Micro Structure of Bitcoin Transaction Process

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***Abstract*-- Bitcoin is a form of digital currency, created and held electronically which are not printed. Bitcoin is a purely online virtual currency, unbacked by either physical commodities or sovereign obligation; instead, it relies on a combination of cryptographic protection and a peer-to-peer protocol for witnessing settlements. Bitcoin is an online communication protocol that facilitates virtual currency including electronic payments. Since its inception in 2009 by an anonymous group of developers (Nakamoto, 2008), Bitcoin has served approximately 41.8 million transactions between 62.8 million accounts. Digital signatures provide part of the solution, but the main benefits are lost if a trusted third party is still required to prevent double-spending. Bitcoin is a complex scheme, and its implementation involves a combination of cryptography, distributed algorithms, and incentive driven behaviour. Moreover, recent developments suggest that Bitcoin operations may involve risks whose nature and proportion are little, if at all, understood. Bitcoin is the world's first decentralized digital currency, allowing the easy storage and transfer of cryptographic tokens. The purpose of this paper is to provide the necessary technical background for understanding Bitcoin's basic operations. We discuss the micro-structure of the Bitcoin transaction process. The discussion pays special attention to the use of cryptography in the Bitcoin protocol. Specically, the protocol uses cryptographic algorithms for the security of transactions and for the implementation of distributed maintenance of a public ledger.**

I. INTRODUCTION

What is needed is an electronic payment system based on cryptographic proof instead of trust, allowing any two willing parties to transact directly with each other without the need for a trusted third party. Transactions that are computationally impractical to reverse would protect sellers from fraud, and routine escrow mechanisms could easily be implemented to protect buyers. In this paper, we propose a solution to the double-spending problem using a peer-to-peer distributed time stamp server to generate computational proof of the chronological order of transactions. The system is secure as long as honest nodes collectively control more CPU power than anycooperating group of attacker nodes. Bitcoin has often been compared to cash as transactions arenear-instantaneous and non-refundable. However Bitcoin goes beyond the scope of cash, allowing truly global transactions, processed at the same speed as local ones. It offers a publictransaction history and it introduces many new and innovativeuses such as smart properties, micropayments, contracts andescrow transactions for dispute mediation.

II.BITCOIN DESIGN PRINCIPLES

Many Bitcoin design principles are familiar from the Internet's architecture. Bitcoin's rules were designed by engineers, not lawyers or regulators. Furthermore, Bitcoin emphasizes decentralization. Rather than store transactions on any single server or set of servers, Bitcoin uses a distributed transaction log with mechanisms to reward honest participation, bootstrap acceptance by early adopters, and guard against concentrations of power. Anyone can create an account, without charge and without any centralized vetting procedure or requirement to provide a real name.

III. ENABLING TECHNOLOGIES

The Bitcoin core consists of the protocol (including an opensource reference implementation), many globally distributed computers connected in a peer-to-peer network on top of standard Internet protocols, and the state of the system, which is encoded in a distributed data structure that holds the system's transaction ledger. The Bitcoin core is surrounded by an ecosystem of agents who use Bitcoin and offer related services, as discussed in subsequent sections. By design, Bitcoin lacks a centralized authority to distribute coins or track who holds which coins. Consequently, the processof issuing currency, verifying validity, and confirming balances is considerably more difficult than in classic bookkeeping systems. The primary innovation in Bitcoin's design is its ability to perform these functions without a centralized authority. Bitcoins are actually recorded as transactions. For instance, some user Charlie does not simply "hold" three bitcoins. Rather, Charlie participates in a publiclyverifiable transaction showing that he received three bitcoins from Bob. Charlie was able to verify that Bob could make that payment because there was a prior transaction in which Bob received three bitcoins from Alice.

Indeed, each bitcoin can readily be traced back through all transactions in which it was used, and thus to its start of its circulation.A consequence of decentralized verification and consensus is that all transactions are readable by everyone in records stored in a widely replicated data structure. In general, transactions are ordered recursively by having the input of a transaction (roughly, the source of funds) refer to the output of a previous transaction (e.g., Bob pays Charlie using bitcoin he received from Alice).

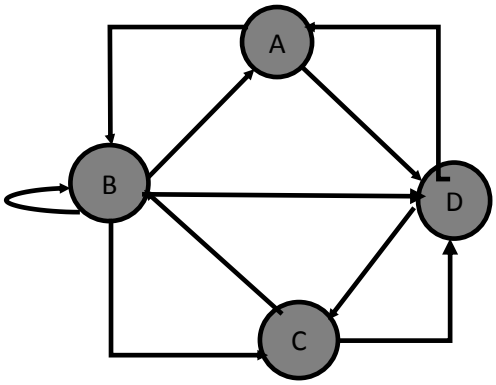
A. The Role of Cryptography

Whereas most encryption conceals information from public scrutiny, Bitcoin uses cryptography for the fundamentally different purpose of enforcing system fairness. First, Bitcoin uses private keys to authorize spending money: Only with an accountholder's private key may funds from that account be spent. Digital signatures then allow others to verify that a given message, purportedly spending funds from a given account, in fact occurred with permission from the authorized user of that account. Notice that no centralized bookkeeper is needed; no single party need know all account holders. Rather, the system is open, and standard public-private cryptography (Diffie and Hellman 1976) lets anyone verify that a message comes from its putative sender. Second, Bitcoin uses cryptographic principles to facilitate an accurate and non- gameable record of transactions, known as the "block chain." In principle the Bitcoin system could use a simple consensus by majority vote, with a majority of connected users able to affirm that a given transaction in fact occurred. But then an attacker could game the system by creating numerous fake identities, known as a Sybil attack (Douceur, 2002). In response, the Bitcoin protocol makes it costly to submit fake votes. Consistent with the Internet's open architecture, anyone can connect multiple computers to the Bitcoin system. But voting requires first working to solve a mathematical puzzle that is computationally hard to solve (although easy to verify). Solving the puzzle provides "proof of work"; in lieu of "one person, one vote," Bitcoin thus implements the principle of "one computational cycle, one vote."

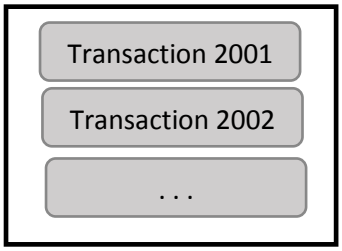
IV. BITCOIN: TRANSACTIONS

Figure1shows a diagram of payments on the Bitcoin users' network. The nodes areentities and the directed arrows depict payments in bitcoin. As the diagram suggests,the entities transactdirectly, that is, in contrast to most traditional payment systemswhere various parties, such as banks, processors, and networks, sit between the payer and payee, there is no designated intermediary in Bitcoin. Each transaction is chronologically recorded in a public ledger, called the block chain, by participants in the network.There is a reward for recording transactions in the block chain, and the participants in the Bitcoin system compete (by solving a computationally intensive cryptographic problem)to make records. A well-defined process, which guarantees consensus, elects the winning participant and the block chain is updated. Importantly, each participant keeps a copy ofthe ledger, and the consensus of the incremental changes guarantees that these copies are identical. Thus, the verification and the record keeping of transactions is decentralized.

Figure 1: The Bitcoinpayment transaction concept



Blockchain



Note:

There are four entities A, B, C and D, transacting directly with each other, i.e.with no intermediary. In addition, the diagram shows the possibility of B transactingwith itself. All transactions are chronologically recorded in a public ledger called a block chain.

The Bitcoin transaction process is fairly complex and computer scientists are activelyinvestigating aspects of its security, privacy, distributed control and incentive schemes. For example, although Bitcoin is referred to as a near-instantaneous payment system (on
average it takes 10 minutes to process a transaction), some have questioned its suitability for fast payments.

A. The Bitcoin transaction process

We now turn to describe the Bitcoin transaction process. Because cryptographic algorithms have implications for the security and privacy of Bitcoin's implementation, we start with a brief overview. Then we turn to describe a transaction record on the public
ledger. Because the public ledger is the main source of information for the activity in the Bitcoin system, its structure naturally determines the scope of our empirical analysis.Finally, we present the process of executing a payment between two parties using the Bitcoin network.

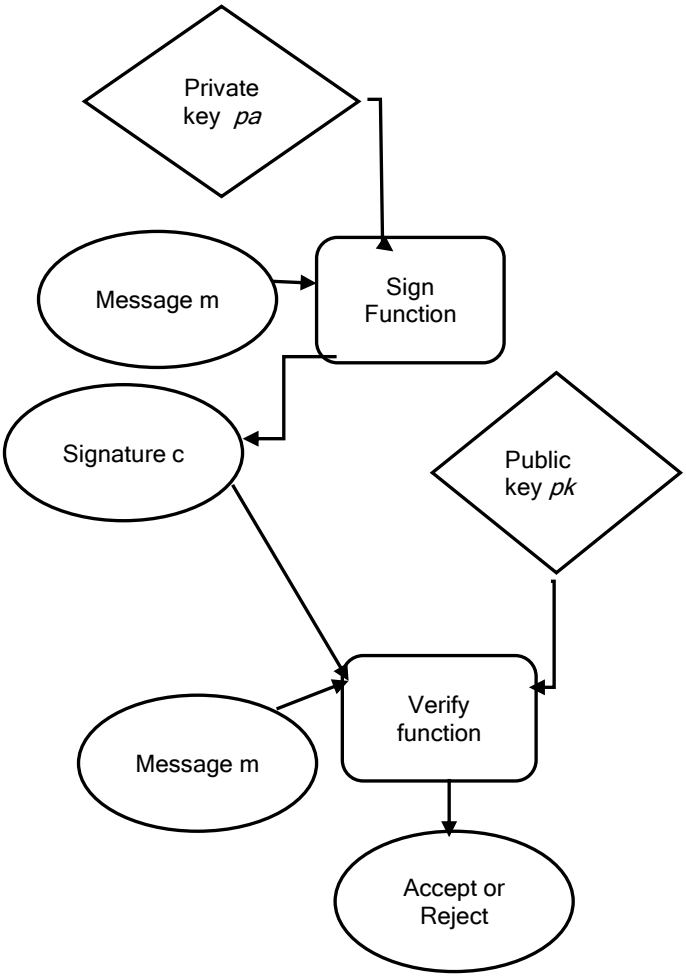
1. Cryptographic basics.

The Bitcoin transaction process uses cryptography to verify transactions, process payments, and control the supply of bitcoins. The particular cryptographic schemes implemented in the Bitcoin protocol are not new and, in fact, are used in a wide range of information security applications. Because the topic is somewhat esoteric in economic applications and, more importantly, because we

believe that cryptographic and distributedalgorithms may have applications to a broader set of economic practices reaching beyondthe payment industry, we review at some length the principles of their operation below.

Bitcoin relies on two cryptographic schemes:digital signaturesandcryptographic hashFunctions. Briefly, the former enables the exchange of accurate (payment) instructionsbetween the parties of a transaction, and the latter is used to enforce discipline in writing
transaction records in the public ledger. Neither of these schemes is unique to Bitcoin; they are widely used to secure commercial and government communications. For the sakeof completeness, we provide a brief outline below.

Figure 2: Public Key Encryption



2.Digitalsignatures

Digital signatures are a way to authenticate a message between a sender and a receiverin a way that ensures:

(i) authentication: the recipient can verify that the message came from the sender,

(ii) non-repudiation: the sender cannot deny sending the message,

(iii) integrity: the message has not been tampered with.The implementation of digital signatures involvespublic key encryption, where a pair ofkeys-|public and private -are generated with certain desirable properties.

Figure2illustrates the process of digitally signing a message (or a unit of data).The “sign" function combines the message with the private key of the sender to produce Signature. The process of obtaining cisin eff-ect signing the message with the identityof the sender, her private key pa. The intended recipient then receives the signed message(the messagemtogether with its signaturec). Before accepting the message, the receiver verifes the authenticity of its sender by comparing the message and the public key of thesender. This is done by the \verify" function that takes as inputs the signed message (mandc) together with the public key pk and produces a binary output state: accept orreject. The sign and verify functions are publicly accessible.

The Bitcoin protocol employs the above scheme to sign transaction messages. Inparticular, transactionmis signed with the private key paand then broadcast to the bitcoin network. All members of the Bitcoin system can verify that this transaction camefrom the owner of public key
Pk by taking the message m, signature c, and public key pk and running the verification algorithm.

3.Cryptographic hash function

In general, a cryptographic hash function takes as input a string of arbitrary length andreturns a string with predetermined length. We will refer to the input as messagemandthe output as hashh. The function is deterministic, meaning that the same inputmwillalways give the same outputh. However, knowing the hash of the message reveals little ifanything about the message. This is fundamental for hash functions and is more formallystated below.

1. Pre-image resistance. Given a hashhit is difficult to and a messagemsuch thathash(m) =h^{20}.
2. Second pre-image resistance. Given messagem1it is difficult to find a di erentmessagem2such that hash(m1) = hash(m2). In other words changing the messageleads to changing the hash.
3. Collision resistance. It is difficult to find two different messages m 1 and m 2 such that hash(m 1) = hash(m 2).

Another desirable property of the hash function is that even small changes in message m are likely to change hash h = hash(m) significantly. This makes it very unlikely for someone to be able to infer the content of the message from the hash. In summary, the output of hash functions is very much unpredictable (looks random) although it is deterministic. Bitcoin mainly uses SHA-256, a type of Secure Hash Algorithm (SHA-2) designed by the National Security Agency and published by the National Institute of Standards and Technology.

V. A BITCOIN TRANSACTION

A. Bitcoin ownership and Bitcoin addresses

From a technical point of view, bitcoins reside in what is known in the bitcoin system as bitcoin addresses. The ownership of a particular amount of bitcoins reduces to the capability of sending payments (over the Bitcoin network) from the bitcoin address(es) with which these bitcoins are being associated. The capability of sending payments from Bitcoin addresses is controlled via digital signatures (we introduced above) that involvepairs of a public key pk and a private key pa. In particular, each bitcoin address is indexed by an unique public ID|an alpha numeric identifier which, in fact, corresponds to the public key pk. The private key pa, which is the counterpart of pk, gives control over the bitcoins held in this address. Specically any payment (message) involving this addressas a sending addresshasto be signed with the proper private key to be considered valid.In simple words, owning the bitcoins in a given bitcoin address amounts to knowing theprivate key which corresponds to the public ID (i.e. the key pk) of that address.

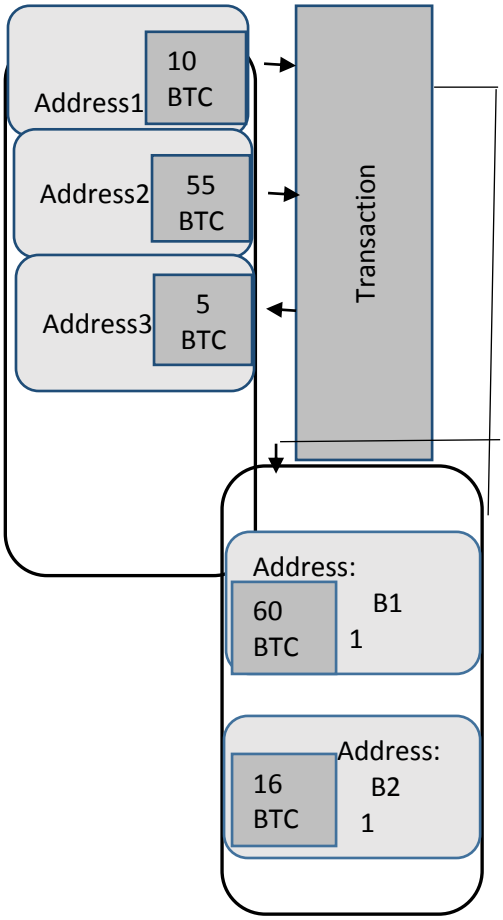
At any point in time every bitcoin address is associated with a given bitcoin balance which is, in effect, public information. This is the case because any participant in the Bitcoin network can deduce the bitcoin balances following a given transaction history that isrecorded in the public ledger. In particular, every existent or proposed (newly broadcast)transaction can be checked for consistency against the preceding history of transactionsi.e. it can be verified that the amounts transacted are available in the corresponding bitcoin addresses.

1. A transaction on the block chain

Entities engage in transactions on the Bitcoin network through a collection of bitcoin addresses, figuratively called their wallet - a set of bitcoin addresses owned by a singleentity.

In particular, each transaction record involves one or more sending addressesand one or more receiving addresses together with how much each of these addressessend and receive. Figure3reflects this description. In the figure, there are two sending

Figure 3: A Bitcoin transaction.



addresses (sending 10 and 55 BTC, respectively) and two receiving addresses (receiving60 and 5 BTC, respectively). Note that a transaction is the atomic record in the ledger, that is the most detailed level of reporting recorded on the block chain. An importantimplication is that because there may be multiple sending and receiving addresses pertransaction record, one cannot assign a particular sending address to the funds being sentto a particular receiving address. A further implication of this observation is that onecannot assign serial numbers to bitcoins and trace their paths on the Bitcoin network.

VI. THE BITCOIN TRANSACTION PROCESS

The Bitcoin transaction process has mechanisms in place which guarantee that (a) the verifcation of each transaction is distributed among multiple participants in the network,(b) the recording of each transaction is time discretized, i.e. transactions are linearlyordered with consecutive time stamps, (c) the participants in the payment network compete and are rewarded for recording a transaction, and(d) multiple nodes cross-checkeach transaction record.

A. [1]Initiating a transaction

Suppose that Alice would like to send Bob 1 bitcoin using the Bitcoin network. To dothat, both Alice and Bob need to have bitcoin addresses. Call theseaddress^{Alice}andaddress^{Bob}. Then Alice needs to issue and (digitally) authenticate a message of the sort

"address^{Alice}is sendingaddress^{Bob}1 bitcoin."

Once Alice signs a transaction message, with her privatekey and broadcasts it, every one on the Bitcoin network can verify that it was Alice whoissued the message and the message has not been tampered with. Moreover, as we pointedout earlier, the digital signatures ensure that no one else could have signed this message,i.e. Alice cannot deny having signed it.

B. Verifying a transaction

Before executing a transaction (which amounts to recording the transaction on the ledger)the Bitcoin protocol has to verify two aspects of the transaction message:
" address^{Alice}is sendingaddress^{Bob}1 bitcoin". First, is it Alice who has broadcast the transactionmessage?As we discussed, the digital signature scheme guarantees that indeed onlythe owner of the private key for this address could have signed the message. Second,are there enough funds at the sending address to guarantee that the transaction can becompleted? Below we discuss how the Bitcoin protocol handles this in a hypotheticalscenario, deferring the complexity of the underlying mechanics for a moment.
Suppose there were a single designated participant who maintains all account balancesand receives each transaction request. In addition, suppose that the protocol requires thattransactions are accepted sequentially, for example, every day there is at most one transaction accepted for verification and clearance. It would have then been trivial in termsof e
ort for this designated entity to verify the integrity of the transaction request andthe availability of funds, and then proceed to record the transaction. Moreover, the factthat transaction requests are accepted sequentially guarantees that duplicated messagesand double spending can be readily detected. Note that this hypothetical scenario doesnot require the books to be either public or private.More generally, although maintenance of records and verification of transactions are core functions of all electronic payment systems, these functions typically occur throughprivate ledgers maintained by trusted third parties.
Decentralized systems such asBitcoin replace third party intermediaries and the records kept by them with the publicledger maintained by a distributed information system. In particular, the public ledger. Note that Bob's authorization is not needed for initiating and eventually recording the transaction.
In payment card systems, for example, banks maintain their own records of the balances of theiraccount-holders. These banks, in turn, use the functionality and record-keeping systems of payment cardnetworks to exchange information needed to allow the transfer of balances between agents in the system allows for decentralized approach to transaction message verification.

C. Blockchain update

After the initial verification of a signed transaction message, a set of participants in the Bitcoin network compete to record the transaction in the block chain. First, the competing nodes group transactions, which have been broadcast since the last record on the block chain, in a block of transactions. The block then is used to define a computationallyintensive task (to be discussed below). The winner of the competition is the node who firstsolves this task. Once the winner is determined, the transaction record is completed.The winning node is entitled to make the record and collect the reward. It remains todescribe the computationally intensive task that defines the competition for recording ablock of transactions.The task on which the nodes compete builds on one of the cryptographic schemeswe discussed above -the hash function.. First, a block ofnewly broadcast transactions is used as an input into the cryptographic hash functionto obtain a hash called adigest. This digest together with announce-|an alpha-numeric string-and the hash of the previous block, are input into another hash function that delivers a block chain hash of the new block. The task that nodes need to solve comprises finding a nounce such that the block chain hash of the new block has certain properties.The first competing node to find a desirable nounce broadcasts this information to the rest of the network, and the ledgeris updated.This scheme is an implementation of Hash cash, a type of proof-of-work system, whose goal is to ensure that computers use a defined number of computational resources to complete some. The nodes that carry out the proof-of-work process are known in the Bitcoin ecosystem as miners. These miners are incentivized to spend computational resources in thisprocess by an award built into the Bitcoin protocol. For the most part the award is a predetermined amount of newly generated bitcoins. The rest of the award, which currently is of much lower value, is voluntary transaction fees that are paid by the initiators of transactions to the miners in order to process their transactions. The initial idea wasthat these voluntary fees would replace the coin-generation reward to incentivize minerswhen that amount goes to zero.

ACKNOWLEDGEMENT

Thank you for all my subordinates.

REFERENCES

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