Zcash Protocol Specification

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February 2, 2016

1 Introduction

Zcash is an implementation of the *Decentralized Anonymous Payment* scheme **Zerocash** [2] with some adjustments to terminology, functionality and performance. It bridges the existing *transparent* payment scheme used by **Bitcoin** with a *confidential* payment scheme protected by zero-knowledge succinct non-interactive arguments of knowledge (*zk-SNARKs*).

2 Concepts

2.1 Integers, Bit Sequences, and Endianness

All integers visible in **Zcash**-specific encodings are unsigned, have a fixed bit length, and are encoded as big-endian.

In bit layout diagrams, each box of the diagram represents a sequence of bits. If the content of the box is a byte sequence, it is implicitly converted to a sequence of bits using big endian order. The bit sequences are then concatenated in the order shown from left to right, and the result is converted to a sequence of bytes, again using big-endian order.

Nathan: An example would help here. It would be illustrative if it had a few differently-sized fields.

$\texttt{Leading}_k(x)$, where k is an integer and x is a bit sequence, returns the leading (initial) k bits of its input.

$\texttt{Trailing}_k(x)$, where k is an integer and x is a bit sequence, returns the trailing (final) k bits of its input.

2.2 Cryptographic Functions

CRH is a collision-resistant hash function. In **Zcash**, the *SHA-256 compression* function is used which takes a 512-bit block and produces a 256-bit hash. This is different from the *SHA-256* function, which hashes arbitrary-length strings. [7]

PRF_x is a pseudo-random function seeded by x. Three *independent* PRF_x are needed in our scheme: $\mathsf{PRF}_x^{\mathsf{addr}}$, $\mathsf{PRF}_x^{\mathsf{sn}}$, and $\mathsf{PRF}_x^{\mathsf{pk}}$. It is required that $\mathsf{PRF}_x^{\mathsf{sn}}$ be collision-resistant across all x — i.e. it should not be feasible to find $(x, y) \neq (x', y')$ such that $\mathsf{PRF}_x^{\mathsf{sn}}(y) = \mathsf{PRF}_{x'}^{\mathsf{sn}}(y')$.

In **Zcash**, the *SHA-256 compression* function is used to construct all three of these functions. The bits 00, 01 and 10 are included (respectively) within the blocks that are hashed, ensuring that the functions are independent.

Nathan: Note: If we change input arity (i.e. $\mathsf{N}^{\mathsf{old}}$), we need to be aware of how it is associated with this bit-packing.

$$a_{pk} := PRF_{a_{sk}}^{addr}(0) \quad = CRH\left(\boxed{\begin{array}{c|c|c|c} \text{256 bit } a_{sk} & 0 & 0 & 0^{254} \end{array}} \right)$$

$$sn := PRF_{a_{sk}}^{sn}(\rho) \quad = CRH\left(\boxed{\begin{array}{c|c|c|c} \text{256 bit } a_{sk} & 0 & 1 & \mathtt{Trailing}_{254}(\rho) \end{array}} \right)$$

$$h_i := PRF_{a_{sk}}^{pk}(i, h_{Sig}) \quad = CRH\left(\boxed{\begin{array}{c|c|c|c|c} \text{256 bit } a_{sk} & 1 & 0 & i & \mathtt{Trailing}_{253}(h_{Sig}) \end{array}} \right)$$

Daira: Should we instead define ρ to be 254 bits and h_{Sig} to be 253 bits?

2.3 Confidential Addresses and Private Keys

Nathan: This term, *confidential address*, may be confusing by comparison to a "private key". In the latter case the adjective is reminding a user of their responsibility to protect its privacy, but in the case of *confidential address* we want users to know "transfers to this address are confidential, but the address itself *may* be published or kept confidential depending on your needs. Two different people can compare addresses to know they have the same *confidential address*."

A key pair $(addr_{pk}, addr_{sk})$ is generated by users who wish to receive coins under this scheme. The tuple parts embody two distinct keypairs used for different purposes called the *spend authority* and the *key-private encryption* keypair. The *confidential address* $addr_{pk}$ is a tuple (a_{pk}, pk_{enc}), containing the public components of the *spend authority* and *key-private encryption* respectively. The $addr_{sk}$ is a tuple (a_{sk}, sk_{enc}), containing the secret components respectively.

Nathan: A diagram could really help here.

Users can accept payment from multiple parties with a single $addr_{pk}$ and the fact that these payments are destined to the same payee is not revealed on the blockchain, even to the paying parties. *However* if two parties collude to compare a $addr_{pk}$ they can trivially determine they are the same. In the case that a payee wishes to prevent this they should create a distinct *confidential address* for each payer.

2.4 Coins

A *coin* (denoted **c**) is a tuple (a_{pk}, v, ρ, r) which represents that a value v is spendable by the recipient who holds the *spend authority* key pair (a_{pk}, a_{sk}) such that $a_{pk} = PRF_{a_{sk}}^{addr}(0)$. ρ and r are tokens randomly generated by the sender. Only a hash of these values is disclosed publicly, which allows these random tokens to blind the value and recipient *except* to those who possess these tokens.

2.4.1 In-band secret distribution

In order to transmit the secret v, ρ, and r (necessary for the recipient to later spend) and also a *memo field* to the recipient *without* requiring an out-of-band communication channel, the *key-private encryption* public key pk_{enc} is used to encrypt these secrets to form a *transmitted coins ciphertext*. The recipient's possession of the associated $(addr_{pk}, addr_{sk})$ (which contains both a_{pk} and sk_{enc}) is used to reconstruct the original *coin* and *memo field*.

The encryption algorithm is defined in terms of crypto_box (i.e. crypto_box_curve25519xsalsa20poly1305) [3] as follows.

Let $pk_{enc,1..N^{new}}$ be the Curve25519 public keys for the intended recipient addresses of each new *coin*, and let $\mathbf{P}_{1..N^{new}}$ be their *coin plaintexts*.

Define:

$$nonce(i, pk_{eph}, pk_{enc,i}) = \mathtt{SHA256}\left(\boxed{\begin{array}{c|c|c} \text{1 byte } i-1 & \text{32 byte } pk_{eph} & \text{32 byte } pk_{enc,i} \end{array}} \right).$$

Then to encrypt:

- Generate a new Curve25519 (public, private) key pair (pk_{eph}, sk_{eph}).

- For i in $\{1..\mathsf{N}^{\mathsf{new}}\}$, let $\mathbf{C}_i = \mathsf{crypto\_box}(\mathbf{P}_i, \mathsf{pk}_{\mathsf{enc},i}, \mathsf{sk}_{\mathsf{eph}}, \mathsf{nonce}(i, \mathsf{pk}_{\mathsf{eph}}, \mathsf{pk}_{\mathsf{enc},i}))$.

- Let $\mathsf{Encrypt}_{\mathsf{pk}_{\mathsf{enc},1..\mathsf{N}^{\mathsf{new}}}}(\mathbf{P}_{1..\mathsf{N}^{\mathsf{new}}}) = (\mathsf{pk}_{\mathsf{eph}}, \mathbf{C}_{1..\mathsf{N}^{\mathsf{new}}})$.

Let $(\mathsf{pk}_{\mathsf{enc}}, \mathsf{sk}_{\mathsf{enc}})$ be the recipient's Curve25519 (public, private) key pair, and let $(\mathsf{pk}_{\mathsf{eph}}, \mathbf{C}_{1..\mathsf{N}^{\mathsf{new}}})$ be the *transmitted coins ciphertext*.

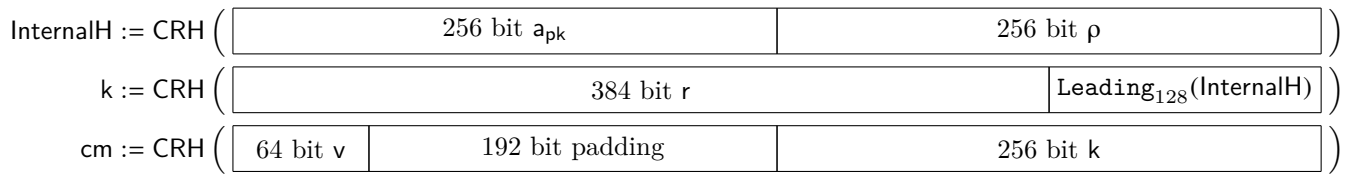Then for each i in $\{1..\mathsf{N}^{\mathsf{new}}\}$, the recipient will attempt to decrypt that ciphertext component as follows:

- $\mathsf{Decrypt}_{\mathsf{sk}_{\mathsf{enc}}}(i, \mathsf{pk}_{\mathsf{eph}}, \mathbf{C}_i) = \mathsf{crypto\_box\_open}(\mathbf{C}_i, \mathsf{pk}_{\mathsf{eph}}, \mathsf{sk}_{\mathsf{enc}}, \mathsf{nonce}(i, \mathsf{pk}_{\mathsf{eph}}, \mathsf{pk}_{\mathsf{enc}}))$

Any ciphertext components that fail to decrypt with a given recipient's private key will be ignored.

This is a variation on the $\mathsf{crypto\_box\_seal}$ algorithm defined in libsodium [6], but with a single ephemeral key used for all encryptions in a given *Pour description*, and with the nonce for each ciphertext component depending on the index i. Also, $\mathsf{SHA256}$ (the full hash, not the compression function) is used instead of $\mathsf{blake2b}$.

2.4.2 Coin Commitments

The underlying v and a_{pk} are blinded with ρ and r using the collision-resistant hash function CRH in a multi-layered process. The resulting hash $\mathtt{cm} = \mathtt{CoinCommitment(c)}$.

$$\mathsf{InternalH} := \mathsf{CRH}\left(\;\boxed{\;256 \text{ bit } \mathsf{a}_{\mathsf{pk}}\quad\;\big|\;256 \text{ bit } \rho\;}\;\right)$$

$$\mathsf{k} := \mathsf{CRH}\left(\;\boxed{\;384 \text{ bit } \mathsf{r}\quad\;\big|\;\mathtt{Leading}_{128}(\mathsf{InternalH})\;}\;\right)$$

$$\mathtt{cm} := \mathsf{CRH}\left(\;\boxed{\;64 \text{ bit } \mathsf{v}\;\big|\;192 \text{ bit padding}\;\big|\;256 \text{ bit } \mathsf{k}\;}\;\right)$$

2.4.3 Serial numbers

A *serial number* (denoted sn) equals $\mathsf{PRF}^{\mathsf{sn}}_{\mathsf{a}_{\mathsf{sk}}}(\rho)$. A *coin* is spent by proving knowledge of ρ and a_{sk} in zero knowledge while disclosing sn, allowing sn to be used to prevent double-spending.

2.5 Coin Commitment Tree
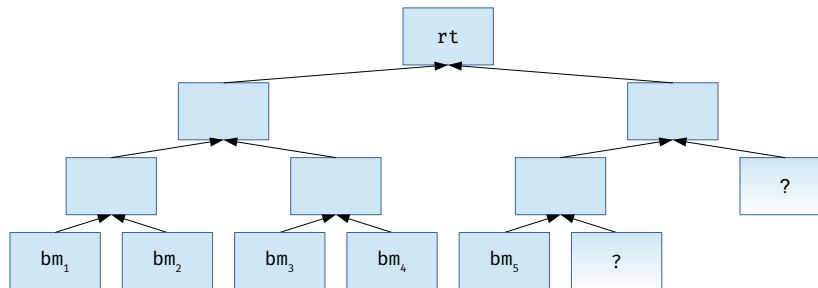
The *coin commitment tree* is an *incremental merkle tree* of depth d used to store *coin commitments* that *Pour transfers* produce. Just as the *unspent transaction output set* (UTXO) used in Bitcoin, it is used to express the

existence of value and the capability to spend it. However, unlike the UTXO, it is *not* the job of this tree to protect against double-spending, as it is append-only.

Blocks in the blockchain are associated (by all nodes) with the root of this tree after all of its constituent *Pour descriptions*' *coin commitments* have been entered into the tree associated with the previous block.

2.6   Spent Serials Map

Transactions insert *serial numbers* into a *spent serial numbers map* which is maintained alongside the UTXO by all nodes.

Eli: a tx is just a string, so it doesn't insert anything. Rather, nodes process tx's and the "good" ones lead to the addition of serials to the spent serials map.

Transactions that attempt to insert a *serial number* into this map that already exists within it are invalid as they are attempting to double-spend.

Eli: After defining *transaction*, one should define what a *legal tx* is (this definition depends on a particular blockchain [view]) and only then can one talk about "attempts" of transactions, and insertions of serial numbers into the spent serials map.

2.7   The Blockchain

At a given point in time, the *blockchain view* of each *full node* consists of a sequence of one or more valid *blocks*. Each *block* consists of a sequence of one or more *transactions*. In a given node's *blockchain view*, *treestates* are chained in an obvious way:

- The input *treestate* of the first *block* is the empty *treestate*.

- The input *treestate* of the first *transaction* of a *block* is the final *treestate* of the immediately preceding *block*.

- The input *treestate* of each subsequent *transaction* in a *block* is the output *treestate* of the immediately preceding *transaction*.

- The final *treestate* of a *block* is the output *treestate* of its last *transaction*.

An *anchor* is a Merkle tree root of a *treestate*, and uniquely identifies that *treestate* given the assumed security properties of the Merkle tree's hash function.

Each *transaction* is associated with a sequence of *Pour descriptions*. TODO They also have a transparent value flow that interacts with the Pour v_{pub}^{old} and v_{pub}^{new}. Inputs and outputs are associated with a value.

The total value of the outputs must not exceed the total value of the inputs.

The *anchor* of the first *Pour description* in a *transaction* must refer to some earlier *block*'s final *treestate*.

The *anchor* of each subsequent *Pour description* may refer either to some earlier *block*'s final *treestate*, or to the output *treestate* of the immediately preceding *Pour description*.

These conditions act as constraints on the blocks that a *full node* will accept into its *blockchain view*.

We rely on Bitcoin-style consensus for *full nodes* to eventually converge on their views of valid *blocks*, and therefore of the sequence of *treestates* in those *blocks*.

Value pool   Transaction inputs insert value into a *value pool*, and transaction outputs remove value from this pool. The remaining value in the pool is available to miners as a fee.

3 Pour Transfers and Descriptions

A *Pour description* is data included in a *block* that describes a *Pour transfer*, i.e. a confidential value transfer. This kind of value transfer is the primary **Zerocash**-specific operation performed by transactions; it uses, but should not be confused with, the `POUR circuit` used for the *zk-SNARK* proof and verification.

A *Pour transfer* spends N^{old} *coins* $\mathbf{c}^{old}_{1..N^{old}}$ and creates N^{new} *coins* $\mathbf{c}^{new}_{1..N^{new}}$. **Zcash** transactions have an additional field `vpour`, which is a sequence of *Pour descriptions*.

Each *Pour description* consists of:

vpub_old which is a value v^{old}_{pub} that the *Pour transfer* removes from the value pool.

vpub_new which is a value v^{new}_{pub} that the *Pour transfer* inserts into the value pool.

anchor which is a merkle root rt of the *coin commitment tree* at some block height in the past, or the merkle root produced by a previous pour in this transaction. Sean: We need to be more specific here.

scriptSig which is a *script* that creates conditions for acceptance of a *Pour description* in a transaction. The `SHA256Compress` hash of this value is h_{Sig}.

Daira: Why `SHA256Compress` and not *SHA-256*? The script is variable-length.

scriptPubKey which is a *script* used to satisfy the conditions of the `scriptSig`.

serials which is an N^{old} size sequence of serials $sn^{old}_{1..N^{old}}$.

commitments which is a N^{new} size sequence of *coin commitments* $cm^{new}_{1..N^{new}}$.

ephemeralKey which is a Curve25519 public key pk_{eph}.

ciphertexts which is a N^{new} size sequence of ciphertext components. (`ephemeralKey` and `ciphertexts` together form the *transmitted coins ciphertext*.)

vmacs which is a N^{old} size sequence of message authentication tags $h_{1..N^{old}}$ that bind h_{Sig} to each a_{sk} of the *Pour description*.

zkproof which is the zero-knowledge proof π_{POUR}.

Merkle root validity A *Pour description* is valid if rt is a Coin commitment tree root found in either the blockchain or a merkle root produced by inserting the Coin commitments of a previous *Pour description* in the transaction to the Coin commitment tree identified by that previous *Pour description*'s *anchor*.

Non-malleability A *Pour description* is valid if the script formed by appending `scriptPubKey` to `scriptSig` returns *true*. The `scriptSig` is cryptographically bound to π_{POUR}.

Balance A *Pour transfer* can be seen, from the perspective of the transaction, as an input and an output simultaneously. v^{old}_{pub} takes value from the value pool and v^{new}_{pub} adds value to the value pool. As a result, v^{old}_{pub} is treated like an *output* value, whereas v^{new}_{pub} is treated like an *input* value.

Commitments and Serials A *transaction* that contains one or more *Pour descriptions*, when entered into the blockchain, appends to the *coin commitment tree* with all constituent *coin commitments*. All of the constituent *serial numbers* are also entered into the *spent serial numbers map* of the *blockchain view and mempool*. A *transaction* is not valid if it attempts to add a *serial number* to the *spent serial numbers map* that already exists in the map.

3.1 Pour Circuit and Proofs

In **Zcash**, N^{old} and N^{new} are both 2.

A valid instance of π_{POUR} assures that given a *primary input* $(rt, sn_{1..N^{old}}^{old}, cm_{1..N^{new}}^{new}, v_{pub}^{old}, v_{pub}^{new}, h_{Sig}, h_{1..N^{old}})$, a witness of *auxiliary input* $(path_{1..N^{old}}, c_{1..N^{old}}^{old}, a_{sk,1..N^{old}}^{old}, c_{1..N^{new}}^{new})$ exists, where:

> for each $i \in \{1..N^{old}\}$: $\mathbf{c}_i^{old} = (a_{pk,i}^{old}, v_i^{old}, \rho_i^{old}, r_i^{old})$
>
> for each $i \in \{1..N^{new}\}$: $\mathbf{c}_i^{new} = (a_{pk,i}^{new}, v_i^{new}, \rho_i^{new}, r_i^{new})$
>
> The following conditions hold:

Merkle path validity for each $i \in \{1..N^{old}\} \mid v_i^{old} \neq 0$: $path_i$ must be a valid path of depth d from $\texttt{CoinCommitment}(\mathbf{c}_i^{old})$ to Coin commitment merkle tree root rt.

Balance $\displaystyle v_{pub}^{old} + \sum_{i=1}^{N^{old}} v_i^{old} = v_{pub}^{new} + \sum_{i=1}^{N^{new}} v_i^{new}$.

Serial integrity for each $i \in \{1..N^{new}\}$: $sn_i^{old} = PRF_{a_{sk,i}^{old}}^{sn}(\rho_i^{old})$.

Spend authority for each $i \in \{1..N^{old}\}$: $a_{pk,i}^{old} = PRF_{a_{sk,i}^{old}}^{addr}(0)$.

Non-malleability for each $i \in \{1..N^{old}\}$: $h_i = PRF_{a_{sk,i}^{old}}^{pk}(i, h_{Sig})$

Commitment integrity for each $i \in \{1..N^{new}\}$: $cm_i^{new} = \texttt{CoinCommitment}(\mathbf{c}_i^{new})$

4 Encoding Addresses, Private keys, Coins, and Pour descriptions

This section describes how **Zcash** encodes public addresses, private keys, coins, and *Pour descriptions*.

Addresses, keys, and coins, can be encoded as a byte string; this is called the *raw encoding*. This byte string can then be further encoded using Base58Check. The Base58Check layer is the same as for upstream **Bitcoin** addresses [1].

SHA-256 compression function outputs are always represented as strings of 32 bytes.

The language consisting of the following encoding possibilities is prefix-free.

4.1 Transparent Public Addresses

These are encoded in the same way as in **Bitcoin** [1].

4.2 Transparent Private Keys

These are encoded in the same way as in **Bitcoin** [1].

4.3   Confidential Public Addresses

A *confidential address* consists of a_{pk} and pk_{enc}. a_{pk} is a SHA-256 compression function output. pk_{enc} is a Curve25519 public key, for use with the encryption scheme defined in section "In-band secret distribution".

4.3.1   Raw Encoding

The raw encoding of a confidential address consists of:

0x92	a_{pk} (32 bytes)	A 33-byte encoding of pk_{enc}

- A byte, **0x92**, indicating this version of the raw encoding of a **Zcash** public address.

- 32 bytes specifying a_{pk}.

- 32 bytes specifying pk_{enc}, using the normal encoding of a Curve25519 public key [4].

Daira: check that this lead byte is distinct from other Bitcoin stuff, and produces 'z' as the Base58Check leading character.

Nathan: what about the network version byte?

4.4   Confidential Address Secrets

A confidential address secret consists of a_{sk} and sk_{enc}. a_{sk} is a SHA-256 compression function output. sk_{enc} is a Curve25519 private key, for use with the encryption scheme defined in section "In-band secret distribution".

4.4.1   Raw Encoding

The raw encoding of a confidential address secret consists of, in order:

0x93	a_{sk} (32 bytes)	sk_{enc} (32 bytes)

- A byte **0x93** indicating this version of the raw encoding of a **Zcash** private key.

- 32 bytes specifying a_{sk}.

- 32 bytes specifying sk_{enc}.

Daira: check that this lead byte is distinct from other Bitcoin stuff, and produces 'z' as the Base58Check leading character.

Nathan: what about the network version byte?

4.5   Coins

Transmitted coins are stored on the blockchain in encrypted form, together with a *coin commitment* cm.

The *coin plaintexts* associated with a *Pour description* are encrypted to the respective *key-private encryption* keys $pk_{enc,1..N^{new}}$, and the result forms a *transmitted coins ciphertext*.

Each *coin plaintext* consists of $(v, \rho, r, memo)$, where:

- v is a 64-bit unsigned integer representing the value of the *coin* in *zatoshi* (1 **ZEC** $= 10^8$ *zatoshi*).

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- ρ is a 32-byte $\mathsf{PRF}^{\mathsf{sn}}_{\mathsf{a_{sk}}}$ preimage.

- r is a 48-byte *COMM trapdoor*.

- memo is a 64-byte *memo field* associated with this *coin*.

The usage of the *memo field* is by agreement between the sender and recipient of the *coin*. It should be encoded as a UTF-8 human-readable string [5], padded with zero bytes. Wallet software is expected to strip any trailing zero bytes and then display the resulting UTF-8 string to the recipient user, where applicable. Incorrect UTF-8-encoded byte sequences should be displayed as replacement characters (U+FFFD). This does not preclude uses of the *memo field* by automated software, but specification of such usage is not in the scope of this document.

Note that the value s described as being part of a *coin* in the **Zerocash** paper is not encoded because the instantiation of $\mathsf{COMM_s}$ does not use it.

4.6   Raw Encoding

The raw encoding of a *coin plaintext* consists of, in order:

0x00	v (8 bytes)	ρ (32 bytes)	r (48 bytes)	memo (64 bytes)

- A byte **0x00** indicating this version of the raw encoding of a *coin plaintext*.

- 8 bytes specifying a big-endian encoding of v.

- 32 bytes specifying ρ.

- 48 bytes specifying r.

- 64 bytes specifying memo.

5   Pours (within a transaction on the blockchain)

TBD.

6   Transactions

TBD.

7   Differences from the Zerocash paper

- Instead of ECIES, we use an encryption scheme based on $\mathsf{crypto\_box}$, defined in section "In-band secret distribution".

- Faerie Gold fix (TBD).

- The paper defines a coin as a tuple $(\mathsf{a_{pk}}, \mathsf{v}, \rho, \mathsf{r}, \mathsf{s}, \mathsf{cm})$, whereas this specification defines it as $(\mathsf{a_{pk}}, \mathsf{v}, \rho, \mathsf{r})$. This is just a clarification, because the instantiation of $\mathsf{COMM_s}$ in section 5.1 of the paper does not use s, and cm can be computed from the other fields.

8 References

[1] Base58Check encoding. `https://en.bitcoin.it/wiki/Base58Check_encoding`. Accessed: 2016-01-26.

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[3] Daniel Bernstein. Cryptography in NaCl. `https://nacl.cr.yp.to/valid.html`. Accessed: 2016-02-01.

[4] Daniel Bernstein. Curve25519: new Diffie-Hellman speed records. In *Public Key Cryptography - PKC 2006. Proceedings of the 9th International Conference on Theory and Practice in Public-Key Cryptography, New York, NY, USA, April 24-26.* Springer-Verlag, 2006. Document ID: 4230efdfa673480fc079449d90f322c0. Date: 2006-02-09. `http://cr.yp.to/papers.html#curve25519`.

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[7] NIST. FIPS 180-4: Secure Hash Standard (SHS). `http://csrc.nist.gov/publications/PubsFIPS.html#180-4`, August 2015. DOI: 10.6028/NIST.FIPS.180-4.