

Countermeasures against Government-Scale Monetary Forgery^{*}

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Abstract. Physical cash is vulnerable to rising threats, such as large-scale, government-mandated forgeries, that digital cash may protect against more effectively. We study mechanisms to combine physical cash with digital cash to remove their respective shortcomings and obtain their combined advantages. We discuss initial mechanisms and examine their cost and benefit trade-offs.

Keywords: Economics of security, Monetary forgeries, Secure payment systems.

1 Introduction

We consider the problem of monetary forgery by an extremely powerful adversary, such as a hostile government. Government-scale monetary forgery differs from traditional forgery perpetrated by organized crime in scale, motivation, and perception. A counterfeiting government has access to manufacturing resources and capabilities that can be considered equivalent to that of the national bank whose currency is being faked. Further, the forged bills may be used to finance hostile activities, such as weapons purchases or terrorism sponsorship. As a result, targeted countries may be willing to consider relatively expensive defenses against government-mandated forgeries.

The core contribution of this paper is to introduce and outline the main technical and economic challenges that stem from the design and deployment of possible countermeasures against government-scale monetary forgery.

An approach to preventing forgery of physical cash is to combine it with digital cash, yielding *physical digital cash*. Physical digital cash consists of regular bills in which the issuing government embeds an easily verifiable cryptographic value. The goal is to devise a monetary system resilient to forgery, which preserves the usability of existing cash and does not require drastic changes to the existing monetary infrastructure.

Physical digital cash presents a number of design trade-offs between the security properties achieved, the technological complexity involved, and the economic costs incurred. We explore these trade-offs by discussing security requirements, comparing different proposals, and examining possible attacks against physical digital cash.

2 Physical Digital Cash Requirements

The macroeconomic impact of monetary forgeries remains small: forged US dollar production would have to increase by a factor of 200 compared to the current amount of

^{*} An extended version of this paper is available [1].

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forgeries in circulation to have a 1% impact on the US inflation rate [1]. Thus, to justify any drastic changes to the current approach of physical security combined with police intervention, the marginal cost of physical digital cash should be tightly constrained - that is, digital extensions required for physical bills should impose a negligible overhead over current production methods (*simple upgrade*). Moreover, people are generally conservative when it comes to currency, and tend to resist drastic changes when they do not perceive any added value. Hence, physical digital cash should present only a *minimal cost to the users* while at the same time providing tangible benefits.

In terms of usability, physical digital cash should provide the same *universal use* characteristics as current physical cash, offering extreme ruggedness and enabling exchange without any digital devices. A single physical digital cash bill should also be *reusable* once it is passed from one owner to another. This is in contrast to digital cash, which is used only once, then destroyed.

To be resistant to any type of counterfeit, physical digital cash should be *forgery-proof*, that is, it must be computationally infeasible to create bills with new denominations or serial numbers. Physical digital cash must also ensure *useless duplication*, that is, it must be impossible to duplicate an existing bill and successfully cash both bills.¹ In addition, bills must be *universally verifiable*, for instance by using a commodity electronic verification device, such as current camera-equipped smart phones. Finally, one of the most salient features of physical cash is *anonymity*. Even though banknotes do not ensure perfect anonymity [5], physical digital cash should provide a level of anonymity equivalent to that provided by physical cash.

3 Physical Digital Cash Techniques

We consider a number of techniques for designing physical digital cash, including novel proposals. We evaluate both the advantages and disadvantages of each system. While none of the techniques perfectly meets all requirements outlined in Section 2, they represent interesting and useful building blocks for future physical digital cash schemes.

Barcode signatures. To keep all the properties of existing physical cash while strengthening the design by cryptographic primitives to make forgery impossible, the issuing authority can sign the sequence number N and denomination D of the bill with its private key R_{gov} . To preserve the ruggedness of physical cash, we propose to embed the digital signature on the bill using a 2-D barcode, e.g., PDF417 [4]. Embedding such signatures maintains *universal use*, makes bills *forgery-proof*, and can be *universally verifiable*, using for instance smart phones with barcode reader software. The manufacturing technology for adding a barcode is trivial, making it a *simple upgrade* to the production process. Finally, a physical digital cash bill does not contain more information than a traditional bill: the signature itself can only be used to verify the authenticity of a bill. Thus, the proposed scheme satisfies our *reusability* and *anonymity* requirements. However, used alone, signatures cannot enforce the *useless duplication* property. Indeed, a duplicated bill would have the same serial number N and denomination D as the original (valid) bill, so that the signature $\{N, D\}_{R_{gov}}$ would remain valid.

¹ This property does not necessarily imply that duplicating a physical digital cash bill is impossible, but merely that the duplicated bill should be useless.

RFID-based protection. An alternative solution, which was once considered for Euro bills [8], is to embed RFID chips in bills. Using an RFID chip offers two primary advantages over 2-D barcodes. First, an RFID chip can perform limited computations and can even interact with a reader. Second, while 2-D barcodes are read-only, some RFID chips have writable memory. Assuming tamper-resistant RFID chips (an assumption we cannot make given current technology), this solution can enforce all desired security properties, using a per-bill public/private key pair [1]. However, RFID chips are less tolerant of daily wear and tear and extreme environmental conditions than the original bill, and may not satisfy the *universal use* requirement. Also, RFID readers have yet not yet penetrated the consumer market, preventing *universal verifiability*, and embedding a computational device in each bill would significantly raise the cost per bill, preventing a *simple upgrade*. Last, RFIDs may be remotely read, which could raise numerous new vulnerabilities [1].

Physical one-way functions. The useless duplication property can be enforced by making each bill structurally unique (physical one-way function). This can be done by randomly sprinkling bits of optical fiber in the fabric of each banknote [7], or by using magnetic polymers [3]. The issuing authority can numerically encode the bill's unique structure, digitally sign the resulting value, and print a machine-readable version of the signature on the bill. The unique physical structure prevents *duplication*, and the signature make bills *forgery-proof*.

Three important problems remain open, however, regardless of the physical one-way function used. First, the manufacturing cost of such bills is hard to assess, but probably does not satisfy our *simple upgrade* requirement. Second, fibers or polymers may break or get dirtied easily, resulting in genuine bills failing the verification process. Third, the equipment needed to verify such enhanced bills is likely to be too high an investment for most merchants, let alone individual users. However, as we discuss later, physical one-way functions may be useful in conjunction with other techniques.

Centralized verification. To make duplication more costly for counterfeiters, the central issuing bank can keep a database of issued serial numbers. When a bank receives a note for deposit, it consults the database to verify that the serial number is legitimate and has not already been deposited elsewhere. Similarly, banks inform the central bank of the serial numbers of notes that leave their control. Since this approach can be applied to unmodified physical cash, it retains the benefits of existing cash. Even *anonymity* remains, since serial number data is already available at the member banks.

The major drawback of the method is that it imposes costs on the central bank, which must maintain the serial number database, as well as on the member banks that must constantly monitor and report on the serial numbers entering and leaving their control. In addition, forged and duplicated bills remain undetected until deposited.

Online verification. Ideally, we could achieve instant detection of duplicates, such that no one would accept a duplicate bill. This could be done by an online verification scheme using a decentralized database that associates each bill's serial number with a cryptographic "lock bit". Once a bill is locked, only the current "owner" of the bill can unlock it. To transfer ownership of a locked bill, the current owner cryptographically unlocks it and allows the new owner to lock it. Participants can check the current state of a particular bill's lock bit and refuse to accept a locked bill.

We describe an online verification scheme that preserves anonymity and handles legacy users in our technical report [1]. The key idea is to allow the current owner of a bill to lock it using a one-time public/private key pair. Such a key pair may be generated by choosing a (private) random number and computing its (public) hash value. The bill is locked under the public value until the owner asks the bank to unlock the bill to pass it on to a different user. The unlock operation is authorized by providing the owner's private value. Because the cryptographic material is not reused across bills or transactions, tracing users is difficult, so that the scheme provides reasonable anonymity.

The whole exchange assumes that users are able to contact the bank during the transaction, using for instance a cellular phone. "Legacy" users unable (or unwilling) to be online can only use unlocked bills. The size of the database of locking materials is non-trivial, but it remains smaller than that of giant databases like web indexes, and therefore appears manageable. More importantly, the economic costs associated to the deployment and maintenance of such an online database warrant further investigation.

Such a scheme could achieve all of the desired properties, with one key assumption: the central bank has to be able to distinguish a duplicate from a real bill through some, possibly costly, secondary verification process. For instance, the physical one-way functions described above could assist in the verification process on the bank side. Used as a back-up verification system, physical one way functions do not need the same level of robustness as when used as the primary mechanism to prevent duplication.

4 Security Analysis

The various techniques outlined above for implementing physical digital cash raise a number of questions regarding possible vulnerabilities of physical digital cash.

Compromised private keys. If the private key R_{gov} used for signing the bills is compromised, then physical digital cash is no longer forgery-proof, and the security level degrades to that of physical cash. Replacing keys is easy, but recalling bills signed with the compromised key may be problematic. One approach is to use many different private keys, and only sign a relatively limited number of bills with a given private key. This can for instance be implemented with forward-secure digital signature schemes [2].

Fake signatures. Setting cryptographic attacks aside, fake bills may be produced with missing or incorrect digital signatures. A missing signature is easy to notice, but, in the absence of scanning equipment, there is no obvious visual distinction between a good and a bad signature. Worse, the visible presence of a digital signature (e.g., a 2-D barcode) may convince users that the bill is good, even though other physical indicators, e.g., the quality of the paper, or the absence of a watermark, may be questionable.

Rogue financial institutions. One whole class of attacks can be characterized as "money laundering," that is, in our context, exchanging fake bills for good bills. For instance, a dishonest merchant may try to pass on bad bills to customers. This type of attack already affects the existing physical cash network, and the defense for physical digital cash is identical: individuals should check bills they are given.

A more elaborate version of money laundering involves an attacker colluding with a rogue bank, which cashes counterfeited bills produced by the attacker without checking them. Then, the counterfeited bills are sent to the bank's currency exchange office,

where they are exchanged for good foreign currency bills from unsuspecting tourists. As long as bills are not verified, they may travel in the network. Monitoring banks is a plausible countermeasure against such an attack. Compared to the large number of bill users, there are relatively few banks in the world, so a centralized authority (e.g., a treasury department) could monitor them effectively. Recent events [6] indicate that such monitoring already exists in practice.

Localized injection. Massive, localized, injection of forged notes can cause serious economic problems if the forgeries cannot be immediately detected. For instance, an attacker using a plane to drop millions in fake currency over a metropolitan area could significantly damage the local economy, with a ripple effect on the national economy.

The only way to counter such an attack is to make the fake bills impossible to spend; that is, to ensure that bills can be immediately verified, and that useless duplication can be readily enforced. Conversely, any method requiring expensive verification devices will have the adverse effect of letting the fake money travel in the network for a longer time period, and possibly to be spent multiple times. Among the techniques we discussed in this paper, inexpensive online verification coupled with a 2-D barcode signature seems more robust against this type of attack than alternative proposals.

5 Conclusion

To significantly strengthen current bills against government-scale monetary forgery, we propose to augment bills with cryptographic material directly embedded in the bill. None of the techniques we investigate or propose, when used in isolation, satisfies all the properties we would like to enforce. However, a combination of these techniques – for instance, coupling our online verification protocol with barcode signatures (with physical one-way functions serving as back-up) – comes very close to implementing all of our requirements. By driving forgeries back to the banks quickly, an online system should work very effectively as a deterrent against counterfeiting, even in the absence of wide deployment. In that respect, a deeper consideration of the economics at stake in the deployment of counterfeit-resistant bills warrants further research.

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