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Let's speak the same language: a formally defined model to describe and compare payment system architectures*

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Abstract

Proposals for new payment system architectures abound. To understand their opportunities and challenges, it is paramount to be able to describe and compare them in a consistent and standardised manner. This paper therefore proposes a formally defined model to represent three key functions of payment system architectures: issuance/withdrawal, holding and transfer of funds. The model defines payment diagrams, using a precisely defined syntax. We illustrate the application of these diagrams for domestic and cross-border account transfers, as well as cash, card, e-money and stablecoin payments. However, the payment diagrams can be used for any type of funds and can be applied across different payment system architectures. We also demonstrate how the diagrams correspond to the balance sheet approach commonly used in economics, and that it offers added value by providing an end-to-end visualisation of every stage of the payment journey. Our model provides a tool for central banks, regulators and the payment industry to better understand and compare existing and new payment system architectures.

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1. Introduction

Technological innovations can transform the way people pay. Today, consumers and businesses mostly use cash or commercial bank money when paying for goods or services. However, digital innovation is widening the range of funds that can be transferred, such as e-money, stablecoins, tokenised bank deposits and innovative forms of central bank money. New technologies have also given rise to new ways to transfer these funds between end users, such as new initiation methods, like mobile apps or contactless cards, and new types of systems, such as fast payment systems. Safe and efficient national and international payment systems are crucial components of a jurisdiction's financial system, as they promote economic growth and development and support financial stability. Therefore, the evolution and design of existing and new payment system architectures have received increasing attention among central banks, governments and other public entities, in their roles as payment system operators, overseers/regulators and catalysts of change (eg BIS (2020), BIS (2023), BIS-CPMI (2024)).

The aim of this paper is to develop a formally defined model to describe and compare the key elements of payment system architectures, using payment diagrams. In this paper, a payment system architecture refers to the key actors, functions, funds and interoperability links underlying a transfer between a payer and payee.[1] There is a rich literature examining the functioning, opportunities and risks of innovations in payments. This literature often describes these innovations using a model consisting of one or more diagrams that are typically developed and tailored for the analyses considered in those papers. While these ad-hoc diagrams serve the purposes of these publications, they impede a consistent comparison across them.[2] Therefore, our paper complements the existing literature with a consistent and formally defined model, which has – to the best of our knowledge – not been used in this field. The model can be used to describe and compare key elements of payment system architectures in a standardised and consistent way. As any model, it is a simplified representation of reality to serve as a useful basis for analysis. We do not put forth a proposal for a new architecture or make recommendations for how one should be designed. Rather we develop a tool to help central banks, regulators and the payments industry in their understanding, assessment and comparison of architectures and in their exploration and design of new ones.

Our proposed payment diagrams are based on a formal language grounded in a precisely defined syntax. A common practice in computer science to model networks is the use of graph languages – languages based on diagrams such as the Petri nets for workflow modelling (Van der Aalst and Van Hee (2000)). Such languages

1 Our interpretation of a payment system architecture includes the interaction between end users and their payment service providers. Therefore, it is wider than a payment system as defined in CPMI-IOSCO (2012) as "a set of instruments, procedures, and rules for the transfer of funds between or among participants; the system includes the participants and the entity operating the arrangement". It is also broader than that of an arrangement such as used in CPMI-IOSCO (2022) as it may comprise different types of funds, payment service providers and interoperability links.

2 Examples of papers that use payment diagrams include Adrian and Mancini-Griffoli (2023), Boar et al (2021), CPMI (2022) and BIS (2023). Moreover, earlier relevant literature includes CPSS (2000) and CPMI-IOSCO (2012), especially Annex D on designs of payment systems.

are particularly suited for modelling complex systems and processes with interaction between multiple entities.

A common practice in economics is to model and visualise payments as updates of the balance sheets of the payer, payee and intermediaries involved (see eg Bindseil and Pantelopoulos (2023)). As we will demonstrate, our payment diagrams are consistent with the balance sheet approach and complement it by providing an end-to-end visualisation of every stage of the payment journey. The balance sheet approach shows changes in recordings of assets and liabilities for each actor in the payment chain. Our payment diagrams add to this by allowing the reader, at a glance, to understand the entire trajectory of a payment, regardless of the type or number of balance sheet updates.

A key challenge in depicting payments in a consistent fashion is achieving comparability across architectures that may differ from each other on many aspects.[3] We address this challenge by disentangling and focusing on three key functions of payment system architectures: issuance/withdrawal, holding[4] and transfer of funds.[5] The inclusion of these three functions reflects that a payment, or transfer of funds, can only take place after the funds have been issued, and the payer and payee are able to hold the funds. We use the term funds throughout the paper, instead of the term money or settlement asset, since a funds transfer is the term used for payments by the BIS Committee on Payments and Market Infrastructures (CPMI).[6] Moreover, not all types of funds considered in this paper may necessarily fulfil all functions of money, as a unit of account, store of value and medium of exchange.

Each payment system architecture consists of either one closed system or multiple interoperable closed systems. We show that interoperability can take three forms: through correspondents, intermediaries or a two-tiered system. The payment diagrams can be used for any type of funds and can be applied across different architectures.

This paper is structured as follows. Section 2 introduces our formal model as reflected in its payment diagrams. Section 3 applies the diagrams to the three key functions, ie issuance/withdrawal, holding and transfer of funds, within a closed system. Section 4 uses the payment diagrams to model three forms of interoperability: through correspondent banks, intermediaries and a two-tiered system. In Section 5, we use these building blocks (closed systems and interoperability) to provide further applications of the payment diagrams, such as the interoperability between payments in cash and bank deposits as well as card, e-money and stablecoin payments. Section 6 then expands the discussion further to visualise cross-border payments. Section 7 concludes.

3 For instance, payment system architectures may differ from each other in terms of funds (eg cash, commercial bank money, e-money, stablecoins), payment initiation method (eg card, online banking, mobile app) and technology used (eg ledger types, communication networks, messaging systems). See Toivonen (2020) for an overview.

4 Depending on the technology used, holdings may be recordings in ledgers or reflect physical possession of funds (as for cash).

5 Note that transfers can be processed (and described) as a series of changes to the holdings by various entities in a system. A transfer can also take place by physically handing over funds (as for cash).

6 The CPMI defines a payment, or funds transfer, as the "payer's transfer of a monetary claim on a party acceptable to the payee. Typically, claims take the form of cash or deposit balances held at a financial institution or central bank." (CPMI Glossary). In addition, we do not use the term settlement asset as it is usually interpreted to be used for settlement by a financial market infrastructure (FMI), and hence too narrow for the purpose of our paper.

2. Formal language to depict the payment system architectures

Appendix 1 presents the formally and precisely defined syntax that we propose to model payment system architectures.

In layman terms, the key elements are the following:

- **Three types of actors**: a payer, payee and one or multiple payment service providers (PSPs). A closed system has one issuing PSP that is responsible for the issuance of the funds used in that system.
- **Three functions**: issuance/withdrawal,[7] holding and the transfer of funds.[8]
  - Funds can be issued and/or withdrawn only through the issuing PSP. The total value of issued funds is recorded by this PSP in its so-called "funds in circulation" (FIC) account, which we represent by a coloured oval.[9]
  - Transparent ovals represent the holdings, recorded in accounts or by physical possession of the funds, of the payer and payee. These holdings always sum to the value of the issuing PSP's FIC account.
  - Fund transfers are displayed by a solid arrow, with the arrowhead pointing in the direction of the payee.
- **Closed systems**: each issuing PSP is responsible for the prevention of counterfeiting and controls the amount of funds that circulate between the actors. Funds cannot leave this closed system. The boundaries of this closed system are depicted by a transparent rectangle with rounded corners.
- **Funds:** we build on the definition of a payment as a transfer of funds, which does not specify the type and design features of the funds. This way, the payment diagrams can be used to model architectures based on different types of funds, eg cash, commercial bank money or e-money. Denomination in domestic or foreign units or other types of funds is indicated by different colours.[10]
- **Interoperability between closed systems:** a payment system architecture can consist of multiple closed systems, and all actors, including PSPs, may hold funds (usually in accounts) in different closed systems. The actor identity relationship across multiple closed systems is displayed by dashed lines between each pair of holdings of the same actor. In fact, this relationship

7 We assume that the issuer of funds provides the technological infrastructure for securing and transferring the funds. We therefore leave it to follow-up work to extend the model to cases in which the issuer and the operator of infrastructure are different entities. This includes the case of multi-asset ledgers as discussed in BIS-CPMI (2024).

8 To ensure that the model can be used for different types of funds, the validation of the transaction, which could be the responsibility of the payee in a cash transaction, or the bank of the payer and/or payee in an account transfer, is not specified as a separate function.

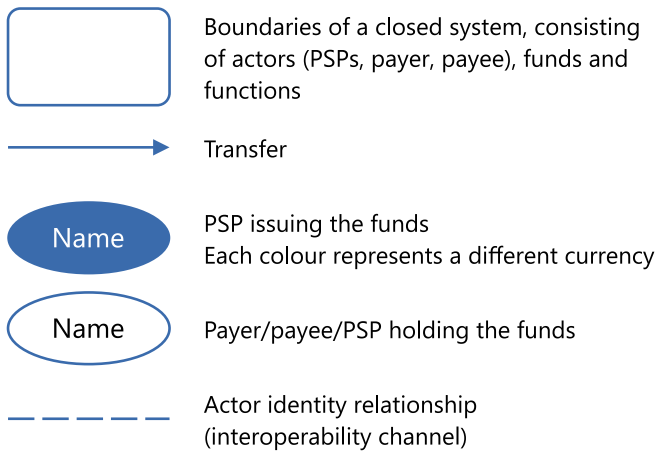
9 The type of assets that the issuing PSP holds against its funds in circulation is outside our model.

10 Note that in principle every closed system has its own funds, so that a different colour should apply. However, in practice, additional policies are in place to ensure the singleness of money within domestic two-tier banking systems (see CPSS, 2003). We therefore use the same colour for different closed systems that make up the two-tier banking system, assuming singleness of money.

visualises how interoperability is achieved between the closed systems – the interoperability channel.

These key elements translate into the graphical notations depicted in Graph 1.

Key elements of a payment diagram Graph 1



Note: Depending on the example, "Name" could be replaced by the name of the respective actor (eg a (central) bank) or the actual name of the payer (eg Alice) and payee (eg Bob).

Source: Authors' elaboration.

3. Modelling closed systems

In this section, we demonstrate how the payment diagrams can be applied to closed systems, ie architectures where a payer (Alice) and payee (Bob) hold the same type of funds with the same issuing PSP (in this case, a bank). We do so while focusing on the three key functions relevant to understanding how the architectures operate: issuance/withdrawal, holding and transfer of funds. In addition, we show how the diagrams correspond to the balance sheet updates approach commonly used. For that purpose, we have added letters to the diagrams that identify the size of the issuance (a), holdings (x and y) and transfer (b).[11]

Issuance/withdrawal

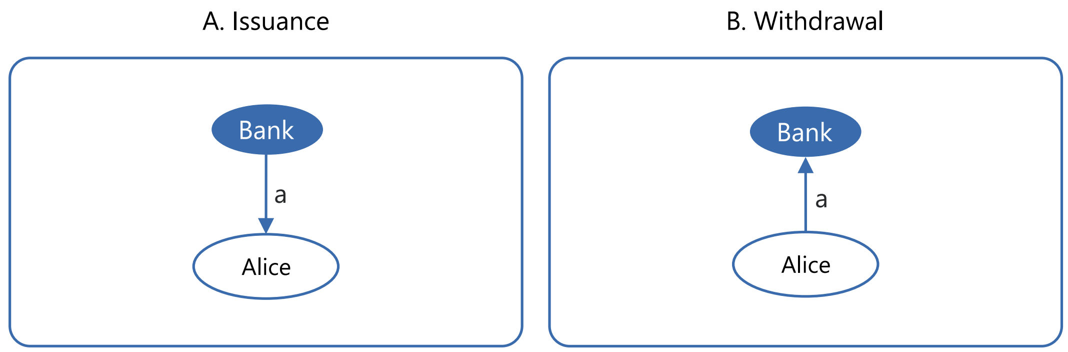
Graph 2.A illustrates the issuance of funds worth a by the issuing bank to Alice's account, eg in the form of a bank loan. This issuance results in a transfer of funds from the issuer to Alice (hence the arrow) and increases the total amount of funds in circulation.[12] The opposite would happen in the case of withdrawal, eg if Alice repays

[11] The payment diagrams in Section 4 will also show the letters, since the corresponding balance sheets are included in the Appendix. In Section 5, we no longer show the corresponding balance sheets. We therefore also leave out the letters in the payment diagrams.

[12] See eg Stellinga et al (2021) for an in-depth analysis of the role of money creation.

her loan to the bank (Graph 2.B). In this case, total funds in circulation would shrink again.

Payment diagrams for issuance and withdrawal Graph 2



Source: Authors' elaboration.

The payment diagrams in Graph 2 allow the reader to see at a glance who the key actors are and how the funds are transferred between them. Also, the underlying reason for the issuance/withdrawal has no influence on the diagrams. This means that the diagrams can be used to depict the payment leg of different sets of balance sheet updates, an example of which is shown in Table 1.[13] Put differently, our payment diagrams are consistent with the balance sheet approach and complement it by focusing on different aspects. Balance sheets use double bookkeeping and show changes in recordings of assets and liabilities for each actor in the payment chain. A key benefit of the payment diagrams is their simplicity and ability to provide an overview of the end-to-end payment.

[13] For a detailed discussion of balance sheet updates, see Bindseil and Pantelopoulos (2023). Since our focus is on the issuance/withdrawal, Table 1 is a simplified notation of the balance sheets and include only the minimum amount of information necessary to highlight the key balance sheet updates of the actors involved. For example, we do not include any other typical balance sheet items, such as a breakdown of the bank's assets. In Table 1.A we assume that the bank provides a loan to Alice, so that her liabilities increase with the amount of the loan. In Table 1.B we assume that Alice pays back the loan.

Example of simplified balance sheet updates corresponding to the payment diagrams in Graph 2 — Table 1

A. Issuance

Bank	
Total assets: **+a**	Account Alice: **+a**
Alice	
Bank account: **+a**	Total liabilities: **+a**

B. Withdrawal

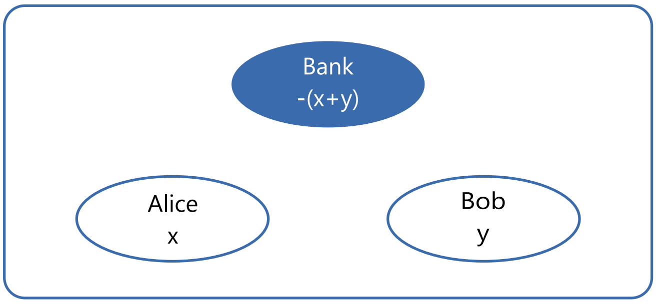
Bank	
Total assets: **-a**	Account Alice: **-a**
Alice	
Bank account: **-a**	Total liabilities: **-a**

Source: Authors' elaboration.

Holding funds

Graph 3 shows the payment diagram for Alice's and Bob's holdings of the funds issued by their bank. Alice's total account holdings are x and Bob's balance equals y. With no other actors in this closed system, the total balance of the bank's FIC account equals $-(x + y)$; hence, it is always negative. This implies that the total of all holdings and issued funds in a closed system is always zero. Table 2 shows an example of a set of simplified balance sheets that correspond to the diagram in Graph 3. In this example, Alice and Bob finance their accounts with a loan from the bank.

Payment diagram for holdings — Graph 3



Source: Authors' elaboration.

Example of simplified balance sheets corresponding to the payment diagram in Graph 3

Table 2

Bank	
Total assets: **x+y**	Account Alice: **x** Account Bob: **y**
Alice	
Bank account: **x**	Total liabilities: **x**
Bob	
Bank account: **y**	Total liabilities: **y**

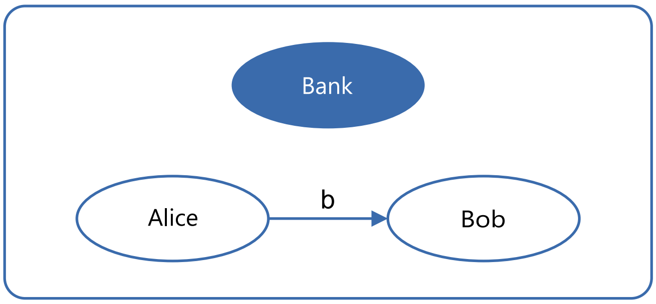
Source: Authors' elaboration.

Funds transfer

In a closed system where both Alice and Bob have an account with the issuing bank, a payment (or funds transfer) of *b* from Alice to Bob can be depicted with a payment diagram as in Graph 4. Unlike the issuance of funds by and withdrawal to the bank, payments between Alice and Bob would not impact the total amount in circulation.

Payment diagram for a funds transfer

Graph 4



Source: Authors' elaboration.

The payment diagrams can be applied irrespective of the reason for the payment, eg whether it is to purchase goods, make a payment for services or a donation, while balance sheet updates may vary with the specific underlying reasons. Table 3 shows an example of a set of balance sheet updates that could correspond to the payment diagram in Graph 4. In this example, the balance sheet updates reflect a payment of a donation to Bob, which could for example be a remittance.

Example of simplified balance sheet updates for the transfer of funds depicted in Graph 4

Table 3

Bank	
Total assets:	Account Alice: **-b** Account Bob: **+b**
Alice	
Bank account: **-b**	Net worth: **-b**
Bob	
Bank account: **+b**	Net worth: **+b**

Source: Authors' elaboration.

4. Modelling of interoperability between closed systems

In this section, we show how the payment diagrams can be used to depict payment system architectures consisting of two interoperable closed systems. We distinguish between three forms of interoperability:

1. **Correspondent banking:** the issuing PSP in one closed system holds an account with a correspondent bank in another closed system.
2. **Intermediaries:** a non-issuing PSP holds an account with an issuing PSP in both closed systems.
3. **Two-tier banking system:** the issuing PSPs of each closed system hold an account in another, third, closed system.

In this section, we start with interoperability between closed systems within one jurisdiction. While each closed system still has its own funds, we assume that they all use the same currency.[14] We will discuss cross-border interoperability in Section 6.

Correspondent banking

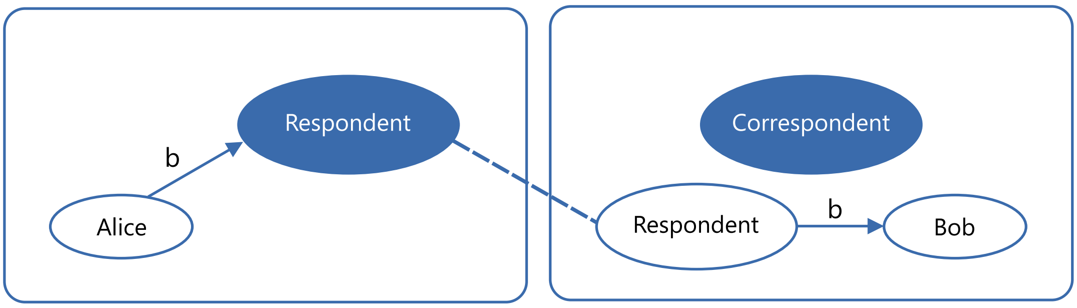
Historically, the first banks that offered payment accounts and payment services emerged around local marketplaces (Kohn (1999)). Payers and payees used the same bank, and their transactions were settled "on-us" (ie internally on the books of that bank), so within the closed system of the bank, as illustrated in Graph 4. However, with the increase in trade, the demand rose for transactions between customers of different banks, both within and across countries. This resulted in the emergence of

[14] In principle, each closed system uses its own funds, so that the colours should differ. In practice, however, the singleness of money usually applies within jurisdictions, which ensures a one-on-one exchange rate (CPSS, 2003). We therefore use this assumption in this section and relax it later on in the paper, eg when we discuss cross-border interoperability.

so-called correspondent banks, ie banks providing accounts to other (domestic or foreign) banks.[15, 16]

Graph 5 illustrates a payment involving two separate closed systems, each demarcated by a rectangle boundary. The funds in each system are blue to illustrate that these systems are using the same currency. This payment could represent the purchase of goods by Alice from Bob. While Alice does not have an account with Bob's bank, her bank does. Alice's bank acts as a respondent bank by holding a "nostro" account at Bob's bank which acts as the correspondent bank and which considers this account as a "vostro" account. This is depicted by the dashed line between the two closed systems.[17]

Payment diagram for a payment using correspondent banking — Graph 5



Source: Authors' elaboration.

Appendix 2.A demonstrates how this payment corresponds to a possible underlying set of balance sheet updates of the various actors involved.

The same structure can be used to model a payment from Bob to Alice; the arrows would just be reversed in that case.

Interoperability through an intermediary

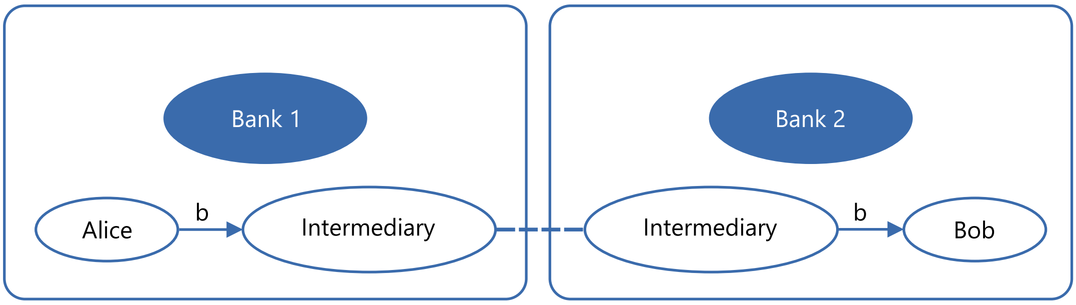
An alternative way in which Alice can make a payment to Bob while they each have an account with a different bank is through an intermediary PSP (Graph 6). This intermediary PSP would hold an account in each closed system so would have access to both types of funds. Importantly, this PSP would not be an issuing PSP, but a customer of two other issuing PSPs. In this model, the intermediary receives a transfer from Alice and pays it to Bob. Just as in the correspondent banking model, the sum of all account updates across the entire architecture is zero. See Appendix 2.B for an example of a corresponding set of balance sheet updates.

15 At the most basic level, correspondent banking requires the opening of accounts by respondent banks with a correspondent bank and the exchange of messages to settle transactions by crediting and debiting those accounts (CPMI, 2016).

16 Historically, initially another model was to use gold to settle obligations between banks.

17 To keep Graph 5 simple, we assume that Bob holds an account directly at the correspondent bank. If this was not the case, another diagram would have been added in the middle, as Bob's bank would also act as a respondent and also hold an account at the correspondent bank.

Payment diagram for a payment using an intermediary PSP Graph 6



Source: Authors' elaboration.

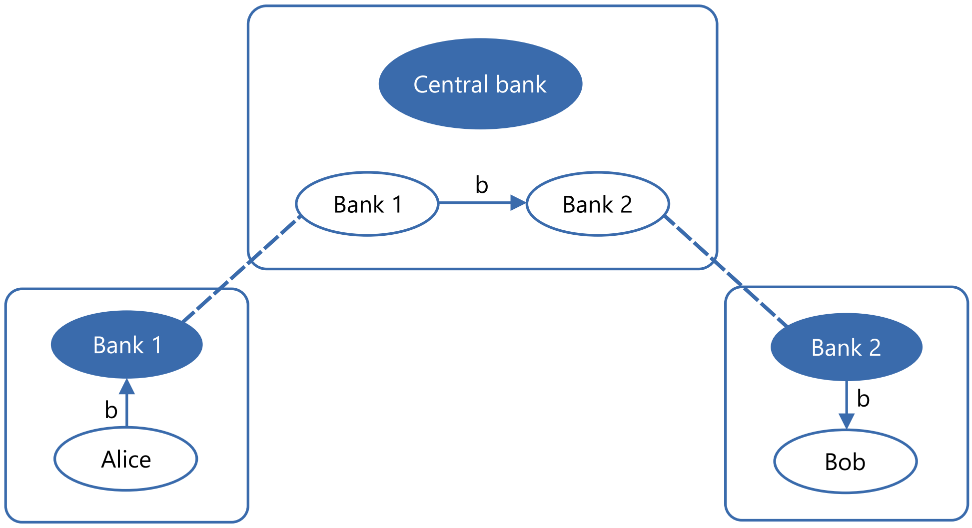
Two-tier banking

Interoperability through correspondent banking, as discussed above, is relatively easy to achieve with two closed systems. However, the complexity grows quadratically with the number of closed systems: for N issuing PSPs, there are $\frac{1}{2}N(N-1)$ connections. Therefore, it is easier if all issuing PSPs have an account at a single PSP that settles the payments between them. Moreover, such institution could provide liquidity to the PSPs at the lower level, if needed. This model reflects today's two-tier banking system in which banks hold accounts at a central bank (Graph 7).[18]

In the example in Graph 7, the transfer between Bank 1 and Bank 2 takes place in the funds issued by the central bank, ie central bank money, while Alice pays and Bob is paid in the funds used in their closed system, ie commercial bank money. In this example, different issuers (ie Bank 1, Bank 2 and the central bank) all issue the same currency denomination. This example illustrates that the settlement of transactions between commercial banks in central bank money ensures that monetary exchange is not subject to fluctuating exchange rates between different forms of privately issued money. This is known as the "singleness of money", which is seen as a crucial factor for a currency to effectively become the primary measure of economic value, or the unit of account, within a modern economy (CPSS (2003); BIS (2023)). See Appendix 2.C for an example of a corresponding set of balance sheet updates.

[18] Gorton (1984) describes how the two-tier banking system evolved in the United States. By 1850, the banks in New York practised a system whereby deposit transfers between entrepreneurs were initiated through cheques, since this was easier than payments in cash. Banks cleared the net obligations in gold. Each dollar stood for a claim on a certain quantity of gold. Therefore, the interbank account transfers were settled through a transfer in gold. The banks could reduce the number of gold transports by settling just once a day, instead of per transaction. But even that became cumbersome, and the banks created a clearing house where they kept a gold account. Instead of transporting the gold once a day, they now changed the account balance at the clearing house. When the Federal Reserve System was established in 1914, it integrated the clearing house structure (Gorton (1984)). Nowadays, we call this structure the two-tier banking system.

Payment diagram for a payment using a second tier | Graph 7



Source: Authors' elaboration.

5. Further illustrations: cash, cards, e-money and stablecoins

The basic building blocks from Sections 3 and 4 can be combined to depict an infinite number of payment system architectures. In this section, we show how the payment diagrams can be used to illustrate the payment system architectures of cash, card, e-money and stablecoin payments. As will become apparent, the architecture of card payments relies on the two-tier banking model discussed in Section 4, whereas e-money and stablecoin payments involve closed systems and can therefore be depicted as in Graph 4 in Section 3. The use of cash can be illustrated with a set of diagrams that combine elements from both Sections 3 and 4.

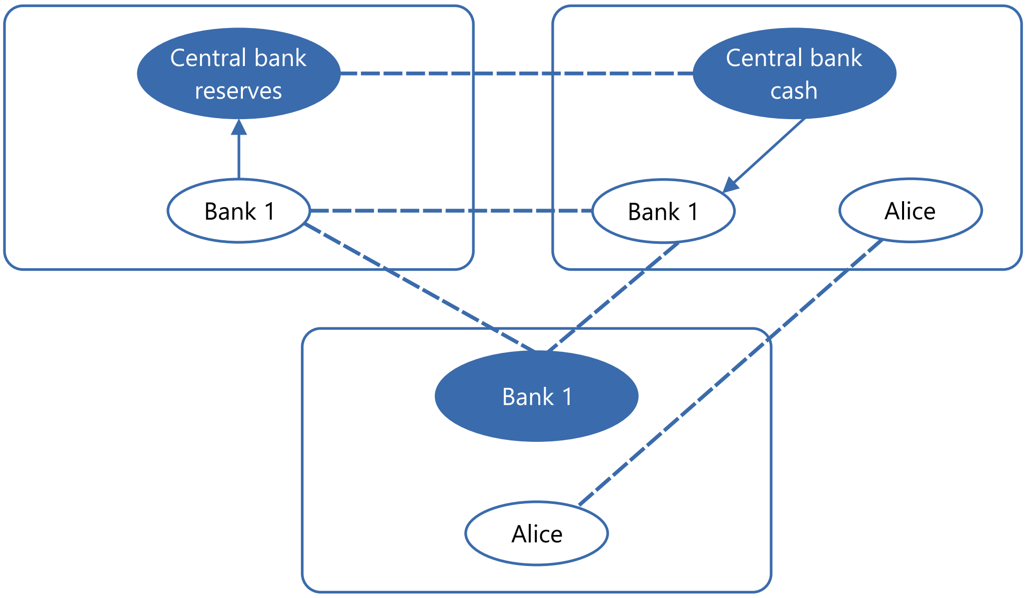
Cash issuance, withdrawals and payments

Graph 8 and Graph 9 show the payment diagrams for the issuance to and withdrawal of cash by Alice, respectively. Both activities require interoperability between central bank reserves and commercial bank deposits, as shown by the dashed blue lines. Graph 8 shows how commercial banks obtain cash from the central bank, paying for this from their reserve accounts at the central bank. Graph 9 shows how, subsequently, Alice withdraws cash from her bank, paying for this from her commercial bank account.

Once Alice has withdrawn the cash, she can use it to pay Bob. The payment diagram of this transfer would exactly be the same as the one in Graph 4 in Section 3, ie closed system, with the payer and payee as the holders of funds and the central bank as the issuing PSP.

Payment diagram for issuance of cash and withdrawal of reserves

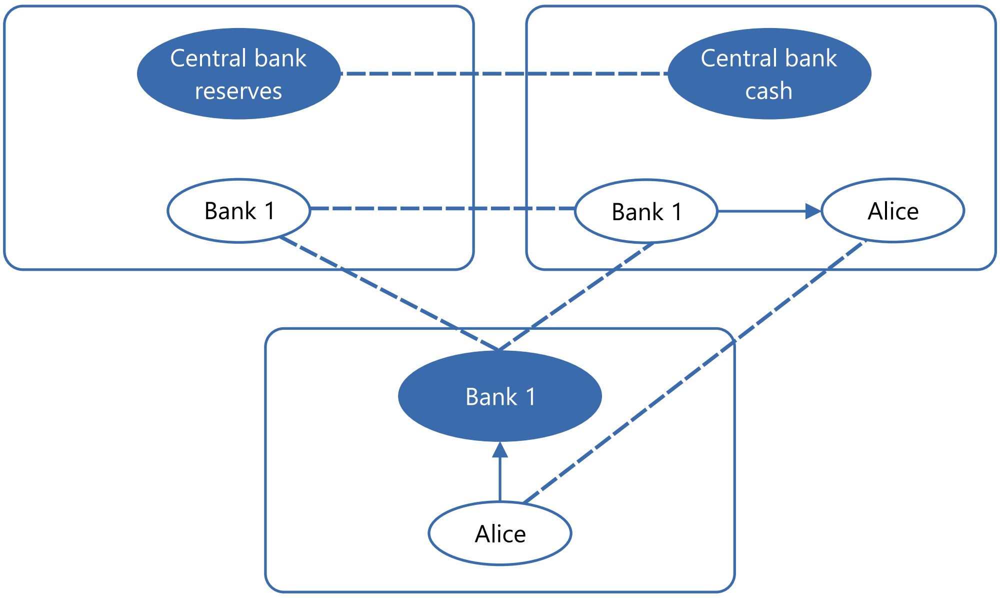
Graph 8



Source: Authors' elaboration.

Payment diagram for cash withdrawals

Graph 9



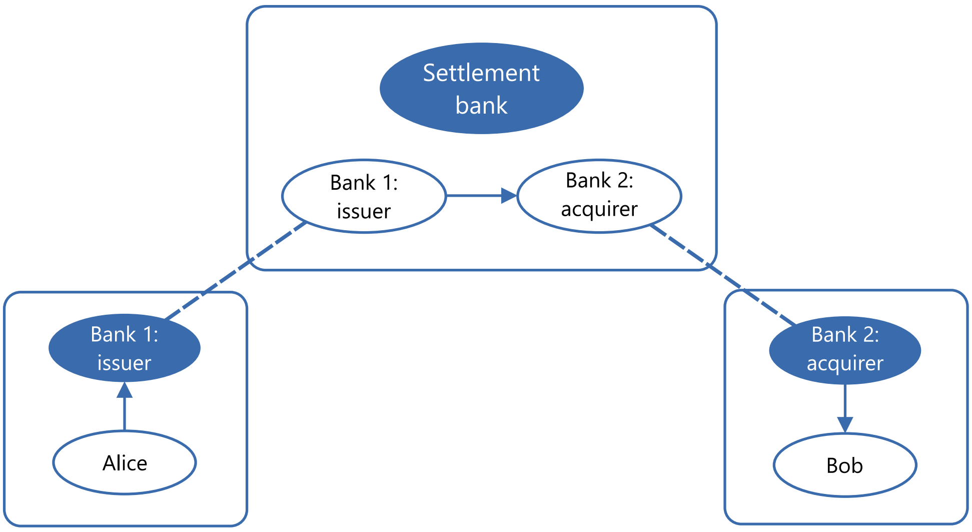
Source: Authors' elaboration.

Card payments

A key feature of card payments is the involvement of a card network (or card scheme) that facilitates the transfer of funds (and information) between the actors by setting the rules for card transactions and providing the infrastructure for processing them. Examples of card networks include Visa, Mastercard, American Express and Discover.[19] Other key players are the card-issuing PSPs (often banks), acquirer PSPs (often banks), card holders (payers), card terminal holders (payees) and a settlement bank, which can be either a commercial or central bank that settles the final outstanding obligations between issuing and acquiring PSPs.

The payment system architecture of card payments (see Graph 10) mimics the two-tier banking system discussed in the previous section. At a high level, a card payment makes the following journey: Alice initiates a payment by presenting her payment card to Bob, who is a merchant in this case. Bob then uses his card terminal to contact his acquiring bank (Bank 2).[20] The acquiring bank uses the "card rails" provided by the card network to check with the issuing bank (Bank 1) whether Alice has enough funds or credit.[21] If so, Bob receives an instant confirmation from the card network through his card terminal. Subsequently, the card network calculates net obligations and informs the issuing and acquiring bank as well as the settlement bank.

Payment diagram for card payments — Graph 10



Source: Authors' elaboration.

[19] The first card scheme, which was the Diners Club credit card scheme, emerged in 1949. It acted as a middleman between the payers (the diners) and the payees (the restaurants) by granting the former credit and providing the latter with customers (Maurer (2009)). The subsequent rise in the use of card schemes has been phenomenal: card schemes now connect roughly 25,000 issuing and acquiring banks around the world, and card payments account for roughly two thirds of all spending in stores (Leibbrandt and De Teran (2021)).

[20] Note that the issuing and acquirer bank can be and are sometimes the same.

[21] In case of a debit card payment, Alice's account balance at Bank 1 has to be sufficient, while with a credit card, Bank 1 will provide her with a credit if she has not yet reached her credit limit.

In turn, the transfer of funds from Alice to Bob is processed in the same way as an account transfer in a two-tier banking system: from Alice to Bank 1, from Bank 1 to Bank 2 (who both have an account at the settlement bank), and from Bank 2 to Bob.[22]

E-money and stablecoin payments

Card payments, as discussed above, build on a two-tier banking system, where the payer and payee hold an account in a different closed system (ie at different PSPs). The case of e-money payments is different. E-money is broadly defined as an electronic store of monetary value on a technical device that may be widely used for making payments to entities other than the e-money issuer.

E-money payments involve a closed system where payers and payees hold the funds that are issued/redeemed by the e-money issuer. This issuance/withdrawal is based on the payer and payee funding/defunding their e-money wallets using fiat money, ie funds from outside the closed system, such as cash on hand or from a bank account. In that sense, the payment system architectures of e-money payments can be depicted as a closed system, as discussed in Section 3, with the extension of a link to the two-tier banking system discussed in Section 4.

Graph 11 illustrates the issuance of e-money to Alice and Bob. Our underlying assumption in this example is that the central bank does not guarantee a one-on-one conversion and that the e-money issuer does not have access to the central bank. Therefore, the singleness of money principle does not necessarily apply in this example. To reflect this, we use a different colour (ie green) for the funds.[23]

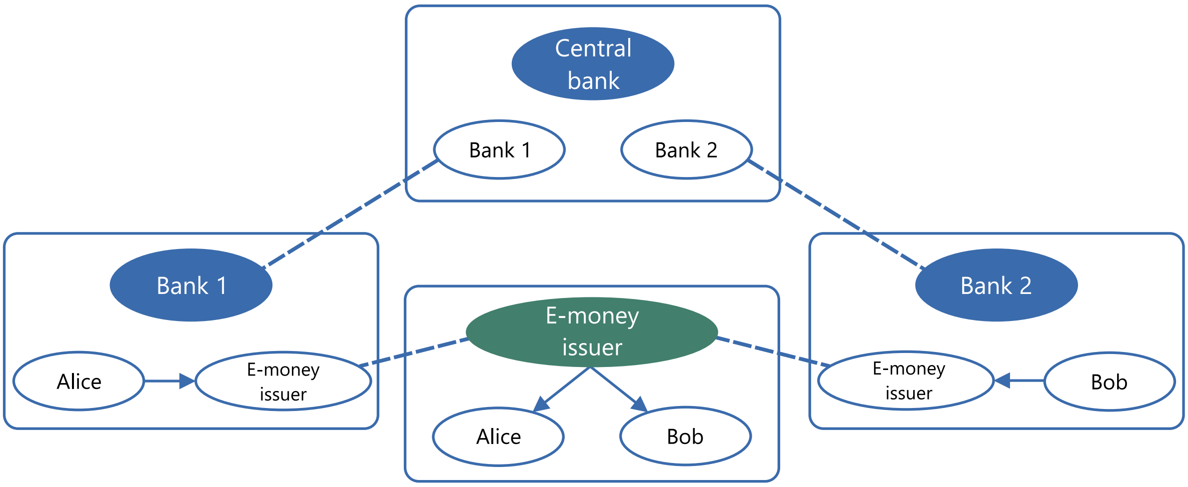
In this example, Alice (Bob) uses her (his) bank account with blue funds at Bank 1 (Bank 2) to fund her (his) e-money account held at the e-money issuer, who holds an account at both banks. In return, Alice and Bob obtain the green funds (ie e-money).[24] Subsequently, Alice and Bob can use their e-money balances to pay each other through a transfer within the closed system (Graph 12 illustrates a transfer from Alice to Bob).

22 Note that the architecture of Graph 10 can be extended in several directions, eg with multiple currencies to represent a cross-border card payment.

23 In practice, this assumption may or may not hold, depending on the presence or absence of policies that guarantee singleness of money. Moreover, the asset backing the e-money – and thereby the stability of its value versus the blue funds – could differ, depending on applicable regulations and the quality of the backing asset. Our simple modelling approach is abstract and does not necessarily apply to existing issuers of e-money in this regard.

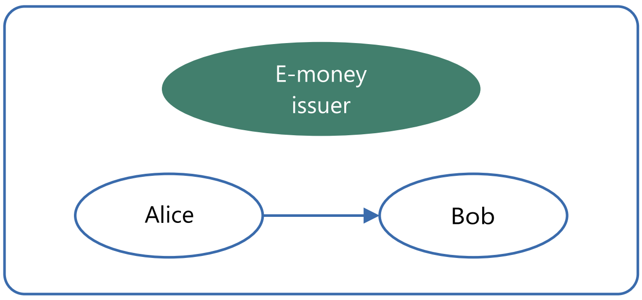
24 The funding/defunding is supposed to happen at a 1:1 exchange rate; however, we use different colours for each type of funds since this exchange rate may not be fully guaranteed.

Payment diagram for the issuance of e-money | Graph 11



Source: Authors' elaboration.

Payment diagram for a transfer of e-money | Graph 12



Source: Authors' elaboration.

Stablecoins have been introduced with the promise to facilitate payments within and across networks based on distributed ledger technology. As unbacked cryptoassets can be too volatile to act as a credible means of payment, stablecoins are a subcategory of cryptoassets that aim (or claim) to maintain a stable value relative to a specified peg (see eg Kosse et al (2023)). Payment diagrams similar to Graph 11 can be used to illustrate stablecoin issuance, holding and transfer. The specifics of the payment diagrams for stablecoins depend on the specifics of the stablecoin, including whether the issuer can hold an account at the central bank, which is currently rare. Moreover, to judge the quality of the asset backing, complementary balance sheet information would be needed, and it would be relevant to know whether the issuer is regulated or not.

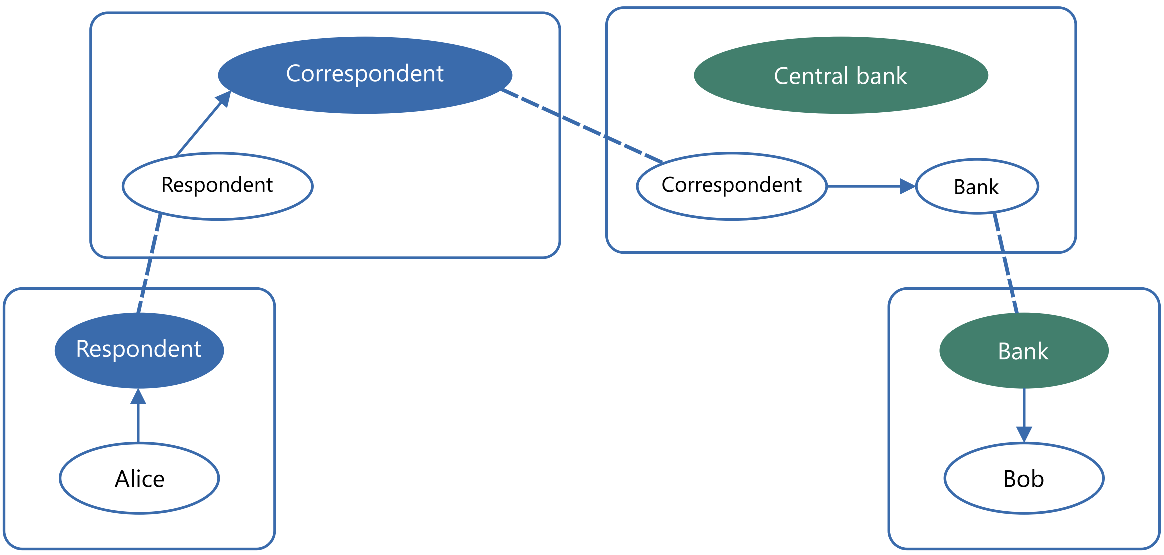
6. Further illustrations: cross-border payments

In this section, we apply the three forms of interoperability discussed in Section 4 to cross-border payments. We refer to the blue funds as the home currency, and the green funds as the foreign currency.

Cross-border interoperability through correspondent banking

Graph 13 shows the payment diagram for a cross-border payment from Alice to Bob when Alice's bank (the respondent bank) holds an account with a correspondent bank that participates in the banking systems of both jurisdictions, indicated by the "blue" and "green" funds. This cross-border correspondent banking model allows any of the customers of the correspondent bank to reach all banks (and their account holders) in the "green" payment system.[25] The correspondent bank provides the exchange rate conversion, since it participates in both systems.

Payment diagram for a cross-border payment using correspondent banking Graph 13



Source: Authors' elaboration.

Cross-border interoperability through an intermediary

Another option to connect Alice and Bob across borders is through an intermediary (usually a bank)[26] that participates directly in the two-tier systems in both jurisdictions. In this model, all banks and their account holders participating in the

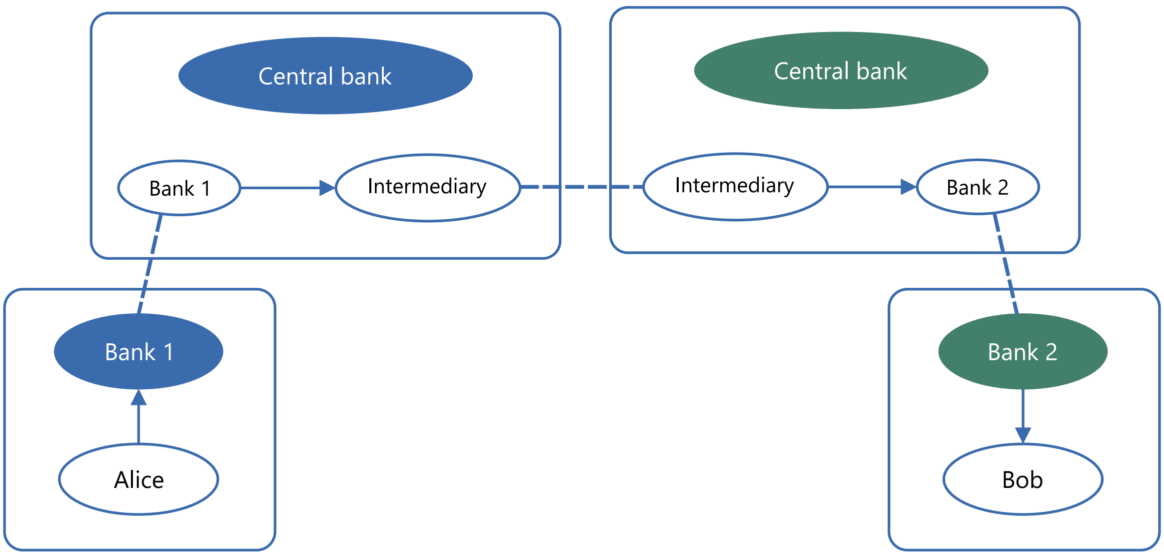
[25] CPMI (2022) therefore uses the terminology of interlinking entire payment systems.

[26] To perform this role, the intermediary would need to be allowed to hold an account at both central banks. The most common case is that therefore this intermediary is a bank. It is not the only option, however, since central bank access policies differ across jurisdictions and in some jurisdictions non-bank intermediaries are also allowed access to a central bank account.

"blue" two-tier system could transact with the intermediary, which in turn would be able to reach all banks and their account holders in the "green" system.[27] The intermediary provides the exchange rate conversion in this model.

Payment diagram for a cross-border payment using an intermediary

Graph 14



Source: Authors' elaboration.

Cross-border interoperability through an additional type of funds

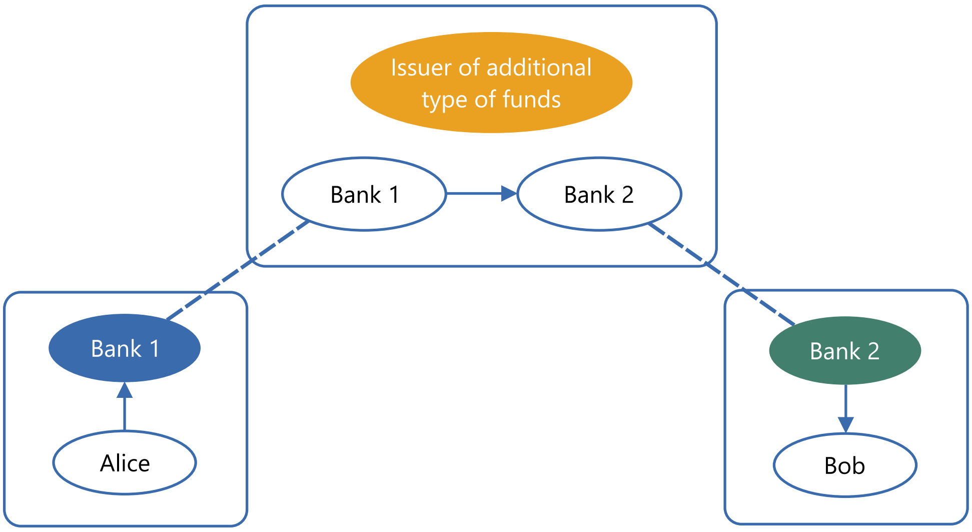
In line with our discussion in Section 4, achieving cross-border interoperability through correspondents or intermediaries is (relatively) simple when it involves two jurisdictions. However, the complexity of creating and maintaining a web of bilateral links grows with the number of jurisdictions involved. The addition of another type of funds could then be considered, within its own closed system (Graph 15).[28] At the time of writing this paper, card schemes had started to explore this type of architecture by using on-chain settlement using stablecoins as the additional funds.[29]

[27] This model has also been referred to as the single-access-point model (CPMI (2022)).

[28] This form of interoperability has also been referred to by some as a "common hub" in a hub-and-spoke model (eg CPMI (2022)).

[29] See Visa Expands Stablecoin Settlement Capabilities to Merchant Acquirers | Visa, and Mastercard Incorporated - Mastercard Transforms Cross-Border Payments for Banks With Industry-First Innovation. Both websites were accessed on 15 November 2024.

Payment diagram for a cross-border payment using an additional type of funds Graph 15



Source: Authors' elaboration.

7. Conclusion

In this paper, we developed a formally defined model to describe and compare the key elements of payment system architectures in a standardised and consistent way. The architectures include key actors, functions, funds, closed systems and interoperability links underlying a transfer between payer and payee. The model defines payment diagrams, using a precisely defined syntax. We demonstrate how the diagrams can be used to depict three forms of interoperability between closed systems, ie through correspondent banks, intermediaries and a tiered system. The model focuses on three key functions that are core to any type of payment system architecture: issuance/withdrawal, holding and transfer of funds.

Our illustrations show that these building blocks can be applied to a wide variety of payments, ranging from cash payments and commercial bank transfers between clients of the same bank, to card, e-money and stablecoin transfers, and for cross-border payments. A key advantage of the payment diagrams compared with the balance sheet approach commonly used is that they provide a simple end-to-end visualisation of every stage of the payment journey.

Our model provides a tool for central banks, regulators and the payment industry to better understand and compare existing and new payment system architectures. With the increase in the number of experiments, implementations and proposals, having a consistent modelling approach is crucial to assess their potential implications.

We acknowledge that, as with any model, our model is an abstraction from reality. It is intended as a starting point for systematically describing and comparing payment system architectures. As payment system architectures may also differ in other ways, there are opportunities for future extensions. For example, the payment messages and information flows that accompany payments could be added to the model. Future extensions may also include fee structures underlying a payment, which would allow for an examination of the competitive implications of different payment infrastructures. Further, the model could be enhanced by adding the goods, services and assets that are traded in exchange for the payments modelled in this paper. This could help study frictions related to differences in the timing of the payment and the delivery of the goods, services and assets, and examine the implications of instant confirmations and delivery-versus-payment solutions. Finally, the model could be enriched to reflect differences in operational involvement of the issuer and issuance/withdrawal of multiple assets on a single platform. Such an extension could include tokenised assets and allow for a separation between the issuer and operator functions, as discussed in BIS-CPMI (2024).

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Appendix 1: Formal language to depict payment system architectures using payment diagrams

Formal language

A *payment diagram* is a 7-tuple (C, A, FIC, col, E, D, T) where:

- C is the set of all closed systems.
- A the set of all accounts.
- FIC (funds in circulation) is a mapping from C to A. Each closed system has its own *payment service provider* (PSP) that is responsible for the issuance of the funds in that system. This PSP also has an account, ie the *funds in circulation account,* the balance of which reflects the total value of funds issued. FIC(c) is the issuing PSP of the closed system c.
- col is a mapping that assigns a colour to a closed system. Each closed system has a its own *colour.* All closed systems have, by definition, their own own funds. However, they may be part of a monetary system that guarantees parity between the different types of funds. In that case, the funds have the same colour.
- E is a mapping that assigns a closed system to each holding and is called its *embedding*. Each holding belongs to one closed system. In this way, the closed system of account a is indicated by E(a), with $E(a) \in C$.
- D describes the *actor identity relationship*. One actor may have multiple holdings and hold funds in different closed systems. Thus, $D \subset A \times A$ is the set of pairs of holdings that are owned by the same actor, which has the folowing properties: for $x, y, z \in A$, $(x,x) \in D$, if $(x,y) \in D$ then also $(y,x) \in D$, and if $(x,y) \in D$ and $(y,z) \in D$ then $(x,z) \in D$.
- T is the set of *transactions* depicted in the payment diagram. A transaction is a series of *fund transfers*, modelled as edges $[(a_1,a_2), (a_2,a_3),......., (a_{n-1},a_n)]$ for all i a_{ij} is an element of A, with the following properties:

    a. Each transaction starts and ends with an transfer of funds within a closed system, ie $E(a_1) = E(a_2)$ and $E(a_{n-1}) = E(a_n)$; holding a_1 is the source (the *payer)* and holding a_n the sink (the *payee)*. The other elements in between are the intermediaries.

    b. Transactions can follow alternative paths, involving different holdings: eg a_1 and a_2 are in the same closed system, a_2 and a_3 have the same owner but are in different closed systems, a_3 and a_4 are in the same closed system, a_4 and a_5 have the same owner but are in different closed systems again. The edges (a_2,a_3) and (a_4,a_5) represent neutral balance adjustments for the same owner etc.

    c. Each transaction is *loop free*, ie for all $i, j \in \{1, 2,...,n\}$, if $i \neq j$ then $a_i \neq a_j$, so no two holdings have the same successor in the transaction.

    d. A transaction represents a payment from payer a_1 to payee a_n. Let q be the quantity that is transferred from a_1 to a_2. The edge (a_2,a_3) represents a neutral balance adjustment. The balance of a_2 is decreased with q, the balance of a_3 is increased with $e \cdot q$, with e being the exchange rate between the funds in E(a_2) and the funds in E(a_3) etc.

Each transaction satisfies the following conservation law: *the sum of all transfers of funds in a transaction is zero.* This is due to the fact that for each edge (funds transfer) inside a closed system, the amount of the transaction is subtracted from the source account and added to the destination account. Note that this is consistent with the rule that the holding of the issuing PSP is always negative and in absolute value equal to the sum of all other holdings in the closed system.

Although a transaction is a sequence of transfers and balance adjustments, the order may deviate from the chronological order of processing (ie when payments are settled on a deferred net basis).

The elements C, col, A, E, FIC and D are the *static* parts of the architecture; the transactions T are the *dynamic* parts. The lifecycle of a transaction is very short compared with the lifecycle of an account or a closed system.

Visualisation

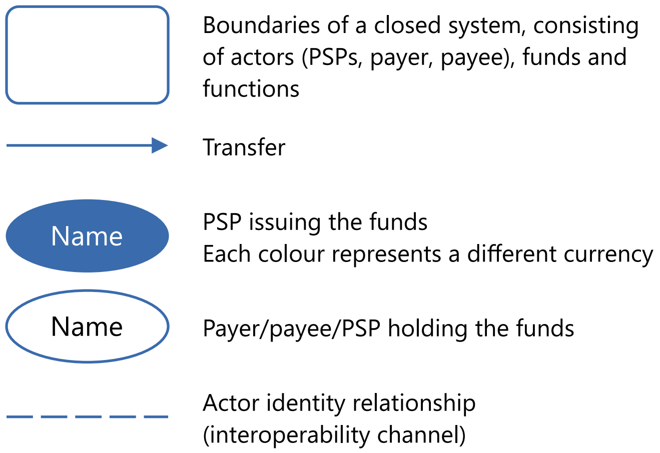
The payment diagrams are depicted as follows (see Graph A1.1):

- The elements of C are rectangles with rounded corners.
- The elements of A, ie the accounts (or holdings), are ovals with the name of the owner.
- The FIC accounts of the PSPs are coloured ovals. Different colours refer to funds in different currencies.
- The embedding function E is displayed by the fact that the oval is (graphically) contained in the rectangle of C.
- The actor identity relationship across multiple closed systems is displayed by *dashed* lines between each pair of accounts held by the same owner.
- A funds transfer is displayed by a *solid* arrow, with the arrowhead pointing in the direction of the payee, ie the solid edges point from a_i to a_{i+1}.
- In a *correct* transaction, the arrows of the solid edges always point from a_i to a_{i+1} and never in opposite direction.

Note that a payment system architecture consisting of one or multiple closed systems can have multiple transactions at the same time.

Key elements of a payment diagram

Graph A1.1



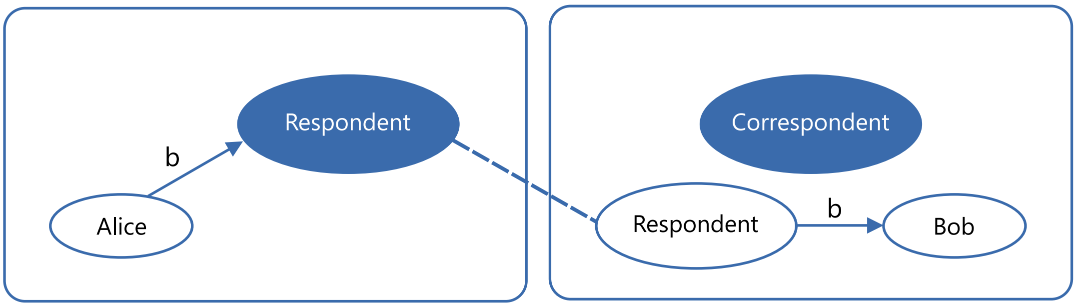
Source: Authors' elaboration.

Appendix 2: Relationship between payment diagram and balance sheet updates

A. A payment using correspondent banking

Payment diagram

Graph A2.1



In our diagram language, this reads as: Alice's account: -b, issuing PSP respondent: +b, nostro account of respondent at correspondent: -b, Bob's account at correspondent: +b. So, the sum of all transfers equals 0.

Source: Authors' elaboration.

Example of simplified balance sheet updates that could correspond to the payment diagram in Graph A2.1

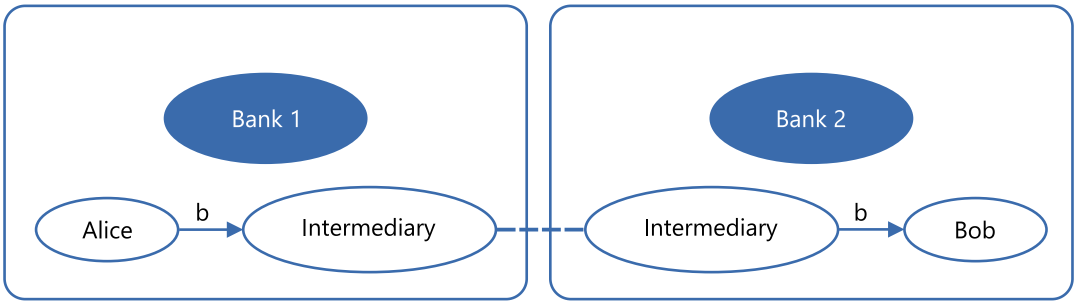
Table A2.1

Alice	
Account at respondent: -b Goods: +b	
Respondent	
Nostro account at correspondent: **-b**	Account Alice: **-b**
Correspondent	
	Vostro of respondent: **-b** Account Bob: **+b**
Bob	
Account at correspondent: +b Goods: -b	

Source: Authors' elaboration.

B. A payment using an intermediary

Payment diagram Graph A2.2



Source: Authors' elaboration.

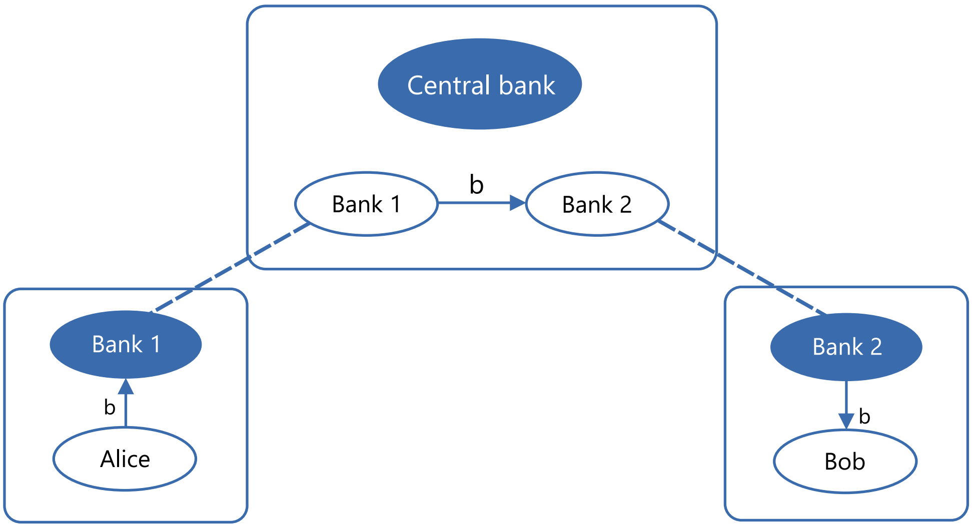
Example of simplified balance sheet updates that could correspond to the payment diagram in Graph A2.2 Table A2.2

Alice	
Account at bank 1: -b Goods: +b	
Bank 1	
	Account Alice: **-b** Account intermediary: **+b**
Intermediary	
Account at bank 1: **+b** Account at bank 2: **-b**	
Bank 2	
	Intermediary: **-b** Account Bob: **+b**
Bob	
Account at bank 2: +b Goods: -b	

Source: Authors' elaboration.

C. A payment using a second tier

Payment diagram — Graph A2.3



Source: Authors' elaboration.

Example of simplified balance sheet updates that could correspond to the payment diagram in Graph A2.3 — Table A2.3

Alice	
Account at bank 1: -b Goods: +b	
Bank 1	
Account at central bank: **-b**	Account Alice: **-b**
Central bank	
	Account bank 1: **-b** Account bank 2: **+b**
Bank 2	
Account at central bank: **+b**	Account Bob: **+b**
Bob	
Account at bank 2: +b Goods: -b	

Source: Authors' elaboration.

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