Distributed Ledger Technology and the Future of Money and Banking

Banking is Necessary, Banks Are Not. Bill Gates 1994

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Abstract:

Nakamoto (2008) outlined an alternative to the current monetary system in which banks are replaced by a peer-to-peer system to issue and transfer digital money: the Bitcoin. While Bitcoin has attracted a substantial investment volume, the system has not achieved the status of a viable alternative monetary system. However, the distributed ledger technology (DLT) underlying the payment system is being applied successfully by financial institutions and is likely to have important implications for the future of money and banking. In this paper we therefore focus on the most advanced distributed ledger application in the financial industry: R3 Corda. This paper is structured as follows. In the first section, we relate the debate about systems of money creation to the rise of Bitcoin. Next, the development of R3 Corda is discussed and the lessons learned for monetary reform. We conclude with an assessment of the scope and likelihood of monetary reform as a consequence of DLT applications by central banks.

Keywords: distributed ledger technology, monetary reform, money, banking, Bitcoin.

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1 Money Creation and distributed ledger technology: Bitcoin

The main reason for proposing a distributed ledger payment system with Bitcoin as an alternative currency is the disenchantment of Nakamoto (2008) with the banking system for money creation (Porter and Rousse, 2016). Not coincidentally, the new system was launched in the midst of the Global Financial Crisis, in 2009. Banks had taken highly risky bets in complex structured financial products that lost most of their value when it became clear that the collateral had been grossly overvalued.

The ensuing crisis of confidence that unfolded after 2009 in the financial system and credit rationing in turn led negative effects which were more severe than in previous banking crises (Claessens et al., 2010) such as substantial decreases in real GDP (Demirguc-Kunt et al., 2006; Hanna and Huang, 2002; Barro and Lee, 2003), corporate profits (Boyd et al., 2014), and welfare losses (Hoggarth et al., 2002; Bordo et al., 2001; Aziz et al., 2000; Boyd et al., 2005; Cecchetti et al., 2009). In addition, the massive use of public funds to bail out failed financial institutions and the close entanglement between the banks and the political system attracted attention not only of the press but also of academia (Blau et al., 2013; Biondi, 2016; Reinke, 2016).

The incidence and intensity of banking crises also led to the re-examination of the way money was created by the banking system. The focus of contention was the monopoly to create money granted by the state to commercial banks with a profit motive (Werner, 2014; Biondi, 2018). Critics (e.g. Porter and Rousse, 2016), have argued that banks could not be trusted with the governance of the monetary system which provided the infrastructure that was critical to the functioning of society. In proposing the alternative distributed ledger driven currency Nakamoto (2008, page 4) argues: "Once a predetermined number of coins have entered circulation, the incentive can transition entirely to transaction fees and be completely inflation free." Nakamoto (2008) designed the payment and money creation system of Bitcoin that would block abuse by authorities by deliberately debasing the currency to reduce the cost of servicing public debts (Aizenman and Marion, 2011).

In the Bitcoin infrastructure designed by Nakamoto (2008), trusted institutions such as banks are replaced by cryptographic techniques and an incentive system ensures that the majority of participants (nodes) behave honestly. That makes Bitcoin a peer-to-peer financial cooperative that creates and transfers currency without a central authority verification.

In the system, Bitcoins are entries in a distributed ledger called a blockchain[2] with specific properties programmed to minimize the probability of fraud such as double-spending or outright theft. One layer of security is the hashing of all information on the blockchain. It uses the SHA-256 algorithm which is a mathematical process that takes input data of any size, performs an operation on it, and returns output data of a fixed size. This fixed string of numbers and letters, which is called the hash, is a unique representation of the input data and changes if any component of the input data is changed. This makes tampering easy to detect digitally. Another layer of security is that each participant in the blockchain is assigned a public cryptographic key (known to all participants) and a private cryptographic key (known to only a specific participant). If an owner wants to transfer Bitcoin he writes a check by digitally signing the hash of the previous transaction and the pubic key of the next owner (the payee) and adding these at the end of the coins being transferred. The check clears when the payee signs with his private key which fits the public key that was sent by the previous owner who wrote the check. The problem is that the payee cannot verify that the owner has not already spent the Bitcoin by signing earlier transactions. The way the Bitcoin blockchain solves this, is by publicly announcing (i.e. broadcasting) all time-stamped proposed transactions to all participants and by installing a system for participants to agree on a single history of the order in which transactions were received. The payee needs proof that the majority of the nodes agree that the proposed transaction was the first broadcasted.[3]

The steps to achieve this are as follows. After new proposed transactions are broadcasted, nodes collect a number of these transactions into a block. Each node works to solve a difficult mathematical puzzle which is specific to their block. This is the proof-of-work required by the blockchain system in order to be able to propose to other nodes to add this new block to the existing chain of blocks that had been approved earlier. If the majority of the nodes accept the proposed block because they do not detect any fraud (i.e. reach consensus on the validity of all transactions that constitute it) it is added to the existing longest blockchain and they start working on the next block, using the hash of the accepted block as the previous hash.

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[2] The words ‘chain’ and the word ‘block’ is mentioned, respectively, 27 and 67 times in the white paper of Satoshi Nakamoto (2008), but the term blockchain does not appear once.

[3] At the time when Nakamoto (2008) designed the Bitcoin rules, it was unlikely that a node would possess sufficient processing power to capture 51% of the total computing power dedicated top roof-of-work activities. Presently, however, this is becoming a realistic scenario given the concentration of computing power in so-called mining farms dedicated to perform the proof-of-work at increasingly higher rates.

A key element that ensures data integrity of the blockchain is the time-sensitivity of the incentives for performing the proof-of-work. As only the node whose block is accepted first by the majority of other nodes obtains a reward in the form of newly issued Bitcoins, all other nodes – after checking the correctness of the proof-of-work performed and presented to them – accept that block in order to start the proof-of work for the next block hoping to be the first to get their block accepted in the next round. The blockchain system is programmed to maintain the time it takes to perform the proof-of-work to approximately ten minutes. The reason for this is that – as long as the expected reward outweighs the cost of performing the proof-of-work – nodes will invest in obtaining the fastest equipment (CPU power) in order to win the race.

By maintaining a constant level of difficulty of the proof-of-work with respect to CPU power, the blockchain is protected from nodes that attempt to tamper with the blockchain by generating an alternate chain faster than the honest chain as it would take an unrealistic amount of computing power to successfully achieve this. Nakamoto (2008, page 4): "The incentive may help encourage nodes to stay honest. If a greedy attacker is able to assemble more CPU power than all the honest nodes, he would have to choose between using it to defraud people by stealing back his payments, or using it to generate new coins. He ought to find it more profitable to play by the rules, such rules that favour him with more new coins than everyone else combined, than to undermine the system and the validity of his own wealth."

The promise of Bitcoin is manifold: censorship-free (no institution which is part of the system could debase the currency or block payments), no bank run risk (avoids deposit guarantee schemes, bank regulation and too-big-to-fail cost), greater security (more difficult to hack than centralized payment system which saves cost of maintain security apparatus and compensating fraud victims), borderless (no cross-border restriction), fast (especially for cross-border payments) and cheap (infrastructure light without banks, payment terminals connected to a dedicated servers and network). Correspondingly, since the launch of Bitcoin in 2009, the total amount of money invested in the cryptocurrency has grown to almost USD 400 billion. (https://coinmarketcap.com/ accessed October 26, 2019).

However, the Bitcoin has a number of flaws that have prevented it from becoming widely used money. These shortcomings originate from the egalitarian and unstructured character of the Bitcoin's blockchain. Nakamoto (2008, page 8): "The network is robust in its unstructured simplicity. Nodes work all at once with little coordination. They do not need to be identified, since messages are not routed to

any particular place and only need to be delivered on a best effort basis. Nodes can leave and rejoin the network at will, accepting the proof-of-work chain as proof of what happened while they were gone. They vote with their CPU power[4], expressing their acceptance of valid blocks by working on extending them and rejecting invalid blocks by refusing to work on them. Any needed rules and incentives can be enforced with this consensus mechanism." This makes the Bitcoin type of blockchain permissionless: individuals do not need permission to perform proof-of-work to verify the addition of new data.

We have categorized the shortcomings with respect to the three primary functions of money: it is a unit of account, a store of value, and a medium of exchange. Nakamoto (2008, page 6) designed the Bitcoin system so that participants stay anonymous: "The traditional banking model achieves a level of privacy by limiting access to information to the parties involved and the trusted third party. The necessity to announce all transactions publicly precludes this method, privacy can still be maintained by breaking the flow of information in another place: by keeping public keys anonymous. The public can see that someone is sending an amount to someone else, but without information linking the transaction to anyone. This is similar to the level of information released by stock exchanges, where the time and size of individual trades, the "tape", is made public, but without telling who the parties were. As an additional firewall, a new key pair should be used for each transaction to keep them from being linked to a common owner." There is no need to reveal one's legal identity to own and transfer Bitcoins. Only a set of private and public keys is needed. And even the publicly known keys are not traceable to legal identity provided the user does not register at an exchange and leaves no traces on the Internet. The anonymity that the Bitcoin system offers has invited illicit transactions to be paid in the cryptocurrency. Bohr and Bashir (2014, page 97) document that over a third of the Bitcoin holders used the currency to purchase illicit goods such as narcotics and gambling services. In addition, they report that: "Several other variables were statistically significant in predicting the accumulation of Bitcoins. Controlling for other factors, the marginal effect of spending Bitcoins on illicit goods (narcotics, gambling services, or other illegal goods) predicted that those users had about 25% - 45% more Bitcoins (within the 95% Confidence Interval) than those who had not spent Bitcoins on illicit goods."

Similarly, Foley et al. (2019, page 1799) find that approximately one-quarter of Bitcoin users are involved in illegal activity and that 46% of all Bitcoin transactions (with a total value of USD 76 billion per year) are illicit. They note: "The recent FBI seizure of over USD 4 million worth of Bitcoin from one such

[4] Some view this as highly asymmetric and unfair voting mechanism and point to the rise of mining farms.

marketplace, the “Silk Road,” provides some idea of the scale of the problem faced by regulators.” Also, Chung (2019) finds that the US tax authorities (Internal Revenue Service) has concluded that Bitcoin is used for tax evasion purposes and is stepping up effort to combat the phenomenon.

The significant use of Bitcoin for illicit purposes makes it unlikely that the currency will function as a unit of account. Authorities will not accept it for the purposes of measuring financial results, wealth and tax liability. There are no signs that the acceptance of Bitcoin as a unit of account will occur due to widely supported societal pressure.

Bitcoin was designed to function as a store of value. Nakamoto (2008) compares Bitcoin to gold and maximizes the total number of Bitcoins to be mined at 21 million. This maximum amount was set by Nakamoto (2008, page 4) to promote store of value function of Bitcoin relative to existing monies[5]: “Once a predetermined number of coins have entered circulation” the system would be “completely inflation free.” He intended it to have the store of value characteristics of gold: “The steady addition of a constant of amount of new coins is analogous to gold miners expending resources to add gold to circulation.” In fact, new issuance depends on system managers and holders and their CPU oligopolistic power as explained before. Scarcity of Bitcoin by itself is not sufficient to ensure it functions as a store of value. If it exhibits characteristics of a highly speculative asset, it negatively affect the functionality as a store of value. Kubat (2015, page 416) examines the store of value function of Bitcoin and concludes: “based on comparing historical volatility for BTC and assets like currencies, gold and shares, that to hoard Bitcoins is more risky than hold other types of assets. It cancels the store of value money function of Bitcoin.” Similarly, Dwyer (2015) finds that the average monthly volatility of Bitcoin is higher than that for gold or a set of foreign currencies. Cheung et al. (2015) show the existence of bubbles in the Bitcoin market and find a number of short-lived bubbles but also three huge bubbles, the last of which led to the demise of the Mt Gox exchange. Cheah and Fry (2015, page 1) also find evidence of speculative bubbles and draw conclusions as to the intrinsic value of Bitcoin: ”we find empirical evidence that the fundamental price of Bitcoin is zero.” Urquhart (2016) concludes that the market for Bitcoin is not efficient as the price does not fully reflect all available information. This makes Bitcoin an unreliable store of value with a highly speculative character.

[5] Historically, economic growth due to innovation has led to expansion of goods and services over time. If the amount of money does not at least keep pace with this rate of expansion, the adoption of a monetary system such as Bitcoin will lead to deflation and have a negative impact on economic growth.

Another element that lowers the functionality of Bitcoin as a store of value is the growing concentration of CPU power that is applied to perform the proof-of-work that is essential for the continuation of the Bitcoin system. As only the first miner to finish the proof of work get the reward in the form of newly minted Bitcoins, there is an incentive to invest in ever faster equipment to solve the increasingly difficult mathematical puzzle. The required investments in faster application-specific integrated circuits (ASICs specially designed to perform Bitcoin's proof-of-work) becomes increasingly prohibitive for aspiring miners. This in turn has led to growing concentration of CPU power in fewer and fewer mining pools which could eventually have the required power to successfully tamper with the blockchain and defraud owners of Bitcoins of their currency.

One important side-effect of the expansion of ever faster CPU power dedicated to the Bitcoin blockchain and the consequently growing difficulty of the proof-of-work is that the electricity used to add new blocks to the Bitcoin chain is becoming problematic. At the current rate it uses more than 75 TerraWatthour per year; the same amount of electricity that is annually consumed in Venezuela. More important than the absolute amount of energy consumed is the amount of energy consumer per transaction. One Bitcoin transaction uses 672 Kilowatt-hour while 100,000 Visa transactions consume 151 Kilowatt-hour[6]. The Bitcoin system is an extremely inefficient payment system and, consequently, Bitcoin is not functioning well as a medium of exchange. Moreover, the capacity of the Bitcoin system is between 4-7 transactions per second (TPS) while Visa processes 1,736 TPS which makes the Bitcoin system not scalable[7].

Baur et al. (2018) analyse transaction data of Bitcoin accounts and show that Bitcoin are used as a speculative investment and not as an alternative currency and medium of exchange. They find that only a minority of the account holders use the currency as a medium of exchange. The reason for this is that excessive speculation pushes the volatility of the price of Bitcoin to levels where it becomes "a distraction" for potential users as a medium of exchange. The authors posit that the balance between potential users and investors may ultimately determine the success of Bitcoin as a medium of exchange.

Overall, the evidence does not support the view that Bitcoin has the properties of money. In order to realize the ideal of giving each individual control of their own digital assets without having to rely on a third party, Nakamoto (2008) had created a system that simply did not have the capacity and speed

[6] https://digiconomist.net/bitcoin-energy-consumption accessed October 26, 2020.
[7] https://towardsdatascience.com/the-blockchain-scalability-problem-the-race-for-visa-like-transaction-speed-5cce48f9d44 accessed October 26, 2020.

required to compete with existing infrastructure. Consequently, Bitcoin is mainly used for speculative purposes which effectively undercuts any potential it had to function as money.

The trade-off between egalitarianism and scalability has been formally tested by Caccioli et al. (2016). Using simulations, they find that fully egalitarian (i.e. permissionless) blockchains become less efficient[8] than permissioned blockchains as the number of nodes exceed 1000. The permissioned blockchain used by Caccioli et al. (2016) is a network in which a small fraction of hubs (the ones which get permission to play as intermediaries in the network) are connected to a substantial fraction of nodes whose degree of power concentration is similar to existing networks. If the network consists of 10,000 nodes, the permissioned network is almost 3.5 times more efficient than a permissionless blockchain. Pappalardo et al. (2018) confirm the inefficiency of the Bitcoin permissionless blockchain finding that 42% of proposed transactions are not included in the Blockchain after one hour and on-fifth of the transactions were not included in the Blockchain after one month[9]. While the Bitcoin blockchain had serious shortcomings in practice, it was widely recognized that the underlying DLT had great potential to increase the efficiency and reliability of financial services (World Economic Forum, 2016). In the following section we analyse the adjustments made to the Bitcoin architecture in order to allow for the application of DLT at financial institutions. From this analysis, we explore the scope of further DLT applications in the monetary system.

2 A Distributed Ledger Technology for Financial Services: R3 Corda

Financial institutions have traditionally been early adopters and intensive users of information and communication technology (ICT) in order to maximize the efficiency of their main activity: verifying, recording and transferring digital information. The benefits of implementing DLT are most pronounced for network activities that are complex, protracted and include verification of information supplied by different parties that do not necessarily trust each other such as clearing and settlement of trades in

[8] Efficiency is defined as the probability of a signals reaching 50% of the nodes.
[9] This would be a hazardous payment system. The actual interbank system clears virtually all transactions in one day and most in few seconds/minutes.

financial instruments[10] (World Economic Forum, 2016; Probst et al., 2016). The resulting disintermediation as well as increased transparency leads to significant cost reductions, especially in regard to transaction or monitoring costs (Pinna and Ruttenberg, 2016).

In the years after the launch of Bitcoin and before the publication of the seminal study by the World Economic Forum (2016), a significant volume of venture capital was invested in projects aiming to find business applications for blockchain. One of these investors was David Rutter, who started R3CEV in early 2013 with Jesse Edwards and Todd McDonald where the R represented Rutter's name, the 3 represented the three partners and CEV stood for crypto, exchanges, and ventures. Rutter had established a reputation as a creative thought leader in the implementation of innovative solutions to financial markets. After over thirty years of experience gained at various financial institution, including ten years as CEO of ICAP, he decided to dedicate his time fully to developing an application of the emerging blockchain technology.

Rutter and his two R3CEV partners met with more than twenty blockchain companies, mostly based in Silicon Valley, California but could not find companies that they considered a good investment. They were disappointed with the lack of understanding of how financial institutions actually worked and the bravado of the persons looking for funding of their ideas. Despite the fact that the aspiring entrepreneurs were not able to explain how they would actually disrupt incumbents such as J.P. Morgan or the Depository Trust & Clearing Corporation, many were able to raise millions of venture capital. As these investments did not generate the promised disruption (Peters and Panayi, 2016; Fico, 2016), this led to doubt as to whether the potential of DLT was grossly overestimated and the situation had evolved into a tech hype comparable to the dot-com bubble that burst in 2000 (Valenzuela, 2016; Evans-Greenwood et al., 2016).

Rutter had built up some experience with the actual implementation of blockchain as a seed investor in Align Commerce (later renamed Veem) the first global payments company that used blockchain, and the distributed ledger company Digital Asset Holdings. During the latter half of his career his focus had been on introducing innovative financial technology to the largest firms on Wall Street. He

[10] The report identifies as one of the key value drivers for DLT application: Clearing and settlement time reduction as DLT disintermediates third parties that support transaction verification/validation and accelerates settlement. While some financial instrument traded in standardized way in the public financial markets, the majority of the financial instruments were not standardized but tailored to the needs of the parties involved and traded in the over-the-counter market.

recognized that applying a blockchain to the labour-intensive, error-prone and tedious process of clearing, settlement and record keeping of traded financial instruments could lower costs significantly. A key insight was that institutions had a common problem and that they were per definition their mirror image as (the agent for) the purchaser and the seller of a financial instrument. Based on this insight, he decided that the best way to develop a solution was to invite the parties involved to participate in a series of roundtable meetings in order to reach agreement on the best IT architecture for a collective problem. His track record for actually solving IT problems and saving time and money for banks, helped convincing these banks to spend time on a technology that many did not understand and many suspected it to be a hype with limited practical use, if any. Rutter on the goal of the three roundtable sessions held in 2014 and 2015: "We held several roundtables […] to deeply consider what the possible implications of the blockchain were, and what it could possibly do to save money, and time, and to create a better paradigm for the world of Wall Street and finance."[11]

The outcome of the roundtables was a joint venture with nine global banks: Barclays, BBVA, Commonwealth Bank of Australia, Credit Suisse, Goldman Sachs, J.P. Morgan, State Street, Royal Bank of Scotland, and UBS. The banks committed both capital and assigned their in-house experts to working groups of the joint venture. The membership of the collaborative network grew to 42 banks by December 2015. In an interview with the Wall Street Journal, Rutter explained the three project phases and the corresponding objectives of the consortium.[12] The objective of the first phase was to design the different ledger architectures which could handle the billions of dollars of diverse and complex transactions of financial instruments that the banks traded amongst each other, similar to the settlements made in a payment system such as DLT-driven Bitcoin system. The second goal was to experiment with different ledger designs in order to determine their potential and limitations. The third goal was to learn from the experiments what worked best and had a high probability of adoption amongst most banks.

In the first phase, three type of ledgers were identified: the centralized, decentralized, and the distributed ledger. A ledger is a record of asset ownership. Before the digital age, a ledger typically would be a book where the bookkeeper would make entries whenever ownership of an asset changed as result of a transaction. When computers became widely available, the ledgers were changed into digital records.

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[11] https://coinreport.net/major-banks-form-consortium-bring-blockchain-technology-financial-markets/ accessed October 26,2020.

[12] https://blogs.wsj.com/moneybeat/2015/09/15/bitbeat-wall-street-city-banks-join-blockchain-focused-consortium/ accessed October 26,2020.

A centralized ledger is a single and complete overview of ownership that is maintained by one trusted third party. In the capital markets this party is known as the central securities depositary. These institutions are organized on a national level (e.g. the US Depositary Trust Company) or internationally (e.g. Euroclear of Clearstream). The shortcoming of this arrangement is that it can be accidentally or maliciously shut down, tampered with or destroyed. It is vulnerable to a single point of failure.

A decentralized ledger is a network of sub-ledgers which – when aggregated – would make up the complete centralized ledger. An example is a retail network where the stores send the ledger containing their inventory status to their head office at the end of the business day. The head office would have a complete record of the inventory by combining the information contained in the received decentralized ledgers. This system has multiple sources of potential error or points of failure.

A distributed ledger is a complete record of ownership and transactions with multiple identical copies distributed over different locations, thereby avoiding the risk of single point of failure. There are three essential differences between a decentralized and a distributed ledger. First, in a decentralized ledger there is a master-slave relationship between the sub-ledgers and the ledger in which the information from the sub-ledgers is aggregated. Second, a distributed ledger is programmed to resolve potential conflicts in simultaneous updates of the ledger. Third, a distributed ledger allows for the incorporation of self-enforcing contracts (a.k.a. smart contracts) to be programmed to update the ledger (Peters and Panayi, 2016). Smart contracts are lines of code which are stored on a blockchain and automatically execute when predetermined terms and conditions are met. However, the distributed ledger requires a continuous effort to ensure there are no difference between de the ledgers in different locations. Traditionally, this had been prohibitively time-consuming. With the advent of cryptography and the blockchain verification protocol, the implementation of DLT to produce a shared ledger across locations containing up-to-date secure and transparent information became feasible.

The banks that formed the R3 consortium identified a shared problem for which DLT is a likely candidate to provide a solution: clearing and settlement of financial instruments that are traded amongst themselves. The majority of these instruments are agreed to verbally by trading floor professionals working for financial institutions each of which maintained their own ledger. Subsequently the agreed trade needs to be formalised, recorded, and the settlement of obligations need to be consummated on an agreed date. In practice, frequent human errors, disagreements between counterparties that did not trust each other and reconciliation of disputes prove to be highly labour-intensive and costly (World Economic Forum, 2016). In addition, identifying and structuring trading data for risk and compliance

purposes add to the costs of securities trading. Analysis of data from the World Bank, the World Federation of Exchanges; Oxera; Financial Times and Oliver Wyman by Santander InnoVentures, in collaboration with its partners Oliver Wyman and Anthemis Group, concludes: "Our analysis suggests that distributed ledger technology could reduce banks' infrastructure costs attributable to cross-border payments, securities trading and regulatory compliance by between $15-20 billion per year by 2022"[13]. R3 member were convinced it made economic sense to pool their resources to collectively develop an encrypted distributed ledger to reap these benefits rather than each bank trying to streamline the clearing and settlement process individually.

In the second phase, experimentation was initiated with different ledger designs in order to determine their potential and limitations. Two working groups were formed from personnel of the 42 R3 consortium banks: the Lab and Research Centre (LRC) based in New York and the Architecture Working Group (AWG) in London. With the functional requirements of the banks in mind, the LRC focused on testing existing DLT and the AWG began developing DLT from scratch.

In the first quarter of 2016, the LRC tested DLT solutions from five vendors: IBM Hyperledger, Intel Sawtooth, Ethereum, Eris Industries, and Chain. The financial transactions were recorded on distributed ledgers hosted on the cloud computing services of Microsoft Azure, IBM Cloud, and Amazon AWS. While the experiments showed that the existing DLT showed potential, none of them provided the complete solution that satisfied the R3 banks. Especially, the privacy and scalability requirements of the banks were not met.

The lead was taken by AWG to develop a proprietary DLT. From the work done at LRC, it was clear that a permissionless and public blockchain like Bitcoin was not appropriate for the banks given the banks' requirement concerning, respectively, scalability and privacy. Existing DLT did not meet the requirements either. Richard Gendal Brown, who had been recruited from IBM to lead the team at AWG was very specific in his approach to come up with a solution: "The reality is that solutions based on selecting the design first and then trying to apply it to arbitrary problems never work out well. Every successful project I've worked on started with the *requirements*, not some cool piece of technology, and I was determined to bring that discipline into our work at R3."[14] He summarized the requirements in non-technical terms

[13] https://santanderinnoventures.com/wp-content/uploads/2015/06/The-Fintech-2-0-Paper.pdf
Accessed October 26, 2020.
[14] https://gendal.me/2016/04/05/introducing-r3-corda-a-distributed-ledger-designed-for-financial-services/
Accessed October 26, 2020.

as follows: “The financial industry is pretty much *defined* by the agreements that exist between its firms and these firms share a common problem: the agreement is typically recorded by *both* parties, in *different* systems and *very large* amounts of cost are caused by the need to fix things when these different systems end up believing different things. Multiple research firms have postulated that tens of billions of dollars are spent each year on this problem. In particular, these systems typically communicate by exchanging *messages*: I send an update to you and just *hope* you reach the same conclusion about the new state of the agreement that I did. It’s why we have to spend so much money on reconciliation to check that we did indeed reach the same conclusions and more money again to deal with all the problems we uncover. Now imagine we had a system for recording and managing financial agreements that was *shared* across firms, that recorded the agreement consistently and identically, that was visible to the appropriate regulators and which was built on industry-standard tools, with a focus on interoperability and incremental deployment and which didn’t leak confidential information to third parties. A system where one firm could look at its set of agreements with a counterpart and know for sure that: *“What I see is what you see and we both know that we see the same thing and we both know that this is what has been reported to the regulator.”* That’s Corda.”

In November 2016 Corda was made available as an open source DLT platform that did not group transaction in blocks but instead recorded agreements (transactions) individually, speeding up process time. Scalability was also increased by using so called notary nodes that were authorized to update the permissioned ledger. The ledger was also private, where information was disclosed on a need-to-know basis. Consensus occurred only between the two counterparties to a transaction and not between all members of the network. Clearly, the private and permissioned blockchain has made serious compromises to the idealistic public and permissionless system that was conceived by Nakamoto (2008) in order to make DLT practically useful for financial institutions.

3 Distributed Ledger Technology and the Future of Money and Banking

3.1 Introduction

The DLT of Bitcoin was designed to eliminate the role of both central and commercial banks in the creation and transfer of money (Nakamoto, 2008). The central point for the criticism of the current monetary system is that banks cannot be trusted to act as reliable guardians of an essential utility. Commercial banks are private enterprises with a profit motive. As any private enterprise, they compete for capital and therefore need to demonstrate that they can generate the return required by their capital providers. It is generally accepted that capital return is proportional to risk (Sharpe, 1964). This means that banks will - as a rule - need to accept risky projects. That is not necessarily problematic as long as the effective risk management ensures that the solvency of banks is rarely at risk. Historically, however, banks have shown that collective return chasing behaviour in specific activities (i.e. herd-like behaviour) to an extent that it interferes with effective risk management and often lead to period of excessive speculation and asset inflation that often end in banking crises (Laeven, 2011). The frequency and intensity of these banking crises lead to high societal costs (Laeven, 2011). To critics of the current monetary system, these costs to society are unacceptably high. Radical monetary reform in which the role of banks in money creation is eliminated is therefore proposed (Wolf, 2014).

However, the analysis performed in the first section of this paper, shows that the architecture of the Bitcoin system has fundamental flaws that stand in the way for Bitcoin to effectively perform the three functions of money and, consequently, the radical monetary reform envisioned by Nakamoto (2008).

Nevertheless, financial institutions discerned potential benefits from implementing DLT and initiated projects to redesign its architecture. Section two describes the evolution of one of the most advanced DLT project, R3 Corda. The actual application of DLT for the clearing and settlement of financial instruments supports the view that such technology may someday prove to be useful in retail payments and perhaps even money creation as well, leading to monetary reform. The purpose of this section is to explore the scope and likelihood of monetary reform as a consequence of DLT

applications by central banks. The starting point of this analysis is the current research on DLT applications by central banks.

3.2 Research on DLT applications by central banks

The success with which financial institutions are applying DLT to improve the efficiency, transparency and security of transactions in financial instruments, has led to a growing interest in central banks in DLT. The white paper *Central Banks and Distributed Ledger Technology: How are Central Banks Exploring Blockchain Today?* (World Economic Forum, 2019) provides an overview of research and experimentation on DLT by central banks (Appendix 1). This section provides an analysis of the likely implementation of DLT by central banks along two dimensions: architecture and application.

3.2.1 Architecture of central bank DLT applications

In the first section of this paper we discussed that the permissionless and public nature of the DLT architecture of Bitcoin is the reason for the very low capacity for processing transactions. The Bitcoin system executes between 4-7 TPS; far lower than the 1,736 TPS which Visa processes. From simulations, Caccioli et al. (2016) find that the scalability can be significantly increased by limiting the number of nodes that have the capacity to verify and approve proposed changes to the distributed ledger. As the time needed to reach consensus is greatly reduced by limiting the number of nodes, the permissioned DLT system can process a far greater number of TPS than a permissionless DLT system (Vukolić, 2016).

A number of alternative solutions to increase the TPS of the Bitcoin DLT architecture have been examined in academic studies: changing the propagation protocol (Rohrer and Tschorsch, 2019; Chawla et al., 2019; Klarman et al. 2019), sharding (Luu et al., 2016; Kokoris-Kogias et al., 2018; Zamani et al., 2018; Wang and Wang, 2019) and increasing block size and/or decreasing the block discovery interval (Göbel and Krzesinski, 2017). From the detailed survey of the studies into increasing the TPS of permissionless DLT systems, Zhou et al. (2020) conclude that – while sharding solutions seem to increase TPS substantially – none of the alternative solutions provide the order of magnitude in TPS that would be sufficient for a permissionless DLT to operate as a system for global payments.

While it is conceivable that future research unveils the adjustments required to convert a public and permissionless DLT such as Bitcoin into a high volume, low latency payment system, at this moment only a permissioned DLT system can potentially compete with the current bank-based payment system (Zhou et al., 2020). This is congruent with the choice for permissioned DLT for Central Bank Digital Currency (CBDC) systems that are being developed by central banks (Dashkevich et al., 2020; Cukierman, 2020; Opare et al., 2020). This CBDC may be issued either as high-powered money accessible only to depository financial institutions, or with access by the general public as is proposed by the central bank of Sweden (Söderberg (2019). Opare et al. (2020, page 110810 and 110842) review and evaluate the architecture and technical capabilities of "all the relevant, publicly available DLT-based CBDC experiments" and conclude "Overall, central banks' preferred choice of DLT platforms for DLT-based CBDC experiments were mainly the permissioned DLT platforms. Particularly, DLT platforms with capabilities for settlement finality and data privacy such as Corda, Quorum and Fabric dominated the CBDC experiment landscape." The overview of experiment practices provided by Opare et al. (2020, pages 110840-110841) shows that the vast majority of the central bank experiments use the Corda architecture.

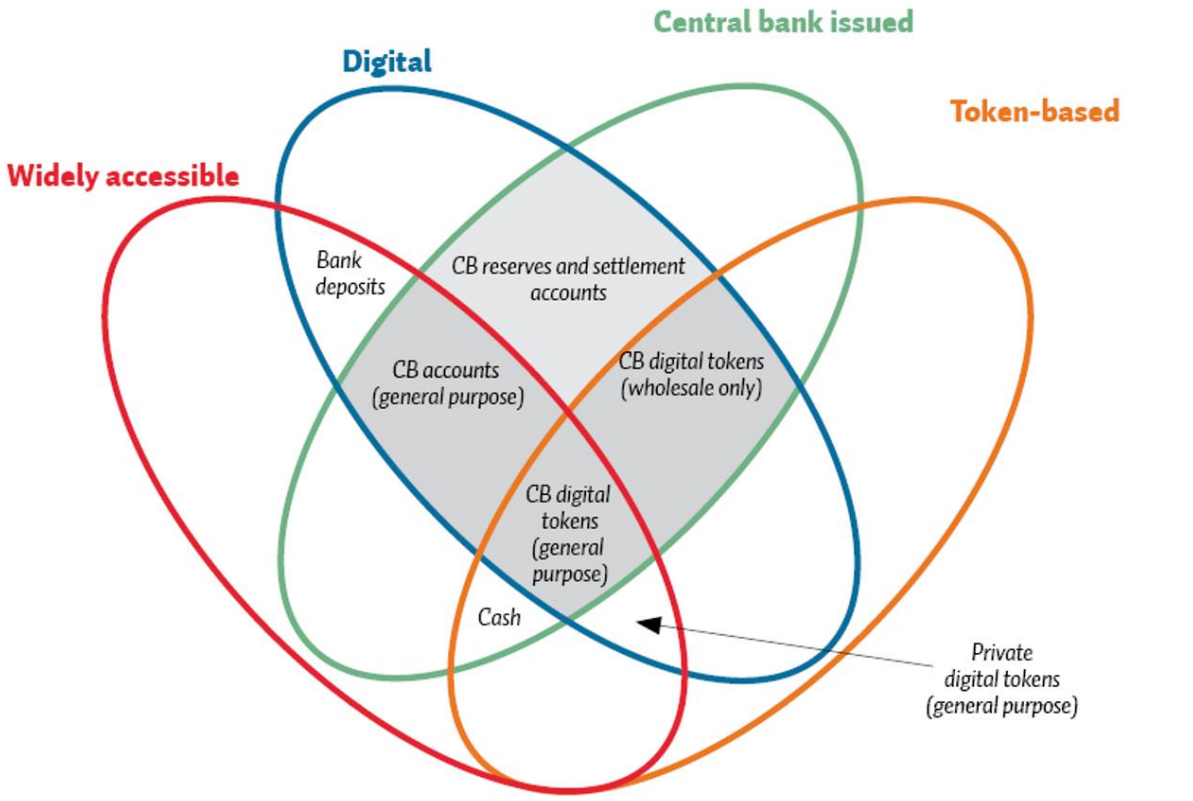
3.2.2 Application of central bank DLT

In line with the applications of Corda by the private sector financial institutions, central banks' experiments have mostly focused on DLT applications in the wholesale interbank market (World Economic Forum, 2019; Opare et al. 2020; Dashkevich et al., 2020). More specifically, the goal was to examine the "applicability of DLT for wholesale interbank payments settlement, securities settlement, bond issuance and management, trade finance and cross-border payments settlements" by "tokenizing wholesale central bank money" to improve the security, safety, efficiency, resilience and scalability of the process (Opare et al. 2020, page 110842). The detailed analysis of "the CBDC experiments examined in this paper demonstrated that it is technologically feasible to leverage DLT to issue CBDCs […] to improve central banks' operational efficiency", security, safety, resilience and scalability (Opare et al. 2020, page 110842).

The review of Opare et al. (2020) shows that – to date – CBDC experiments are generally focused on digital tokens to settle interbank wholesale interbank transactions; the shaded area which is the

result of the intersection of token-based, central bank issued and digital domains and is labelled ‘CB digital tokens (wholesale only)’ in figure 1.

The money flower: a taxonomy of money **FIGURE 1**



Source: BIS (2018) based on Bech and Garatt (2017) | ESB

A limited number of central banks (e.g. Sweden, Israel and Uruguay) are developing plans to replace cash with CBDC. However, “in terms of design, most central banks seem to be contemplating forms of account-based CBDC” (Mancini-Griffoli et al. 2018, page 28) and not token-based since “CBDC offering full anonymity and large-value transactions would undermine financial integrity relative to cash and current noncash fund transfer system” (Mancini-Griffoli et al. 2018, page 21). Similarly, from their systematic overview of CBDC projects Dashkevich et al., 2020, page 139930) conclude that ; “An account-based CBDC could be utilised with payments through the transfer of claims recorded on an account [23]. It is the preferred design choice of central banks.” On this issue, Fernández de Lis (2018, page 50) observes: “It is very difficult that the same central banks that require commercial banks to

implement costly mechanisms to prevent money laundering and the financing of terrorism (the AML/CFT regulation) are issuing at the same time the means to carry such activities. One may argue that this is already the case with cash. But anonymity is intrinsic to cash, whereas in the case of CBDCs it would be a deliberate decision." Therefore, in practice, the few general purpose CBDC projects focus on the shaded area which results from the intersection of widely accessible, central bank issued and digital domains labelled 'CB accounts (general purpose)' in figure 1 (Opare et al., 2020).

In a number of studies the different reasons why central banks are considering a general purpose CBDC are assessed. Engert and Fung (2017, page 8) assess six reasons and conclude that : "motivations for CBDC considered here are not compelling […] However, improving financial stability (section 2.3) might provide a motivation for the issuance of CBDC, and increasing contestability in payments (section 2.4) seems most likely to provide a sound motivation to issue CBDC." Kiff et al. (2020, page 7) assess eight motivations and: "found no universal case for CBDC adoption yet, and that demand for CBDC will depend on the attractiveness of alternative forms of money." On alternative forms of money Kiff et al. (2020, page 11) observe that "CBDC may be aimed at mitigating the market dominance of private payment systems or reducing concentration risk in such payment systems." Other studies share the conclusion that the dual concern about the decreasing use of cash and the rise of a limited number of private payment systems is the reason for the potential introduction of a CBDC as an alternative for cash (Bindseil, 2020; Bofinger and Haas, 2020; Cukierman, 2020; Boar, et al., 2020; Brunnermeier et al., 2019; Agur et al., 2019; Barontini and Holden, 2019).

Kiff et al. (2020, page 11) discuss the risks of market concentration of private market payment systems: "Payment systems may tend to become natural monopolies, reflecting strong network externalities (the value of using a given payment network is greater the larger the user community, including savings from netting transactions), economies of scale (decreasing average costs, including high fixed development and maintenance costs), and economies of scope, (gains from aggregating data to provide additional services – Bolt and Humphrey, 2005, and Gowrisankaran and Stavins, 2004). However, some private money issuers may not internalize the social cost of possible systemic disruptions from operational failure, including cyberattacks, and thus may underinvest in security. Also, monopolistic private issuers may abuse that power and lead to inefficiency by offering partial, inadequate and expensive services. They could also commercialize collected user data, although these could also invite competition, depending on the barriers to entry. These arguments might justify CBDC

issuance or some jurisdictions' decision to deploy fast payment systems, which also gives them control over an essential piece of the payment architecture."

In the current bank-based system architecture, central banks play a pivotal role. Central banks provide both the cash and the interbank payments network to settle all payment transactions. The role of central banks is significantly reduced when, for instance, transactions are executed in the alternative, private payment infrastructure of the credit card companies. The bulk of the transactions are processed in their proprietary private payment system as credit card companies use the bank-based system only periodically (typically on a monthly basis) to settle the balance of their clients' accounts. Credit card companies are highly lucrative, have successfully captured a significant proportion (34% in the US and 12% in EMEA) of the payments revenue pool and are likely to attract market entry by: " 'big tech' players on creating payments ecosystems across their billions of global users" (Bruno et al., 2019, page 13).

According to Kiff et al. (2020), Brunnermeier et al., (2019), and Bofinger and Haas (2020, page 5): "the real threat to the role of central banks in payment systems are private payment systems like PayPal and possibly Libra. They could lead to closed payment systems that no longer rely on traditional bank deposits." On the scope and feasibility of the Facebook private payment system Brunnermeier et al. (2019, page 10) state: " Facebook has a social network with links to 3 billion people. Once those networks have been established, information can be diffused across them cheaply and near-instantaneously. That information can then be automatically converted into whatever form is most convenient for the receiver. Modern technology makes frictionless, unintermediated peer-to-peer transactions possible using digital tokens." Kiff et al. (2020, page 14) elaborate on the potential negative consequences: "payment systems like Facebook's Libra could gain a substantial share of payments markets […] reduce commercial bank deposits […] hinder credit provision […] could be difficult to supervise and/or regulate."

While the Libra payment system of Facebook is not yet operational, giants like Amazon (Bhandary, 2019) and Alibaba (Lu, 2018) leverage their two-sided market power in the retail market to provide payment and lending services. Alibaba's fintech unit Ant Financial operates a private online payment systems with more than 1 billion active users (about a third of which live outside China) generating over USD 15 trillion of transaction volume in 2019 and growing at an annual rate of 36% in the first half of 2020 (The Economist, 2020).

Bofinger and Haas (2020, page 21) conclude that these developments indicate that the negative consequences described by Kiff et al. (2020) are material and – given that payment systems have natural monopolistic tendencies – constitute a market failure that justifies state intervention "A clear market failure can be identified here: very few credit card companies and PayPal have remarkably high market power because these two-sided markets are not sufficiently contestable. Facebook's Libra project shows that further large platforms can be created here that escape state influence."

Bofinger and Haas (2020, page 21) analyse from a systemic perspective what state intervention would optimally mitigate the market failure. They reject the state intervention of issuing a general purpose CBDC that could be held in individual accounts at the central bank: "From a systemic point of view, it makes little sense for central banks to become active as traditional commercial banks and thus compete with existing commercial banks. First, there is no clear market failure that could justify such state intervention and the implications and risk of such an intervention could be severe as our analysis shows. Second, the central bank would then still operate within the existing payment systems. This would not make any substantial contribution to the objectives of payment security and payment efficiency stated by the central banks in the BIS Survey by Barontini and Holden (2019). The systemic perspective, therefore, suggests that the focus should not be on new payment objects but rather on new payment systems."

Issuing a general purpose CBDC would lead to a severe risk of bank runs (Pichler et al., 2020; Cukierman, 2020; Bindseil, 2020; Bofinger and Haas, 2020; Kumhof and Noone, 2019; Engert and Fung, 2017), of commercial bank disintermediation (Opare et al., 2020; Cukierman, 2020; Bofinger and Haas, 2020; Kiff et al., 2020; Bindseil, 2020; Pichler et al., 2020;, Adrian and Mancini-Griffoli, 2019; Engert and Fung, 2017), and of credit crunches (Pichler et al., 2020; Cukierman, 2020; Bofinger and Haas, 2020; Bindseil, 2020) and would potentially undermine the stability of the financial system. "Central banks must therefore reason about the type of CBDC to issue carefully in order not to disrupt the stability of existing financial systems." Opare et al. (2020, page 110843).

Instead of issuing a general purpose CBDC that functions as a medium of exchange, central banks should issue a store of value CBDC that can only be accessed by central bank licensed institutions (the shaded area labelled 'CB reserves and settlement accounts' in figure 1) in order to improve the stability and efficiency of payments (Bofinger and Haas, 2020; Cukierman, 2020; Kiff et al., 2020; Adrian and Mancini-Griffoli, 2019).

4 Monetary reform

Central banks would require privately-issued digital money which is commonly referred to as sCBDC[15] to be fully backed by store of value CBDC and the issuers to be licensed, regulated and supervised by the central bank. This would make the alternative payment systems more stable and contestable than would be the case if the issuers (typically big tech companies like Facebook, Alibaba and Amazon that are well positioned to offer a fully-fledged alternative to the bank-based system) were left unregulated. There are two reasons why a full reserve requirement would make the payment system more stable. First, if left unregulated, issuers of private digital money such as Facebook are likely to rely on bank deposits and government bonds as collateral: "The designers of Libra plan to use bank deposits and government bonds as collateral. But, as indicated, the stability of bank deposits in a crisis is limited. As for government bonds, massive sales by Libra would likely result in price losses. These problems could be avoided if suppliers of stable coins could use CBDCs as collateral" (Bofinger and Haas 2020, page 9). Second, if left unregulated, payment platform providers such as Ant Financial are likely to expand into providing credit and fund this activity in a manner that significantly adds to the volume of shadow banking which generally has proven to destabilize the financial system (Biondi, 2016; Biondi, 2018; Biondi and Zhou, 2019; Moe, 2018): "In barely half a decade Ant has reached 1.7trn yuan in outstanding consumer loans, or roughly a 15% share of China's consumer-lending market. Its loans to small businesses total about 400bn yuan, about 5% of the micro-enterprise loan market. From a financial perspective, Ant's biggest innovation is the way that it funds the credit. Initially, it made the loans and then packaged them as securities, sold to other financial institutions. But regulators feared parallels with the securitisation boom that preceded the financial crisis of 2007-09. They required that the originators of securities hold capital much like any bank—a rule that cut into Ant's margins. So Ant devised a new approach. It now identifies and assesses borrowers, but passes them on to banks which

[15] Adrian and Mancini-Griffoli (2019, page 1) introduced the term synthetic CBDC (sCBDC) to refer to the privately-issued digital money that – under this regime – is a one-on-one representation of the store of value CBDC that the issuer holds at the central bank." Central banks will play an important role in molding this future. The rules they set will bear heavily on the adoption of new digital monies, and on the pressure these exert on commercial banks. One solution is to offer selected new e-money providers access to central bank reserves, though under strict conditions. Doing so raises risks, but it also has various advantages. Not least, central banks in some countries could partner with e-money providers to effectively provide "central bank digital currency (CBDC)," a digital version of cash. We call this arrangement "synthetic CBDC."

extend the loans. Ant collects a technology service fee.“ (The Economist, 2020). The payment providers are no longer active as potentially destabilizing shadow banks because “The Peoples Bank of China requires the country’s large payment providers, Alipay and WeChat Pay, to hold client funds at the central bank in the form of reserves” (Kiff et al., 2020, page 25).

In addition to the full reserve requirement, central banks should “offer special purpose licenses that allow nonbank fintech firms to hold reserve balances, subject to an approval process” (Adrian and Mancini-Griffoli 2018, page 12) in order to “ensure interoperability of payments and thus protect consumers from the growth of e-money monopolies offering payments among a large network of users.” (Adrian and Mancini-Griffoli 2018, page 13). Also, “Central banks could establish clear conditions to grant licenses to e-money providers, including strict supervision and oversight by the central bank or other authorities, though according to lighter regulation with respect to banks engaged in maturity transformation. For instance, selected providers would be responsible for appropriate customer screening, transaction monitoring and reporting in accordance with financial integrity regulation, as well as security of wallets and customer data.” (Kiff et al. 2019, page 27). One of the challenges for regulators is to reconcile the opposite objectives of allowing payment providers to reap the benefits of network effects while limiting the degree of market concentration (Sun, 2020). Given the global scale on which the most likely market entrants such as Ant Financial, Paypal, Facebook, and Amazon and are operating, central banks will have to respond on a global scale. Bofinger and Haas (2020, page 20):” Thus, if central banks want to maintain a dominant or at least an important role in the global financial system it is not enough and perhaps even not necessary to develop new payment objects. It also insufficient to develop national schemes or schemes that are not fully integrated into the existing ecosystem of global payment systems. While it would be a particularly challenging task for central banks to create a supranational retail payment form, a more modest approach is tying payment platforms to central bank reserves (synthetic CBDCs).” A number of central banks[16] have taken the initiative to evaluating the role of CBDC in global payment systems: “Current electronic retail money represents a claim on an intermediary, rather than functioning as the digital equivalent of cash. CBDCs could potentially provide a cash-like certainty for peer-to-peer payments. At the same time, they should offer convenience, resilience, accessibility, privacy and ease of use in cross-border payments. Different technical designs meet these

[16] Bofinger and Haas (2020, page 21): “The newly created central bank group of the Bank of England, the Bank of Japan, the European Central Bank, the Sveriges Riksbank, the Swiss National Bank, and the Bank for International Settlements for CBDCs is a promising step for more research in this field.”

criteria to varying degrees, with attendant technical trade-offs. We explore these issues. The aim is not to promote or highlight any particular approach, but to lay some groundwork for more systematic discussions." (BIS 2020, page 85).

How central banks may respond to the dual concern about the decreasing use of cash and the rise of a limited number of private payment systems remains an open question. What is becoming clear is that central banks are likely to take an active role which, in turn, leads to some degree of monetary reform: "As central banks play a key role in payment systems, both the declining use of cash and related developments in the private sector may require them to "step up" and take a more active role." (BIS 2020, page 96). Similar views were expressed by Christine Lagarde (2019) on the occasion of her first press conference as ECB president: "My personal conviction is that given the developments we are seeing, not so much in the bitcoin segment but in the stablecoins projects, [...] we'd better be ahead of the curve if that happens because there is clearly a demand out there that we have to respond to." Lagarde (2019).

The resulting reform will certainly not be that envisioned by Nakamoto (2008) in which central banks and commercial banks were entirely eliminated. Central banks will not easily lose their key role in payment systems but commercial banks are experiencing increasing international competition (e.g. Ant Financial, Paypal) which is likely to grow from further market entry. It is conceivable that market entry will have an impact on fractional reserve banking given that "The reserve backing allows sCBDC providers to offer a credible guarantee of redemption at face value" (Kiff et al. 2020, page 27). If this makes sCBDC more attractive than deposits, it would put pressure on commercial banks to offer similar guarantees to their depositors: "Similar synthetic CBDC solutions could be provided by private banks as a service for their customers. Banks could e.g. offer to back all deposits voluntarily with 90 or even 100 percent central bank reserves." (Bofinger and Haas, 2020, page 9).

To conclude, the monetary reform in response to market entry in the global payment system and the technically feasible applications of DLT is more likely to increase rather than decrease the role of central banks. However, the increased competition and diversity that results from the development of central bank supported alternatives to the bank-based payment system, could lead to a more stable and efficient financial system.

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Appendix 1: White papers, reports, and speeches related to the intersections of central banking, blockchain technology, and/or CBDC (central bank digital currencies).

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Last updated: Nov. 18, 2019

Central Banks

Joint research or multi-party work:

- VoxEU, "The Future of Digital Money" blog debates (2019) https://voxeu.org/debates/future-digital-money

- Bank of Canada, Monetary Authority of Singapore
    - "Enabling cross-border high-value transfer using distributed ledger technologies" (2019) https://www.accenture.com/_acnmedia/PDF-99/Accenture-Cross-Border-Distributed-Ledger-Technologies.pdf

- Bank of Canada, Bank of England, Monetary Authority of Singapore
    - "Cross-border interbank payments and settlements: Emerging opportunities for digital transformation" (2018) https://www.bankofengland.co.uk/-/media/boe/files/report/2018/cross-border-interbank-payments-and-settlements.pdf?la=en&hash=48AADDE3973FCB451E725CB70634A3AAFE7A45A3

- European Central Bank, Bank of Japan
  Project Stella reports (2016-2019)
    - Phase 3: "Synchronised cross-border payments" (2019) https://www.ecb.europa.eu/paym/intro/publications/pdf/ecb.miptopical190604.en.pdf
    - "Securities settlement systems: delivery-versus-payment in a distributed ledger environment" (2018) http://www.boj.or.jp/en/announcements/release_2018/data/rel180327a1.pdf
    - "Payment systems: liquidity saving mechanisms in a distributed ledger environment" (2017) https://www.ecb.europa.eu/pub/pdf/other/ecb.stella_project_report_september_2017.pdf

Central banks

- Bank of Canada

- Project Jasper collection (2017-2018) https://www.bankofcanada.ca/research/digital-currencies-and-fintech/fintech-experiments-and-projects/
- Staff discussion & working papers:
  - "Crypto 'money': Perspective of a couple of Canadian central bankers" (2019) https://www.bankofcanada.ca/wp-content/uploads/2019/02/sdp2019-1.pdf
  - "Central bank digital currency and banking" (2019) https://www.bankofcanada.ca/2019/05/staff-working-paper-2019-20/
  - "A tale of two countries: Cash demand in Canada and Sweden" (2019) https://www.bankofcanada.ca/2019/08/staff-discussion-paper-2019-7/
  - "Should the central bank issue e-money?" (2018) https://www.bankofcanada.ca/wp-content/uploads/2018/12/swp2018-58.pdf
  - "A policy framework for e-money" (2018) https://www.bankofcanada.ca/2018/04/staff-discussion-paper-2018-5/
  - "Central bank digital currency and monetary policy" (2018) https://www.bankofcanada.ca/wp-content/uploads/2018/07/swp2018-36.pdf
  - "Central bank digital currency: Motivations and implications" (2017) https://www.bankofcanada.ca/wp-content/uploads/2017/11/sdp2017-16.pdf
  - "Central bank digital currencies: A framework for assessing why and how" (2016) https://www.bankofcanada.ca/2016/11/staff-discussion-paper-2016-22/

- Bank of England
  - Staff working papers and reports
    - "Central bank digital currencies: design principles and balance sheet implications" (2018) https://www.bankofengland.co.uk/working-paper/2018/central-bank-digital-currencies---design-principles-and-balance-sheet-implications
    - "Broadening narrow money: monetary policy with a central bank digital currency" (2018) https://www.bankofengland.co.uk/-/media/boe/files/working-paper/2018/broadening-narrow-money-monetary-policy-with-a-central-bank-digital-currency.pdf
    - The macroeconomics of central bank issued digital currencies" (2016) https://www.bankofengland.co.uk/working-paper/2016/the-macroeconomics-of-central-bank-issued-digital-currencies
    - "Central banks and digital currencies," speech by Ben Broadbent (2016) https://www.bankofengland.co.uk/speech/2016/central-banks-and-digital-currencies
    - "The economics of digital currencies" (2014) https://www.bankofengland.co.uk/-/media/boe/files/digital-currencies/the-economics-of-digital-currencies
    - "Innovations in payment technologies and the emergence of digital currencies" (2014) https://www.bankofengland.co.uk/-/media/boe/files/quarterly-bulletin/2014/innovations-in-payment-technologies-and-the-emergence-of-digital-currencies.pdf
  - Speech by Mark Carney at Jackson Hole

        - "The growing challenges for monetary policy in the current international monetary and financial system" (2019) https://www.bankofengland.co.uk/-/media/boe/files/speech/2019/the-growing-challenges-for-monetary-policy-speech-by-mark-carney.pdf?la=en&hash=01A18270247C456901D4043F59D4B79F09B6BFBC
    - Digital currencies research home page: https://www.bankofengland.co.uk/research/digital-currencies

- Bank of Finland
    - "The great illusion of digital currencies" (2018) https://helda.helsinki.fi/bof/bitstream/handle/123456789/15564/BoFER_1_2018.pdf?sequence=1&isAllowed=y
    - "Central bank digital currency" (2017) https://helda.helsinki.fi/bof/bitstream/handle/123456789/14952/BoFER_5_2017.pdf?sequence=1&isAllowed=y

- Bank of France
    - Production implementation: Blockchain for Banking Services Pilot (2016+) SEPA Creditor Identifiers (SCI) repository sharing between banks (powerpoint presentation available)
    - Working paper #642, "Monetary policy and digital currencies: Much ado about nothing?" (2017) https://www.banque-france.fr/sites/default/files/medias/documents/dt-642.pdf

- Bank of Israel
    - "Report of the team to examine the issue of central bank digital currencies" (2018) https://www.boi.org.il/en/NewsAndPublications/PressReleases/Documents/Digital%20currency.pdf

- Bank of Japan
    - "Digital innovation, data revolution, and central bank digital currency" (2019) https://www.boj.or.jp/en/research/wps_rev/wps_2019/data/wp19e02.pdf

- Bank of Korea
    - "Central bank digital currency and financial stability" (2019) http://www.bok.or.kr/viewer/skin/doc.html?fn=201901310941017800.pdf&rs=/webview/result/E0002902/201901

- Bank of Lithuania
    - Digital Collector Coin (DCC) retail CBDC test (related public documents available upon request to Bank of Lithuania or WEF)
    - LBChain Platform-Service - blockchain technology sandbox
        - Website: https://www.lb.lt/en/pre-commercial-procurement
        - 2019 update: https://www.lb.lt/en/news/lbchain-project-six-financial-products-already-being-tested [lb.lt]

        - RFP web page: https://www.lb.lt/uploads/documents/files/apie-mus/atskaitomybe-ir-skaidrumas/ikiprekybinis-pirkimas/Pre-Commercial_Procurement_conditions.pdf

- Bank of Thailand
    - Project Inthanon phase 1 report (2019) https://www.bot.or.th/English/FinancialMarkets/ProjectInthanon/Documents/Inthanon_Phase1_Report.pdf

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    - "Distributed ledger technical research in Central Bank of Brazil" (2017) https://www.bcb.gov.br/htms/public/microcredito/Distributed_ledger_technical_research_in_Central_Bank_of_Brazil.pdf
    - Project Pier data and information exchange project: https://www.bcb.gov.br/en/#!/c/news/1853

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    - "Central bank digital currency in Denmark?" (2017): https://www.nationalbanken.dk/en/publications/Documents/2017/12/Analysis%20-%20Central%20bank%20digital%20currency%20in%20Denmark.pdf

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    - 5th Annual Macroprudential Conference, Session 2 - "Central bank digital currency: the future of money and banking?" (2019) https://www.bundesbank.de/de/bundesbank/forschung/konferenzen/5th-annual-macroprudential-conference-779116
    - BLOCKBASTER DLT prototype with Deutsche Borse (2016-2018) https://www.bundesbank.de/resource/blob/766672/29feab3f9079540441e3abda1ed2d2c1/mL/2018-10-25-blockbaster-final-report-data.pd

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    - Ulrich Bindseil, "CBDC - Financial system implications and control" (2019) https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3385283
    - Yves Mersch, "Digital base money: An assessment from the ECB's perspective" (2017) https://www.ecb.europa.eu/press/key/date/2017/html/sp170116.en.html

- Hong Kong Monetary Authority
    - "Whitepaper 2.0 on distributed ledger technology" (2017) https://www.hkma.gov.hk/media/eng/doc/key-functions/finanical-infrastructure/infrastructure/20171025e1.pdf

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    - "Whitepaper on distributed ledger technology" 1.0 (2016) https://www.hkma.gov.hk/media/eng/doc/key-functions/finanical-infrastructure/Whitepaper_On_Distributed_Ledger_Technology.pdf

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    - Project Ubin collection (2017-2019) https://www.mas.gov.sg/schemes-and-initiatives/Project-Ubin

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    - Gabriel Soderberg, "The e-krona – now and for the future" (2019) https://www.riksbank.se/globalassets/media/rapporter/ekonomiska-kommentarer/engelska/2019/the-e-krona--now-and-for-the-future.pdf
    - Petition to Riksdag: "The state's role in the payment market" (2019) https://www.riksbank.se/en-gb/press-and-published/notices-and-press-releases/press-releases/2019/the-riksbank-proposes-a-review-of-the-concept-of-legal-tender/
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    - Cecilia Skinglsey, "Considerations for a cashless future" (2018) https://www.riksbank.se/en-gb/press-and-published/speeches-and-presentations/2018/skingsley-considerations-for-a-cashless-future/
    - e-krona reports collection (2017-2019) https://www.riksbank.se/en-gb/payments--cash/e-krona/

- e-krona project: Action plan for 2018 (2017) https://www.riksbank.se/globalassets/media/rapporter/e-krona/2017/handlingsplan_ekrona_171221_eng.pdf
- Cecilia Skingsley, "Should the Riksbank issue an e-krona?" (2016) https://www.bis.org/review/r161128a.pdf

- Swiss National Bank
  - Speech by Thomas Jordan: "Financial market infrastructures: Walking the line between stability and innovation" (2016) https://www.snb.ch/en/mmr/speeches/id/ref_20160926_tjn
  - Speech by Andrea Maechler: "The financial markets in changing times – Changes today and tomorrow: the digital future" (2018) https://www.snb.ch/en/mmr/speeches/id/ref_20180405_amr

- US Federal Reserve
  - Federal Reserve Bank of Philadelphia working papers
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      - Presentation: https://www.bis.org/events/eopix_1810/keister_pres.pdf
  - St. Louis Federal Reserve staff and working papers
    - David Andolfatto, "Assessing the impact of central bank digital currency on private banks" (2018) https://s3.amazonaws.com/real.stlouisfed.org/wp/2018/2018-026.pdf
    - Aleksander Berensten and Fabian Schar, "The case for central bank electronic money and the non-case for central bank cryptocurrencies" (2018) https://research.stlouisfed.org/publications/review/2018/02/13/the-case-for-central-bank-electronic-money-and-the-non-case-for-central-bank-cryptocurrencies
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    - Larry D. Wall, "Some Blockchain Challenges" (2018) https://www.frbatlanta.org/cenfis/publications/notesfromthevault/06-some-blockchain-challenges-2018-06-27
  - Board of Governors speeches
    - Lael Brainard, "Cryptocurrencies, digital currencies, and distributed ledger technologies: What are we learning?" (2018) https://www.federalreserve.gov/newsevents/speech/brainard20180515a.htm
    - Lael Brainard, "Distributed ledger technology: implications for payments, clearing, and settlement" (2016) https://www.federalreserve.gov/newsevents/speech/brainard20161007a.htm
  - Joint staff working papers

- "Distributed ledger technology in payments, clearing, and settlement" (2016) https://www.federalreserve.gov/econresdata/feds/2016/files/2016095pap.pdf

International Organizations & Market Infrastructure

- BIS Committee on Payments and Market Infrastructure (CPMI), Markets Committee, and others
  - "The future of money and payments" (2019) https://www.bis.org/speeches/sp190322.pdf
  - "Proceeding with caution - a survey on central bank digital currency" (2019) https://www.bis.org/publ/bppdf/bispap101.htm
  - "Central bank digital currencies" (2018) https://www.bis.org/cpmi/publ/d174.htm
  - "Cryptocurrencies: Looking beyond the hype" (2018) https://www.bis.org/publ/arpdf/ar2018e5.htm
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  - "Monetary policy with negative interest rates: decoupling cash from electronic money" (2019) https://www.imf.org/en/Publications/WP/Issues/2018/08/27/Monetary-Policy-with-Negative-Interest-Rates-Decoupling-Cash-from-Electronic-Money-46076
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- Speech by Christine Lagarde: "Winds of Change: The Case for New Digital Currency": https://www.imf.org/en/News/Articles/2018/11/13/sp111418-winds-of-change-the-case-for-new-digital-currency

- ISSA (International Securities Services Association)
  - "DLT: Principles for industry-wide acceptance" (2018) https://www.issanet.org/e/pdf/2018-06_ISSA_DLT_report_version_1.0.pdf
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- SWIFT
  - "GPI real-time Nostro Proof of Concept" (2018) https://www.swift.com/news-events/press-releases/swift-completes-landmark-dlt-poc
  - "SWIFT on Distributed Ledger Technologies" (2016) https://www.swift.com/insights/press-releases/swift-and-accenture-outline-path-to-distributed-ledger-technology-adoption-within-financial-services

- World Economic Forum
  - "Central banks and distributed ledger technology: How are central banks researching blockchain today?" (2019) http://www3.weforum.org/docs/WEF_Central_Bank_Activity_in_Blockchain_DLT.pdf

Technology, Consulting, Finance, and Other

- Accenture
  - "Do central banks need to issue currency?" (speech at Hamburg Institute of International Economics by Ousmène Mandeng, Senior Advisor to Accenture's Global Blockchain practice) https://www.economicsadvisory.com/comments/18-9-5-Do-central-banks-need-to-issue-currency.html
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- Positive Money

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