse selection problems and that other (non-ultimate/non-quasi-ultimate) means of payments can become “de-anchored” from the ultimate means of payment, as it should not be possible for the convertibility promise to be jeopardised/abandoned if the issuer is not subject to liquidity/credit risks.
- *Second*, a single entity should issue the ultimate/quasi-ultimate settlement asset, otherwise the means of payment can suffer from issues like those just noted above (i.e. lack of

interoperability). The implied monopoly power of the issuer also instils the need for a publicly owned/accountable entity to issue the means of payment.

- *Third*, settlement should be final (i.e. deterministic) and not leave residual contingent claims/liabilities between the payer/payee – i.e. economic activity can occur with settlement finality. "Complete" settlement allows all parties to engage in economic activity with greater fluidity, in the sense that once a payment is executed by the payer, all claims/liabilities will be extinguished in full. Indeed, the very fact that another counterparty (e.g. a merchant bank like in the case of bills of exchange, or an endorser) may fail to fulfil an obligation (e.g. if the merchant bank were to not pay-out the payee on the settlement date as stated on the bill) can result in the payee not accepting the means of payment in the first place, and they may insist that their claim vis-à-vis the payer be eliminated via some other means of payment (e.g. a gold coin) that does offer a larger degree of settlement finality.
- *Fourth,* in the context of account-based payments, there is seeming inevitability in the fact that there will exist a large degree of centralisation during the course of settlement, otherwise the payment and settlement technologies that underpin the means of payment may not be interoperable, and thus, each means of payment will each circulate as if on a deserted island. This creates the precondition for a publicly owned entity to at the very least lay out the regulatory environment for which value transfers will occur. In addition, centralisation permits greater latitude for settlement finality, as final settlement only depends on one "actor". If on the other hand settlement finality were to rely on say a consensus between numerous counterparties, there is a higher probability that the exact moment of settlement finality can become somewhat unclear.

3. The role of central bank money in means of payment fungibility

Fungibility in means of payments is predominantly safeguarded through the introduction of central bank money as a quasi-ultimate settlement medium to **ensure that the monetary system operates with an ultimate "anchor"**.

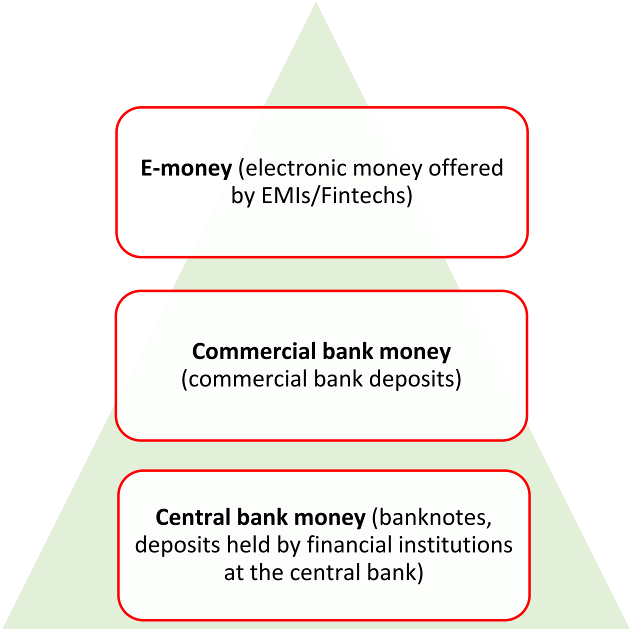
What are some of the characteristics that qualify central bank money as the ultimate anchor? By design, central bank money is free of any credit risks (as the central bank can in principle issue liquidity without constraints).[19] It is also free of any liquidity risks, as it is not convertible into some form of precious metal (e.g. gold/silver coins) like in times past. Central bank money also exhibits homogeneity and thus does not incur any adverse selection problems, is scalable, and through legalisation, can only be issued by the central bank.[20]

In acting as the floor to means of payments, all other means of payments are in effect "layered" on top of central bank money, thereby forming a means of payment "pyramid" of sorts, as shown below in Figure 2.

Figure 2: Means of payment pyramid

[19] As Bunea et al (2016, 14) assert: "Central banks are protected from insolvency due to their ability to create money and can therefore operate with negative equity."

[20] An additional prerequisite to ensure that central bank money remains the anchor to the monetary system is through the central bank maintaining price stability by way of an inflation target, and that the monetary authorities achieve such a target in a credible way.



Aside from **retail means of payments** (e.g. banknotes, commercial bank deposits, e-money), the figure also incorporates some **wholesale means of payments** (e.g. central bank money in the form of deposits held by financial institutions at the central bank), that allow the financial representatives of the payer/payee to settle payments so that the account of the payee can be credited.

Means of payments can thereby be segregated along the lines of **retail or wholesale payments:**

- **Retail payments:** payments between individuals and/or between individuals and non-financial firms. Examples of retail payments include payments that are "peer-to-peer" (P2P – i.e. a payment between two individual traders), "peer-to-merchant" (P2M), "business-to-business" (B2B), and between individual traders and the government as well as other public entities (e.g. for the payment of taxes, fines etc. – "person-to-government" (P2G) – or indeed the other way around, i.e. "government-to-person" – G2P).
- **Wholesale payments:** payments which transpire as a result of high-value time-critical payments between banks and other financial market infrastructures (FMIs). Examples of wholesale payments include pure interbank payments – i.e. payments between banks not related to customer orders. **Wholesale payments also include payments that settle retail payments.** For instance, a household pays to a firm commercial bank money, and banks settle in a payment system in central bank money, which permits the bank of the firm to credit their deposit account in commercial bank money.

Further still**, retail and wholesale payments can be differentiated by whether the underlying means of payment is account or token-based**:

- In the realm of **retail payments, the means of payment can either be account or token-based.** For example, aside from token-based **central bank money** in the form of banknotes, individual traders also have access to account-based means of payments like **commercial bank money** in the form of deposits with financial institutions, and **e-money** issued by electronic money institutions (EMIs)/Fintechs (i.e. electronic money stored on either hardware or software-based products; examples include pre-paid cards in the case of the former, and mobile phones/tablets in the latter case) – sometimes known colloquially as "mobile money"

(Buckley, Arner and Zetzsche, 2024, 185). E-money is distributed by EMIs/Fintechs following a receipt of funds from end-users for the purposes of making payments, and is backed by each EMI/Fintech itself holding deposits at a commercial bank.[21] Unlike commercial bank deposits, no long-term store of value function is associated with e-money, as EMIs/Fintechs do not pay interest on deposits (e.g. PayPal). Though end-users can also deposit funds in e.g. narrow banks (that, unlike EMIs/Fintechs, offer a long-term store of value function through paying attractive interest rates on deposits). In any case, privately issued means of payments remain fungible as they **all may be converted one way or another into central bank money by end-users** (e.g. e-money is convertible into commercial bank money, which in turn is convertible into banknotes).

- By contrast in **wholesale payments, the means of payment is always account-based**, either via commercial banks holding deposits at the central bank, or if financial institutions hold deposits at say an automated clearing house (ACH) or some other FMI (such as a central securities depository).

In what remains in sections 3.1 and 3.2, each fungibility element is unpacked as it respectively pertains to both account and token-based means of payments, and an explanation is provided as to how fungibility is safeguarded through central bank money.

3.1 Account-based means of payments

Central bank money enables **settlement finality** as through creditors (e.g. the financial institution of the payee) gaining stocks of risk-free IOUs, settlement is quasi-ultimate, stipulating that claims for all intents and purposes do not figuratively exist given that there is no need to monitor the creditworthiness of the central bank. Thus, settlement becomes irrevocable and unconditional, and as a direct consequence, the bank can proceed to credit the deposit account of the payee in commercial bank money without any residual positions remaining between the payer/payee or their financial representatives – i.e. settlement is deterministic. Settlement finality is also of particular importance as it allows a clear determination to be made as to the exact moment when a potential transfer of claims/assets/value will become final and irrevocable, particularly as during the payment process the payer/initiator of the payment may have a right to revoke a payment (see e.g. Cranston et al, 2018, 345-346; Pages and Humphrey, 2005). The exact moment of settlement finality is defined by legislation (e.g. through the EU's Settlement Finality Directive).

Moreover, in the central bank providing accounts to financial institutions by way of acting as a correspondent to the domestic financial system, **interoperability** between payment and settlement technologies allows counterparties to debit/credit accounts etc. once a payment has been triggered by some payment instrument (e.g. a credit card) or otherwise (see e.g. Lawson and Herrada, 2022). Cheng and Torregrossa (2022) unpack how in running real-time gross settlement (RTGS) payment systems, central banks facilitate interoperability between various payment and settlement technologies:

> *"Viewed through the lens of…"interoperability," the liabilities of different banks could be viewed as separate "systems" of money, so to speak…all customers that have accounts at Alpha Bank could be viewed as users of the Alpha Bank "system," whereas all customers that have accounts at Beta Bank are users of the Beta Bank "system," with each bank capable of executing transfers on its own books between its customers. But what of transfers between customers of different banks? The accounts and payment services that the Federal Reserve provides help to bridge these individual*

[21] However in some jurisdictions, EMIs/Fintechs are now permitted to hold deposits at the central bank.

bank "systems" and allow them to "interoperate"...Alpha Bank would pay Beta Bank through the Federal Reserve, which would typically process a transaction by receiving instructions from Alpha Bank, delivering instructions to Beta Bank, and settling the amount of a transaction by effecting changes to the banks' master account balances (that is, decrease the Reserve Bank liability to Alpha Bank as reflected in its master account balance and increase to the Reserve Bank lability to Beta Bank as reflect in its master account balance)."

Although in some cases settlement can occur in a medium other than central bank money,[22] the central bank may continue to enable interoperability by way of (i) acting as a regulator/overseer of private payment systems (see e.g. Cranston et al, 2018, 344-345), or (ii) in the event where multiple ACHs are employed, the central bank may sit between the multiple ACHs by operating a central "hub" to facilitate inter-ACH interoperability (see e.g. Bindseil and Pantelopoulos, 2023, chapter 4).

Finally, with **commercial bank money convertible into central bank money** (via commercial banks holding deposits at the central bank), the former is tradeable at par as end-users are able to substitute commercial bank deposits into risk-free positions by obtaining banknotes. Similarly, as **e-money issued by EMIs/Fintechs is convertible into commercial bank money** – through EMIs/Fintechs buttressing their liabilities by holding deposits at commercial banks – the cross-exchange rate between e-money issued by different entities equates to unity, as two stocks of e-money can be separately converted into commercial bank money at par.

3.2 Token-based means of payments

Settlement finality is accomplished in token-based means of payments without leaving any residual financial positions between the payer or payee, as payments are made outside of any payment system, as the means of payment is physically passed from the payer to the payee (i.e. settlement is P2P/disintermediated). Further, central banks employ quality control techniques and incorporate security features to detract from and prevent counterfeiting (see e.g. RBA, 2022) so as to ensure **interoperability** between banknotes. In times past, the counterfeiting of banknotes was even punishable by death (Salmon, 2011).

Finally, as the ultimate anchor to the monetary system, the element of **convertibility** does not apply to token-based means of payments, as banknotes are not convertible into another "higher" form of settlement medium (as the convertibility of banknotes into precious metal was abandoned following the collapse of the gold standard during the interwar years). It is widely supposed that the first central bank to issue banknotes was the Stockholms Banco in 1661. Such operations ended in 1664 after the bank was unable to redeem its notes into specie and was succeeded by the Swedish Riksbank in 1668. However, after heeding the lessons from the Stockholms Banco, the Riksbank was prohibited from

[22] Retail payments can also be settled in commercial bank money that is backed by central bank money. This is because financial institutions may hold deposits on the books of an automated clearing house (ACH – which constitutes the retail payment system), whereby in turn the ACH buttresses its liabilities by it itself holding stocks of deposits at the central bank. Depending on the arrangement – as opposed to banks prefunding their deposit accounts vis-à-vis the ACH at say the beginning of the day – financial institutions may also be permitted to incur negative balances in their deposit accounts, so long as any negative balances are rectified by the end of the day. In any case, settlement can transpire merely across the books of the ACH, meaning that settlement is backed by (but not directly settled in) central bank money. Even so, a financial institution can continue to credit the deposit account of the payee, as if the ACH were to default, the claims of banks vis-à-vis the ACH would be novated in the sense that the deposits of banks at the ACH would become deposits at the central bank.

initially issuing notes (Roberds and Velde, 2014; Bindseil 2019, 72; Desan, 2014, 304). The second central bank to do so (and more successfully) was the Bank of England in July 1694.

4. Stablecoins as means of payments

4.1 Taxonomy of stablecoins

Unlike unbacked crypto-assets (e.g. Bitcoin, Ether etc.), stablecoins operate under the premise of **price stability** by being either (i) backed by and convertible into commercial bank money/other assets/crypto-assets, or (ii) through "algorithmic" backing, as summarised in Table 2 below (see also e.g. G7 Working Group on Stablecoins, 2019; Arner, Auer and Frost, 2020; Chanson and Senner, 2022).

Table 2: Stablecoin type segregated by stabilisation mechanism

	Stabilisation mechanism through convertibility into…
Tokenised funds	Commercial bank money (e.g. bank deposits)
Off-chain collateralised	Off-chain assets other than cash (e.g. securities)
On-chain collateralised	Unbacked crypto-assets (e.g. Ether); "tokenised" assets (e.g. securities)
Algorithmic	N/A

Amongst others (see e.g. G7 Working Group on Stablecoins, 2019; ECB Crypto-Asset Task Force, 2020; Delivorias, 2021; Bains et al, 2022a; Baughman et al, 2022), Bullmann, Klemm and Pinna (2019) detail the **stabilisation mechanisms that underpin the various arrangements of stablecoins:**

- **(A) Tokenised funds[23]:** the stablecoin issuer (or a custodian who acts on behalf of the stablecoin issuer, such as a crypto-asset service provider – CASP) distributes stablecoin tokens (that are backed by funds – e.g. commercial bank money etc.) that are stored in a distributed ledger as opposed to a "traditional" centralised ledger maintained by a single entity. The process of tokenisation can be thought of as the act of moving, from a legal and technical perspective, the representation of ownership of an asset (and the transferability of ownership) into a ledger, where in this case the ledger resides on a blockchain (Bindseil, Coste and Pantelopoulos, 2025).[24] At the time of writing, the largest stablecoin issuer is Tether which primarily issues USDT, a dollar denominated token. Tether claims that every Tether in circulation is "100% backed by reserves".[25] The composition of reserves is at the discretion of Tether. Tether asserts that over 85% of its reserves are composed in cash, cash equivalents and other short-term deposits, but only 0.12% of this consists of actual cash and bank deposits.[26] In many ways, e-money constructs are analogous to tokenised funds from a functional perspective, in the sense that the issuer of the stablecoin fully backs its liabilities by e.g. holding deposits at a commercial bank etc.
- **(B) Off-chain collateralised stablecoins:** stablecoins are backed by assets other than cash (e.g. securities) which, as with tokenised funds, requires a custodian to hold such assets. An example of off-chain collateralised stablecoins could be where stablecoins are backed

[23] The term is here used outside of legal classification of these initiatives as "electronic money" or as "funds"
[24] Like the term "stablecoin" (see below), the term "tokenised" is by and large a redundant one. This is because it remains ambiguous as to why "tokenisation" – the act of moving an asset from one ledger to another – is specific to DLT. For example, paying in banknotes (central bank money) into a bank and obtaining a bank deposit is "tokenisation", but does not involve the use of DLT/cryptographic techniques etc.
[25] https://tether.to/en/transparency/#usdt
[26] https://tether.to/en/transparency/#reports

(primarily) by securities, which are held at a custodian which holds the assets at a central securities depository (CSD) on behalf of the stablecoin issuer. However, it may be that there are several degrees of separation between the custodian and the CSD. For instance, a stablecoin issuer in the EU may have a local custodian in the EU which has local custodian in the US for USD securities which then holds the securities at CSD on behalf of the custodian. The implication here is that the custody chain may be indefinitely lengthy. Coste et al (2021) (see also Coste 2024)

- **(C) On-chain collateralised stablecoins:** issued stablecoins are backed by on-chain collateral,[27] and as recorded/managed by way of smart contract do not require the use of a custodian/CASP to fulfill convertibility[28]; i.e. the issue of any on-chain stablecoins rely on decentralised finance (DeFi).[29] One example of on-chain collateralised stablecoins is the **Dai Stablecoin System** by MakerDAO (pegged 1:1 vis-a-vis the US Dollar), which are buttressed by on-chain collateral predominantly in the form of tokenised US securities. In its whitepaper, MakerDAO (2017, 2) describes the fully decentralised construct:

  > *"The Maker Protocol, built on the Ethereum blockchain, enables users to create currency. Current elements of the Maker Protocol are the Dai stablecoin, Maker Collateral Vaults, Oracles, and Voting. MakerDAO governs the Maker Protocol by deciding on key parameters (e.g., stability fees, collateral types/rates, etc.) through the voting power of MKR holders. The Maker Protocol, one of the largest decentralized applications (dapps) on the Ethereum blockchain, was the first decentralized finance (DeFi) application to earn significant adoption."*

- **(D) Algorithmic stablecoins:** stablecoins distributed by the stablecoin issuer are not backed (i.e. convertible into) by any assets. In reality, what is "backing" the stablecoin is the belief (i.e. the expectation) that the stablecoin will be able to be employed as a means of payment at some point in the future, which is of course largely contingent on the stablecoin maintaining its price stability. Needless to say, if such beliefs/expectations were to be placed into jeopardy, the stablecoin loses its price stability vis-a-vis other means of payments etc. In rudimentary terms (on the presumption that the algorithmic stablecoin is pegged 1:1 against the US Dollar), if the price of any distributed algorithmic stablecoins were to rise above 1 USD, new coins may be issued to devalue all stablecoins in circulation. On the flipside, if the price of the stablecoin were to fall below 1 US Dollar, coins must be removed from circulation, which, at the risk of stating the obvious, is more challenging. One prominent example of an algorithmic stablecoin was **Terra USD** (now more or less defunct).

4.2 Terminological issues with stablecoins

Tokens vs coins

Despite the fundamental disparities amid token-based vs crypto-assets, the inference that crypto-assets are "tokens" does not imply that they are token-based in terms of their *properties* as a means of payment. Still, **why are for instance stablecoins described as tokens and not as "coins" as the suffix implies?** Unless the crypto-asset is the native means of payment to the underlying blockchain, the crypto-asset (irrespective of whether it is backed or unbacked) is a token. In other words, whilst Bitcoin is a coin as it is native to the Bitcoin blockchain, stablecoins/tokenised funds such as Tether exist as

[27] This could be a range of assets so long as the asset resides on the blockchain – i.e. is "on-chain". One example would be so-called "tokenised" securities – i.e. securities which are recorded on a blockchain.

[28] It is to be noted that this set-up means that DAI does not achieve convertibility in USD but in USDC.

[29] In addition, the smart contract creates an amount of stablecoins that are sent to the end-user in accordance with some over-collateralisation protocol.

tokens as they are not native to the underlying blockchain (e.g. Tether is issued on Bitcoin and Ethereum blockchains). Likewise, Ether is a coin as it is native to the underlying Ethereum blockchain. Needless to say, this is regardless of whether one believes that unbacked crypto-assets like Bitcoin are not suitable as a means of payment (or indeed as a store of value/investment vehicle) due to their inherent price instability (see e.g. Bindseil, Papsdorf and Schaaf, 2022).

Stablecoin as a term

As unpacked above, the term "stablecoin" encompasses a wide range of assets that purportedly seek to maintain a stable value relative to other asset(s). Nonetheless, there is generally no attempt to segregate whether a stablecoin is "truly" a stablecoin, given that many stablecoins have not accomplished price stability in a credible fashion. For these reasons, Bindseil, Coste and Pantelopoulos (2025) argue that **the term "stablecoin" should only apply to tokens that have a credible avenue to accomplish (and maintain) stability vis-à-vis a currency/asset that serves as a currency (e.g. Euros, AUD etc.).** For instance, so-called algorithmic stablecoins have, by and large, not been able to achieve stability. The authors suggest that the term "stablecoin" is by and large a redundant one, and at best should be applied to representations of e-money on DLT, as the term "money" insinuates that the token is considered to be of sufficient quality by regulators that it can be treated as a true means of payment. Nevertheless, to be consistent with the extant literature, in this paper we will continue to utilise/refer to the "conventional" terminological interpretations of stablecoins (i.e. tokenised funds/off-chain collateralised/on-chain collateralised/algorithmic) for ease of interpretation.

5. Settlement finality with blockchain/DLT

Having unpacked the elements that generally constitute means of payment fungibility and surveying why in many cases historical means of payments were problematic in terms of their underlying fungibility (section 2) – in addition to divulging the role of central bank money in means of payment fungibility (section 3) and describing the various guises of stablecoins (despite our objections regarding terminologies) (section 4) – we now turn our attention in this section to studying whether blockchain/DLT is able to offer settlement finality. This will then be followed by a discussion with regard to blockchain ecosystem interoperability (section 6) and convertibility in the context of stablecoins (section 7).

5.1 Blockchain in the literal/holistic sense vs blockchain as a form/type of DLT

"Blockchain" can be interpreted in two ways: (1) in a "literal" sense – i.e. the actual database; or, (2) in a more "holistic" sense with regard to the actual operative environment in which the database resides and functions – i.e. a "blockchain network". In our view, rather than depicting blockchain in a vanilla/literal sense, **it is more appropriate to interpret "blockchain" in the more holistic sense (blockchain = blockchain network)** in which the blockchain exists/functions namely by way of (a) the ledger – the blockchain itself in its most literal form; (b) the network – the specific arrangement whereby participants (i.e. nodes) operate within a specific environment to maintain the ledger; (c) the consensus mechanism – the process by which nodes agree as to the correct state of the ledger to facilitate settlement etc.

In interpreting blockchain in the more holistic sense, **it can also be emphasized that blockchain is a *form/type* of DLT.** Blockchain (in the literal sense) and DLT form a symbiotic relationship in that by the blockchain (i.e. the database) residing in its operative environment, blockchain = blockchain network, which is a form/type of DLT. Thus, despite their symbiotic relationship, blockchain (the literal interpretation) and DLT are strictly distinct. Likewise, that blockchain networks are a form/type of DLT also does not imply that a *blockchain network is DLT* (as the latter is an umbrella-like term).

5.2 Settlement finality

As alluded to above, settlement finality refers to the irrevocable and unconditional transfer of an asset or financial instrument etc. This concept is fundamental in ensuring the stability and reliability of payment systems.

In traditional centralised payment systems, there is a clear designated payment system operator responsible for ensuring settlement.[30] The operator receives transaction requests from participants, verifies the authenticity and validity of these transactions ensuring they comply with system rules, maintains and update the ledger that records transactions, and defines the moment of irrevocability guaranteeing that once a transaction is settled it is irrevocable and unconditional. Settlement finality is further underscored through regulatory requirements in major jurisdictions, requiring that operators of designated payment systems define the moment of irrevocability of transfer orders.

By contrast, **decentralised payment systems operate differently as there is no single identifiable operator responsible for ensuring settlement finality.** These systems rely on a consensus mechanism among participants to achieve distributed agreement about the ledger's state and updates. **This consensus can be achieved using several means, including proof-of-work as well as proof-of-stake:**

Settlement finality with proof-of-work

Proof-of-work – the consensus mechanism used in the Bitcoin network – is a decentralized consensus mechanism requiring network members to expend effort (using their own CPU power) to solve encryption puzzles to gain the right to update the network. In the Bitcoin white paper, Nakamoto (2008, 3) proposed a Byzantine Fault Tolerant[31] consensus mechanism that combines proof-of-work with the "longest chain" rule to create a consensus protocol:

> *"The majority decision is represented by the longest chain, which has the greatest proof-of-work effort invested in it. If a majority of CPU power is controlled by honest nodes, the honest chain will grow the fastest and outpace any competing chains. To modify a past block, an attacker would have to redo the proof-of-work of the block and all blocks after it and then catch up with and surpass the work of the honest nodes. We will show later that the probability of a slower attacker catching up diminishes exponentially as subsequent blocks are added"*

In doing so, **the Bitcoin payment system achieves probabilistic settlement**. Transactions achieve finality based on the probability that they will remain part of the longest chain – the one accepted by

[30] It is to be noted that centralised systems can still use several nodes to process transactions, and ensure business continuity in case of unavailability of one or several nodes.

[31] As described by Lamport, Shostak and Pease (1982), the "Byzantine Generals Problem" is a construct where the Byzantine army is split into numerous divisions, whereby each is led by a General, with all Generals communicating to devise a joint plan of attack. The implication is that if more than one-third of Generals (i.e. nodes) are malicious – suffer from a Byzantine fault – it is not possible to achieve a consensus (some of the first consensus protocols – like in the case of Lamport (1989) – assumed away the presence of malicious actors).

the network as legitimate.[32] Each new block added to the chain exponentially decreases the likelihood of a successful alteration of any preceding block, as an attacker would need to control a majority of the computing power and reproduce the work for the targeted block and all subsequent blocks faster than the rest of the network can add new blocks. This concept underscores that while transaction reversal is theoretically possible, the probability reduces with each additional block, and becomes more or less negligible after a certain number of blocks have been processed (typically between 3-6 blocks); i.e. settlement finality or "block finality" becomes more deterministic. However, this method of achieving settlement finality contrasts with the traditional definition of settlement that requires pinpointing the precise moment at which a transaction is irrevocable, which is not possible in probabilistic systems.

Settlement finality with proof-of-stake

Proof-of-stake – the consensus mechanism increasingly adopted in blockchain networks such as Ethereum – is a decentralized consensus mechanism that requires network participants to hold and sometimes lock up a certain amount of the network's tokens to gain the right to validate blocks of transactions. Proof-of-stake aims to achieve network security through economic incentives.[33] Validators are chosen to create new blocks based on the amount of value they hold and are willing to "stake" as collateral. The proof-of-stake protocol is also designed to be more energy-efficient and scalable than proof-of-work (e.g. given that proof-of-work e.g. requires a large amount of computational power and hence energy). The security of the network is maintained not by computational work but by the economic stake that validators have in the network's continuity and integrity. To attempt a fraudulent validation or to modify a past block, a validator would be required to risk their staked tokens, which could be slashed for dishonest behavior. This economic penalty significantly reduces the likelihood of malicious activity.

Unlike in proof-of-work, **the finality of transactions with proof-of-stake is deterministic.** Ethereum, for instance, utilizes mechanisms which aim to achieve deterministic finality, meaning that once a block has been finalized, it cannot be changed, reversed, or forked under normal network conditions.[34] This finality mechanism contrasts sharply with the probabilistic finality in proof-of-work, where finality gradually increases as more blocks are added to the chain. In proof-of-stake, the exact moment a transaction becomes irrevocable can be pinpointed once it is included in a finalized block, aligning more closely with traditional financial system's definitions of settlement finality.

Yet as proof-of-stake still relies on a consensus principle, under exceptional circumstances, **a majority of stakeholders could decide to fork the ledger** and decide to return to previous state of consensus, creating two ledgers that share the same transaction history but diverging post-fork. In the event of a

[32] This is because for various reasons (see below), a fork may emerge in the blockchain, leading to two separate mutually exclusive paths. Should a fork emerge, one path will eventually be considered as legitimate, whereas the other path will not.

[33] This is not to suggest that consensus mechanisms like proof-of-work also do not utilise economic incentive mechanisms.

[34] Forks differ to that of ledger conflicts (though the end-result is per se the same – i.e. a fork emerges). Yaga et al (2018) note that as a result of information asymmetries amid network participants (e.g. if the speed at which network participants receive information differ), there is the possibility that multiple blocks can be published at roughly the same point in time, causing different versions of the blockchain to exist at any given moment. That is to say, the blockchain may diverge from one continuous chain into two. While the authors suggest that conflicts with regard to what is the "correct" or "official" version of the chain are typically resolved quickly, the possibility that a block(s) may be overwritten can lead to transactions not being accepted/confirmed (i.e. settled) until multiple additional blocks have been laid on top of the transaction(s) in question.

fork, the tokens are duplicated across both chains and different validators may decide to continue processing a different path of the ledger, and different issuers may decide to recognise a different version of the ledger. This situation is particularly pertinent in scenarios where the ledger facilitates transactions involving tokens that are backed by financial claims, such as stablecoins. During a fork, while tokens are replicated on both chains, only one set of these tokens retains the right to claim, determined solely by the issuer. Clear communication from the issuer is crucial for ensuring settlement finality, affirming which ledger holds transactions backed by the legitimate claim to the underlying assets.

In conclusion, each system strives to attain settlement finality through means best aligned with its underlying philosophy. Traditional systems rely on the robust legal frameworks and efficient institutional processes typical of jurisdictions with a strong rule of law, providing a high degree of finality through legal and operational mechanisms. On the other hand, decentralized systems like permissionless DLTs (i.e. permissionless blockchain networks) can offer/achieve settlement finality independently of such legal structures but require continuous consensus that can shift or be re-rolled. Each approach reflects different philosophies about security, autonomy, and reliance on institutional, or technological solutions.

6. Interoperability between blockchain ecosystems

Boar et al (2021; see also CPMI, 2024) classify payment system interoperability into three types: **technical, semantic and business:**

- **Technical Interoperability:** This involves implementing the same technical standards, such as message formats and data infrastructures, allowing hardware and software infrastructures to connect directly. For stablecoins, it means using standardized protocols and interfaces to ensure seamless interaction between different technologies.
- **Semantic Interoperability**: This ensures that systems can interpret data and information uniformly. For stablecoins, it means having a common language for transaction data so that all participating systems understand and process information consistently.
- **Business Interoperability:** This involves agreeing on rights and obligations, determining who can access platforms, and setting the terms for clearing and settling obligations among payment systems. For stablecoins, this means establishing protocols for how different issuers can interact and settle transactions across various platforms while addressing risks such as payment failures.

For stablecoins to achieve full fungibility and avoid fragmentation across means of payments, they must exhibit **blockchain ecosystem interoperability in two critical directions – horizontal and vertical** – whereby horizontal interoperability can be further segregated into two dimensions:

- **Horizontal interoperability in the 1st dimension:** interoperability of stablecoins issued by the same issuer on identical/different blockchains.
- **Horizontal interoperability in the 2nd dimension:** interoperability of stablecoins issued by different issuers on identical/different blockchains.
- **Vertical interoperability with traditional payment systems**: i.e. the ability to convert the stablecoin into the pegged asset available in the financial system.

In the subsequent sections, we begin by unpacking whether horizontal interoperability can be accomplished in both the first and second dimensions (sections 6.1 and 6.2). This is then followed by a discussion of interoperability in the vertical sense (section 6.3).

6.1 Horizontal blockchain interoperability in the 1st dimension

6.1.1 Technical Interoperability

Technical interoperability requires systems to use the same underlying technical infrastructure to connect and process transactions seamlessly. When tokens are issued on the same blockchain (be it by the same issuer, or even in the case of two different issuers), they inherently share the same underlying infrastructure, which significantly facilitates **technical interoperability.** This common infrastructure means that all tokens share the same consensus mechanisms, transaction validation processes, and network infrastructures. Since all participants (nodes, smart contracts, wallets) interact with a unified ledger, they process and verify transactions in a consistent manner and can agree on the state of the ledger.

On the flipside, if a single issuer were to release **two similar stablecoins with identical rights and using similar token standards** (e.g. ERC-20 on Ethereum and the equivalent BEP-20 on Binance Smart Chain) **but on two different ledgers,**[35] they may **achieve semantic and business interoperability but lack technical interoperability.** Though both token standards might have similar structures (for instance, how balances are queried or transfers are made), the fact that the stablecoins are issued on different ledgers means their technical environments are not inherently compatible. The lack of technical interoperability means that – while the stablecoins might be understood and treated similarly from a business perspective and their data may be interpreted in a consistent way – the different blockchains prevent direct interaction. For instance, a smart contract or application designed to handle stablecoins on one ledger will not be able to process or transfer stablecoins from another ledger unless specific bridging mechanisms or cross-chain solutions are implemented. In other words, despite the stablecoins exhibiting semantic interoperability (given that they follow similar token standards) and business interoperability (because they have the same rights), the fact that they are on different ledgers results in a breakdown of technical interoperability, limiting their ability to interact seamlessly across platforms and thus diminishing fungibility.

To achieve technical interoperability (and buttress fungibility), stablecoins have three main options, each varying in complexity and reliability:

- **Issue tokens on the same ledger**: the most straightforward and reliable option is to issue all stablecoins on the same ledger. This ensures seamless interaction between systems, applications, and smart contracts without the need for additional infrastructure or complexity.
- **Issue native tokens on multiple ledgers**: issuers can provide native versions of the stablecoin on multiple blockchains (e.g. STC 1 BLK 1 and STC 1 BLK 2). This avoids reliance on cross-chain bridges or wrapped tokens, ensuring that each blockchain has its own native stablecoin, although it requires the issuer to manage stablecoins across multiple ecosystems.
- **Implement cross-chain solutions**: if stablecoins are issued on different ledgers, cross-chain solutions, such as bridges or wrapped tokens, can be used. These solutions enable tokens to

[35] For instance, STC 1 BLK 1 and STC 1 BLK 2; i.e. STC Issuer 1 issues tokens on both blockchain 1 and blockchain 2.

move between ledgers but add operational complexity and introduce certain risks, such as dependency on third-party mechanisms.[36]

6.1.2 Semantic Interoperability

Semantic interoperability requires systems to interpret and process data consistently. It focuses on establishing a shared understanding of the data's structure, format, and meaning, enabling seamless interaction. If a single issuer were to release two similar stablecoins on the same ledger – with identical rights but using different token standards (e.g. some tokens issued Ethereum using ERC-20 and others using ERC-721) – they may achieve **technical** and **business interoperability** but lack **semantic interoperability**. This is because if two stablecoins issued under different standards present their data differently – such as how balances are queried, transfers are made, or metadata is encoded – smart contracts or applications may not be able to process them correctly. This can lead smart contracts or applications designed to handle stablecoins issued under one standard to not recognize or properly interact with a stablecoin issued under a different standard. The smart contract expects certain data formats or functions, which might not exist in the second standard, leading to misinterpretation or failure in processing transactions.

In this scenario, despite the stablecoins being on the same ledger (thereby achieving **technical interoperability**) and sharing the same rights and business terms (enabling **business interoperability**), their differing token standards mean that systems, smart contracts, and applications designed to work with one standard may not be able to interpret or interact with the other correctly, leading to a breakdown in semantic interoperability (and therefore fungibility).

To accomplish semantic interoperability, several options are available that allow for consistent data interpretation and interaction across systems (some of which involve trade-offs):

- **Adopt common standards**: issuers can use widely accepted token standards within the ecosystem, ensuring compatibility across platforms and reducing fragmentation. This facilitates smooth operations and improves usability across applications.
- **Adopt retro-compatible standards**: whenever a need for a new standard is identified, new tokens using this standard should to the largest extent possible be widely compatible with previous common standards. This facilitates smooth transition and maintain interoperability during the transition period.
- **Ensure compatibility across custom tokens**: if customization is strictly required, issuers can align key functions with the ecosystem's dominant standard to prevent compatibility issues with smart contracts and applications, ensuring that tokens are still understood uniformly.
- **Use wrappers for non-compatible tokens**: for stablecoins issued under non-compatible standards, issuers can create wrapped tokens that conform to a widely adopted standard. This approach allows for seamless interaction with other tokens and platforms while retaining the benefits of the original token. However, this involves risks and costs associated with the wrapper.
- **Add custom logic for cross-standard interaction**: platforms may implement custom programming or logic to facilitate interaction between tokens that follow different standards. While this ensures cross-token compatibility, it introduces added complexity to the system.

[36] See Pantelopoulos (2025a, chapter 13) for an elaboration on wrapped tokens and cross-chain bridges.

6.1.3 Business Interoperability

Business interoperability requires systems to operate under the same rights, obligations, and agreements regarding how transactions are cleared and settled. If a single issuer were to release two similar stablecoins on the **same ledger** with **similar token standards** but with different **legal rights** (e.g. one often redemption rights under laws of one jurisdiction and another version offer redemption rights under laws of another jurisdiction), they may achieve **semantic** and **technical interoperability** but lack **business interoperability**.

Even though the stablecoins share the same ledger and token standard – meaning they can be processed technically in the same way – the different legal frameworks governing each version may make them different in practice. For example, an EU-compliant stablecoin may involve different redemption rights and backing of the reserves than a non-EU version. Another example is “tainted” tokens; i.e. tokens that are flagged or blacklisted for having illicit or questionable origins (e.g. stolen from hacks, money laundering, or sanctioned entities). Certain exchanges, wallets, and platforms may refuse to accept tainted tokens that can be traced as coming from illicit activities, leading to a breakdown in business interoperability (the same unit of stablecoin not being accepted or frozen upon reception).

Such disparities, such as who is eligible to use the tokens, how they can be redeemed, and at which cost or which jurisdictions they operate under, creates a gap in **business interoperability (and thus fungibility)**. While the tokens can be moved and interpreted seamlessly across platforms (by way of technical and semantic interoperability), the differing **rights and obligations** attached to each version limits their ability to be used interchangeably in all business contexts; i.e. business interoperability cannot in some cases be achieved. As a consequence, while the technical and semantic aspects of these tokens remain intact, their ability to be settled and transferred across platforms can be restricted, and their fungibility as means of payments jeopardised, depending on the compliance policies of the businesses involved.

6.2 Horizontal blockchain interoperability in the 2nd dimension

Drawing on the discussion immediately above, **blockchain ecosystem interoperability between stablecoins from different issuers** (be it on identical or different blockchains) – analogous to stablecoins from the same issuer – **is primarily limited by business interoperability**, rather than **technical** or **semantic interoperability**. The impact on fungibility is as follows:

Technical Interoperability: if stablecoins from different issuers (e.g. STC 1 and STC 2) are issued on the same ledger (i.e. STC 1 BLK 1, STC 2 BLK 1), they typically have technical interoperability. This means that both tokens can be transferred, stored, and processed by the same infrastructure without issue. Therefore, technical interoperability does not significantly inhibit fungibility. If on the other hand stablecoins from different issuers were to exist on different blockchains (e.g. STC 1 BLK 1, STC 2 BLK 2), technical interoperability can be accomplished through workaround solutions such as those mentioned above (e.g. wrapping, bridges etc.), albeit with trade-offs (e.g. security risks).

Semantic Interoperability: if both stablecoins adhere to similar token standards (irrespective of whether they reside on identical/different blockchains), their data structures – such as how balances are queried and transactions are conducted – can be uniformly understood by platforms and applications. Hence, semantic interoperability usually does not create a barrier to interoperability and thus fungibility.

Business Interoperability: the main limitation to fungibility arises from **business interoperability**. As with stablecoins from a single issuer, since stablecoins from different issuers are governed by different legal frameworks, rights, and obligations, they are not always interchangeable on a business level. Factors like the issuer's policies on redemption, compliance with regulations, and trust in the issuer can make one stablecoin more acceptable or valuable in certain contexts, thereby limiting their fungibility between users, platforms, or jurisdictions.

In short, while technical and semantic interoperability may not pose significant challenges, it is **business interoperability** which constitutes the primary factor in inhibiting the fungibility of stablecoins from different issuers on identical/different blockchain ecosystems. Several options can improve **business interoperability** and enhance fungibility between stablecoins from different issuers, making stablecoins from different issuers more easily interchangeable and accepted across ecosystems:

- **Align with international best practices**: encouraging stablecoin issuers to follow international standards for governance, transparency, and oversight helps build trust across markets. Alignment with global regulatory frameworks and best practices increases the likelihood that different stablecoins will be treated as interchangeable by users and platforms.
- **High quality of reserve assets**: requiring stablecoin issuers to maintain adequate reserves, composed of high-quality liquid assets, ensures that stablecoins are fully backed and redeemable. This increases confidence in their value and interchangeability, improving business interoperability.
- **Promote deep and liquid markets**: establishing deep liquidity pools where stablecoins can be easily exchanged or swapped between each other's reduces friction and cost in transactions, making them more fungible in practice.
- **Free redemption**: ensuring that stablecoins offer rapid and free redemption processes enhances their business interoperability. When users can quickly and reliably redeem stablecoins for fiat or other assets without additional costs, it reduces the perception that one stablecoin is more reliable or accessible than another, improving their interchangeability across platforms.

6.3 Vertical Interoperability with traditional payment systems

When considering **vertical interoperability** between traditional payment systems and stablecoins, the goal is to enable seamless interaction across these different financial infrastructures, allowing **payers to send one form of value (e.g. stablecoins) and payees to receive another (e.g. bank deposits, e-money, or perhaps CBDCs in the future)**. This ensures flexibility in how value is transferred across different systems.

Here's how the three types of interoperability – technical, semantic, and business – apply in the vertical context, along with their impact on fungibility:

Technical interoperability: traditional payment systems (e.g. ECB's TARGET2, or EBA Clearing's STEP2) and stablecoins operate on fundamentally different infrastructures; one using centralized systems and the other using decentralized blockchain networks. To bridge the two, there must be integration layers (e.g. gateways, APIs) that enable value transfer across them. Any lack of technical interoperability between traditional payment systems and stablecoins limits fungibility because users cannot seamlessly transfer value between the two ecosystems without complex intermediary steps, such as using third-party exchanges or conversion platforms.

Semantic interoperability: traditional payment systems and stablecoins often use different data standards for transaction messages. Traditional systems rely on standardized messaging formats like ISO 20022, while stablecoins use blockchain-specific transaction formats. To achieve seamless interaction between the two, there must be a harmonization of data structures or use of translation layers that can bridge these differences. A lack of semantic interoperability limits fungibility because inconsistent interpretation of transaction data can cause errors or delays, making it difficult for users to seamlessly send one form of value (e.g. stablecoins) and receive another (e.g. bank deposits) without manual reconciliation or intermediary adjustments.

Business interoperability: this involves aligning the rights, obligations, and rules between traditional payment systems and stablecoins, including regulatory requirements, settlement practices, and user access. Traditional payment systems are typically heavily regulated and adhere to strict compliance standards, involving consumer protection, fraud protection, redemption rights, and Know Your Customer (KYC) and Anti-Money Laundering (AML) requirements – which differ in each jurisdiction – while stablecoin ecosystems are often governed by less consistent frameworks or subject to lighter requirements. These different practices pose a challenge to business interoperability and thus fungibility. Due to differing regulations, some traditional payment systems may not fully accept or settle transactions involving stablecoins, reducing their interchangeability. In addition, stablecoin users may face limitations in redeeming or converting stablecoins into traditional fiat through regulated payment systems, further impacting their fungibility.

To improve **technical interoperability**, several options can be envisaged, such as establishing **integration layers** including granting central bank to non-bank PSPs that issue stablecoins who can act as a bridge to traditional payment system. Alternatively, intermediaries can play the role of facilitating communication between traditional systems and blockchain networks.

With regards to **semantic interoperability**, enabling tokens standards for stablecoin that are compatible with **standardized data formats** or using **data translation layers** that harmonize transaction messaging with traditional systems (e.g., ISO 20022) can reduce friction and ensure consistent interpretation of transaction data, allowing for smoother transfers between systems.

For **business interoperability**, issuers and intermediaries can facilitate seamless transfers between traditional payment systems and stablecoins by offering **cost-free redemption**. Additionally, intermediaries can perform **KYC/AML compliance** to meet regulatory requirements, ensuring that banks accept payments and maintain trust between ecosystems. These measures enhance fungibility and enable smoother cross-system interactions.

7. Stablecoins and convertibility

Convertibility refers to the ability of a means of payment to be readily redeemed at par to the pegged asset. Convertibility of private retail money implies that it must be readily tradable at par with the "ultimate" (or quasi-ultimate) means of payment – i.e. central bank money in the form of banknotes. Convertibility into central bank money is crucial, because it ensures that the holder of a means of payment that is lower on the hierarchy of money[37] can readily trade it with other means of payments

[37] For instance from the perspective of credit risk, banknotes would be higher on the hierarchy of money than say commercial bank deposits or e-money deposits with a EMI/Fintech.

that are of higher credit quality that in turn can be converted into central bank money. Convertibility is generally ensured by the issuer. If the issuer cannot guarantee the convertibility of the means of payment into other means of payments, the holder may potentially incur additional costs and/or delays, or in the extreme may be unable to convert their means of payment – both of which impact on the asset's value and usability.

Convertibility requires that the institution ensuring convertibility has enough assets of sufficiently high quality to meet redemption demands in the pegged asset. For banks, whose economic function is to perform maturity transformation and therefore actively take-on some degree of credit and liquidity risk, the convertibility of deposits or other liabilities into higher level money is usually preserved due to:

- The bank holding sufficient liquidity to meet their client's demands in stress situations and sufficient capital to cover for potential losses.
- A credible supervisory authority ensuring that the bank maintains sufficient capital and liquidity buffers to withstand stress scenarios and fulfill their obligations to clients.
- A credible deposit guarantee scheme protecting depositors in case of failure which reduces the severity of bank runs ex-ante.
- The central bank acting as "market-maker of last resort" enabling the bank to monetize less-liquid assets that they cannot liquidate in the market.

For non-banks issuing e-money (e.g. EMIs/Fintechs), whose economic function is to not actively expose itself to credit and liquidity risks, the convertibility of e-money liabilities typically entails the EMI/Fintech backing its liabilities:

- (i) by keeping reserves in the pegged currency held at the central bank;
- (ii) by keeping deposit accounts with commercial banks;
- (iii) by investing the liabilities of its clients in other instruments bearing low credit, market and & liquidity risk that can be readily converted into bank deposits without losing value such as short-term government bonds.[38]

In a nutshell, convertibility requires that the institution/entity ensuring convertibility having access to the pegged asset and the capacity to readily transfer it to the client seeking redemption. For issuers of stablecoins, this requires that the issuer has accounts and assets in the financial system that they can effectively use so that end-users can in one-way or another redeem their stablecoins into commercial bank money (or, perhaps eventually into central bank money). If the issuer of say a euro-denominated stablecoin were to lack access to the Euro-financial system – even if they were to theoretically record liabilities in euros and allegedly back them with euro- denominated assets – the stablecoin issuer would not be able to offer an avenue for end-users to convert their claims into e.g. commercial bank money/central bank money.

Against such logic, **it can be concluded that stablecoins which do not offer convertibility into (or eventual convertibility into) higher level money that is either central bank money or convertible into central bank money cannot be considered to be fungible means of payments** (i.e. not fungible with other stablecoins issued by the same/different issuers on the same/different blockchain ecosystems, let alone with e.g. commercial bank money/central bank money). This holds if the stablecoin seeks to achieve price stability through some form of algorithm (like in the case of algorithmic stablecoins) – as

[38] The exact composition of the reserve depends on the regulatory requirements in each jurisdiction and on the institution's risk appetite.

the underlying mechanism is unable to offer the convertibility into some other asset – or otherwise (i.e. pegged to the price of another asset, be it off- or on-chain).

8. Conclusion

Irrespective of the technologies which underpin means of payments, **fungibility is an overriding precondition for fluidity in payment and settlement.** This paper presented a framework to study the elements which generally constitute means of payment fungibility, namely (1) settlement finality; (2) interoperability; (3) and seamless convertibility into the quasi-ultimate means of payment.

Given the perception that stablecoins can serve as genuine means of payments, this paper proceeded to apply the framework to the various guises of stablecoins and **offers the following conclusions as to whether stablecoins issued by different issuers on different blockchains are fungible** (on the presumption that central bank money is itself homogenous in terms of its unit of account):

- **Tokenised funds are fungible means of payments,** so long as (a) they operate on ledgers than offer a credible mechanism for settlement finality; (b) issuers have a sufficiently strong liquidity and capital positions to comply with their regulatory requirements and to meet their client obligations etc.; and that (c) the underlying payment and settlement technologies are interoperable with other "traditional" payment and settlement technologies.
- **Off-chain collateralised stablecoins are fungible means of payments,** whenever they meet the conditions (a), (b) and (c) as stipulated above, and that the issuer has adequate capital to cover potential variations in the volatility of liquid off-chain assets in a stressed situation.
- **On-chain collateralised stablecoins are prima facie fungible means of payments,** provided that conditions (a), (b) and (c) as described above are fulfilled, and on the proviso that the on-chain collateral can be readily converted into off-chain assets.
- Finally, as **algorithmic stablecoins** deriving their stability from a mechanism built into their protocol that do not rely on having direct backing by a "traditional" counterparty, end-users do not hold a claim on a counterparty that can facilitate convertibility into central bank money. To this end, **algorithmic stablecoins are not fungible means of payments.**

It is envisaged that by exploring means of payment fungibility in the context of stablecoins, **this paper also contributes to the literature with regard to the determinants of means of payment fungibility in a more general sense.** Indeed given the ever-increasing "electronification" of payment habits in society and thus the downward trend of banknotes as means of payments (and hence a decline in the frequency at which commercial bank money is converted into central bank money), exploring the determinants of means of payment fungibility is of particular importance given current debates with regard to whether a "retail CBDC"[39] should be issued by central banks – in which the general public will be granted access to electronic central bank money rather than just banknotes. In taking stock of the elements that generally constitute means of payment fungibility as outlined in this paper, an absence of convertibility into central bank money thereby raises essential questions as to how means of payment fungibility may be impacted in the future.[40]

[39] Again, see Bindseil, Coste and Pantelopoulos (2025) for a discussion on terminologies relating to CBDC.

[40] Debates as to whether the lack of convertibility into central bank money will completely jeopardise retail means of payment fungibility vary. For instance, Brunnermeir, James and Landau (2021), as well as Bofinger and Haas (2023), suggest that even if banknotes were to completely disappear, the fact that banks will still be

References

Allen, M. (2016). Currency depreciation and debasement in medieval Europe. *Money in the Western Legal Tradition: Middle Ages to Bretton Woods*, 41-52.

Arner, D. W., Auer, R., & Frost, J. (2020). Stablecoins: risks, potential and regulation. *BIS Working Papers* No. 905.

Bains, P., Ismail, A., Melo, F., & Sugimoto, N. (2022a). Regulating the crypto ecosystem: the case of stablecoins and arrangements. *International Monetary Fund FinTech Notes* 2022/008.

Bains, P., Ismail, A., Melo, F., & Sugimoto, N. (2022b). Regulating the Crypto Ecosystem: The Case of Unbacked Crypto Assets. *International Monetary Fund FinTech Notes*, *2022/*007.

Baughman, G., Carapella, F., Gerszten, J., & Mills, D. (2022). The stable in stablecoins. *FEDS Notes*.

BdF. (2018). *Payments and market infrastructure in the digital age*. BdF publication.

Bidder, Rhys and Ezeji-Okoye, Kene and Osborne, Matthew and Patchay, Jannah and Paul, Varun and Rhodes, Tom and Soucie Watts, Elise and Whitworth, Andrew, Single minded? Stablecoins and the singleness of money (2025). Qatar Centre for Global Banking & Finance - Occasional papers series (https://www.kcl.ac.uk/news/stablecoin-regulation-and-the-singleness-of-money), Available at SSRN: https://ssrn.com/abstract=5311253 or http://dx.doi.org/10.2139/ssrn.5311253

BIS. (2020). BIS Annual Economic Report. *Bank of International Settlements*.

BIS. (2025). BIS Annual Economic Report 2025 III. The next-generation monetary and financial system. *Bank of International Settlements*.

Bindseil, U. (2019). *Central Banking Before 1800: A Rehabilitation*. Oxford University Press.

Bindseil, U., Coste, C., & Pantelopoulos, G. (2025). Digital money and finance: a critical review of terminologies. *Journal of Financial Market Infrastructures, 12 (2),* 73-118.

Bindseil, U., & Pantelopoulos, G. (2023). *Introduction to payments and financial market infrastructures*. Springer Nature.

Bindseil, U., Papsdorf, P., & Schaaf, J. (2022). The encrypted threat: Bitcoin's social cost and regulatory responses, *SUERF Policy Brief* No. 262.

Boar, C., Claessens, S., Kosse, A., Leckow, R., & Rice, T. (2021). Interoperability between payment systems across borders. *BIS Bulletin* No. 49.

Bofinger, P., & Haas, T. (2023). The Digital Euro (CBDC) as a Monetary Anchor of the Financial System. *SUERF Policy Note* No. 309.

equipped with deposit accounts at the central bank will be sufficient to preserve central bank money as the monetary anchor. For a contrasting perspective, see e.g. Panetta (2021) or Pantelopoulos (2025b). That aside, there are other justifications for issuing a retail CBDC, such as ensuring competition in the retail payments market.

Brunnermeier, M. K., James, H., & Landau, J. P. (2021). The digitization of money. *BIS Working Paper* No. 941.

Brunnermeier, M. K., & Landau, J. P. (2022). The digital euro: policy implications and perspectives.

Brunnermeier, M. K., & Niepelt, D. (2019). On the equivalence of private and public money. *Journal of Monetary Economics*, *106*, 27-41.

Bunea, D., Karakitsos, P., Merriman, N., & Studener, W. (2016). Profit distribution and loss coverage rules for central banks. *ECB Occasional Paper* No. 169.

Bullmann, D., Klemm, J., & Pinna, A. (2019). In search for stability in crypto-assets: are stablecoins the solution?. *ECB Occasional Paper* No. 230.

Chanson, M., & Senner, R. (2022). Stablecoins' Quest for Money: Who is Afraid of Credit?. *The Journal of FinTech*, *2*(01n02), 2250002.

Cheng, J., & Torregrossa, J. (2022). What is money? A lawyer's perspective on the evolution of the US payment system and dollars in the digital age. *Journal of Payments Strategy & Systems*, *16*(1), 28-38.

Cipolla, C. M. (1963). Currency depreciation in medieval Europe. *The Economic History Review*, *15*(3), 413-422.

Clapham, J. H. (1944). *The bank of England, a History, Volume I*. Cambridge University Press.

CPMI. (2024). Service level agreements for cross-border payment arrangements. Recommendations and key features. Bank of International Settlements, Basle.

CPSS-IOSCO. (2012). Principles for financial market infrastructures. Bank of International Settlements, Basle.

Coste, C-E. (2024) *Toss a stablecoin to your banker. ECB Occasional Paper* No. 353.

Coste, C-E. Tcheng, C. Vansieleghem, I. (2021) *One size fits some: analysing profitability, capital and liquidity constraints of custodian banks through the lens of the SREP methodology.* ECB Occasional Paper No. 230.

Cranston, R., Avgouleas, E., Van Zwieten, K., Hare, C., & Van Sante, T. (2018). *Principles of banking law*. Oxford University Press.

De Roover, R. (1948). *Money, banking and credit in mediaeval Bruges: a study in the origins of banking*. Mediaeval Academy of America.

Dean, S. (1884). *History of Banking and Banks from the Bank of Venice to 1883*. Boston: Pelham Studios, Boylston Street.

Delivorias, A. (2021). Stablecoins, private-sector quest for cryptostability. European Parliamentary Research Service, European Parliament briefing. Available at: https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698803/EPRS_BRI(2021)698803_EN.pdf

Durfee, J. Lee, M-J. Torregrossa, J. & Wang, S. (2025) *Interoperability of Blockchain Systems and the Future of Payments.* Liberty Street Economics

Durfee, J. Lee, M-J. & Torregrossa, J. (2025) *An Interoperability Framework for Payment Systems.* Liberty Street Economics

Einzig, P. (1962). *The history of foreign exchange*. London: Macmillan.

ECB Crypto-Asset Task Force. (2020). Stablecoins: Implications for monetary policy, financial stability, market infrastructure and payments, and banking supervision in the euro area. *ECB Occasional Paper Series* No. 247.

Garratt, R., & Shin, H. S. (2023). Stablecoins versus tokenised deposits: implications for the singleness of money. *BIS Bulletin* No. 73.

Geva, B. (2003). Settlement Finality and Associated Risks in Funds Transfers-When Does Interbank Payment Occur. *Penn St. Int'l L. Rev.*, *22*, 33.

Gorton, G. B. (2017). The history and economics of safe assets. *Annual Review of Economics*, *9*, 547-586.

Gorton, G. B., & Zhang, J. Y. (2023). Taming wildcat stablecoins. *U. Chi. L. Rev.*, *90*, 909.

Greenberg, J. R. (2020). *Bank Notes and Shinplasters: The Rage for Paper Money in the Early Republic*. University of Pennsylvania Press.

G7 Working Group on Stablecoins. (2019). Investigating the impact of global stablecoins. Bank of International Settlements, Basle.

HM Treasury, FCA and Bank of England. (2018). Cryptoassets Taskforce: final report.

Holmstrom, B. (2015). Understanding the role of debt in the financial system. *BIS Working Paper* No. 479.

Hsu, M. J. (2022). Thoughts on the architecture of stablecoins, April, 2022. Remarks before the Institute of International Economic Law at Georgetown University Law Centre. https://www.occ.gov/news-issuances/speeches/2022/pub-speech-2022-37.pdf

IMF. (2020). Digital money across borders: macro-financial implications

Jobst, C., & Kernbauer, H. (2016). *The quest for stable money: Central banking in Austria*, *2016*. University of Chicago Press.

Kahn, C. M., & Roberds, W. (2007). Transferability, finality, and debt settlement. *Journal of Monetary Economics*, *54*(4), 955-978.

Kindleberger, C. P. (1984). *A Financial History of Western Europe*. Routledge.

Kohn, M. (1999a). Bills of Exchange and the Money Market to 1600. *Working Paper 99–04*, Dartmouth College.

Kohn, M. (1999b). Early deposit banking. *Working Paper 99–03*, Dartmouth College.

Kohn, M. (1999c). Merchant banking in the medieval and early modern economy. *Working Paper 99–05*, Dartmouth College.

Kruse, Jürgen. (1782). Allgemeiner und besonders Hamburgischer Kontorist Welcher von den Währungen, Münzen, Gewigten, Maassen, Wechsel-Arten und Usanzen der vornehmsten in und ausser Europa gelegenen Städte und Länder. 4th edition, 2 volumes.

MakerDAO. (2017). The Dai Stablecoin System. Whitepaper. Available at: https://makerdao.com/whitepaper/DaiDec17WP.pdf

Mell, P., & Yaga, D. (2023). Understanding Stablecoin Technology and Related Security Considerations. *NIST Internal Report* 8404.

Moshenskyi, S. (2008). *History of the weksel: Bill of exchange and promissory note*. New York: Xlibris.

Mueller, R. C. (1997). *The Venetian money market: banks, panics, and the public debt, 1200-1500*. JHU Press.

Mundell, R. A. (1961). A theory of optimum currency areas. *The American economic review*, *51*(4), 657-665.

Nabilou, H. (2022). Probabilistic settlement finality in proof-of-work blockchains: Legal considerations. *Available at SSRN 4022676*.

Nangle, T. (2025) Are stablecoins money? *FT Alphaville*

Pages, H., & Humphrey, D. (2005). Settlement finality as a public good in large-value payment systems. *ECB Working Paper* No. 506.

Panetta, F. (2021). Central bank digital currencies: a monetary anchor for digital innovation. Speech by Fabio Panetta, Member of the Executive Board of the ECB, at the Elcano Royal Institute, Madrid, 5 November.

Pantelopoulos, G. (2025a). *Between payments and credit: an introduction to the IOU economy*. Springer Nature.

Pantelopoulos, G. (2025b). Bridging heterogeneities in retail means of payments. Available at SSRN: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5350276

Read, F. (1926). The Origin, Early History, and Later Development of Bills of Exchange and Certain Other Negotiable Instruments. *Canadian Business Review*, *4*, 440.

RBA. (2022). Review of banknote distribution arrangements: conclusions paper. August 2022.

Roberds, W., & Velde, F., R. (2014). Early public banks. *Federal Reserve Bank of Atlanta Working Paper Series* No. 1014-9.

Roberds, W., & Velde, F. R. (2016). The descent of central banks (1400–1815). In *Central Banks at a Crossroads: What Can We Learn from History*, 18-61.

Salmon, C. (2011). Balancing security and aesthetics: the evolution of modern banknote design. Speech at the British Numismatic Society. https://www.bankofengland.co.uk/-/media/boe/files/speech/2011/balancing-security-and-aesthetics-speech-by-chris-salmon.pdf

Schär, F. (2021). Decentralized finance: On blockchain-and smart contract-based financial markets. *Federal Reserve Bank of St. Louis Review*.

Sumner, W. G., Eds. (1896). *A History of Banking in All the Leading Nations: The United States, by WG Sumner* (Vol. 1). The Journal of Commerce and Commercial Bulletin, New York.

Ugolini, S. (2017). *The evolution of central banking: theory and history*. London: Palgrave Macmillan.

Usher, A. P. (1914). The origin of the bill of exchange. *Journal of Political Economy*, *22*(6), 566-576.

Usher, A. P. (1943). *The early history of deposit banking in Mediterranean Europe*. Harvard University Press.

Yaga, D., Mell, P., Roby, N., & Scarfone, K. (2018). Blockchain technology overview. *NIST Internal Report* 8202.

Acknowledgements

We would like to thank Ulrich Bindseil and all the participants from the workshop on 12 May 2025, for helpful discussions and comments. We also would like to thank participants to an ECB seminar held in May 2025 for their helpful comments and questions. All remaining errors are ours. This research is independently conducted by the authors and not directly connected to the Eurosystem's digital euro project. It should not be interpreted as reflecting the ECB's position on the design of the digital euro.

Charles-Enguerrand Coste
European Central Bank, Frankfurt am Main, Germany; email: charlesenguerrand.coste@ecb.europa.eu

George Pantelopoulos
University of Newcastle, Newcastle, Australia; email: george.pantelopoulos@newcastle.edu.au

Postal address 60640 Frankfurt am Main, Germany
Telephone +49 69 1344 0
Website www.ecb.europa.eu

PDF ISBN 978-92-899-7436-3 ISSN 1725-2806 doi:10.2866/6693699 QB-01-25-209-EN-N