



# **DAGCOIN**

# **WHITEPAPER**

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14th of May 2018, Daft version 0.3



# DAGCOIN

## VISION

The vision of Dagcoin is to be one of the most used everyday currencies in the future world. A world, where innovative technologies have enabled access to digital money and its benefits to every person on our planet.

## MISSION

The mission of Dagcoin is to create a cryptocurrency built on advanced technology and valued by fundamental parameters that prevent price manipulation. To create a stable cryptocurrency with near instant transaction speeds and unnoticeably low transaction fees. A currency that the people can trust for their everyday transactions, and which attracts a wide community of users and merchants.

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## 2. Abstract

There are more than 700 different cryptocurrencies available around the world. Majority of them are based on blockchain technology, which was invented in 2009. When bitcoin first came live. Blockchain technology has been going through many improvements such as proof of stake instead of proof of work, many different mining algorithms are in use and latest improvement, segwit, went live with litecoin and other coins. Still there are some major issues regarding the blockchain technology.

First issue regarding blockchain is scalability. On a bigger scale - listening transactions, putting them into the blocks and trying to get confirmation and consensus over the blocks - it just takes time. It doesn't matter much, either it's POW or POS, even compared to some centralised transaction platforms, such blockchain designs are too slow.

Another issue is the cost of proof of work. Today, bitcoin transaction, which initially was made to bring down the cost of the money transactions, is one of the most expensive transactions in the world. POW isn't energy effective way to secure ledgers.

Third issue is the fact what the cryptocurrency community has been acknowledged that some way, majority of the miners, are holding the key of final word for the new improvements and enhancements inside the network. Miners are like a separate interest group, with their own economic incentives, besides being the inducers who are transacting inside the network. That has been the blocker to introduce new features in bitcoin blockchain. For example the activation of segwit and ethereum blockchain moving from POW to POS.

## 3. Introduction

Dagcoin is a decentralized cryptocurrency which is meant for wide usage mainly in developing economies but can be used all around the world.

Dagcoin was initially built on top of the Byteball network. Byteball was first introduced by Anton Churyumov in 2015 and has been in live since September 2016. In May 2018 a genesis unit of Dagcoin's independent Dagchain was created, marking the beginning of the new era with an enhanced and tailormade technology.

Dagcoin's data is stored and ordered using directed acyclic graph (DAG) rather than blockchain. This allows all users to secure each other's transactions by referencing earlier transactions created by other users, and also removes scalability limits common for blockchains, such as blocksize issue.

The consensus algorithm used to protect from double-spends is based on establishing a total order within the DAG. This is achieved by selecting a chain, called main chain, which gravitates towards units issued by commonly recognized reputable users — witnesses.

All together there have been issued 9 000 000 000 dags which means 90<sup>15</sup> microdags.

By using Dag-chain, Dagcoin is the first cryptocurrency that is targeting developing markets with the capability of being an everyday currency. Having solved the issues of scalability and keeping the cost of transactions fee-s very low, the only challenge is to spread the knowledge about cryptocurrencies and Dagcoin. For this, extensive marketing campaigns will be run in social media and in traditional marketing channels alongside with affiliate marketing.

It is important to educate the end user on what is cryptocurrency and what are the benefits of using it.

## 4. Dagchain

### What is blockchain?

Most cryptocurrencies are based on innovational blockchain technology.

A **blockchain** is a public ledger of all transactions that have ever been executed. It is constantly growing as 'completed' blocks are added to it with a new set of recordings. The blocks are added to the blockchain in a linear, chronological order.

To use conventional banking as an analogy, the blockchain is like a full history of banking transactions. Transactions are entered chronologically in a blockchain just the way bank transactions are. Blocks, meanwhile, are like individual bank statements.

### Blockchain challenges:

#### Transactions per second

The ever-growing size of the blockchain is a problem for storage and synchronization. Bitcoin network can process 7 transactions per second and the most capable blockchains could theoretically process a few thousand transactions per second. VISA being the largest payments network is capable of processing 56 000 transactions per second. As cryptocurrency should help the unbanked, the need for transactions is much higher than even VISA can handle.

#### Transaction fees

Transaction fees rise with the increase of transactions. Users can pay bigger fees to the miners to motivate them to confirm transactions faster.

Blockchain is great for smart contracts and corporate bureaucracy, but not for everyday currency.

#### DAG chain

In addition to the information of the transaction, a DAG chain unit includes the signatures of one or more users who created the unit and references to one or more previous units (parents) identified by their hashes.

Units are linked to each other such way that each unit includes one or more hashes of earlier units, which serves both to confirm earlier units and establish their partial order. The set of links among units forms a DAG (directed acyclic graph). There is no single central entity that manages or coordinates admission of new units into the database, everyone is

allowed to add a new unit provided that he signs it and pays a fee. The fee is collected by other users who later confirm the newly added unit by including its hash within their own units. As new units are added, each earlier unit receives more and more confirmations by later units that include its hash, directly or indirectly.

Unlike blockchains where issuing a block is a rare event and only a privileged caste of users is in practice engaged in this activity, a new unit starts accumulating confirmations immediately after it is released, and confirmations can come from anyone, every time another new unit is issued. There is no two-tier system of ordinary users and miners. Instead, users help each other: by adding a new unit its author also confirms all previous units.

References to parents is what establishes the order (only partial order so far) of units and generalizes the chain structure. Since we are not confined to one-parent–one-child relationships between consecutive units, we do not have to strive for near-synchrony and can safely tolerate large latencies and high throughputs.

## **First uses of DAG chain**

### **Draft**

Back in 2015, Sergio Demian Lerner, a cryptocurrency specialist from Argentina, posted his draft (drafted already in 2012) of a coin based on DAG chain, which he named Dagcoin. This never became a project and remained just a draft, so no actual coin was created.

### **IOTA**

In the end of 2015 a cryptotoken optimized for the Internet-of-Things (IoT) industry called IOTA, was introduced. Instead of the global blockchain, the main innovation behind IOTA is a DAG that they call Tangle – a blockless distributed ledger which is scalable and lightweight.

### **Byteball**

Byteball was introduced in the middle of 2016. Byteball is a decentralized system that allows tamper proof storage of arbitrary data, including data that represents transferrable value such as currencies, property titles, debt, shares, etc. There is an internal currency called ‘bytes’ that is used to pay for adding data into the decentralized database. Other currencies (assets) can also be freely issued by anyone to represent property rights, debt, shares, etc.



## Dagcoin

Dagcoin is a decentralized cryptocurrency where the transactions are stored in the DAG Chain. Scalable technology, long-term strategy and unique concept are built up in a way that make this currency most usable, stable and reliable. Wide and comprehensive ecosystem supports worldwide adoption.



## 5. Byteball

Byteball is a decentralized system that allows tamper proof storage of arbitrary data, including data that represents transferrable value such as currencies, property titles, debt, shares, etc. Storage units are linked to each other such that each storage unit includes one or more hashes of earlier storage units, which serves both to confirm earlier units and establish their partial order. The set of links among units forms a DAG (directed acyclic graph). There is no single central entity that manages or coordinates admission of new units into the database, everyone is allowed to add a new unit provided that he signs it and pays a fee equal to the size of added data in bytes. The fee is collected by other users who later confirm the newly added unit by including its hash within their own units. As new units are added, each earlier unit receives more and more confirmations by later units that include its hash, directly or indirectly. There is an internal currency called 'bytes' that is used to pay for adding data into the decentralized database. Other currencies (assets) can also be freely issued by anyone to represent property rights, debt, shares, etc.

Users can send both bytes and other currencies to each other to pay for goods/services or to exchange one currency for another; the transactions that move the value are added to the database as storage units. If two transactions try to spend the same output (double-spend) and there is no partial order between them, both are allowed into the database but only the one that comes earlier in the total order is deemed valid.

Total order is established by selecting a single chain on the DAG (the main chain) that is attracted to units signed by known users called witnesses. A unit whose hash is included earlier on the main chain is deemed earlier on the total order. Users choose the witnesses by naming the user trusted witnesses in every storage unit.

Witnesses are reputable users with real-world identities, and users who name them expect them to never try to double-spend. As long as the majority of witnesses behave as expected, all double-spend attempts are detected in time and marked as such. As witnesses-authored units accumulate after a user's unit, there are deterministic (not probabilistic) criteria when the total order of the user's unit is considered final.

Users store their funds on addresses that may require more than one signature to spend (multisig). Spending may also require other conditions to be met, including conditions that are evaluated by looking for specific data posted to the database by other users (oracles).

Users can issue new assets and define rules that govern their transferability. The rules can include spending restrictions such as a requirement for each transfer to be cosigned by the issuer of the asset, which is one way for financial institutions to comply with existing regulations.

Users can also issue assets whose transfers are not published to the database, and therefore not visible to third parties. Instead, the information about the transfer is exchanged privately between users, and only a hash of the transaction and a spend proof (to prevent double-spends) are published to the database.

## 6. Dagcoin

### Definition

Dagcoin is a blockless Direct Acyclic Graph cryptocurrency. The advantage of leveraging such technology is that dags are not mined and therefore the whole process of transaction validating is lighter and scalable.

9 billion dagcoins have been defined. The definition though actually created  $90^{15}$  base units, called microdags ( $\mu$ dags). One dag is equivalent to one thousand millidags (mdags) and one mdag is equivalent to one thousand  $\mu$ dags.

Dagcoin was defined with the following technical specifications:

cap	9000000000000000
is_private	FALSE
is_transferrable	TRUE
auto_destroy	FALSE
fixed_denominations	FALSE
issued_by_definer_only	TRUE
cosigned_by_definer	FALSE
spender_attested	FALSE

### Codebase

The Dagcoin codebase is for the moment made of 3 distinct projects: the client, an explorer and a faucet.

The client is available for the following platforms: Windows, Mac, Linux and Android.

Some additional features were required, as initially Dagcoin was created as an asset on the Byteball network. These features were developed specifically for this asset, such as a faucet.

An additional feature, exchange hub, aimed to address the problem of transferring the asset from one end-user to another without them having to prefund their wallet with bytes to cover the fee needed to be paid for the units to be validated and processed by witnesses.

# 7. The exchange hub network

## Current Situation

We wanted to allow our end users to transfer assets without having to deal with the underlying Byteball network.

This is not easily achievable given the fact that for any transfer a new byteball unit is required, whose creation requires in its turn an expense of bytes.

What we need is therefore a way to provide our customers with the bytes they need transparently.

## Exchange Hubs and their functionalities

An exchange hub is an entity available on the asset's (and therefore byteball) network whose responsibility is to provide bytes (necessary for creating new transactions) to asset's clients who need or require them.

Funding hubs:

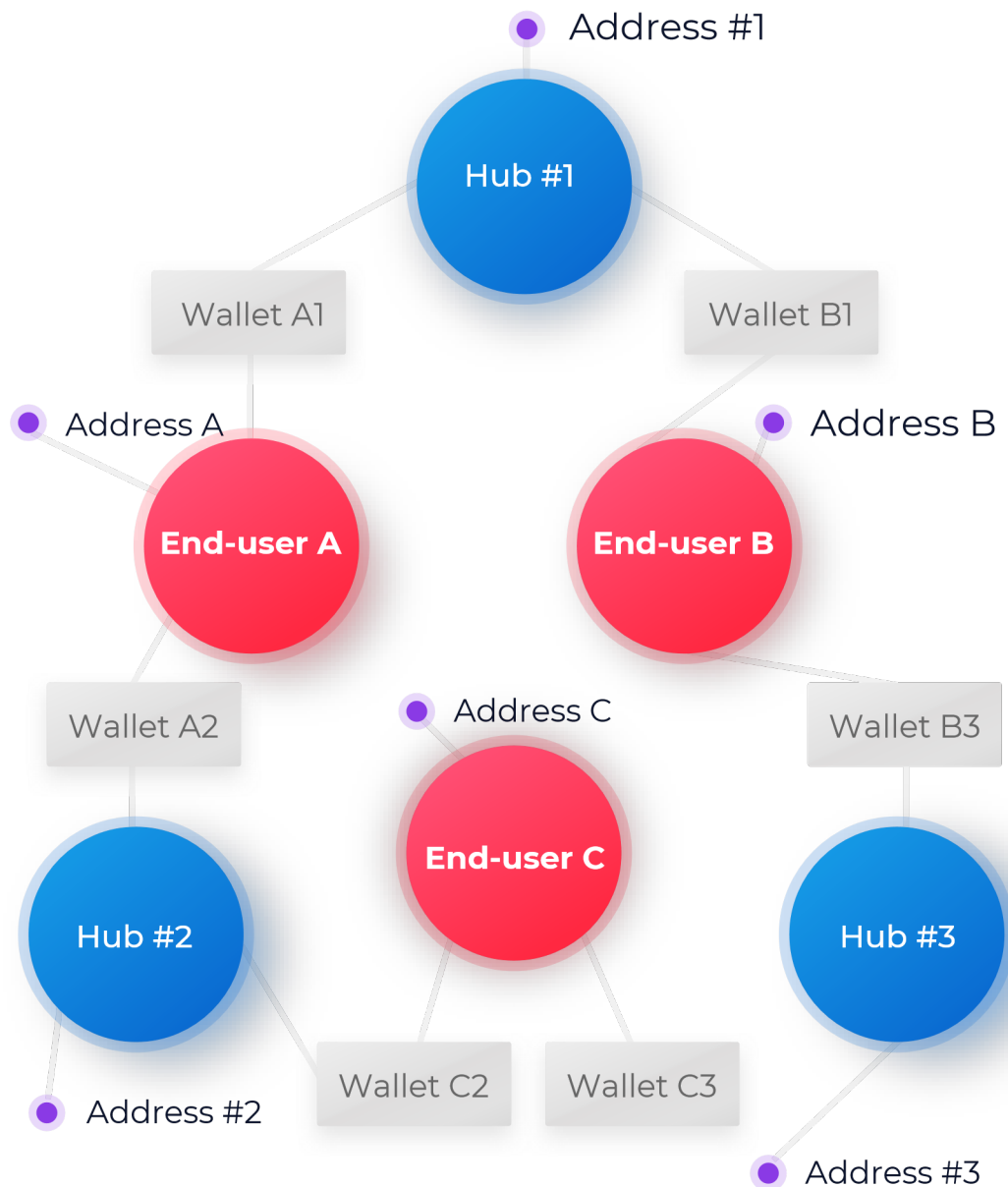
- Hubs work as an exchange office: they propose to exchange assets for bytes at a certain rate
- They work, similarly to witnesses, independently from each other in a way that anyone can have the possibility to become a hub. Potentially any client has this possibility.
- Their service can't be centralized or controlled completely by anyone
- Offer exchange rates: client may choose the best offer.

## Shared Address Solution

### Technical Assumptions to be Verified

- It is possible to share an address among wallets
- It is possible for the owner of the address to authorize or deny transactions. If the address is shared among many clients, a transaction can be denied or authorized only by the address owner (the hub).

A hub shares a richly funded address with clients who are interested in its service. The client can use such address as a fee payer for an asset transaction upon approval from the hub owning the address.



Each customer wallet would contain one address per hub it is subscribed to.

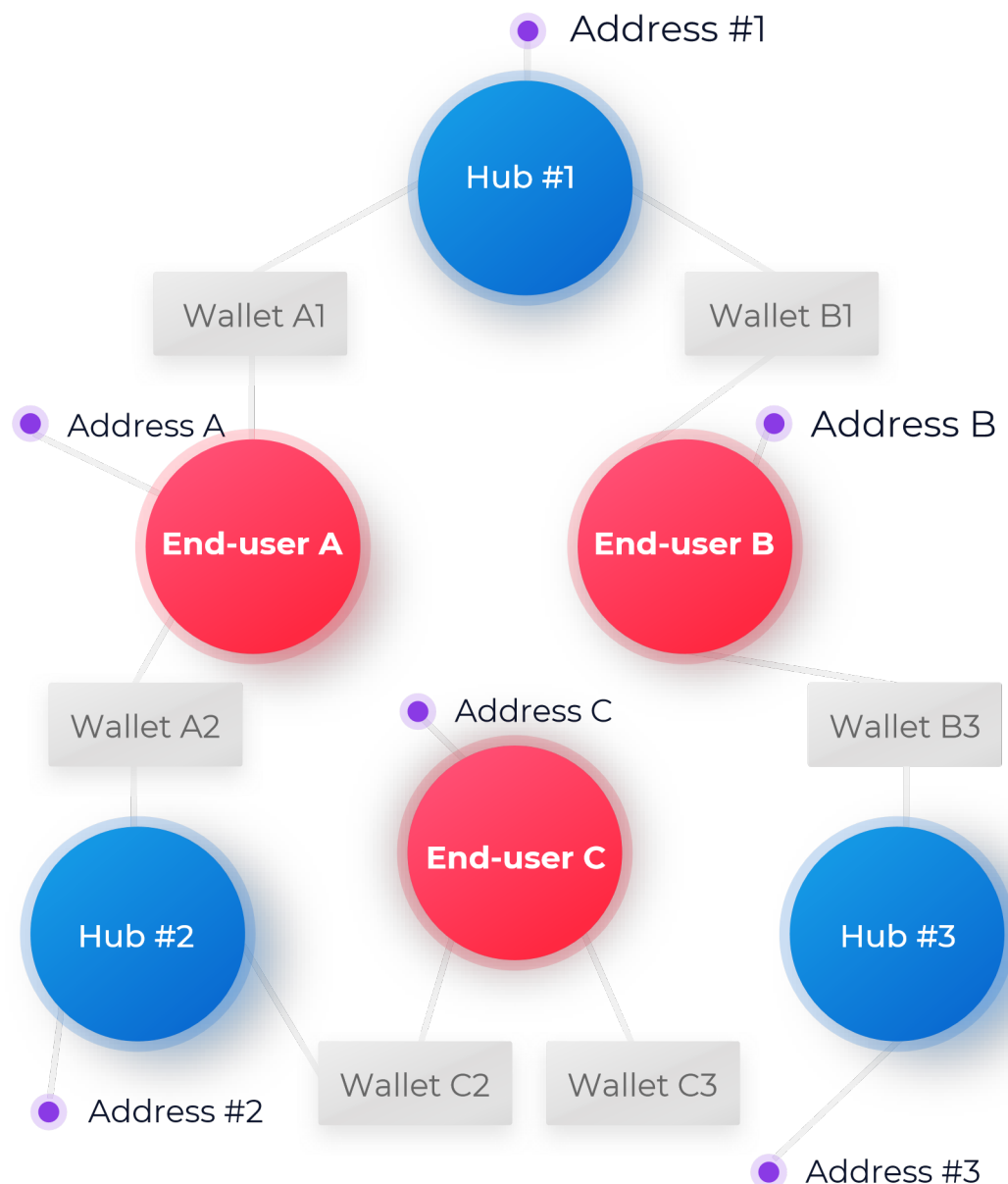
When it needs funds to create a new transaction, it uses this address as fee payer.

The hub will then sign the transaction.

## Shared Wallet Solution

## Technical Assumptions to be Verified

- Even in a shared wallet it is still possible to keep addresses separated and distinguish between the owners of the shared wallet
- One owner can hold his or her belongings in an address inside the wallet which no one else can manipulate.
- Using funds from an address requires the authorization of the real owner.



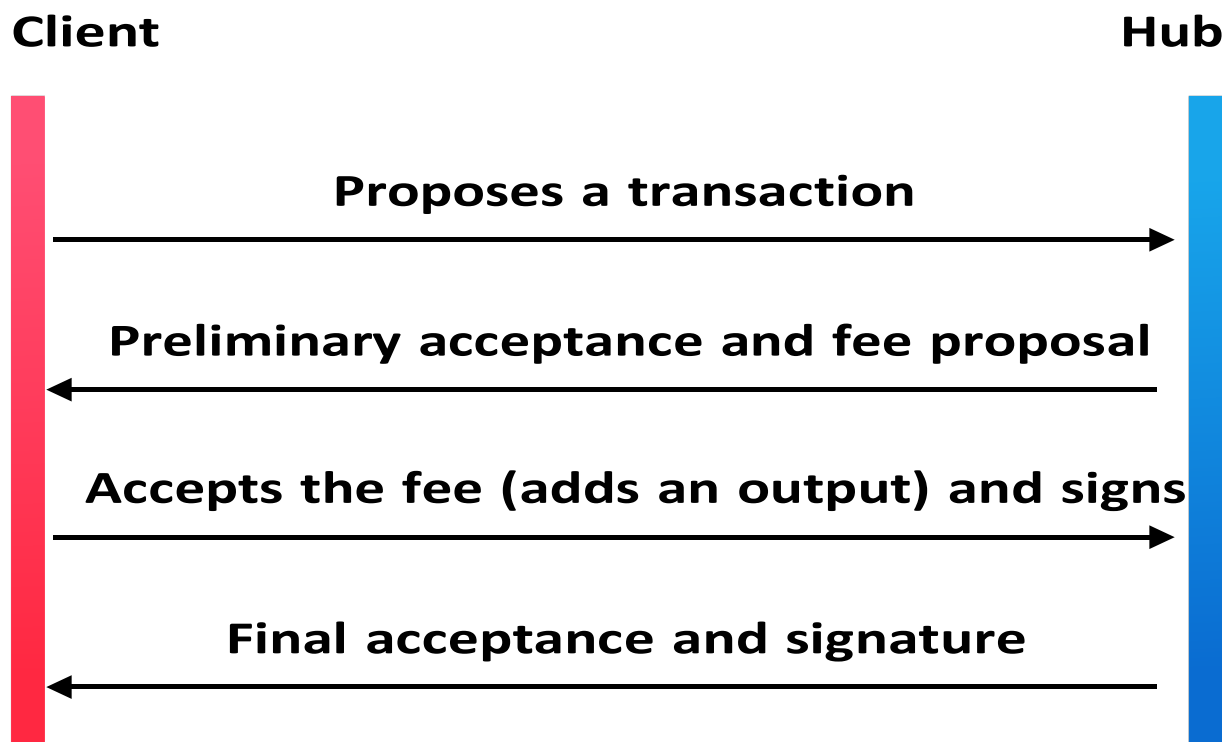
Upon client creation, a new wallet is created and shared with a hub. In this wallet there is an address private to the customer where the customer holds his valuables (assets) and a shared address where the hub holds some funds (bytes).

In this image it is shown that a solution based on shared wallet would in effect create a network of shared wallets between hubs and end users.

In such wallets, the end user address would be private to the end user and the shared address public to both. Creating a transaction using funds (bytes) from the hub shared address would require the hub to cosign.

## Hub funding protocol

Whatever is the underlying implementation (shared address or wallet or something else), the funding protocol will work more or less in the same way.



Imagine a scenario where one client wants to send some assets to another client without possessing the required bytes for creating the transaction.

We have the following actors:

1. Client A with a private address (#A) where some assets are stored.
2. Client B with a private address (#B) used for asset exchanges
3. Exchange Hub 1 with a public address (#1).

Client A has one only choice: using an exchange hub to fuel its transaction. A must find a hub, whose list can be possibly included in the code or through a discovery service.

From each hub A receives an address richly endowed with bytes to include in its wallet.

1. When A wants to send some assets to B, it creates a transaction setting as paying address the one received from the hub and asks the hub for a quote (an exchange rate to estimate the final price). The fee at this point is not final yet.
2. The hub 1 proposes a quote which the client may accept or refuse (in that case it must find a different hub to proceed)
3. A adds an output to the transaction containing a transfer of assets to the hub address equivalent to the amount of bytes required by the transaction if they were converted using the hub proposed exchange rate. Then it signs it. The fee in bytes in this moment is final.
4. The hub verifies that the transaction is correct (size, fee, exchange rate) and, if everything is as it should be, cosigns it, validating the transaction.

# 8. Extracts from Byteball Whitepaper

## 1. Database structure

When a user wants to add data to the database, he creates a new storage unit and broadcasts it to his peers. The storage unit includes (among other things):

- The data to be stored. A unit may include more than one data package called a message. There are many different types of messages, each with its own structure. One of the message types is payment, which is used to send bytes or other assets to peers.
- Signature(s) of one or more users who created the unit. Users are identified by their addresses. Individual users may (and are encouraged to) have multiple addresses, like in Bitcoin. In the simplest case, the address is derived from a public key, again similar to Bitcoin.
- References to one or more previous units (parents) identified by their hashes.

References to parents is what establishes the order (only partial order so far) of units and generalizes the blockchain structure. Since we are not confined to one-parent-one-child relationships between consecutive blocks, we do not have to strive for near-synchrony and can safely tolerate large latencies and high throughputs: we'll just have more parents per unit and more children per unit. If we go forward in history along parent-child links, we'll observe many forks when the same unit is referenced by multiple later units, and many merges when the same unit references multiple earlier units (developers are already used to seeing this in git). This structure is known in graph theory as directed acyclic graph (DAG). Units are vertices, and parent-child links are the edges of the graph.

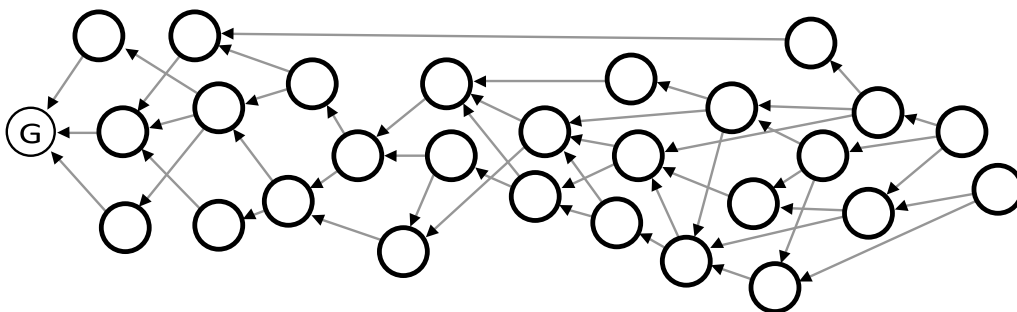


Figure 1. Storage units connected into a DAG. Arrows are from child to parent, G is the genesis unit.





In the special case when new units arrive rarely, the DAG will look almost like a chain, with only occasional forks and quick merges.

Like in blockchains where each new block confirms all previous blocks (and transactions therein), every new child unit in the DAG confirms its parents, all parents of parents, parents of parents of parents, etc. If one tries to edit a unit, he will also have to change its hash. Inevitably, this would break all child units who reference this unit by its hash as both signatures and hashes of children depend on parent hashes. Therefore, it is impossible to revise a unit without cooperating with all its children or stealing their private keys. The children, in turn, cannot revise their units without cooperating with their children (grandchildren of the original unit), and so on. Once a unit is broadcast into the network, and other users start building their units on top of it (referencing it as parent), the number of secondary revisions required to edit this unit hence grows like a snowball. That's why we call this design Byteball (our snowflakes are bytes of data).

Unlike blockchains where issuing a block is a rare event and only a privileged caste of users is in practice engaged in this activity, in a new Byteball unit starts accumulating confirmations immediately after it is released and confirmations can come from anyone, every time another new unit is issued. There is no two-tier system of ordinary users and miners. Instead, users help each other: by adding a new unit its author also confirms all previous units.

Unlike Bitcoin, where an attempt to revise a past transaction requires a large computational effort, an attempt to revise a past record in Byteball requires coordination with a large and growing number of other users, most of whom are anonymous strangers. The immutability of past records is therefore based on the sheer complexity of coordinating with such a large number of strangers, who are difficult to reach, have no interest in cooperation, and where every single one of them can veto the revision.

By referencing its parents, a unit includes the parent. It doesn't include the full content of the parent; rather, it depends on its information through the parent's hash. In the same way, the unit indirectly depends on and therefore includes the parents of the parent, their parents, and so on, and every unit ultimately includes the genesis unit.

There is a protocol rule that a unit cannot reference redundant parents – that is such parents that one parent includes another. For example, if unit B references unit A, then unit C cannot reference both units A and B at the same time. A is already, in a way, contained within B. This rule removes unnecessary links that don't add any new useful connectivity to the graph.

## 2. Native currency: bytes

Next, we need to introduce some friction to protect against spamming the database with useless messages. The barrier to entry should roughly reflect the utility of storage for the user and the cost of storage for the network. The simplest measure for both of these is the size of the storage unit. Thus, to store your data in the global decentralized database you



have to pay a fee in internal currency called bytes, and the amount you pay is equal to the size of data you are going to store (including all headers, signatures, etc). Similar to pound sterling, which was equal to one pound of silver when it was first introduced, the name of the currency reflects its value. To keep the incentives aligned with the interests of the network, there is one exception in size calculation rules. For the purposes of calculating unit size, it is assumed that the unit has exactly two parents, no matter the real number.

Therefore, the size of two hashes of parent units is always included in the unit size. This exception ensures that users will not try to include just one parent in an effort to minimize cost. The cost is the same no matter how many parents are included.

To keep the DAG as narrow as possible, we incentivize users to include as many parents as possible (as mentioned before, this does not negatively affect payable size), and as recent parents as possible, by paying part of the unit's fees to those who are first to include it as a parent. We'll define later what exactly is 'first'.

Bytes can be used not only for payment of storage fees (also called commissions), but also can be sent to other users to pay for goods or services or in exchange for other assets. To send a payment, the user creates a new unit that includes a payment message such as the following (from now on, we use JSON to describe data structures):

```
{
  inputs: [
    {
      unit: "hash of input unit",
      message_index: 2, // index of message where
                        this utxo was created
      output_index: 0 // index of output where
                      this utxo was created
    },
    ... ],
  outputs:
  [
    {
      address: "RECEIVER ADDRESS",
      amount: 15000 // in bytes
    },
    ... ]
}
```

```
...  
]  
}
```

The message contains:

- An array of outputs: one or more addresses that receive the bytes and the amounts they receive.
- An array of inputs: one or more references to previous outputs that are used to fund the transfer. These are outputs that were sent to the author address(es) in the past and are not yet spent.

The sum of inputs should be equal to the sum of outputs plus commissions (input amounts are read from previous outputs and are not explicitly indicated when spending). The unit is signed with the author's private keys.

The total number of bytes in circulation is 1015, and this number is constant.

All bytes are issued in the genesis unit, then transferred from user to user. Fees are collected by other users who help to keep the network healthy (more details about that later), so they stay in circulation. The number 1015 was selected as the largest round integer that can be represented in JavaScript.

Amounts can only be integers. Larger units of the currency are derived by applying standard prefixes: 1 kilobyte (Kb) is 1,000 bytes, 1 megabyte (Mb) is 1 million bytes, etc.

### 3. Double-spends

If a user tries to spend the same output twice, there are two possible situations:

1. There is partial order between the two units that try to spend the same output, i.e. one of the units (directly or indirectly) includes the other unit, and therefore comes after it. In this case, it is obvious that we can safely reject the later unit.
2. There is no partial order between them. In this case, we accept both. We establish a total order between the units later on, when they are buried deep enough under newer units (see below how we do it). The one that appears earlier on the total order is deemed valid, while the other is deemed invalid.

There is one more protocol rule that simplifies the definition of total order.

We require, that if the same address posts more than one unit, it should include (directly or indirectly) all its previous units in every subsequent unit, i.e. there should be partial order between consecutive units from the same address. In other words, all units from the same author should be serial.

If someone breaks this rule and posts two units such that there is no partial order between them (nonserial units), the two units are treated like double-spends even if they don't try to spend the same output. Such nonserials are handled as described in situation 2 above.

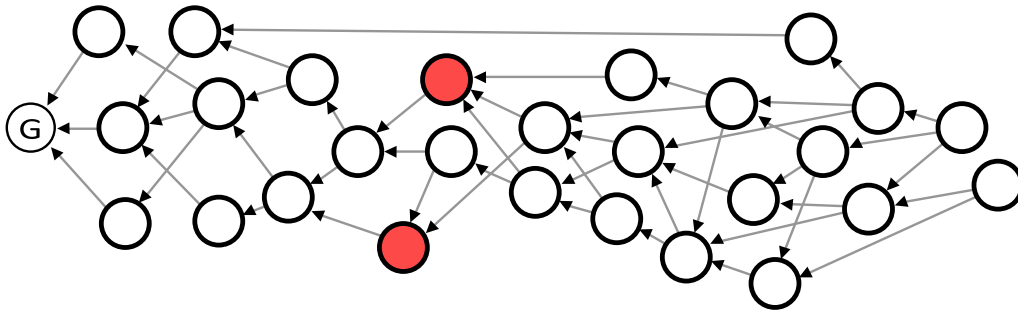


Figure 2. Double-spends. There is no partial order between them.

If a user follows this rule but still tries to spend the same output twice, the double-spends become unambiguously ordered and we can safely reject the later one as in situation 1 above. The double-spends that are not nonserials at the same time are hence easily filtered out.

This rule is in fact quite natural. When a user composes a new unit, he selects the most recent other units as parents of his unit. By putting them on his parents list, he declares his picture of the world, which implies that he has seen these units.

He has therefore seen all parents of parents, parents of parents of parents, etc up until the genesis unit. This huge set should obviously include everything that he himself has produced, and therefore has seen.

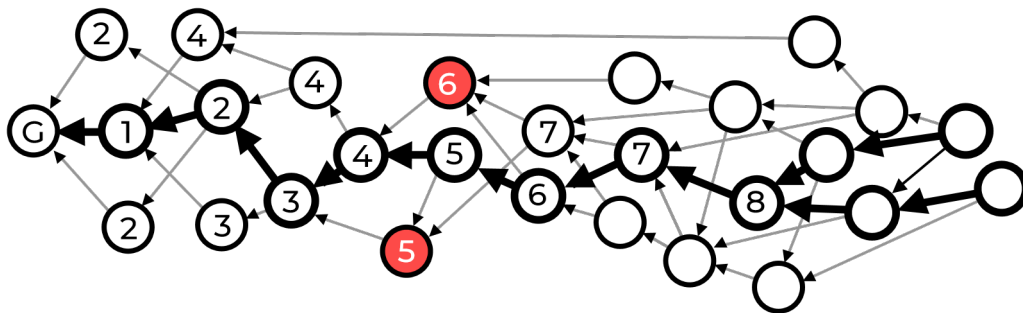
By not including a unit (even indirectly, through parents) the user denies that he has seen it. If we see that by not including his own previous unit a user denies having seen it, we'd say it's odd, something fishy is going on. We discourage such behavior.

## 4. The main chain

Our DAG is a special DAG. In normal use, people mostly link their new units to slightly less recent units, meaning that the DAG grows only in one direction. One can picture it as a thick cord with many interlaced wires inside. This property suggests that we could choose a single chain along child-parent links within the DAG, and then relate all units to this chain. All the

units will either lie directly on this chain, which we'll call the main chain, or be reachable from it by a relatively small number of hops along the edges of the graph. It's like a highway with connecting side roads.

One way to build a main chain is to develop an algorithm that, given all parents of a unit, selects one of them as the "best parent". The selection algorithm should be based only on knowledge available to the unit in question, i.e. on data contained in the unit itself and all its ancestors. Starting from any tip (a childless unit) of the DAG, we then travel backwards in history along the best parent links.



Traveling this way, we build a main chain and eventually arrive at the genesis unit.

Note that the main chain built starting from a specific unit will never change as new units are added. This is because on each step we are traveling from child to parent, and an existing unit can never acquire new parents.

If we start from another tip, we'll build another main chain. Of note here is that if those two main chains ever intersect while they go back in history, they will both go along the same path after the intersection point. In the worst case, the main chains will intersect only in genesis. Given that the process of unit production is not coordinated among users, however, one might expect to find a class of main chains that do converge not too far from the tips.

Figure 3. Main chains built from different childless units intersect and then go along the same path. Of the two double-spends, the one with the lower main chain index (5) wins, while the other (with CI=6) is deemed invalid.

Once we have a main chain (MC), we can establish a total order between two conflicting nonserial units. Let's first index the units that lie directly on the main chain. The genesis unit has index 0, the next MC unit that is a child of genesis has index 1, and so on traveling forward along the MC we assign indexes to units that lie on the MC. For units that do not lie on the MC, we can find an MC index where this unit is first included (directly or indirectly). In such a way, we can assign an MC index (MCI) to every unit.

Then, of the two nonserials, the one that has a lower MCI is considered to come earlier and deemed valid, while the other is invalid. If both nonserials happen to have the same MCI, there is tiebreaker rule that the unit with the lower hash value (as represented in base64 encoding) is valid. Note that we keep all versions of the double-spend, including those that

eventually lose. DagCoin [3] was the first published work that suggested storing all conflicting transactions and deciding which one to treat as valid.

The MC built from a specific unit tells us what this unit's author thinks about the order of past events, i.e. his point of view about the history. The order then implies which nonserial unit to consider valid, as described above. Note that by choosing the best parent among all parents of a given unit, we are simultaneously making a choice among their MCs: the MC of the unit in question will be the MC of its best parent extended forward by one link.

Recognizing that many (or even all) parent units might be created by an attacker, and remembering that the choice of best parent is essentially the choice among versions of history, we should require from our best parent selection algorithm that it favors histories that are "real" from the point of view of the child unit. We hence need to devise a "reality test" that our algorithm would run against all candidate MCs to select the one that scores best.

## 5. Witnesses

Looking for a "reality test", observe that some of the participants of our network are non-anonymous reputable people or companies who might have a long established reputation, or they are businesses interested in keeping the network healthy. We'll call them witnesses. While it is reasonable to expect them to behave honestly, it is also unreasonable to totally trust any single witness. If we know the

Byteball addresses of several witnesses, and also expect them to post frequently enough, then to measure the reality of a candidate MC one might travel along the MC back in time and count the witness-authored units (if the same witness is encountered more than once, he is not counted again). We would stop traveling as soon as we had encountered the majority of witnesses. We would then measure the length of the longest path on the graph from the point at which we stopped to the genesis. We'll call this length the level of the unit where we stopped, and the witnessed level of the parent whose MC we are testing. The candidate MC that yields the greater witnessed level is considered more "real", and the parent bearing this MC is selected as best parent. In case there are several contenders with a maximum witnessed level, we would select the parent whose own level is the lowest. If the tie persists, we would select the parent with the smallest unit hash (in base64 encoding).

This algorithm allows the selection of the MC that gravitates to units authored by witnesses, and the witnesses are considered to be representative of reality. If, for example, an attacker forks from the honest part of the network and secretly builds a long chain of his own units (shadow chain), one of them containing a double-spend, and later merges his fork back into the honest DAG, the best parent selection algorithm at the merger point will choose the parent that drives the MC into the honest DAG, as this is where the witnesses were active. The witnesses were not able to post into the shadow chain simply because they didn't see it before the merger. This selection of MC reflects the order of events as seen by the

witnesses and the user who appointed them. After the attack is over, the entire shadow chain will land on the MC at one point, and the doublespend.

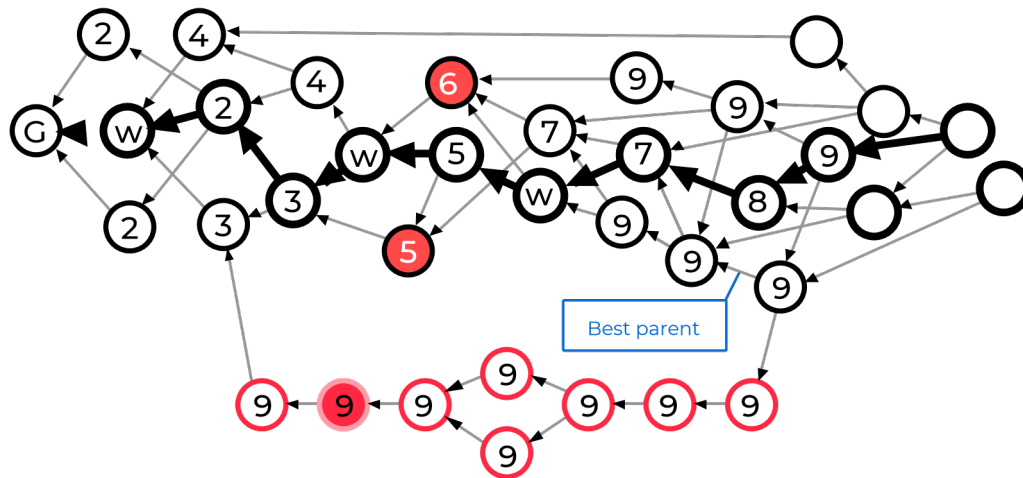


Figure 4. When an attacker rejoins his shadow DAG into the lit DAG, his units lose competition to become best parent as the choice favors those paths that have more witnesses (marked with w).

contained in the shadow chain will be deemed invalid because its valid counterpart comes earlier, before the merger point.

This example shows why the majority of witnesses has to be trusted to post only serially. The majority should not collude with the attacker and post on his shadow chain. Note that we trust the witnesses only to be signs of reality and to not post nonserial units on any shadow chains. We are not giving any of them control over the network or any part thereof. Even for this small duty, it is users who appoint the witnesses and they can change their decisions at any time.

The idea of looking at some known entity as a sign of reality is not new. It has long been known, and some companies have engaged in such activity, that to prove that some data existed before a specific date, one can hash the data and publish the hash in some hard-to-modify and widely witnessed media, like printed newspaper. Witnesses in Byteball serve the same function as the newspaper.

Like newspapers, they are well known and trusted. As for newspapers where trust is limited to trusting them to publish the data they are given, witnesses in Byteball are only trusted to post serially, and not much more. Like newspapers, witnesses don't know what's behind the hashes they are witnessing and have few reasons to best parent care.

Newspapers are hard to modify (but possible, and in 1984 they do it), while everything produced by witnesses is protected by digital signatures, which makes any modifications impossible. For reliability, we have several witnesses, not just one, and for speed and convenience, these are online.

Having decided on a list of witnesses, we can then select best the parent and the corresponding history that best fits the definition of reality as “somewhere where these witnesses live”. At the same time, the parents themselves might have different witness lists and consequently different definitions of reality. We want the definitions of reality, and histories that follow from them, to converge around something common. To achieve this, we introduce the following additional protocol rule.

The “near-conformity rule”: best parents must be selected only among those parents whose witness list differs from the child’s witness list by no more than one mutation. This rule ensures that witness lists of neighboring units on the MC are similar enough, therefore their histories mostly agree with one another. The parents whose witness list differs by 0 or 1 mutation will be called compatible (with the unit that includes them directly), while the others are incompatible. Incompatible parents are still permitted, but they have no chance of becoming best parent. If there are no compatible potential parents among childless units (an attacker could flood the network with his units that carry a radically different witness list), one should select parents from older units.

The above means that each unit must list its witnesses so that they can be compared. We require that the number of witnesses is exactly 12. This number 12 was selected because:

- it is sufficiently large to protect against the occasional failures of a few witnesses (they might prove dishonest, or be hacked, or go offline for a long time, or lose their private keys and go offline forever);
- it is sufficiently small that humans can keep track of all the witnesses to know who is who and change the list when necessary;
- the one allowed mutation is sufficiently small compared with the 11 unchanged witnesses.

In case a user thinks that any of the witnesses has lost his credibility, or there are just better candidates, the user can replace the witness with a new witness in his list, bearing in mind that his witness list may not differ from that of other units by more than one position. This means that any changes can happen only gradually, and a general consensus is required for a change bigger than one position.

## 6. Finality

As new units arrive, each user keeps track of his current MC which is built as if he were going to issue a new unit based on all current childless units. The current MC may be different at different nodes because they may see different sets of childless units. We require that the current MC be built without regard of witness lists, i.e. the user’s own witness list doesn’t matter and even incompatible parents can be selected as best parents. That means that if two users have the same set of childless units, but have different witness lists, their current MCs will still be identical. The current MC will constantly change as new



units arrive. However, as we are about to show, a part of the current MC that is old enough will stay invariant.

We expect witnesses (or rather the majority thereof) to behave honestly, therefore necessarily include their previous unit in the next unit authored by the same witness. This means that when a witness composes a new unit, only recent units are candidates to be chosen as parents. We might expect, therefore, that all future current MCs will converge no farther (when traveling back in time) than a particular stability point. Indeed, the genesis unit is a natural initial stability point.

Assume we have built a current MC based on the current set of childless units, and there was some point on this MC that was previously believed to be stable, i.e. all future current MCs are believed to converge on or before this point (again, when traveling back in time), and then travel along the same route. If we can find a way of advancing this point forward (away from the genesis), we can prove by induction that a stability point exists.

Note that if we forget about all parents except the best parent, our DAG will be reduced to a tree that consists only of best parent links. Obviously, all MCs will go along the branches of this tree. We then need to consider two cases – when the tree does branch in the current stability point and when it does not – and decide if we can advance the stability point to the next MCI.

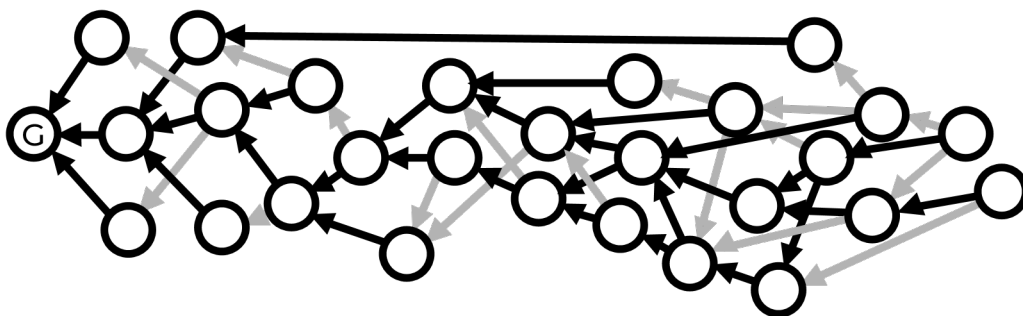


Figure 5. A tree composed of best-parent links. All but one branches stop growing after some point.

First, assume the tree does not branch. We then need to consider the possibility that a new branch will still be added and somehow supported by the witnesses so that it outgrows the existing branch. The other possibility is that the witnesses put so much weight in support of the existing branch, that the requirement of including one's previous unit leaves them no options but continue supporting the existing branch. Let's quantify the latter possibility.

Remember that best parent is selected as the parent with the greatest witnessed level. Let's travel back in time along the current MC from the tip until we meet the majority of witnesses (we are referring to witnesses as defined by the unit lying on the current stability point). If at least one of them lies earlier than the current stability point, we do not try to

advance the stability point, otherwise we proceed. In this case, all these witnesses are already “invested” into the current MC. Among these witnesses, we find the minimum witnessed level  $\text{min\_wl}$ . When any of these witnesses posts a new unit, this unit might have parents whose MC leads to the current MC and parents whose MC leads to a competing branch, and the parent with the highest witnessed level will be selected as best parent and will define the direction of the next current MC. Since the witness has to include its previous unit, the witnessed level of the parent leading to the current MC will be at least  $\text{min\_wl}$ .

The witnessed level of any parent leading to the alternative branch will never exceed the level of the current stability point, even if all remaining (minority) witnesses flock to the alternative branch. Therefore, if the current MC grows far enough so that  $\text{min\_wl}$  is greater than the level of the current stability point, the majority of witnesses will have to increase support for the existing current MC, the alternative branch has then lost all chances to win, and we can move the stability point forward to the next MCI.

Next, assume the tree does branch. We need to find a condition where the alternative branches will lose any chance to outgrow the current MC. Let's start by defining  $\text{min\_wl}$  as in the previous case. Among all units on the alternative branches, we then select those that increase the witness level, i.e. their own witnessed level is greater than that of every parent. Among these, we find the maximum level. Then, even if all the remaining (minority) witnesses gather on the alternative branches, the witnessed level on the alternative branches will never exceed this maximum level. Therefore, if this maximum level is less than  $\text{min\_wl}$ , game is over for the alternative branches, and we can advance the stability point along the current MC.

Thus, there is a point on the current MC before which the MC will never change (assuming the majority of witnesses don't post nonserial units). The total order defined relative to this MC is therefore also final. If we had nonserials, our decision about which one of them is valid, is final as well. If a new nonserial ever appears that conflicts with anything already on the stable MC, the new nonserial unit will definitely be ordered after the old counterpart, and the new one will be deemed invalid. Therefore, any payment made in the unit included on the stable MC is already irreversible. Unlike Bitcoin where transaction finality is only probabilistic, this is deterministic transaction finality.

Every user builds his own (subjective) current MC based on the units that he sees. Since the propagation of new units is not instant, and they may arrive in different order to different users, the users will have different current MCs and different opinions about the last stable point of the MC at any given time.

However, since the current MC is defined solely by the set of units known to the user, in case user B hasn't yet advanced his stability point to the same MCI as user A, he will inevitably do that later – i.e. as soon as he receives the same units as user A, or more. Thus the opinions of different users about the state of any given unit are eventually consistent.

## 7. Storage of nonserial units

When we decide that a unit is a nonserial, we still have to store it. However, part of its data is replaced with a hash of the data. This rule serves two purposes. First, to reduce storage consumed by a unit that nobody paid for (the entire content of the nonserial unit is deemed invalid, including its payment of commissions). Second, to reduce the utility of the nonserial to the user who sent it, because the hash replaces all useful data that the author wanted to store (for free). This prevents attackers from abusing nonserials as a way to store large amounts of data for free.

The hash that is stored instead of the full content still has some utility to the attacker, as he can store the original data himself and use the hash to prove that the data existed. But remember that:

1. He still has to pay for one unit that is deemed valid
2. If the attacker is already internally storing metadata that is necessary to interpret Byteball data, he could do equally well by just combining all his data into a Merkle tree and using Byteball to store only its Merkle root for the cost of one small unit.

Under this design, there is therefore no self-interest in trying to send nonserials.

It ought to be mentioned that we cannot just reject nonserials the first time we see them. If we did, an attacker could send his nonserials to different users in different order. Different users would then stick to the versions they first received and reject everything based on the other version, so the attacker would succeed in partitioning the network. That's why we have to store both versions and then decide on their order. Even more, users should forward nonserials to peers just like any other units, as the sooner peers learn about the nonserials the better.

We still try to avoid including nonserials if possible: the parent selection algorithm excludes nonserials as long as they are childless. For this reason, it's desirable to help peers learn about nonserials as soon as possible.

## 8. Balls

After a unit becomes stable (i.e. it is included on the stable part of the MC) we create a new structure based on this unit, we call it a ball:

```
ball: {unit: "hash of  
  
unit",  
  
parent_balls: [array of hashes of balls based on parent  
units],
```

```
is_nonserial: true, // this field included only if the unit
is nonserial

skiplist_balls: [array of earlier balls used to build
skiplist]

}
```

Every ball includes information about all its ancestor balls (via parents), hence the amount of information it depends on grows like snowball. We also have a flag in the ball that tells us if it ended up being invalid (nonserial), and we have references to older balls that we'll use later to build proofs for light clients.

We can only build a ball when the corresponding unit becomes stable and we know for certain whether it is serial. Since the current MCs as viewed by different users are eventually consistent, they will all build exactly the same ball based on the same unit.

## 9. Last ball

To protect the balls (most importantly, the `is_nonserial` flag) from modification, we require each new unit to include a hash of the last ball that the author knows about (which is the ball built from the last stable unit, and it lies on the MC). This way, the last ball will be protected by the author's signature. Later on, the new unit itself will be (directly or indirectly) included by witnesses.

If someone who doesn't have the entire Byteball database wants to know if a particular unit is serial, he would give us a list of witnesses he trusts to behave honestly, and we would build a chain of recent units that includes the majority of the said witnesses, then read last ball from the oldest unit of the chain, and use balls to build a hash tree that has the last ball at the top and includes the requested unit somewhere below. This hash tree is similar to a very tall Merkle tree, with additional data fed in at each node. The tree can be optimized using the skiplist.

The reference to the last ball also lets users see what their peers think about the stability point of the MC and compare it with their own vision.

We also require that the last ball lies no sooner than last ball of every parent. This ensures that the last ball either advances forward along the MC or stays in the same position, but never retreats.

To further reduce the degrees of freedom of adversaries, we add one more requirement: a unit's witness list must be compatible with that of each unit that lies on the trailing part of the unit's MC between this unit and the last ball's unit.

This requirement ensures that all changes to the witness list first reach stability point before trying another change. Otherwise, an attacker might inject a significantly modified witness

list onto the MC and stop posting from the addresses of the new witnesses. In such instances, the stability point would not be able to advance past the stretch occupied by the attacker's witnesses.

The requirement that witness lists of all contemporary units are mostly similar means that all users have mostly similar views about who can be trusted to serve as lighthouses for the community at the current time. This is similar to biology, where organisms of the same species have to have mostly the same genes.

Small variance of the witness list allows for evolutionary change that still preserves the integrity of the system.

## 10. Witness list unit

It is expected that many users will want to use exactly the same witness list. In this case, to save space, they don't list the addresses of all 12 witnesses. Rather, they give a reference to another earlier unit, which listed these witnesses explicitly. The witness list unit must be stable from the point of view of the referencing unit, i.e. it must be included into the last ball unit.

## 11. Unit structure

This is an example of a unit:

```
{  
  
  version: '1.0', alt:  
    '1',  
  messages: [ { app: 'payment',  
    payload_location: 'inline',  
    payload_hash:  
      'AegecfpDzh8xvdyIABdynrcP6CTd4Pt42gvRiv0Ftjg=', payload:  
        {  
          inputs: [{ unit:
```



```
'7yctnKyuAk5P+mFgFQDdDLza88nkceXYjsTs4e3doQA=',
message_index: 0,
output_index: 1
} ],
outputs:
[
{ address: 'DJ6LV5GPCLMGRW7ZB55IVGJRPDJPOQU6',
amount: 208 },
{ address: 'Z36JFFX2AH7X5JQ2V2C6AQUUOWFESKZ2',
amount: 3505 }
]
}
} ],
authors:
[ { address:
'DJ6LV5GPCLMGRW7ZB55IVGJRPDJPOQU6',
authenticifiers: { r:
'3eQPIFiPVLrWbWEzxUR5thqn+z1FfLXUrzAmgemAqOk
35UvDpa4h
79Fd6TbPbGfb8VMiJzqdNGHCKyAj1786mw=='
}} ],
parent_units:
[
'B63mnJ4yNNAE+6J+L6AhQ3EY7EO1Lj7QmAM9PS8X0pg=',
'D601/D9L8vCMhv+8f70JecF93UoLKDp3e2+b92Yh2mI=',
'ZxqzWP6q6hDNF50Wax8HUK2121H/KSIRdW5a6T9h3DM='
], last_ball:
'8S2ya9lULt5abF1Z4lIJ4x5zYY9MtEALCl+jPDLsnsw=',
last_ball_unit: 'bhdxFqVUut6V3N2D6Tyt+/
YD6X0W+QnC95dMcJJWdtw=', witness_list_unit:
```

```
'f252ZI2MN3xu8wFJ+LktVDGsay2Udzi/AUauE9ZaifY='  
}
```

Here:

- version is the protocol version number. The unit will be interpreted according to this version of the protocol;
- alt is an identifier of alternative currency, we'll discuss this later;
- messages is an array of one or more messages that contain actual data;
  - o. app is the type of message, e.g. 'payment' for payments, 'text' for arbitrary text messages, etc;
  - o. payload\_location says where to find the message payload. It can be 'inline' if the payload is included in the message, 'uri' if the payload is available at an internet address, 'none' if the payload is not published at all, is stored and/or shared privately, and payload\_hash serves to prove it existed at a specific time;
  - o. payload\_hash is a hash of the payload in base64 encoding;
  - o. payload is the actual payload (since it is 'inline' in this example). The payload structure is app-specific. Payments are described as follows:
    - inputs is an array of input coins consumed by the payment. All owners of the input coins must be among the signers (authors) of the unit;
- unit is hash of the unit where the coin was produced.

To be spendable, the unit must be included in last\_ball\_unit;
- message\_index is an index into the messages array of the input unit. It indicates the message where the coin was produced;
- output\_index is an index into the outputs array of the
  - message\_index'th message of the input unit. It indicates the output where the coin was produced;
  - outputs is an array of outputs that say who receives the money;
- address is the Byteball address of the recipient;
- amount is the amount he receives;

- authors is an array of the authors who created and signed this unit.  
All input coins must belong to the authors;
  - o. address is the author's Byteball address;
  - o. authenticifiers is a data structure that proves the author's authenticity. Most commonly these are ECDSA signatures;
- parent\_units is an array of hashes of parent units. It must be sorted alphabetically;
- last\_ball and last\_ball\_unit are hashes of last ball and its unit, respectively;
- witness\_list\_unit is hash of the unit where one can find the witness list.

All hashes are in base64 encoding.

Note that there is no timestamp field in the unit structure. In Byteball, there are no protocol rules that rely on clock time. It's simply not needed, as it is enough to rely on the order of events alone.

Timestamp is still added to units when they are forwarded from node to node. However, this is only advisory and used by light clients to show in wallets the approximate time when a unit was produced, which may significantly differ from the time it was received as light clients may go offline for extended periods of time.

## 12. Commissions

As mentioned before, the cost to store a unit is its size in bytes. The commission is split into two parts: headers commission and payload commission. Payload commission is equal to the size of messages; headers commission is the size of everything else. The two types of commissions are distributed differently.

Headers commission goes to one of the future units which takes the payer unit as parent. The receiver is selected only after both the payer unit's MCI and the next MCI become stable. To determine the receiver, we take those children whose MCI is equal to or 1 more than the MCI of the payer. The hashes of each of these children are concatenated with the hash of the unit lying on the next MCI (relative to the payer), and the child with the smallest hash value (in hex) wins the headers commission. This hashing with the next MC unit is designed to introduce unpredictability (the next MC unit is not known beforehand) and render useless any attempts to improve one's chances of receiving commission by playing with one's own unit hash. At the same time, restricting candidates to those whose MCI is no more than 1 greater than the MCI of the payer, incentivizes the selection of the most recent units as parents. This is useful to keep the DAG as narrow as possible.

We pay only the headers commission and not the entire commission to those who are quick to pick our unit as parent, for the following reason. If we did pay the entire commission, we would have incentivized abusive behavior: split one's data into several chunks and build a long chain of one's own units storing one chunk per unit. All the commissions paid in a



previous unit would then be immediately collected by the same user in the next unit. As we pay only the headers commission, such behavior is not profitable because to produce each additional element of the chain one has to spend additional headers commission – roughly the same as one earns. We use the remaining (payload) commission to incentivize others whose activity is important for keeping the network healthy.

Payload commission goes to witnesses. To incentivize witnesses to post frequently enough, we split payload commission equally among all witnesses who are quick enough to post within 100 MC indexes after the paying unit (the faster they post, the faster this unit becomes stable). If all 12 witnesses have posted within this interval, each receives 1/12 of the payload commission. If only one witness has posted, he receives the entire payload commission. In the special case that no witness has posted within this interval, they all receive 1/12 of payload commission. If the division produces a fractional number, it is rounded according to mathematical rules. Because of this rounding, the total commission paid out to witnesses may not be equal to the total payload commission received from the unit's author(s), so the total money supply will change slightly as well. Obviously, the distribution happens only after MCI+100 becomes stable, where MCI is the MCI of the paying unit.

To spend the earned headers commissions or witnessing commissions, the following input is used:

```
inputs: [  
  
    {  
        type: "headers_commission", from_main_chain_index:  
        123,  
  
        to_main_chain_index: 196  
    },  
    {  
  
        type: "witnessing", from_main_chain_index:  
        60, to_main_chain_index: 142  
  
    }, ...  
  
]
```

Such inputs sweep all headers or witnessing commissions earned by the author from commission paying units that were issued between main chain indexes from\_main\_chain\_index and to\_main\_chain\_index. Naturally, to\_main\_chain\_index must be stable.

When a unit signed by more than one author earns headers commission, there is so far ambiguity as to how the commission is split among the authors. To remove the ambiguity,

each unit that is signed by more than one author must include a data structure that describes the proportions of revenue sharing:

```
unit: {  
  
    ...  
  
    earned_headers_commission_recipients: [  
  
        {address: "ADDRESS1", earned_headers_commission_share:  
          30},  
  
        {address: "ADDRESS2",  
          earned_headers_commission_share: 70} ],  
  
    ...  
  
}
```

The addresses who receive the commissions needn't be the same as the author addresses the commission can be sent to any address. Even if the unit is signed by a single author, it can include this field to redirect headers commissions elsewhere.

## 13. Confirmation time

Confirmation time is the time from a unit entering the database to reaching stability. It depends on how often the witnesses post, since to reach stability we need to accumulate enough witness-authored units on the MC after the newly added unit. To minimize the confirmation period, the witnesses should post frequently enough (which they are already incentivized to do via commission distribution rules)

but not too frequently. If two or more witnesses issue their units nearly simultaneously (faster than it typically takes to propagate a new unit to other witnesses), this may cause unnecessary branching of the tree composed of best-parent links, which would delay stability. For this reason, the best confirmation times are reached when the witnesses are well connected and run on fast machines so that they are able to quickly validate new units. We estimate the best confirmation times to be around 30 seconds; this is only reachable if the flow of new units is large enough so that the witnesses earn more from witnessing commissions than they spend for posting their own units.

Despite the period of full confirmation being rather long, a node that trusts its peers to deliver all new units without filtering may be reasonably sure that once a unit was included by at least one witness, plus a typical latency has elapsed (the time it takes a new unit to travel from peer to peer), the unit will most likely reach finality and be deemed valid. Even if a double-spend appears later, it will be likely ordered after this unit.

## 14. Partitioning risk

The network of Byteball nodes can never be partitioned into two parts that would both continue operating without noticing. Even in the event of a global network disruption such as a sub-Atlantic rat cutting the cable that connects Europe and America, at least one of the sides of the split will notice that it has lost the majority of witnesses, meaning that it can't advance the stability point, and nobody can spend outputs stuck in the unstable part of the MC. Even if someone tries to send a double-spend, it will remain unstable (and therefore unrecognized) until the connection is restored. The other part of the split where the majority of witnesses happens to be, will continue as normal.

## 15. Censorship

By design, it is already impossible to modify or erase any past records in Byteball.

It is also quite hard to stop any particular types of data from entering the database.

First, the data itself can be concealed and only its hash be actually posted to the database to prove that the data existed. The data may only be revealed after the hash is stored and its unit has been included by other units so that it has become unrevisable.

Second, even when the data is open, the decision to include or not include it in the database is delegated to numerous anonymous users who might (and in fact are incentivized to) take the new unit as a parent. Someone who tries to censor undesirable units will have to not only avoid including them directly (as parents) but also indirectly, through other units. (This is different from Bitcoin where miners or mining pools can, and do, filter individual transactions directly. Besides, Bitcoin users have no say in who is to become a miner.) As the number of units which include the "offending" unit snowballs, any attempt to avoid it would entail censoring oneself. Only the majority of witnesses can effectively impose forbidden content rules – if users choose such witnesses.

## 16. Choosing witnesses

Reliance on witnesses is what makes Byteball rooted in the real world. At the same time, it makes it highly dependent on human decisions. The health of the system depends on users responsibly setting the lists of witnesses they do trust. This process cannot be safely automated, for example if most users start autoupdating their witness lists to match the lists of most recently observed units, just to be compatible, this can be easily exploited by an attacker who floods the network with his own units that gradually change the predominant witness list to something of the attacker's choosing.

While the maximalist recommendation could be "only edit witness lists manually", which is too burdensome for most users, a more practical approach to witness list management is tracking and somehow averaging the witness lists of a few "captains of industry" who either have interest in caring for the network health or who have earned a good reputation in

activities not necessarily connected with Byteball. Some of them may be acting witnesses themselves.

Unlike witness lists, the lists of captains of industry don't have to be compatible, and failing to update the list frequently enough doesn't have any immediate negative implications such as being unable to find compatible parents and post a new unit. We expect that most users will use one of a relatively small number of most popular wallets, and such wallets will be set up by default to follow the witness list of the wallet vendor, who in turn likely watches the witness lists of other prominent players. Witnesses also have their witness lists, and it is recommended that users elect those witnesses who they trust to keep their witness lists representative of ordinary users' beliefs. This is very important because no change to the predominant witness list can pass without approval of the majority of the current witnesses. It is recommended that witnesses and would-be witnesses publicly declare their witness list policy (such as following and averaging witness lists of other reputable users), and that users evaluate their fitness for the job based on this policy, among other factors. Any breach of the declared policy will be immediately visible and will likely trigger a witness replacement campaign.

The same is true for an unjustified amendment to the policy. The policy binds the witness and makes him follow public opinion, even when it turns against the witness himself or his friends.

As mentioned before, our protocol rules require that:

1. best parent is selected only among parents whose witness list has no more than 1 mutation;
2. there should be no more than 1 mutation relative to the witness list of the last ball unit;
3. there should be no more than 1 mutation relative to the witness lists of all the unstable MC units up to the last ball unit;
4. the stability point advances only when the current witnesses (as defined in the current stability point) post enough units after the current stability point.

These rules are designed to protect against malicious and accidental forks. At the same time, they imply that any changes of the predominant witness list have to be gradual, and each step has to be approved by the majority of the current witnesses.

A one-position change has to first reach stability and recognition of the majority of old witnesses before another change can be undertaken. If the community decides abruptly that two witnesses need to be replaced immediately, then after one change makes its way onto the MC, the second change will be blocked by rule 3 above until the first change reaches stability.

Despite all the recommendations above it is still possible that due to the negligence of industry leaders, such witnesses are elected who later form a cartel and collectively block all

attempts to replace any one of them in an attempt to keep the profits they are earning from witnessing commissions. If they do behave this way, it will be evident to everybody because their witness lists will remain unchanged, while the witness lists of most other industry leaders will differ by one mutation (the maximum allowed to remain compatible). If the old witnesses do not give in despite such evident pressure, the only recourse of the pro-change users is a “revolution” – i.e. to start a new coin that inherits all the balances, user addresses, etc from the old coin at some point but starts with a new witness list and adds a special protocol rule to handle this incompatible change at the moment of the schism. To distinguish from the old coin, they would then assign a new value to the ‘alt’ field (this what ‘alt’ is for) and use it in all units issued under the new coin. As a result, users will hold two coins (the old alt=“1”, and the new e.g. alt=“2”) and will be able to spend both independently. If the split was justified, the old coin will probably be abandoned, but all the data accumulated prior to the schism will be available as normal in the new coin. Since the protocol is almost identical (except for the rule that handles the schism and the change of alt), it will be easy to update software installed on all user and merchant devices.

If someone just wants to start a new coin to experiment with another set of protocol rules, he can also use the ‘alt’ field to inherit everything from the old coin, make the switch comfortable for users, and have a large set of users with balances from day one.

## 17. Skiplist

Some of the balls contain a skiplist array which enables faster building of proofs for light clients (see below). Only those balls that lie directly on the MC, and whose MC index is divisible by 10, have a skiplist. The skiplist lists the nearest previous MC balls whose index has the same or smaller number of zeros at the end. For example, the ball at MCI 190 has a skiplist that references the ball at MCI 180. The ball at MCI 3000 has a skiplist that references the balls at MCIs 2990, 2900, and 2000.

## 18. Light clients

Light clients do not store the entire Byteball database. Instead, they download a subset of data they are interested in, such as only transactions where any of the user’s addresses are spending or being funded. Light clients connect to full nodes to download the units they are interested in. The light client tells the full node the list of witnesses it trusts (not necessarily the same witnesses it uses to create new units) and the list of its own addresses.

The full node searches for units the light client is interested in and constructs a proof chain for each unit in the following way:

1. Walk back in time along the MC until the majority of requested witnesses are met. Collect all these MC units.
2. From the last unit in this set (which is also the earliest in time), read the last ball.

3. Starting from this last ball, walk back in time along the MC until any ball with a skiplist is met. Collect all these balls.
4. Using the skiplist, jump to an earlier ball referenced from the skiplist. This ball also has a skiplist, jump again. Where there are several balls in skiplist array, always jump by the largest distance possible, so we accelerate jumping first by 10 indexes, then by 100, then by 1000, etc.
5. If the next jump by the skiplist would throw us behind the target ball, decelerate by jumping by a smaller distance. Ultimately, leave the skiplist and walk along the MC one index at a time using just parent links.

This chain has witness-authored units in the beginning, making it trustworthy from the light client's point of view. All the elements of the chain are linked by either parent unit links (while accumulating the witnesses), or by last ball reference, or by parent ball links, or by skiplist links. At the end of the chain, we have the unit whose existence was to be proved.

## 19. Multilateral signing

A unit can be signed by multiple parties. In such instances, the authors array in the unit has two or more elements.

This can be useful, for example. if two or more parties want to sign a contract (a plain old dumb contract, not a smart one). They would both sign the same unit that contains a text message (app='text'). They don't have to store the full text of the contract in the public database, and pay for it

– a hash would suffice (payload\_location='none'), and the parties themselves can store the text privately.

Another application of multilateral signing is an exchange of assets. Assume user A wants to send asset X to user B in exchange for asset Y (the native currency 'bytes' is also an asset – the base asset). Then they would compose a unit that contains two payment messages: one payment sends asset X from A to B, the other payment sends asset Y from B to A. They both sign the dual-authored unit and publish it. The exchange is atomic – that is, either both payments execute at the same time or both fail. If one of the payments appears to be a double-spend, the entire unit is rendered invalid and the other payment is also deemed void.

This simple construction allows users to exchange assets directly, without trusting their money to any centralized exchanges.

## 20. Addresses

Users are identified by their addresses, transaction outputs are sent to addresses, and, like in Bitcoin, it is recommended that users have multiple addresses and avoid reusing them. In some circumstances, however, reuse is normal. For example, witnesses are expected to repeatedly post from the same address.

An address represents a definition, which is a Boolean expression (remotely similar to Bitcoin script). When a user signs a unit, he also provides a set of authenticifiers (usually ECDSA signatures) which, when applied to the definition, must evaluate it to true in order to prove that this user had the right to sign this unit. We write definitions in JSON. For example, this is the definition for an address that requires one ECDSA signature to sign:

```
[ "sig",  
{ "pubkey": "Ald9tkgiUZQQ1djpZgv2ez7xf1ZvYAsTLhudhvn0931w" } ]
```

The definition indicates that the owner of the address has a private key whose public counterpart is given in the definition (in base64 encoding), and he will sign all units with this private key. The above definition evaluates to true if the signature given in the corresponding authenticifier is valid, or otherwise false. The signature is calculated over all data of the unit except the authenticifiers.

Given a definition object, the corresponding address is just a hash of the initial definition object plus a checksum. The checksum is added to avoid typing errors. Unlike usual checksum designs, however, the checksum bits are not just appended to the end of the unchecksummed data. Rather, they are inserted into multiple locations inside the data. This design makes it hard to insert long strings of illegal data in fields where an address is expected. The address is written in base32 encoding. The above definition corresponds to address

A2WWHN7755YZVMXCBLMFWRSLKSZJN3FU.

When an address is funded, the sender of the payment knows and specifies only the address (the checksummed hash of the definition) in the payment output.

The definition is not revealed and it remains unknown to anyone but the owner until the output is spent.

When a user sends his first unit from an address, he must reveal its definition (so as to make signature verification possible) in the authors array:

```
unit: {  
  
    ...  
  
    authors: [ { address:  
  
        'DJ6LV5GPCLMGRW7ZB55IVGJRPDJPOQU6',
```

```
definition: [

    "sig",

    {"pubkey": "AsnvZ3w7N1lZGJ+P+bDZU0DgOwJcGJ51bjsWpEqfq
Bg6"} ],

authenticifiers:

{

    r:

    '3eQPIFiPVLrWBwEzxUR5thqn+z1FfLXUrzAmgemAqOk35UvDpa4
h

    79Fd6TbPbGfb8VMiJzqdNGHCKyAjl786mw=='

}

] ],

...

}
```

If the user sends a second unit from the same address, he must omit the definition (it is already known on Byteball). He can send the second unit only after the definition becomes stable, i.e. the unit where the definition was revealed must be included in the last ball unit of the second unit.

Users can update definitions of their addresses while keeping the old address. For example, to rotate the private key linked to an address, the user needs to post a unit that contains a message such as:

```
unit: {

    ...

    messages: [

        ...

        {

            app: "address_definition_change",

            definition_chash: "I4Z7KFNIYTPHPJ5CA5OFC273JQFSZPOX"

        },

    ],

}
```



```
...  
],  
...  
}
```

Here, `definition_chash` indicates the checksummed hash of the new address definition (which is not revealed until later), and the unit itself must be signed by the old private keys. The next unit from this address must:

- include this `address_definition_change` unit in its last ball unit, i.e. it must be already stable;
- reveal the new definition in the authors array in the same way as for the first message from an address.

After the change, the address is no longer equal to the checksummed hash of its current definition.

Rather, it remains equal to the checksummed hash of its initial definition.

The definition change is useful if the user wants to change the key(s) (e.g. when migrating to a new device) while keeping the old address, e.g. if this address already participates in other long-lived definitions (see below).

## 20.1. Definition syntax

### 20.1.1. Logical operators

A definition can include “and” conditions, for example:

```
["and", [  
    ["sig", {pubkey: "one pubkey in base64"}],  
    ["sig", {pubkey: "another pubkey in base64"}]  
]]
```

which is useful when, in order to sign transactions, signatures from two independent devices are required, for example, from a laptop and from a smartphone.

“Or” conditions, such as this:

```
["or", [  
    ["sig", {pubkey: "one pubkey in base64"}],  
    ["sig", {pubkey: "another pubkey in base64"}]  
]]
```

```
["sig", {pubkey: "laptop pubkey"}],  
["sig", {pubkey: "smartphone pubkey"}],  
["sig", {pubkey: "tablet pubkey"}]  
]]
```

are useful when a user wants to use the same address from any of his devices.

The conditions can be nested:

```
["and", [  
  ["or", [  
    ["sig", {pubkey: "laptop pubkey"}],  
    ["sig", {pubkey: "tablet pubkey"}]  
  ]],  
  ["sig", {pubkey: "smartphone pubkey"}]  
]]
```

A definition can require a minimum number of conditions to be true out of a larger set, for example, a 2-of-3 signature:

```
["r of set", {  
  required: 2, set:  
  [  
    ["sig", {pubkey: "laptop pubkey"}],  
    ["sig", {pubkey: "smartphone pubkey"}],  
    ["sig", {pubkey: "tablet pubkey"}]  
  ]  
}]
```

("r" stands for "required") which features both the security of two mandatory signatures and the reliability, so that in case one of the keys is lost, the address is still usable and can be used to change its definition and replace the lost 3rd key with a new one.

Also, different conditions can be given different weight, of which a minimum is required:

```
[ "weighted and", { required:
  50,
  set: [
    {weight: 40, value: ["sig", {pubkey: "CEO pubkey"}] },
    {weight: 20, value: ["sig", {pubkey: "COO pubkey"}] },
    {weight: 20, value: ["sig", {pubkey: "CFO pubkey"}] },
    {weight: 20, value: ["sig", {pubkey: "CTO pubkey"}] }
  ]
}]
```

### 20.1.2. Delegation to other addresses

An address can contain reference to another address:

```
[ "and", [
  ["address", "ADDRESS 1 IN BASE32"],
  ["address", "ADDRESS 2 IN BASE32"]
]]
```

which delegates signing to another address and is useful for building shared control addresses (addresses controlled by several users). This syntax gives the users the flexibility to change definitions of their own component addresses whenever they like, without bothering the other user.

### 20.1.3. Signatures and authenticifiers

In most cases, a definition will include at least one signature (directly or indirectly):

```
[ "sig", {pubkey: "pubkey in base64"}]
```

Instead of a signature, a definition may require a preimage for a hash to be provided:

```
[ "hash", {"hash": "value of sha256 hash in base64"}]
```

which can be useful for cross-chain exchange algorithms [7]. In this case, the hash preimage is entered as one of the authenticifiers.

The default signature algorithm is ECDSA on curve secp256k1 (same as Bitcoin). Initially, it is the only algorithm supported. If other algorithms are added in the future, algorithm identifier will be used in the corresponding part of the definition, such as for the quantum secure NTRU algorithm:

```
["sig", {algo: "ntru", pubkey: "NTRU public key in base64"}]
```

Multisignature definitions allow one to safely experiment with unproven signature schemes when they are combined with more conventional signatures.

The authenticifiers object in unit headers contains signatures or other data (such as hash preimage) keyed by the path of the authenticifier-requiring subdefinition within the address definition. For a single-sig address such as

```
["sig", {pubkey: "pubkey in base64"}]
```

the path is simply “r” (r stands for root). If the authenticifier-requiring subdefinition is included within another definition (such as and/or), the path is extended by an index into the array where this subdefinition is included, and path components are delimited by a dot. For example, for address definition:

```
["and", [  
  ["sig", {pubkey: "one pubkey in base64"}],  
  ["sig", {pubkey: "another pubkey in base64"}]  
]]
```

the paths are “r.0” and “r.1”. For a deeper nested definition:

```
["and", [  
  ["or", [  
    ["sig", {pubkey: "laptop pubkey"}],  
    ["sig", {pubkey: "tablet pubkey"}]  
  ],  
  ["sig", {pubkey: "smartphone pubkey"}]  
]]
```

the paths are “r.0.0”, “r.0.1”, and “r.1”. When there are optional signatures, such as 2-of-3, the paths tell us which keys were actually used.

## 20.1.4. Definition templates

A definition can also reference a definition template:

```
["definition template", [  
    "hash of unit where the template was  
    defined", {param1: "value1", param2:  
    "value2"}  
]]
```

The parameters specify values of variables to be replaced in the template. The template needs to be

saved before (and as usual, be stable before use) with a special message type

app='definition\_template', the template itself is in message payload, and the template looks like

normal definition but may include references to variables in the syntax @param1, @param2.

Definition templates enable code reuse. They may in turn reference other templates.

## 20.1.5. Cosigning

A subdefinition may require that the unit be cosigned by another address:

```
["cosigned by", "ANOTHER ADDRESS IN BASE32"]
```

## 20.1.6. Querying whether an address was used

Another possible requirement for a subdefinition: that an address was seen as author in at least one unit included into the last ball unit:

```
["seen address", "ANOTHER ADDRESS IN BASE32"]
```

## 20.1.7. Data feeds

One very useful condition can be used to make queries about data previously stored in Byteball:

```
["in data feed", [  
    ["ADDRESS1", "ADDRESS2", ...],  
    ]
```

```
"data feed name",  
  
"=",  
  
"expected value"  
  
]]
```

This condition evaluates to true if there is at least one message that has "data feed name" equal to "expected value" among the data feed messages authored by the listed addresses "ADDRESS1", "ADDRESS2", .. (oracles). Data feed is a message type that looks like this:

```
unit: {  
  
    ...  
  
    messages: [  
  
        ...  
  
        {  
  
            app: "data_feed", payload_location:  
            "inline", payload_hash: "hash of  
            payload",  
            payload: {  
                "data feed name": "value",  
                "another data feed name": "value2",  
                ...  
            }  
        },  
  
        ...  
    ],  
  
    ...  
}
```

Data fields can be used to design definitions that involve oracles. If two or more parties trust a particular entity (the oracle) to provide true data, they can set up a shared control address that gives the parties different rights depending on data posted by the oracle(s). For example, this address definition represents a binary option:

```
[ "or", [
  [ "and", [
    [ "address", "ADDRESS 1",
    [ "in data feed", [ ["EXCHANGE ADDRESS",
    "EURUSD", ">", "1.1500"]
  ]],
  [ "and", [
    [ "address", "ADDRESS 2",
    [ "in data feed", [ ["TIMESTAMPER ADDRESS",
    "datetime", ">", "2016-10-01 00:00:00"]
  ]]]
]]
]]
```

Initially, the two parties fund the address defined by this definition (to remove any trust requirements, they use multilateral signing and send their stakes in a single unit signed by both parties). Then if the EUR/USD exchange rate published by the exchange address ever exceeds 1.1500, the first party can sweep the funds. If this doesn't happen before Oct 1, 2016 and the timestamping oracle posts any later date, the second party can sweep all funds stored on this address. If both conditions are true and the address balance is still non-empty, both parties can try to take the money from it at the same time, and the double-spend will be resolved as usual.

The comparison operators can be "=", "!=", ">", ">=", "<", and "<=". The data feed message must come before the last ball unit as usual. To reduce the risks that arise in case any single oracle suddenly goes offline, several feed provider addresses can be listed.

Another example would be a customer who buys goods from a merchant but he doesn't quite trust that merchant and wants his money back in case the goods are not delivered. The customer pays to a shared address defined by:

```
[ "or", [
  [ "and", [
    [ "address", "MERCHANT ADDRESS",
```

```
["in data feed", [{"FEDEX ADDRESS"},
  "tracking", "=", "123456"]]

]],

["and", [

  ["address", "BUYER ADDRESS"],

  ["in data feed", [{"TIMESTAMPER ADDRESS"},
    "datetime", ">", "2016-10-01 00:00:00"]]

]]

]]
```

The definition depends on the FedEx oracle that posts tracking numbers of all successfully delivered shipments. If the shipment is delivered, the merchant will be able to unlock the money using the first condition. If it is not delivered before the specified date, the customer can take his money back. This example is somewhat crazy because it requires FedEx to post each and every shipment.

### 20.1.8. Merkle data feeds

For a more realistic way to achieve the same goal, there is another syntax:

```
["in merkle", [

  ["ADDRESS1", "ADDRESS2", ...],

  "data feed name",

  "hash of expected value"

]]
```

which evaluates to true if the specified hash of expected value is included in any of the merkle roots posted in the data feed from addresses "ADDRESS1", "ADDRESS2",... Using this syntax, FedEx would only periodically post merkle roots of all shipments completed since the previous posting. To spend from this address, the merchant would have to provide the merkle path that proves that the specified value is indeed included in the corresponding merkle tree. The merkle path is supplied as one of the authenticifiers.

### 20.1.9. Self-inspection

A definition can also include queries about the unit itself. This subdefinition



```
[ 'has', { what: 'input'|'output', asset: 'assetID'
  in base64 or "base" for bytes', type:
  'transfer'|'issue', own_funds: true,
  amount_at_least: 123, amount_at_most: 123,

  amount: 123,
  address: 'INPUT OR OUTPUT ADDRESS IN BASE32'
}]
```

evaluates to true if the unit has at least one input or output (depending on the ‘what’ field) that passes all the specified filters, with all filters being optional.

A similar condition ‘has one’ requires that there is exactly one input or output that passes the filters.

The ‘has’ condition can be used to organize a decentralized exchange.

Previously, we discussed the use of multilateral signing to exchange assets.

However, multilateral signing alone doesn’t include any mechanism for price negotiation. Assume that a user wants to buy 1,200 units of another asset for which he is willing to pay no more than 1,000 bytes. Also, he is not willing to stay online all the time while he is waiting for a seller. He would rather just post an order at an exchange and let it execute when a matching seller comes along. He can create a limit order by sending 1,000 bytes to an address defined by this definition:

```
["or", [
  ["address", "USER ADDRESS"],
  ["and", [
    ["address", "EXCHANGE ADDRESS"],
    ["has", { what: "output", asset: "ID of
      alternative asset",
      amount_at_least: 1200,
      address: "USER ADDRESS"
    }
  ]
]]
```

```
]]
```

The first or-alternative lets the user take back his bytes whenever he likes, thus cancelling the order. The second alternative delegates the exchange the right to spend the funds, provided that another output on the same unit pays at least 1,200 units of the other asset to the user's address. The exchange would publicly list the order, a seller would find it, compose a unit that exchanges assets, and multilaterally sign it with the exchange.

One can also use the 'has' condition for collateralized lending. Assume a borrower holds some illiquid asset and needs some bytes (or another liquid asset).

The borrower and a lender can then multilaterally sign a unit. One part of the unit sends the bytes he needs to the borrower, the other part of the unit locks the illiquid asset into an address defined by:

```
["or", [
    ["and", [
        ["address", "LENDER ADDRESS"],
        ["in data feed", [{"TIMESTAMPER ADDRESS"},
            "datetime", ">", "2017-06-01 00:00:00"]]
    ]],
    ["and", [
        ["address", "BORROWER ADDRESS"],
        ["has", {
            what: "output", asset:
            "base", amount:
            10000,
            address: "LENDER ADDRESS"
        }]
    ]],
    ["and", [
        ["address", "LENDER ADDRESS"],
        ["address", "BORROWER ADDRESS"]
    ]
]]
```

```
]]
```

The first or-alternative allows the lender to seize the collateral if the loan is not paid back in time. The second alternative allows the borrower to take back the collateral if he also makes a payment of 10,000 bytes (the agreed loan size including interest) to the lender. The third alternative allows the parties to amend the terms if they both agree.

The following requirement can also be included in a subdefinition:

```
['has equal', { equal_fields:
    ['address', 'amount'],
    search_criteria: [
        {what: 'output', asset: 'asset1', address: 'BASE32'},
        {what: 'input', asset: 'asset2', type: 'issue',
        own_funds:
            true, address: 'ANOTHERBASE32'}
    ]
}]
```

It evaluates to true if there is at least one pair of inputs or outputs that satisfy the search criteria (the first element of the pair is searched by the first set of filters, the second by the second) and some of their fields are equal.

A similar condition ‘has one equal’ requires that there is exactly one such pair.

Another subdefinition may compare the sum of inputs or outputs filtered according to certain criteria to a target value or values:

```
['sum', {
    filter: { what:
        'input'|'output', asset:
        'asset or base', type:
        'transfer'|'issue',
        own_funds: true, address:
        'ADDRESS IN BASE32'
```

```
    }, at_least:  
  
    120, at_most:  
  
    130,  
  
    equals: 123  
  
  ]]
```

### 20.1.10. Negation

Any condition that does not include “sig”, “hash”, “address”, “cosigned by”, or “in merkle” can be negated:

```
[ "not", [ "in data feed", [ [ "NOAA ADDRESS",  
  "wind_speed", ">", "200" ] ] ]
```

Since it is legal to select very old parents (that didn’t see the newer data feed posts), one usually combines negative conditions such as the above with the requirement that the timestamp is after a certain date.

## 20.2. General requirements

Address definition must have at least one “sig”, explicitly or implicitly (such as through an “address”). To avoid consuming too many resources for validation, the total number of operations is limited to 100 per definition, including operations in referenced definitions such as “address” and “definition template”.

This number is one of just 9 arbitrary constants that we have in Byteball, the other 8 being: total

number of witnesses: 12; max allowed mutations: 1; max number of MC indexes for a witness to get

paid: 100; number of parents counted for header size: 2; max number of messages per unit: 128; max

number of inputs or outputs per message: 128; max number of authors per unit: 16; and total money

supply: 1015. For comparison, Bitcoin has at least 17 constants [8], while Ethereum defines 30 constants for fee schedule alone [9].

Note that the definition language described above is declarative and consists entirely of Boolean statements, which puts it closer to the language of conventional legal contracts. However, in terms of its expressive power, the language does not come anywhere close to Ethereum smart contracts language. In fact, it doesn't even allow for a trivial 'Hello world' program to be written. This was not our goal.

The Byteball definition language was not designed to be comprehensive; rather, it is designed to be comprehensible to the greatest possible number of people, who are not necessarily programmers. Its straightforward syntax allows everyone to interpret and compose simple definitions without the help of a developer (a "lawyer" for the era of smart contracts), and chances of mistakes are minimized.

## 21. Assets

We have designed a database that allows immutable storage of any data. Of all classes of data, the most interesting for storage in a common database are those that have social value, i.e. the data that is valuable for more than one or two users.

One such class is assets. Assets can be owned by anybody among a large number of people, and the properties of immutability and total ordering of events that we have in Byteball are very important for establishing the validity of long chains of ownership transfers. Assets in Byteball can be issued, transferred, and exchanged, and they behave similarly to the native currency 'bytes'.

They can represent anything that has value, for example debt, shares, loyalty points, airtime minutes, commodities, other fiat or crypto currencies.

To define a new asset, the defining user sends a message like this:

```
unit: {  
    ...  
    messages: [  
        ...  
        {  
            app: "asset",  
            payload_location: "inline", payload_hash:  
                "hash of payload",
```

```
payload: { cap: 1000000,
  is_private: false,
  is_transferrable: true,
  auto_destroy: false,
  fixed_denominations: false,
  issued_by_definer_only: true,
  cosigned_by_definer: false,
  spender_name_attested: true,
  attestors: [
    "2QLYLKHMUG237QG36Z6AWLVH4KQ4MEY6",
    "X5ZHWBYBF4TUYS35HU3ROVDQJC772ZMG"
  ]
},
...
],
...
}
```

Here:

- cap is the maximum amount that can be issued. For comparison with the predefined native currency bytes, the bytes cap is 1015;
- is\_private indicates if the asset is transferred privately or publicly (see below). Bytes are public;
- is\_transferrable indicates if the asset can be transferred between third parties without passing through the definer of the asset. If not transferrable, the definer must always be either the only sender or the only receiver of every transfer. Bytes are transferrable;

- `auto_destroy` indicates if the asset is destroyed when it is sent to the definer. Bytes are not auto-destroyed;
- `fixed_denominations` indicates if the asset can be sent in any integer amount (arbitrary amounts) or only in fixed denominations (e.g. 1, 2, 5, 10, 20, etc), which is the case for paper currency and coins. Bytes are in arbitrary amounts;
- `issued_by_definer_only` indicates if the asset can be issued by definer only. For bytes, the entire money supply is issued in the genesis unit;
- `cosigned_by_definer` indicates if every transfer must be cosigned by the definer of the asset. This is useful for regulated assets. Transfers in bytes needn't be cosigned by anybody;
- `spender_attested` indicates if the spender has to be attested in order to spend. If he happened to receive the asset but is not yet attested, he has to pass attestation with one of the attestors listed under the definition, in order to be able to spend. This requirement is also useful for regulated assets. Bytes do not require attestation;
- `attestors` is the list of attestor addresses recognized by the asset definer (only if `spender_attested` is true). The list can be later amended by the definer by sending an `'asset_attestors'` message that replaces the list of attestors;
- `denominations` (not shown in this example and used only for `fixed_denominations` assets) lists all allowed denominations and total number of coins of each denomination that can be issued;
- `transfer_condition` is a definition of a condition when the asset is allowed to be transferred. The definition is in the same language as the address definition, except that it cannot reference anything that requires an authenticifier, such as `"sig"`. By default, there are no restrictions apart from those already defined by other fields;
- `issue_condition` is the same as `transfer_condition` but for issue transactions.

There can be no more than 1 `'asset'` message per unit. After the asset is defined, it is identified by the hash of the unit where it was defined (hence the 1 asset per unit requirement).

A transfer of an asset looks like a transfer of bytes, the difference being that there is an extra field for the asset ID:

```
unit: {  
  
    ...  
  
    messages: [  

```

```
...
{
  app: "payment", payload_location:
  "inline", payload_hash: "hash of
  payload",
  payload: {
    asset: "hash of unit where the
    asset was defined", inputs: [
      {
        unit: "hash of source unit",
        message_index: 0,
        output_index: 1
      },
      ... ],
    outputs:
    [
      {
        address: "BENEFICIARY ADDRESS",
        amount: 12345
      },
      ...
    ]
  }
},
...
```

```
],
```



```
...  
}
```

Before it can be transferred, an asset is created when a user sends an issue transaction. Issue transactions have a slightly different format for inputs:

```
unit: {  
  ...  
  messages: [  
    ...  
    {  
      app: "payment", payload_location:  
        "inline", payload_hash: "hash of  
        payload",  
      payload: { asset: "hash of unit where the  
        asset was defined", inputs: [  
          {  
            type: "issue",  
            amount: 1000000, serial_number:  
            1, address: "ISSUER ADDRESS" //  
            only  
            when multi-authored  
          },  
          ... ],  
        outputs:  
          [  
            {  
              address: "BENEFICIARY ADDRESS",
```



amount: 12345

```
    },  
    ...  
  ]  
}  
},  
...  
],  
...  
}
```

The entire supply of capped arbitrary-amounts assets must be issued in a single transaction. In particular, all bytes are issued in the genesis unit. If the asset is capped, the serial number of the issue must be 1. If it is not capped, the serial numbers of different issues by the same address must be unique.

An asset is defined only once and cannot be amended later, only the list of attestors can be amended.

It's up to the definer of the asset what this asset represents. If it is issuer's debt, it is reasonable to expect that the issuer is attested or waives his anonymity to earn the trust of the creditors.

While end users are free to use or not to use an asset, asset definers can impose any requirements on transactions involving the asset.

By combining various asset properties the definer can devise assets that satisfy a wide range of requirements, including those that regulated financial institutions have to follow. For example, by requiring that each transfer be cosigned by the definer, financial institutions can effectively veto all payments that contradict any regulatory or contractual rules. Before cosigning each payment, the financial institution (who is also the definer and the issuer) would check that the user is indeed its client, that the recipient of the funds is also a client, that both clients have passed all the Know Your Client (KYC) procedures, that constantly changing laws, regulations, and internal rules, including those that were introduced after the asset was defined.

## 22. Private messaging

For private payments to work, users need a way to securely deliver private payloads to each other. Users, or rather their devices, also need to communicate to assemble signatures for multi-sig addresses.

Since we cannot expect user devices to be constantly online and easily reachable (most of them will be behind NAT), we need a store-and-forward intermediary that is always online, easily reachable, and able to temporarily store any data addressed to a user device.

In Byteball, such an intermediary is called the hub, and its operation is similar to email. A hub is a Byteball node that additionally offers a service of storing and forwarding private messages to connected devices. There can be many hubs. Each device that runs a wallet code subscribes to a hub of its choice, and can be reached via this hub (the home hub). The choice of home hub can be changed at any time.

Each device has a permanent private key that is unique to the device. The hash of the corresponding public key (more precisely, the hash of the single-sig definition based on this public key) is called the device address, and it is written in base32 like the payment addresses. The full device address, including its current hub, can be written as `DEVICEADDRESSINBASE32@hubdomainname.com`. If the device moves to another hub, the part of its full address before `@` stays the same. Unlike email, the name cannot be already “taken”.

Every device connects to its home hub using websockets. The hub sends the new messages to the device and the device stays connected to the hub, so that if a new message arrives while the device is connected the new message is delivered immediately. The hub doesn't keep copies of the messages that were successfully accepted by the device. The connection to the hub is TLS encrypted.

When a device wants to send something to another device, it connects to the recipient's hub and sends the message. Unlike email, there is no relay – the sender connects directly to the recipient's hub. All communication between devices is end-to-end encrypted and digitally signed so that even the hub (who is the only man in the middle) cannot see or modify it. We use ECDSA for signing and ECDH+AES for encryption.

Before exchanging encrypted messages the devices must be paired, i.e. learn each other's public key. This can happen in various ways, e.g. by scanning a QR code that encodes the public key and hub domain name of one of the devices, by sending this information over email, or by clicking a `byteball://` link on a secure website.

For forward security, every device generates a temporary private key and uploads the corresponding public key to its home hub. Afterwards, the device rotates the key from time to time but keeps a copy of the previous key in case someone sent a message to the previous key while the hub was replacing it. The hub keeps only one version of the temporary public key per subscribed device.

The sending device follows these steps to send a message:

1. connects to the recipient's hub;
2. receives the current temporary public key of the recipient from the hub;
3. generates its own one-time ephemeral key pair;
4. derives ECDH shared secret from the recipient's temporary public key and own ephemeral private key;
5. AES-encrypts the message using this shared secret;
6. adds its own ephemeral public key;
7. signs the package with its own permanent key; and
8. sends it to the hub.

The recipient device verifies the signature, derives ECDH secret using the peer's ephemeral public key and own temporary private key, and decrypts the message.

If the sending device fails to connect to the recipient's hub, it encrypts the message to the recipient's permanent key (this encryption is not forward secure since it uses a permanent key) and stores the encrypted message locally for future retries. The purpose of this encryption is to avoid having unencrypted messages lying around. After connection to the recipient's hub succeeds, the device sends this encrypted message, thus encrypting it again (this time, with forward security), so the message is doubleencrypted. Note that this is not because single encryption is insufficient, but because we don't want to store unencrypted content for an indefinite time while the connections are retried.

Note that the communication is among devices, not users. Users may (and are recommended to) hold several devices, such as a laptop, a smartphone, and a tablet, and set up multisig addresses with redundancy (such as 2of-3) that depend on keys stored on multiple devices. When a user needs to sign a transaction, he initiates it on one of his devices. This device then sends the partially signed transaction to the other devices using private messages, collects all the signatures, and publishes the transaction. The private keys stored on each device should never leave that device. When the user replaces one of his devices in a 2-of-3 address, he just uses the other 2 devices to change the address definition and replace the key of the old device with the key of a new device.

The private messages can also be used for encrypted texting between devices. These messages are strictly peer-to-peer, never go into the Byteball database, and can be safely discarded after they are read.

When users pay in blackbytes or other private assets, they have to send private payloads and absolutely need devices that can communicate. They need to know each other's device addresses before they even learn each other's payment addresses. Once their devices have established communication, the payee can send his payment address to the payer via chat message. Such a payment scenario also makes it easy to generate a unique

payment address for every incoming payment. A merchant can run a chat bot that communicates with users via text messages. When the user is ready to pay the bot generates a new payment address and sends it to the user in a chat message.

## 23. Conclusion

We have proposed a system for decentralized immutable storage of arbitrary data, including data of social value such as money. Every new unit of data implicitly confirms the existence of all previous units. Revision of past records similar to that in 1984 becomes impossible, as every new unit also implicitly protects all previous units from modification and removal. There is an internal currency that is used to pay for inclusion of data in the decentralized database. The payment is equal to the size of the data to be stored, and other than this payment there are no restrictions on access to the database. Other assets can also be issued and their ownership can be tracked on the database.

When tracking payments in the internal currency and other assets, double-spends are resolved by choosing the version of history that was witnessed by known reputable users. Settlement

finality is deterministic. Assets can be issued with any rules that govern their transferability, allowing regulated institutions to issue assets that meet regulatory requirements. At the same time, transfers can be hidden from third parties by sending their content privately, directly from payer to payee, and publishing spend proofs to ensure that each coin is spent only once.

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