RGB I.0
Scalable consensus for client-side validated smart contracts

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Abstract

This paper defines a novel type of consensus for a smart contract system, named RGB, which is based on the concept of client-side validation, separating the contract state and operations from the blockchain. With this approach, contracts are sharded (each contract is a standalone shard), kept, and validated only by contract participants, providing native scalability and privacy mechanisms, exceeding abilities of all existing blockchain-based smart contracts while not compromising on security or decentralization. The client-side validated distributed smart contracting system is designed to operate on top of an UTXO-based blockchain (e.g., Bitcoin) without relying on it for transaction ordering or state replication. Instead, RGB employs a novel SONIC (State machine with Ownership Notation Involving Capabilities) architecture, leveraging the zk-AluVM virtual machine and zero-knowledge STARK proofs for scalability, security, and formal verification. The protocol emphasizes partially replicated state machines (PRiSM), polynomial computation, and capability-based access control, which makes it distinct from traditional blockchain-based smart contract systems.

1 Introduction

The idea of smart contracts, originating from Nick Szabo [?], has been an inspiration for almost a generation. However, all existing attempts, such as blockchains, different types of sidechains, rollups, state channels, and others, fail to achieve all the required properties of the following trilemma:

- be scalable independently of the number of participants;
- be universal ("Turing-equivalent");
- be decentralized, permissionless and trustless.

Client-side validation is the paradigm proposed by Peter Todd in 2016 [?]. Its core idea is the fact that the state validation in a distributed system does not need to be performed globally by all parties to the decentralized protocol; instead, only parties involved in a specific state transition need to perform the validation. With this approach, the state transition does not need to be published globally; instead, it is sufficient to make sure that a cryptographic commitment for it can be verified as final and singular by all parties participating in the state transition. This is achievable with a new class of cryptographic protocols, proposed by Peter Todd, named single-use seals [?], which allows to prove both finality and singularity of the transition in a noninteractive way.

Based on ideas of Peter Todd, Giacomo Zucco has proposed an early idea of RGB, a client-side validated asset system, leveraging Bitcoin transactions (both on-chain and off-chain, like in Lightning network) as a single-use-seal protocol [?]. However, it was lacking programmability, support for non-trivial state, ability for a Bitcoin UTXO to be used by multiple assets, and was not zk-friendly.

In our work, we have developed the original idea of RGB into the first universal client-side validated distributed smart contracting system, solving all of the above-mentioned issues. RGB employs a novel SONIC (State machine

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with Ownership Notation Involving Capabilities) architecture, leveraging the zk-AluVM virtual machine and zero-knowledge STARK proofs for scalability, security, and formal verification. The protocol operates as partially replicated state machines (PRiSM); it uses polynomial computation, and capability-based access control, which makes it distinct from traditional smart contract systems. The protocol operates on top of a UTXO-based blockchain (so-called *layer 1*) as a finality gadget; however, it is not used for ordering of transactions or storing a state, unlike all other smart contract systems. Thus, layer 1 in strict computer science terms does not serve as an RGB consensus, since it does not fulfill any of the properties defining a distributing consensus protocol:

- ordering of transactions (RGB transactions are not published or broadcast via blockchain);
- state machine replication (no state is replicated via layer 1);
- atomic broadcasts (since the ordering of layer 1 transactions doesn't matter for RGB).

Instead, RGB runs its own *client-side validated consensus*, where blockchain consensus acts as one of the components, the *single-use seal* medium. This paper provides a complete formal description of the first version of the RGB consensus.

2 Used Notations

We use standard mathematical symbols, including symbols of set theory.

The order of the elements in a set is indicated by $\succ$ and $\prec$.

Terms are defined by $\triangleq$, sets are indexed by subscripts $s_i \in \mathcal{S}$, logical conditions are done with $\wedge$ (AND), $\vee$ (OR) and $\neg$ (NOT), $\iff$ is used for *if and only if* condition, $\Rightarrow$ for *than*, $\nRightarrow$ for *else*, and $\perp$ is a program termination.

Data types are defined using standard mathematical number sets, such as natural numbers $\mathbb{N}$, integers $\mathbb{Z}$, nonzero natural numbers $\mathbb{N}^{+} \triangleq \mathbb{N} \setminus \{0\}$ and finite field $\mathbb{F}_q$ (where q is the order of the finite field). The bit dimensions (except for the finite field elements) are given as a subscript: $\mathbb{N}_{256}$ with $\mathbb{N}_8 \triangleq \mathbb{N}_8$ used for both 8-bit unsigned integers and bytes. Binary strings (scalar arrays) of fixed size are given using power notation, for instance, $\mathbb{N}_8^{32}$ is a 32-byte string.

Named data types are represented with capital Latin letters using LaTeX MATHBB font style. For example, the Boolean type is defined as a set $\mathbb{B} \triangleq \{0, 1\}$.

Scalar variables are given with Latin and Greek lowercase letters.

Tuples (ordered fixed-size set of objects of a different type) are denoted with angular brackets $\langle \ldots \rangle$ to list the tuple elements and with small Latin serif letters (such as a, x) to represent immutable values.

Multivalued tuples that may change over time (tuple variables) are denoted with capital Latin or Greek serif letters (like C). To represent a sequence or individual tuple values which evolve over time (like state objects), with individual values being a lowercase indexed version of the same letter ($\mathsf{c}_0, \mathsf{c}_i$, etc.)

We use a tuple name and serif index to represent a named element of a tuple, such as in $\mathsf{c}_i \triangleq \langle \mathsf{C}_{\mathsf{Id}},\ \ldots \rangle$.

Variable-size sets of the same-typed objects (ordered or unordered) are denoted with calligraphic uppercase Latin letters (like $\mathcal{S}$). For representing set elements we use braces $\{\ldots\}$ and set builder notation [6]. The type of variable-sized sets is given as an element type with a power component specifying the range of cardinality allowed for the set. For example, $\mathbb{N}_8^{[0,32)}$ indicates a sequence of bytes with cardinality (length) in the range of 0 to $2^{32}-1$.

Sets are differentiated by the ordering of their elements using index notation:

- $\{\cdots\}_{\prec}$ for partially ordered sets;
- $\{\cdots\}_{\preceq}$ for totally ordered sets;
- no index for unordered sets.

Unicode strings are represented as a sequence made up of $\mathbb{U}$ set elements (UTF-8 character set); ASCII strings as a sequence made up of $\mathbb{S}$ set elements. If there are constraints on the type of ASCII characters that can be used in a string, the constraint is either given verbally as an index (for example, $\mathbb{S}_{\mathsf{printable}}$), or as a wildcard '$\mathbb{S}_*$' with detailed explanation of the constraints given in the text.

Functions with a well-defined algorithm are denoted by small-case Latin serif names, followed by a dot, function domain, arrow, and function codomain, such as $\mathsf{evaluate} : \mathcal{A} \to \mathcal{B}$. The application of the function to the arguments is written as $\mathsf{evaluate}(a_i)$. Variables having function type are written as small Greek letters in italics, ϕ, and their application as $\phi(x)$. Inline functions depending on their previous values are defined using $\mapsto$ instead of $\to$.

All numbers are encoded into and from a byte-strings with a little-endian convention.

3 Protocol Overview

In technical terms, RGB operates as *partially replicated state machines* (PRiSM), which uses *polynomial computer architecture* SONIC (State machine with Ownership Notation Involving Capabilities).

Partially replicated means that the state is not replicated in all instances of the state machine; instead, only a part of the state required by each of the instances is propagated.

Polynomial computer means that the trace of the operations by the consensus protocol can be arithmetized to polynomials, making it possible to use any zk-STARK prover for zero-knowledge compression.

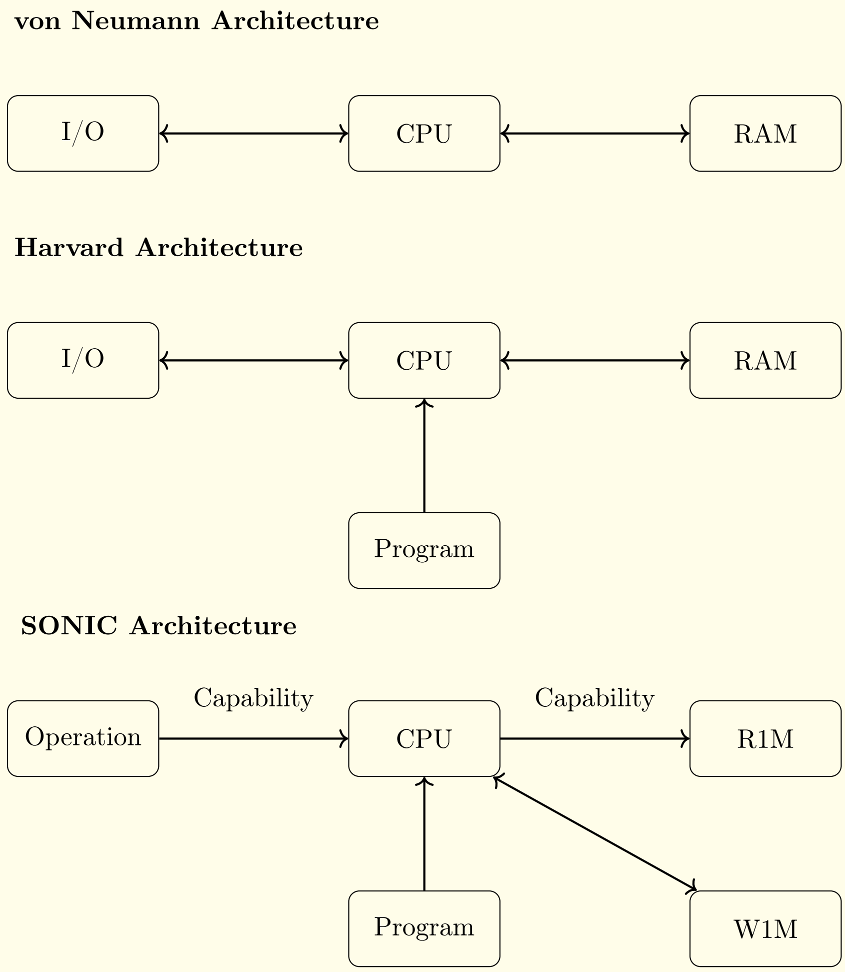
Ownership notation involving capabilities means that some types of state in RGB are assigned to specific parties (actors), and this assignment is made using *capabilities*, which are implemented using a single-use seal cryptographic scheme.

Components:

- SONIC polynomial computer (its consensus-related layer named "UltraSONIC") with capability-based memory and zk-AluVM virtual machine, used for contract state evaluation/validation;
- RGB contracts with state and transitions;
- commitment schemes, using cryptographic hash functions;
- single-use seals, for providing capabilities and for finality.

The version of RGB consensus described in this document is named **RGB-I.0**. You can find more about RGB version numbering in the RGB-6 standard [2].

Figure 1: Comparison of different computer architectures



4 SONIC Architecture

Most modern computers use modified von Neumann and Harvard architecture, derived from it. While offering a convenient user experience, these architectures were not designed neither for arithmetization, required in creation of zk-STARK proofs, nor for distributed system requirements, nor for security and formal verification. For example, random-memory access has become the source of most hacks and security bridges for over 50 years. So, while it is possible to adopt von Neumann-style architecture for zk-STARK provers (one may refer to Cairo [8]), this results in large proof size, high computational resource demand and no ability in doing formal analysis of any program.

Instead of following such an approach, RGB is using a different architecture, named SONIC, which is specifically designed for formal verification, UTXO-based models, and security. The architecture uses a virtual machine zk-AluVM, immutable memory cells of two types (read-once memory, R1M; and write-once memory, W1M), and capability-based R1M access.

4.1 zk-AluVM virtual CPU

AluVM [9] is a modular framework for developing RISC instruction set architectures and registry-based virtual machines, based on category theory. RGB uses zk-AluVM version of it, which comes with GFA256 instruction set architecture, supporting arithmetic operations with finite field elements. It is extended by USONIC and RGB-specific instructions for accessing operation data and memory. The complete specification on the instruction set architecture is given in Annex A.

4.2 Memory

The SONIC architecture supports two types of addressed memory:

Read-once memory (R1M), or *destructible memory* $\mathcal{D}$, having capability-based access and used for storing *owned state* accessible only by a valid actor providing a 256-bit *authentication token*;

Write-once memory (W1M), or *immutable memory* $\mathcal{I}$, which can be accessed by any party and is used to define a global contract state.

Both types of memory are made of addressable memory cells. An address consists of a 256-bit id of operation and 16-bit output number which creates the memory cell:

$$\mathbb{A} \triangleq \mathbb{N}_8^{32} \times \mathbb{N}_{16} \tag{1}$$

$$\mathsf{a} \triangleq \langle \mathsf{Id}(c_i), j \rangle \in \mathbb{A} \tag{2}$$

Memory data are based on *composed values* data type, which is an ordered sequence of zero to four finite field elements:

$$\mathbb{V} \triangleq \bigcup_{n=0}^{4} \mathbb{F}_q^n \tag{3}$$

Read-once memory cells consist of a single *composed value* σ, an *authentication token* α, and an optional *locking condition* $\mathcal{L}$:

$$\mathbb{D} \triangleq \mathbb{V} \times \mathbb{F}_q \times \{\varnothing, \ell\} \tag{4}$$

$$\forall \mathsf{d}_i \in \mathcal{D}(\mathsf{a}) : \mathsf{d}_i \triangleq \langle \sigma, \alpha, \mathcal{L} \rangle \in \mathbb{D} \tag{5}$$

A locking condition, when present as ℓ, is an entry point into the AluVM program (see next section), which should succeed on execution in order for the cell to be read and destroyed. If a locking condition is not present, the memory cell is destroyed on the first read operation and cannot be anymore accessed or referenced.

Immutable memory cells consist of a single *composed value* σ, and an optional binary raw data $\mathcal{R}$, up to 2^{16} bytes:

$$\mathbb{I} \triangleq \mathbb{V} \times \{\varnothing, \mathbb{N}_8^{[0;2^{16})}\}_{\preceq} \tag{6}$$

$$\forall \mathsf{e}_i \in \mathcal{I}(\mathsf{a}) : \mathsf{e}_i \triangleq \langle \sigma, \mathcal{R} \rangle \in \mathbb{I} \tag{7}$$

The raw data do not participate in the validation process and thus are never arithmetized. Their purpose is to provide more context information for the user, and they are parsed and processed using ABI rules and the standard library code (see the RGB-1010 standard [3]).

4.3 Program

AluVM operates as a Turing machine, running on a "tape" of SONIC program, with the following modifications:

- the machine can't change the cells on the tape (the program is read-only);
- it has access to external data outside of the tape:
  - current contract operation,
  - addressable (see Section 4.2);

- its execution is bounded by so-called *complexity measure*; each execution of an instruction increase complexity counting register in AluVM virtual CPU, and when the value exceeds a limit provided as a part of a contract Codex (see Section 5.1), it halts, ending in a failed state.

The machine executes a single instruction at each step. The complete list of all instructions and their encodings, as well as information about registers (i.e. Instruction Set Architecture), is given in the Annex A.

AluVM comes with a set of special-purpose control registers. Three of these registers influence the halting conditions of the machine:

CH Halting register. When set to `true`, halts program when **CK** is set to the failed state.

CK Check register, which is set for any failure (accessing register in `None` state, zero division, etc.). Can be reset if **CH** is `false`.

CO Test register, which acts as a Boolean test result (also a carry flag). Its value is checked by branching and some halting instructions.

CA Complexity accumulator / counter. Each instruction has a computational complexity measure. This register sums up the complexity of the instructions executed.

CL Complexity limit. If this register has a value set, once **CA** reaches or exceeds its value, the VM will set **CK** to a failed state.

The program halts on the following conditions:

1. On an unconditional halting instruction execution (see table of all instructions);
2. On a conditional halting instruction execution *if* the value of instruction-specific register (**CO** or **CK**) is set;
3. On any invalid operation (division by zero, accessing non-existing value or memory cell, etc.) *if* the **CH** is set;
4. On a jump to an unknown location (unknown library id or an offset outside the bounds of the library code segment);
5. Once the complexity limit given in **CL** is exceeded, *if* the **CL** register contains a value, and **CH** is set.

The complexity limit **CL** and halting flag **CH** are initialized using contract parameters from a Codex (see Section 5.1). When a complexity limit and halting are defined, an AluVM program is guaranteed to halt; allowing termination analysis.

Execution of a program results in an execution trace consisting of instructions, input values (values in registers before instruction was executed), output values (new values in registers once the instruction is executed) and hidden parameters, coming from the external data if they were accessed. The execution trace may be encoded using elements of the finite field $\mathbb{F}_q$ and fed to a zk-STARK prover. Specific details of the encoding and selection of zk-STARK prover is outside of the scope of this document and are a subject of future work.

To run a program, AluVM must be provided with an unordered set of known *libraries*, used by the program, and an *entry point* $\mathsf{e} \triangleq \langle \mathsf{Id_{lib}} \in \mathbb{N}_8^{32}, p \in \mathbb{N}_{16} \rangle$, consisting of a library id $\mathsf{Id_{lib}}$ and an offset p in the library code segment. The number of known libraries is unbounded; so the complexity limit mechanism is the only way to bound the computation of a program. For information about the AluVM library, its structure, constraints, etc. please refer to the documentation [9].

5 Contracts

Contract is an instance of RGB protocol. RGB consensus operates on the contract level, and doesn't include (as of version I.0) any cross-contract functionality[1].

Since RGB operates as a partially-replicated state machine, each party has a partial view over contracts, named *local contract*. A local contract is defined as

$$\mathsf{C} \triangleq \langle \Theta, \mathcal{O} \setminus \{\mathsf{c}_0\} \rangle \tag{8}$$

where Θ is a contract issue and $\mathcal{O}$ is the locally known part of the contract operations (excluding the genesis operation c_0 already present in Θ, see below).

The contract *issue* defines *unique* and *global* properties of a contract; it must be known to all parties (i.e., present in each *local contract* instance) and it is represented by a tuple

$$\Theta \triangleq \langle v, \mathsf{m}, \mathsf{k}, \mathsf{c}_0 \rangle \tag{9}$$

The meaning of the symbols is given in Table 1.

The commitment to the *issue* data represents a unique and global *contract id* $\mathsf{Id}(\mathsf{C})$, or $\mathsf{C_{Id}}$.

[1] However, one may still achieve cross-contract interaction outside of the consensus layer, for instance using atomic swaps.

Table 1: Specification of symbols used in the RGB contract

Symbol	Type	Value range	Meaning
v	$\mathbb{N}_8$	constant 0	RGB issue data structure version
m	$\langle \mathbb{B}, \mathbb{N}_8, \mathbb{N}_{64}, \mathbb{B}^{48}, \mathbb{S}_*^{[1,100)?}, \mathbb{S}_{\mathsf{printable}}^{[1,4096)} \rangle$	n/a	Contract metadata
k	See Section 5.1	n/a	Codex
c_0	See Section 5.3	n/a	Genesis operation

The contract metadata m define contract-specific parameters, which include (in the order of their position in the tuple):

1. boolean indicating whether the contract is a test contract,
2. a specific consensus layer 1 used by the contract,
3. ISO 8601 timestamp of the moment the contract is issued,
4. a set of feature flags (must be zeros for RGB-I.0),
5. optional name of the contract, which must start with a capital letter or a _ symbol, and may contain up to 99 ASCII letters, numbers, or _ symbol,
6. an identity string of the contract issuer, made of ASCII printable characters.

5.1 Codex

The codex is a set of parameters and rules that define the contract business logic but do not define any form of a state. The *contract business logic* does not mean the way state transitions are created; instead, it defines how an arbitrary state transition, created with any possible rules, gets validated. If it passes the validation, its business logic is valid; otherwise, the state transition is invalid and does not apply. This paves the way to huge scalability as well as much more compact zk-STARK proofs; since any zk-proof just proves a result of a computation, not specifying the exact way of performing the computation itself. The mistake of blockchain developers was to put the actual state transition function into the blockchain, which does not scale. Client-side validation, implemented in RGB, fixes that.

Thus, an RGB codex defines a state transition *validation* functions, which are differentiated by a state transition type: one contract may have multiple forms of state transition, which can be seen as mutating methods of the contract.

Next, a codex defines the following contract parameters:

- Specific finite field size, which defines finite field $\mathbb{F}_q$ order q and bit dimensions for finite field type variables, denoted hereinafter as $\|q\|_{\mathsf{bits}}$;
- cryptographic hash function used in commitment schemes;
- specific single-use seal protocol, which also defines the subset of specific blockchain networks, and commitment schemes;
- specific blockchain.

More formally, codex is a tuple

$$\mathsf{k} \triangleq \langle v, n, d, t, f, q, \Gamma, \Lambda, V \rangle \tag{10}$$

Table 2: Specification of symbols used in the RGB codex

Symbol	Type	Value range	Meaning
v	$\mathbb{N}_8$	constant 0	RGB codex data structure version
n	$\mathbb{N}_8^{[0,255]}$	n/a	Contract name, parsed as Unicode UTF-8 string
t	$\mathbb{N}_{64}$	any	ISO 8601 timestamp of codex creation
f	$\mathbb{B}^{32}$	constant 0	Feature flags (must be zeros in RGB-I.0)
q	$\mathbb{Z}_q$	$[0, \mathbb{Z}_q)$	Finite field order
Γ	$\langle \mathbb{B}, \mathbb{B}, \mathbb{N}_{64} \rangle$	n/a	zk-AluVM configuration for state transition verification
Λ	$\langle \mathbb{B}, \mathbb{B}, \mathbb{N}_{64} \rangle$	n/a	zk-AluVM configuration for memory access lock verification
V	$\mathbb{N}_{16} \rightarrow \langle \mathbb{N}_8^{32}, \mathbb{N}_{16} \rangle$	any	Entry points for verification functions using AluVM libs

Configurations for a zk-AluVM are 3-tuples, which values correspond to:

1. Boolean flag indicating whether a VM must halt on the first occurrence of a failure;
2. Boolean indicating whether a complexity limit is set;
3. 64-bit natural number representing the complexity limit (of the 2 is set).

For details on complexity limits, please address AluVM documentation [9].

The same codex may be used by multiple contracts in the same way as a class, defined with a programming language, may instantiate multiple objects.

It is important to note that multiple contracts may reuse the same codex. In this way, there appears a natural differentiation between contract issuers and codex developers, with the former being specializing in financial services, assets, etc; and the second being specialists in computer science.

5.2 Contract State

A *local contract state* is fully defined by a set of its operations, $\mathcal{O}$.

Since RGB consensus needs to operate as a polynomial computer with a computation trace being arithmetizable as a set of polynomial constraints, the state of a contract at the level of consensus must be always represented by a mathematical construct made of elements of the finite field $\mathbb{Z}_q$, provided in the [contract codex](codex). This state is not human-readable and must be processed using a specific ABIs and interfaces to be read by humans; however, this part lies outside the consensus definition, belonging to the RGB standard library, defined in RGB-1010 standard [3].

Contract memory is a tuple $\langle \mathcal{D}, \mathcal{I} \rangle$, consisting of destructible $\mathcal{D}$ and immutable $\mathcal{I}$ memory cells, as described in the Section 4.2.

- The destructible memory cells represent a *read-once memory* (R1M), which is defined by contract operations destructible outputs and removed once accessed by any of the contract operations referencing it as one of its inputs.
- The immutable memory cells represent a *write-once multiple-access* memory (W1M), which is defined by contract operations immutable outputs, and accessed by contract operations immutable inputs.

The state of the memory is defined as a result of executing the $\mathsf{evaluate} : \mathcal{O} \to \langle \mathcal{D}, \mathcal{I} \rangle$ procedure, as described in the Section 5.5.

5.3 Contract Operation

Contract operation is a tuple

$$o_i \triangleq \langle \mathsf{c}_i, S_i, u_i \rangle \tag{11}$$

consisting of:

- client-side information of contract state change, represented by a tuple c_i;
- an unordered map of seal definitions performed by an operation, $S_i(x) : y_x \in \mathcal{Y}_\rangle \to s_x$, where s_x is a seal definition;
- a seal closing witness information, which values must belong to a set of either unit value, or a specific witness w_i: $u_i \in \{\varnothing, w_i\}$.

A client-side part of the operation is represented by a tuple

$$\mathsf{c}_i \triangleq \langle v, \mathsf{C_Id}, \phi, \lambda, \Upsilon, \mathcal{A}, \mathcal{B}, \mathcal{Y}, \mathcal{Z} \rangle \tag{12}$$

which meaning is given in the table 3.

Table 3: Specification of symbols used in the RGB operation

Symbol	Type	Meaning
v	$\mathbb{N}_8$	RGB consensus version (must be set to 0)
$\mathsf{C_Id}$	$\mathbb{N}_8^{32}$	Contract id
ϕ	$\mathbb{N}_{16}$	Call id
λ	$\mathbb{N}_{16}$	Nonce
Υ	$\mathbb{V}$	Witness data
$\mathcal{A}$	$\{\mathbb{A} \times \mathbb{V}\}_{\preceq}^{[0,2^{16})}$	Destructible memory refs (input)
$\mathcal{B}$	$\{\mathbb{A}\}_{\preceq}^{[0,2^{16})}$	Immutable memory refs (input)
$\mathcal{Y}$	$\{\mathbb{D}\}_{\preceq}^{[0,2^{16})}$	Destructible memory declaration (output)
$\mathcal{Z}$	$\{\mathbb{I}\}_{\preceq}^{[0,2^{16})}$	Immutable memory declaration (output)

Contract *genesis* is a special type of operation, containing no input:

$$\mathsf{c}_0 \triangleq \langle \pi, \mathsf{k}_{\mathsf{Id}}, \phi, \lambda, \Upsilon, \varnothing, \varnothing, \mathcal{Y}, \mathcal{Z} \rangle \tag{13}$$

Each operation is identified by an operation id, $\mathsf{Id}(c_i)$, which is computed by hashing serialized data for the client-side part of the operation, as described in Section 6. For the genesis, the value of k_{Id} is replaced with the value of C_{Id} before the operation id is computed.

5.4 Set of Operations

Each contract is defined by a partially ordered set of contract operations $\mathcal{O} \triangleq \{o_i\}$. An element of this set is a tuple, $o_i \triangleq \langle c_i, S_i, u_i \rangle$, consisting of:

- client-side information of contract state change, c_i;
- an unordered map of seal definitions performed by an operation, $S_i : d_j \in \mathcal{Y}_i \to s_j$, where s_j is a seal definition;
- a seal closing witness information, which values must belong to a set of either unit value, or a specific witness w_i: $u_i \in \{\varnothing, w_i\}$.

The set $\mathcal{O}$ has an initial element, called *genesis* o_0, for which $u_i = \varnothing$. There might be other operations for which $u_i = \varnothing$; these operations are named *state extensions*.

All operations in $\mathcal{O}$ are partially ordered via rule

$$\begin{aligned} o_i \prec o_j \iff & (\exists\ y \in \mathcal{Y}_i : y_{\mathsf{addr}} \in \mathcal{A}_j) \\ & \vee (\exists\ x \in \mathcal{X}_i : x_{\mathsf{addr}} \in \mathcal{B}_j) \end{aligned} \tag{14}$$

which means that if there exists at least one output of c_i which is used by c_j, or a global state defined in c_i which is read by c_j, than o_i precedes c_j.

If the $\mathcal{O}$ is not a directed acyclic graph and the above rule can't be fulfilled without collisions, the operation set must be recognized as invalid.

5.5 Evaluate Procedure

The contract state is evaluated using the following $\mathsf{evaluate}$ procedure applied to the set of contract operations:

$$\begin{aligned} \mathsf{evaluate} \triangleq \forall o_i \in O : \\ (\forall\ a \in \mathcal{A}_i\ \exists!\ d \in \mathcal{D}_i : \mathsf{addr}(d) = a) \\ \wedge\ (\forall\ b \in \mathcal{B}_i\ \exists!\ e \in \mathcal{I}_i : \mathsf{addr}(e) = b) \\ \wedge\ \mathsf{verify}(w_i, \mathcal{Y}_i) \\ \wedge\ \mathsf{exec}(\mathsf{k}, \wp, \mathcal{I}_i, \mathcal{D}_i, c_i) \\ \Rightarrow \begin{cases} \mathcal{D}_{i+1} \mapsto (\mathcal{D}_i \setminus \mathcal{A}_i) \cup \mathcal{Y}_i, \\ \mathcal{I}_{i+1} \mapsto \mathcal{I}_i \cup \mathsf{global}(c_i) \end{cases} \\ \not\Rightarrow \bot \end{aligned} \tag{15}$$

The first part of the algorithm checks whether an operation is correct, and depending on the result, the contract state is either evolved (middle expression) or the further validation terminates.

The addr procedure returns a memory address for a given memory cell.

The verify procedure performs verification of a set of single-use seals and a witness according to the LNPBP-8 standard [4].

The exec procedure executes verification program and programs checking fulfillment of individual lock conditions for the spent inputs, and is provided with codex data, a set of known AluVM libraries $\wp$, access to the memory and client-side operation data. It succeeds if and only if at the halting of the AluVM machine its register **CK** is not set.

6 Commitments

Commitments are created using binary data serialization using strict encoding [7], specifically:

1. Numbers are serialized in little-endian format, using a number of bytes required to cover the bit dimension of the used numeric type.
2. Sum types (enums, including primitive and with associated data) are prefixed with a 8-bit tag.
3. Fixed-size arrays are encoded as is, with no prefixing.
4. Variable-size collections (objects representable as mathematical sets, either ordered or unordered, including sequences, partially ordered sets, ordered sets, maps) are prefixed with the size of the collection (cardinal number) in little-endian format, using the number of bytes which fully covers the maximal allowed collection dimension; followed by elements of the collection, serialized one after other.

5. Totally ordered sets must be serialized in the order of the elements
6. Partially ordered and unordered sets do not participate in the RGB consensus.
7. Maps are serialized with elements corresponding to the key and value, composed as a tuple. Keys of the ordered maps must represent a totally ordered set and define the order of the serialization of key-value tuples.
8. Product types (tuples) are serialized according to the order of their elements, with no prefixes.

Data are serialized into the hashers, which usually uses a prefix (tagged) to uniquely codify the type of the produced commitment. Collections may also be merklized, in order to allow compact profs of inclusion. The complete structure of data serialization for producing commitments, including tagged prefixes and details of merklization, is given in the Annex B.

7 Additional Information

7.1 RGB on Bitcoin

When RGB is used on top of Bitcoin, the following parameters apply:

1. A *contract issue* must reference specific bitcoin blockchain & network as a value for its m_2 field (layer 1 in contract metadata) using the Table 1.
2. TxO-based single-use seals must be used, as they are defined in the LNPBP-10 standard [5].

7.2 Security Assumptions

The security of RGB consensus relies on the following two assumptions

- The selected cryptographic hash function is collision-resistant;
- The used single-use seal protocol is secure.

7.3 Reference Implementation

The reference implementation is provided in repositories, and libraries are listed in the Consensus section of RGB-3 standard [1].

8 Acknowledgments

The whole work was inspired by the earlier ideas of Peter Todd on the client-side validation [?] and single-use seals [?] protocols. Giacomo Zucco was the first, who had analyzed its possible applications and implications for Bitcoin blockchain and Lightning Network. Adam Borko had suggested ideas and critics on the zk-STARK compatibility of the protocol. Olga Ukolova had provided a lot of feedback and comments during the protocol design phase.

References

[1] RGB-3 Standard, https://github.com/RGB-WG/RFC/blob/master/RGB-0003.md

[2] RGB-6 Standard, https://github.com/RGB-WG/RFC/blob/master/RGB-0006.md

[3] RGB-1010 Standard, https://github.com/RGB-WG/RFC/blob/master/RGB-1010.md

[4] LNPBP-8, https://github.com/LNP-BP/LNPBPs/blob/master/lnpbp-0008.md

[5] LNPBP-10, https://github.com/LNP-BP/LNPBPs/blob/master/lnpbp-0010.md

[6] https://en.wikipedia.org/wiki/Set-builder_notation

[7] Strict Encoding, https://docs.rs/strict_types

[8] : https://cairo-lang.org

[9] : https://docs.rs/aluvm

A RGB Instruction Set Architecture

B Commitments Specification

Glossary

authentication token unique identifier, an element of the finite field $\mathbb{F}_q$, used for capability-based access to write-once memory cell. 4, 11

composed value a variable length sequence of field elements in $\mathbb{F}_q$, from zero to four. 4

destructible memory see *read-once memory*. 4

immutable memory see *write-once memory*. 4, 11

locking condition program defining access rights for an *immutable memory* cell, which must be satisfied with a witness in the spending operation input. 4, 11

read-once memory capability-based memory, an element of which ("cell") can be read only once, by providing an *authentication token* and fulfilling optional *locking condition*. Once accessed, the memory cell is destroyed. 4, 7, 11

write-once memory memory, an element of which ("cell") can be created only once, cannot be changed or destroyed, and can be accessed (read) multiple times by any party. 11