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Authors: A. Davidson A. Faz-Hernandez N. Sullivan C. A. Wood
Brave Software *Cloudflare, Inc.* *Cloudflare, Inc.* *Cloudflare, Inc.*

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Oblivious Pseudorandom Functions (OPRFs) Using Prime-Order Groups

Abstract

An Oblivious Pseudorandom Function (OPRF) is a two-party protocol between a client and a server for computing the output of a Pseudorandom Function (PRF). The server provides the PRF private key, and the client provides the PRF input. At the end of the protocol, the client learns the PRF output without learning anything about the PRF private key, and the server learns neither the PRF input nor output. An OPRF can also satisfy a notion of 'verifiability', called a VOPRF. A VOPRF ensures clients can verify that the server used a specific private key during the execution of the protocol. A VOPRF can also be partially oblivious, called a POPRF. A POPRF allows clients and servers to provide public input to the PRF computation. This document specifies an OPRE, VOPRE, and POPRF instantiated within standard prime-order groups, including elliptic curves. This document is a product of the Crypto Forum Research Group (CFRG) in the IRTF.

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1. Introduction

A Pseudorandom Function (PRF) $F(k, x)$ is an efficiently computable function taking a private key k and a value x as input. This function is pseudorandom if the keyed function $K(_) = F(k, _)$ is indistinguishable from a randomly sampled function acting on the same domain and range as $K(_)$. An Oblivious PRF (OPRF) is a two-party protocol between a server and a client, wherein the server holds a PRF key k and the client holds some input x . The protocol allows both parties to cooperate in computing $F(k, x)$, such that the client learns $F(k, x)$ without learning anything about k and the server does not learn anything about x or $F(k, x)$. A Verifiable OPRF (VOPRF) is an OPRF, wherein the server also proves to the client that $F(k, x)$ was produced by the key k corresponding to the server's public key, which the client knows. A Partially Oblivious PRF (POPRF) is a variant of a VOPRF, where the client and server interact in computing $F(k, x, y)$, for some PRF F with server-provided key k , client-provided input x , and public input y , and the client receives proof that $F(k, x, y)$ was computed using k corresponding to the public key that the client knows. A POPRF with fixed input y is functionally equivalent to a VOPRF.

OPRFs have a variety of applications, including password-protected secret sharing schemes [JKKX16], privacy-preserving password stores [SJKS17], and password-authenticated key exchange (PAKE) [OPAQUE]. Verifiable OPRFs are necessary in some applications, such as Privacy Pass [PRIVACY-PASS]. Verifiable OPRFs have also been used for password-protected secret sharing schemes, such as that of [JKK14].

This document specifies OPRF, VOPRF, and POPRF protocols built upon prime-order groups. The document describes each protocol variant, along with application considerations, and their security properties.

This document represents the consensus of the Crypto Forum Research Group (CFRG). It is not an IETF product and is not a standard.

1.1. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "NOT RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in BCP 14 [RFC2119] [RFC8174] when, and only when, they appear in all capitals, as shown here.

1.2. Notation and Terminology

The following functions and notation are used throughout the document.

- For any object x , we write $\text{len}(x)$ to denote its length in bytes.
- For two-byte arrays x and y , write $x \parallel y$ to denote their concatenation.
- $\text{I2OSP}(x, \text{xLen})$ converts a non-negative integer x into a byte array of specified length xLen , as described in [RFC8017]. Note that this function returns a byte array in big-endian byte order.
- The notation $T \ U[N]$ refers to an array called U , containing N items of type T . The type `opaque` means one single byte of uninterpreted data. Items of the array are zero-indexed and referred to as $U[j]$, such that $0 \leq j < N$.

All algorithms and procedures described in this document are laid out in a Python-like pseudocode. Each function takes a set of inputs and parameters and produces a set of output values. Parameters become constant values once the protocol variant and the ciphersuite are fixed.

The `PrivateInput` data type refers to inputs that are known only to the client in the protocol, whereas the `PublicInput` data type refers to inputs that are known to both the client and server in the protocol. Both `PrivateInput` and `PublicInput` are opaque byte strings of arbitrary length no larger than $2^{16} - 1$ bytes. This length restriction exists because `PublicInput` and `PrivateInput` values are length-prefixed with two bytes before use throughout the protocol.

String values, such as "DeriveKeyPair", "Seed-", and "Finalize", are ASCII string literals.

The following terms are used throughout this document.

PRF: Pseudorandom Function

OPRF: Oblivious Pseudorandom Function

VOPRF: Verifiable Oblivious Pseudorandom Function

POPRF: Partially Oblivious Pseudorandom Function

Client: Protocol initiator. Learns PRF evaluation as the output of the protocol.

Server: Computes the PRF using a private key. Learns nothing about the client's input or output.

2. Preliminaries

The protocols in this document have two primary dependencies:

Group: A prime-order group implementing the API described below in [Section 2.1](#). See [Section 4](#) for specific instances of groups.

Hash: A cryptographic hash function whose output length is N_h bytes.

[Section 4](#) specifies ciphersuites as combinations of Group and Hash.

2.1. Prime-Order Group

In this document, we assume the construction of an additive, prime-order group, denoted `Group`, for performing all mathematical operations. In prime-order groups, any element (other than the identity) can generate the other elements of the group. Usually, one element is fixed and defined as the group generator. Such groups are uniquely determined by the choice of the prime p that defines the order of the group. (However, different representations of the group for a single p may exist. [Section 4](#) lists specific groups that indicate both the order and representation.)

The fundamental group operation is addition `+` with identity element `I`. For any elements `A` and `B` of the group, `A + B = B + A` is also a member of the group. Also, for any `A` in the group, there exists an element `-A`, such that `A + (-A) = (-A) + A = I`. Scalar multiplication by `r` is equivalent to the repeated application of the group operation on an element `A` with itself $r - 1$ times; this is denoted as `r * A = A + ... + A`. For any element `A`, `p * A = I`. The case when the scalar multiplication is performed on the group generator is denoted as `ScalarMultGen(r)`. Given two elements `A` and `B`, the discrete logarithm problem is to find an integer `k`, such that `B = k * A`. Thus, `k` is the discrete logarithm of `B` with respect to the base `A`. The set of scalars corresponds to $\text{GF}(p)$, a prime field of order p , and is represented as the set of integers defined by $\{0, 1, \dots, p - 1\}$. This document uses types `Element` and `Scalar` to denote elements of the group and its set of scalars, respectively.

We now detail a number of member functions that can be invoked on a prime-order group.

`Order()`: Outputs the order of the group (i.e., p).

Identity(): Outputs the identity element of the group (i.e., I).

Generator(): Outputs the generator element of the group.

HashToGroup(x): Deterministically maps an array of bytes x to an element of Group. The map must ensure that, for any adversary receiving $R = \text{HashToGroup}(x)$, it is computationally difficult to reverse the mapping. This function is optionally parameterized by a domain separation tag (DST); see [Section 4](#). Security properties of this function are described in [\[RFC9380\]](#).

HashToScalar(x): Deterministically maps an array of bytes x to an element in $\text{GF}(p)$. This function is optionally parameterized by a DST; see [Section 4](#). Security properties of this function are described in [\[RFC9380\]](#), [Section 10.5](#).

RandomScalar(): Chooses at random a nonzero element in $\text{GF}(p)$.

ScalarInverse(s): Returns the inverse of input Scalar s on $\text{GF}(p)$.

SerializeElement(A): Maps an Element A to a canonical byte array buf of fixed-length N_e .

DeserializeElement(buf): Attempts to map a byte array buf to an Element A and fails if the input is not the valid canonical byte representation of an element of the group. This function can raise a `DeserializeError` if deserialization fails or A is the identity element of the group; see [Section 4](#) for group-specific input validation steps.

SerializeScalar(s): Maps Scalar s to a canonical byte array buf of fixed-length N_s .

DeserializeScalar(buf): Attempts to map a byte array buf to Scalar s . This function can raise a `DeserializeError` if deserialization fails; see [Section 4](#) for group-specific input validation steps.

[Section 4](#) contains details for the implementation of this interface for different prime-order groups instantiated over elliptic curves. In particular, for some choices of elliptic curves, e.g., those detailed in [\[RFC7748\]](#), which require accounting for cofactors, [Section 4](#) describes required steps necessary to ensure the resulting group is of prime order.

2.2. Discrete Logarithm Equivalence Proofs

A proof of knowledge allows a prover to convince a verifier that some statement is true. If the prover can generate a proof without interaction with the verifier, the proof is noninteractive. If the verifier learns nothing other than whether the statement claimed by the prover is true or false, the proof is zero-knowledge.

This section describes a noninteractive, zero-knowledge proof for discrete logarithm equivalence (DLEQ), which is used in the construction of VOPRF and POPRF. A DLEQ proof demonstrates that two pairs of group elements have the same discrete logarithm without revealing the discrete logarithm.

The DLEQ proof resembles the Chaum-Pedersen [\[ChaumPedersen\]](#) proof, which is shown to be zero-knowledge by Jarecki, et al. [\[JKK14\]](#) and is noninteractive after applying the Fiat-Shamir transform [\[FS00\]](#). Furthermore, Davidson, et al. [\[DGSTV18\]](#) showed a proof system for batching

DLEQ proofs that has constant-size proofs with respect to the number of inputs. The specific DLEQ proof system presented below follows this latter construction with two modifications: (1) the transcript used to generate the seed includes more context information and (2) the individual challenges for each element in the proof is derived from a seed-prefixed hash-to-scalar invocation, rather than being sampled from a seeded Pseudorandom Number Generator (PRNG). The description is split into two subsections: one for generating the proof, which is done by servers in the verifiable protocols, and another for verifying the proof, which is done by clients in the protocol.

2.2.1. Proof Generation

Generating a proof is done with the `GenerateProof` function, as defined below. Given Element values A and B , two non-empty lists of Element values C and D of length m , and Scalar k , this function produces a proof that $k * A == B$ and $k * C[i] == D[i]$ for each i in $[0, \dots, m - 1]$. The output is a value of type `Proof`, which is a tuple of two Scalar values. We use the notation `proof[0]` and `proof[1]` to denote the first and second elements in this tuple, respectively.

`GenerateProof` accepts lists of inputs to amortize the cost of proof generation. Applications can take advantage of this functionality to produce a single, constant-sized proof for m DLEQ inputs, rather than m proofs for m DLEQ inputs.

Input :

```
Scalar k
Element A
Element B
Element C[m]
Element D[m]
```

Output:

```
Proof proof
```

Parameters:

```
Group G
```

```
def GenerateProof(k, A, B, C, D):
    (M, Z) = ComputeCompositesFast(k, B, C, D)

    r = G.RandomScalar()
    t2 = r * A
    t3 = r * M

    Bm = G.SerializeElement(B)
    a0 = G.SerializeElement(M)
    a1 = G.SerializeElement(Z)
    a2 = G.SerializeElement(t2)
    a3 = G.SerializeElement(t3)

    challengeTranscript =
        I2OSP(len(Bm), 2) || Bm ||
        I2OSP(len(a0), 2) || a0 ||
        I2OSP(len(a1), 2) || a1 ||
        I2OSP(len(a2), 2) || a2 ||
        I2OSP(len(a3), 2) || a3 ||
        "Challenge"

    c = G.HashToScalar(challengeTranscript)
    s = r - c * k

    return [c, s]
```

The helper function `ComputeCompositesFast` is as defined below and is an optimization of the `ComputeComposites` function for servers since they have knowledge of the private key.

Input :

Scalar k
 Element B
 Element $C[m]$
 Element $D[m]$

Output :

Element M
 Element Z

Parameters:

Group G
 PublicInput contextString

```
def ComputeCompositesFast(k, B, C, D):
    Bm = G.SerializeElement(B)
    seedDST = "Seed-" || contextString
    seedTranscript =
        I2OSP(len(Bm), 2) || Bm ||
        I2OSP(len(seedDST), 2) || seedDST
    seed = Hash(seedTranscript)

    M = G.Identity()
    for i in range(m):
        Ci = G.SerializeElement(C[i])
        Di = G.SerializeElement(D[i])
        compositeTranscript =
            I2OSP(len(seed), 2) || seed || I2OSP(i, 2) ||
            I2OSP(len(Ci), 2) || Ci ||
            I2OSP(len(Di), 2) || Di ||
            "Composite"

        di = G.HashToScalar(compositeTranscript)
        M = di * C[i] + M

    Z = k * M

    return (M, Z)
```

When used in the protocol described in [Section 3](#), the parameter contextString is as defined in [Section 3.2](#).

2.2.2. Proof Verification

Verifying a proof is done with the VerifyProof function, as defined below. This function takes Element values A and B , two non-empty lists of Element values C and D of length m , and a Proof value output from GenerateProof. It outputs a single boolean value indicating whether or not the proof is valid for the given DLEQ inputs. Note this function can verify proofs on lists of inputs whenever the proof was generated as a batched DLEQ proof with the same inputs.

Input :

```
Element A
Element B
Element C[m]
Element D[m]
Proof proof
```

Output:

```
boolean verified
```

Parameters:

```
Group G
```

```
def VerifyProof(A, B, C, D, proof):
    (M, Z) = ComputeComposites(B, C, D)
    c = proof[0]
    s = proof[1]

    t2 = ((s * A) + (c * B))
    t3 = ((s * M) + (c * Z))

    Bm = G.SerializeElement(B)
    a0 = G.SerializeElement(M)
    a1 = G.SerializeElement(Z)
    a2 = G.SerializeElement(t2)
    a3 = G.SerializeElement(t3)

    challengeTranscript =
        I2OSP(len(Bm), 2) || Bm ||
        I2OSP(len(a0), 2) || a0 ||
        I2OSP(len(a1), 2) || a1 ||
        I2OSP(len(a2), 2) || a2 ||
        I2OSP(len(a3), 2) || a3 ||
        "Challenge"

    expectedC = G.HashToScalar(challengeTranscript)
    verified = (expectedC == c)

    return verified
```

The definition of `ComputeComposites` is given below.

Input :

```
Element B
Element C[m]
Element D[m]
```

Output :

```
Element M
Element Z
```

Parameters:

```
Group G
PublicInput contextString
```

```
def ComputeComposites(B, C, D):
    Bm = G.SerializeElement(B)
    seedDST = "Seed-" || contextString
    seedTranscript =
        I2OSP(len(Bm), 2) || Bm ||
        I2OSP(len(seedDST), 2) || seedDST
    seed = Hash(seedTranscript)

    M = G.Identity()
    Z = G.Identity()
    for i in range(m):
        Ci = G.SerializeElement(C[i])
        Di = G.SerializeElement(D[i])
        compositeTranscript =
            I2OSP(len(seed), 2) || seed || I2OSP(i, 2) ||
            I2OSP(len(Ci), 2) || Ci ||
            I2OSP(len(Di), 2) || Di ||
            "Composite"

        di = G.HashToScalar(compositeTranscript)
        M = di * C[i] + M
        Z = di * D[i] + Z

    return (M, Z)
```

When used in the protocol described in [Section 3](#), the parameter `contextString` is as defined in [Section 3.2](#).

3. Protocol

In this section, we define and describe three protocol variants referred to as the OPRF, VOPRF, and POPRF modes. Each of these variants involves two messages between the client and server, but they differ slightly in terms of the security properties; see [Section 7.1](#) for more information. A high-level description of the functionality of each mode follows.

In the OPRF mode, a client and server interact to compute $\text{output} = F(\text{skS}, \text{input})$, where `input` is the client's private input, `skS` is the server's private key, and `output` is the OPRF output. After the execution of the protocol, the client learns the output and the server learns nothing. This interaction is shown below.

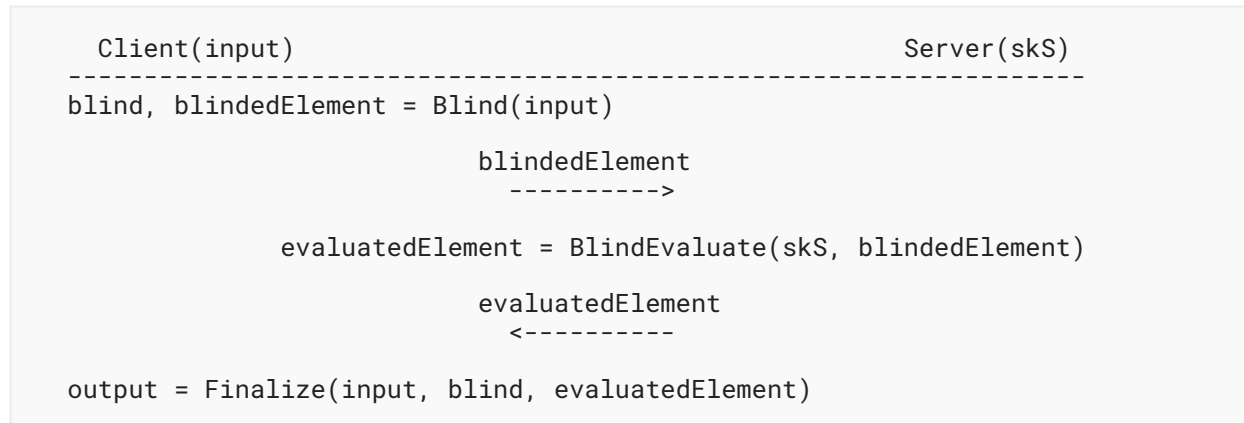


Figure 1: OPRF Protocol Overview

In the VOPRF mode, the client additionally receives proof that the server used `skS` in computing the function. To achieve verifiability, as in [JKK14], the server provides a zero-knowledge proof that the key provided as input by the server in the `BlindEvaluate` function is the same key as is used to produce the server's public key, `pkS`, which the client receives as input to the protocol. This proof does not reveal the server's private key to the client. This interaction is shown below.

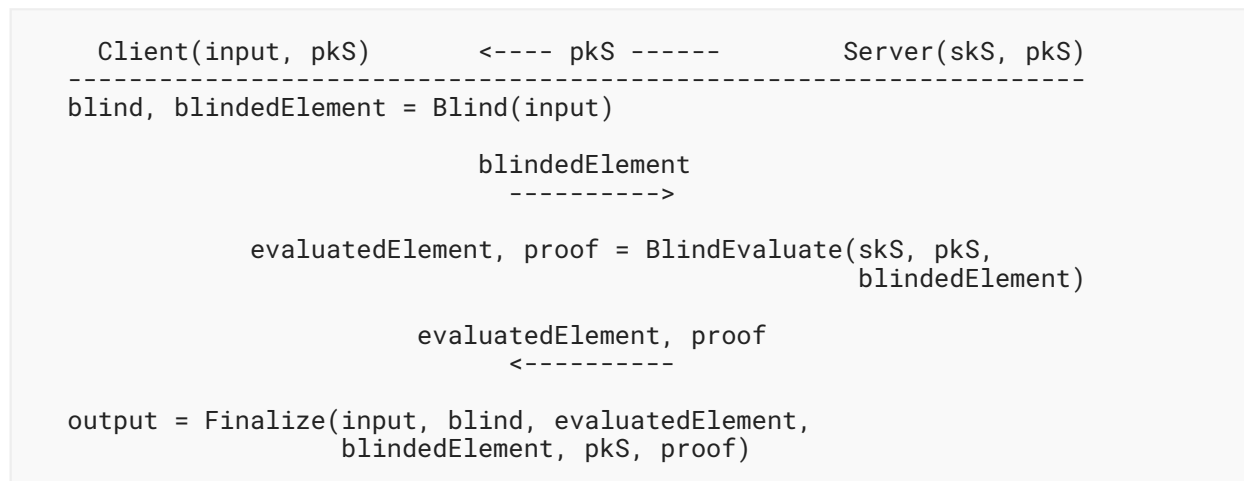


Figure 2: VOPRF Protocol Overview with Additional Proof

The POPRF mode extends the VOPRF mode such that the client and server can additionally provide the public input `info`, which is used in computing the PRF. That is, the client and server interact to compute $\text{output} = F(\text{skS}, \text{input}, \text{info})$, as is shown below.

```

Client(input, pkS, info) <---- pkS ----- Server(skS, pkS, info)
-----
blind, blindedElement, tweakedKey = Blind(input, info, pkS)
                                     blindedElement
                                     ----->
evaluatedElement, proof = BlindEvaluate(skS, blindedElement,
                                       info)
                             evaluatedElement, proof
                             <-----
output = Finalize(input, blind, evaluatedElement,
                  blindedElement, proof, info, tweakedKey)

```

Figure 3: POPRF Protocol Overview with Additional Public Input

Each protocol consists of an offline setup phase and an online phase, as described in Sections 3.2 and 3.3, respectively. Configuration details for the offline phase are described in Section 3.1.

3.1. Configuration

Each of the three protocol variants are identified with a one-byte value (in hexadecimal):

Mode	Value
modeOPRF	0x00
modeVOPRF	0x01
modePOPRF	0x02

Table 1: Identifiers for Protocol Variants

Additionally, each protocol variant is instantiated with a ciphersuite or suite. Each ciphersuite is identified with an ASCII string identifier, referred to as identifier; see Section 4 for the set of initial ciphersuite values.

The mode and ciphersuite identifier values are combined to create a "context string" used throughout the protocol with the following function:

```

def CreateContextString(mode, identifier):
    return "OPRFV1-" || I2OSP(mode, 1) || "-" || identifier

```

3.2. Key Generation and Context Setup

In the offline setup phase, the server generates a fresh, random key pair (sk_S , pk_S). There are two ways to generate this key pair. The first of which is using the `GenerateKeyPair` function described below.

Input: None

Output:

Scalar sk_S
Element pk_S

Parameters:

Group G

```
def GenerateKeyPair():  
    skS = G.RandomScalar()  
    pkS = G.ScalarMultGen(skS)  
    return skS, pkS
```

The second way to generate the key pair is via the deterministic key generation function `DeriveKeyPair`, as described in [Section 3.2.1](#). Applications and implementations can use either method in practice.

Also during the offline setup phase, both the client and server create a context used for executing the online phase of the protocol after agreeing on a mode and ciphersuite identifier. The context, such as `OPRFServerContext`, is an implementation-specific data structure that stores a context string and the relevant key material for each party.

The OPRF variant server and client contexts are created as follows:

```
def SetupOPRFServer(identifier, skS):  
    contextString = CreateContextString(modeOPRF, identifier)  
    return OPRFServerContext(contextString, skS)  
  
def SetupOPRFClient(identifier):  
    contextString = CreateContextString(modeOPRF, identifier)  
    return OPRFClientContext(contextString)
```

The VOPRF variant server and client contexts are created as follows:

```
def SetupVOPRFServer(identifier, skS):
    contextString = CreateContextString(modeVOPRF, identifier)
    return VOPRFServerContext(contextString, skS)

def SetupVOPRFClient(identifier, pkS):
    contextString = CreateContextString(modeVOPRF, identifier)
    return VOPRFClientContext(contextString, pkS)
```

The POPRF variant server and client contexts are created as follows:

```
def SetupPOPRFServer(identifier, skS):
    contextString = CreateContextString(modePOPRF, identifier)
    return POPRFServerContext(contextString, skS)

def SetupPOPRFClient(identifier, pkS):
    contextString = CreateContextString(modePOPRF, identifier)
    return POPRFClientContext(contextString, pkS)
```

3.2.1. Deterministic Key Generation

This section describes a deterministic key generation function, `DeriveKeyPair`. It accepts a seed of 32 bytes generated from a cryptographically secure random number generator and an optional (possibly empty) `info` string. Note that, by design, knowledge of `seed` and `info` is necessary to compute this function, which means that the secrecy of the output private key (`skS`) depends on the secrecy of `seed` (since the `info` string is public).

Input:

```
opaque seed[32]
PublicInput info
```

Output:

```
Scalar skS
Element pkS
```

Parameters:

```
Group G
PublicInput contextString
```

Errors: `DeriveKeyPairError`

```
def DeriveKeyPair(seed, info):
    deriveInput = seed || I2OSP(len(info), 2) || info
    counter = 0
    skS = 0
    while skS == 0:
        if counter > 255:
            raise DeriveKeyPairError
        skS = G.HashToScalar(deriveInput || I2OSP(counter, 1),
                             DST = "DeriveKeyPair" || contextString)
        counter = counter + 1
    pkS = G.ScalarMultGen(skS)
    return skS, pkS
```

3.3. Online Protocol

In the online phase, the client and server engage in a two-message protocol to compute the protocol output. This section describes the protocol details for each protocol variant. Throughout each description, the following parameters are assumed to exist:

G: a prime-order group implementing the API described in [Section 2.1](#)

contextString: a `PublicInput` domain separation tag constructed during context setup, as created in [Section 3.1](#)

skS and **pkS**: a `Scalar` and `Element` representing the private and public keys configured for the client and server in [Section 3.2](#)

Applications serialize protocol messages between the client and server for transmission. `Element` values and `Scalar` values are serialized to byte arrays, and values of type `Proof` are serialized as the concatenation of two serialized `Scalar` values. Deserializing these values can fail; in which case, the application **MUST** abort the protocol, raising a `DeserializeError` failure.

Applications **MUST** check that input Element values received over the wire are not the group identity element. This check is handled after deserializing Element values; see [Section 4](#) for more information and requirements on input validation for each ciphersuite.

3.3.1. OPRF Protocol

The OPRF protocol begins with the client blinding its input, as described by the `Blind` function below. Note that this function can fail with an `InvalidInputError` error for certain inputs that map to the group identity element. Dealing with this failure is an application-specific decision; see [Section 5.3](#).

```
Input:
    PrivateInput input

Output:
    Scalar blind
    Element blindedElement

Parameters:
    Group G

Errors: InvalidInputError

def Blind(input):
    blind = G.RandomScalar()
    inputElement = G.HashToGroup(input)
    if inputElement == G.Identity():
        raise InvalidInputError
    blindedElement = blind * inputElement

    return blind, blindedElement
```

Clients store `blind` locally and send `blindedElement` to the server for evaluation. Upon receipt, servers process `blindedElement` using the `BlindEvaluate` function described below.

```
Input:
    Scalar skS
    Element blindedElement

Output:
    Element evaluatedElement

def BlindEvaluate(skS, blindedElement):
    evaluatedElement = skS * blindedElement
    return evaluatedElement
```

Servers send the output `evaluatedElement` to clients for processing. Recall that servers may process multiple client inputs by applying the `BlindEvaluate` function to each `blindedElement` received and returning an array with the corresponding `evaluatedElement` values.

Upon receipt of `evaluatedElement`, clients process it to complete the OPRF evaluation with the `Finalize` function described below.

Input:

```
PrivateInput input
Scalar blind
Element evaluatedElement
```

Output:

```
opaque output[Nh]
```

Parameters:

```
Group G
```

```
def Finalize(input, blind, evaluatedElement):
    N = G.ScalarInverse(blind) * evaluatedElement
    unblindedElement = G.SerializeElement(N)

    hashInput = I2OSP(len(input), 2) || input ||
                I2OSP(len(unblindedElement), 2) || unblindedElement ||
                "Finalize"
    return Hash(hashInput)
```

An entity that knows both the private key and the input can compute the PRF result using the following `Evaluate` function.

Input:

Scalar sk_S
PrivateInput input

Output:

opaque output[Nh]

Parameters:

Group G

Errors: InvalidInputError

```
def Evaluate(skS, input):
    inputElement = G.HashToGroup(input)
    if inputElement == G.Identity():
        raise InvalidInputError
    evaluatedElement = skS * inputElement
    issuedElement = G.SerializeElement(evaluatedElement)

    hashInput = I2OSP(len(input), 2) || input ||
                I2OSP(len(issuedElement), 2) || issuedElement ||
                "Finalize"
    return Hash(hashInput)
```

3.3.2. VOPRF Protocol

The VOPRF protocol begins with the client blinding its input, using the same `Blind` function as in [Section 3.3.1](#). Clients store the output blind locally and send `blindedElement` to the server for evaluation. Upon receipt, servers process `blindedElement` to compute an evaluated element and a DLEQ proof using the following `BlindEvaluate` function.

Input :

```
Scalar skS
Element pkS
Element blindedElement
```

Output :

```
Element evaluatedElement
Proof proof
```

Parameters:

```
Group G
```

```
def BlindEvaluate(skS, pkS, blindedElement):
    evaluatedElement = skS * blindedElement
    blindedElements = [blindedElement] // list of length 1
    evaluatedElements = [evaluatedElement] // list of length 1
    proof = GenerateProof(skS, G.Generator(), pkS,
                          blindedElements, evaluatedElements)
    return evaluatedElement, proof
```

In the description above, inputs to `GenerateProof` are one-item lists. Using larger lists allows servers to batch the evaluation of multiple elements while producing a single batched DLEQ proof for them.

The server sends both `evaluatedElement` and `proof` back to the client. Upon receipt, the client processes both values to complete the VOPRF computation using the `Finalize` function below.

Input :

```
PrivateInput input
Scalar blind
Element evaluatedElement
Element blindedElement
Element pkS
Proof proof
```

Output :

```
opaque output[Nh]
```

Parameters:

```
Group G
```

Errors: VerifyError

```
def Finalize(input, blind, evaluatedElement,
             blindedElement, pkS, proof):
    blindedElements = [blindedElement] // list of length 1
    evaluatedElements = [evaluatedElement] // list of length 1
    if VerifyProof(G.Generator(), pkS, blindedElements,
                  evaluatedElements, proof) == false:
        raise VerifyError

    N = G.ScalarInverse(blind) * evaluatedElement
    unblindedElement = G.SerializeElement(N)

    hashInput = I2OSP(len(input), 2) || input ||
                I2OSP(len(unblindedElement), 2) || unblindedElement ||
                "Finalize"
    return Hash(hashInput)
```

As in `BlindEvaluate`, inputs to `VerifyProof` are one-item lists. Clients can verify multiple inputs at once whenever the server produced a batched DLEQ proof for them.

Finally, an entity that knows both the private key and the input can compute the PRF result using the `Evaluate` function described in [Section 3.3.1](#).

3.3.3. POPRF Protocol

The POPRF protocol begins with the client blinding its input, using the following modified `Blind` function. In this step, the client also binds a public info value, which produces an additional `tweakedKey` to be used later in the protocol. Note that this function can fail with an `InvalidInputError` error for certain private inputs that map to the group identity element, as well as certain public inputs that, if not detected at this point, will cause server evaluation to fail. Dealing with either failure is an application-specific decision; see [Section 5.3](#).

Input:

```
PrivateInput input
PublicInput info
Element pkS
```

Output:

```
Scalar blind
Element blindedElement
Element tweakedKey
```

Parameters:

```
Group G
```

Errors: InvalidInputError

```
def Blind(input, info, pkS):
    framedInfo = "Info" || I2OSP(len(info), 2) || info
    m = G.HashToScalar(framedInfo)
    T = G.ScalarMultGen(m)
    tweakedKey = T + pkS
    if tweakedKey == G.Identity():
        raise InvalidInputError

    blind = G.RandomScalar()
    inputElement = G.HashToGroup(input)
    if inputElement == G.Identity():
        raise InvalidInputError

    blindedElement = blind * inputElement

    return blind, blindedElement, tweakedKey
```

Clients store the outputs `blind` and `tweakedKey` locally and send `blindedElement` to the server for evaluation. Upon receipt, servers process `blindedElement` to compute an evaluated element and a DLEQ proof using the following `BlindEvaluate` function.

Input :

```
Scalar skS
Element blindedElement
PublicInput info
```

Output :

```
Element evaluatedElement
Proof proof
```

Parameters:

```
Group G
```

Errors: InverseError

```
def BlindEvaluate(skS, blindedElement, info):
    framedInfo = "Info" || I2OSP(len(info), 2) || info
    m = G.HashToScalar(framedInfo)
    t = skS + m
    if t == 0:
        raise InverseError

    evaluatedElement = G.ScalarInverse(t) * blindedElement

    tweakedKey = G.ScalarMultGen(t)
    evaluatedElements = [evaluatedElement] // list of length 1
    blindedElements = [blindedElement] // list of length 1
    proof = GenerateProof(t, G.Generator(), tweakedKey,
                        evaluatedElements, blindedElements)

    return evaluatedElement, proof
```

In the description above, inputs to `GenerateProof` are one-item lists. Using larger lists allows servers to batch the evaluation of multiple elements while producing a single batched DLEQ proof for them.

`BlindEvaluate` triggers `InverseError` when the function is about to calculate the inverse of a zero scalar, which does not exist and therefore yields a failure in the protocol. This only occurs for `info` values that map to the private key of the server. Thus, clients that cause this error should be assumed to know the server private key. Hence, this error can be a signal for the server to replace its private key.

The server sends both `evaluatedElement` and `proof` back to the client. Upon receipt, the client processes both values to complete the POPRF computation using the `Finalize` function below.

Input:

```
PrivateInput input
Scalar blind
Element evaluatedElement
Element blindedElement
Proof proof
PublicInput info
Element tweakedKey
```

Output:

```
opaque output[Nh]
```

Parameters:

```
Group G
```

Errors: VerifyError

```
def Finalize(input, blind, evaluatedElement, blindedElement,
             proof, info, tweakedKey):
    evaluatedElements = [evaluatedElement] // list of length 1
    blindedElements = [blindedElement] // list of length 1
    if VerifyProof(G.Generator(), tweakedKey, evaluatedElements,
                  blindedElements, proof) == false:
        raise VerifyError

    N = G.ScalarInverse(blind) * evaluatedElement
    unblindedElement = G.SerializeElement(N)

    hashInput = I2OSP(len(input), 2) || input ||
                I2OSP(len(info), 2) || info ||
                I2OSP(len(unblindedElement), 2) || unblindedElement ||
                "Finalize"
    return Hash(hashInput)
```

As in `BlindEvaluate`, inputs to `VerifyProof` are one-item lists. Clients can verify multiple inputs at once whenever the server produced a batched DLEQ proof for them.

Finally, an entity that knows both the private key and the input can compute the PRF result using the `Evaluate` function described below.

Input:

```
Scalar skS
PrivateInput input
PublicInput info
```

Output:

```
opaque output[Nh]
```

Parameters:

```
Group G
```

Errors: InvalidInputError, InverseError

```
def Evaluate(skS, input, info):
    inputElement = G.HashToGroup(input)
    if inputElement == G.Identity():
        raise InvalidInputError

    framedInfo = "Info" || I2OSP(len(info), 2) || info
    m = G.HashToScalar(framedInfo)
    t = skS + m
    if t == 0:
        raise InverseError
    evaluatedElement = G.ScalarInverse(t) * inputElement
    issuedElement = G.SerializeElement(evaluatedElement)

    hashInput = I2OSP(len(input), 2) || input ||
                I2OSP(len(info), 2) || info ||
                I2OSP(len(issuedElement), 2) || issuedElement ||
                "Finalize"
    return Hash(hashInput)
```

4. Ciphersuites

A ciphersuite (also referred to as 'suite' in this document) for the protocol wraps the functionality required for the protocol to take place. The ciphersuite should be available to both the client and server, and agreement on the specific instantiation is assumed throughout.

A ciphersuite contains instantiations of the following functionalities:

Group: A prime-order group exposing the API detailed in [Section 2.1](#), with the generator element defined in the corresponding reference for each group. Each group also specifies HashToGroup, HashToScalar, and serialization functionalities. For HashToGroup, the domain separation tag (DST) is constructed in accordance with the recommendations in [\[RFC9380\]](#), [Section 3.1](#). For HashToScalar, each group specifies an integer order that is used in reducing integer values to a member of the corresponding scalar field.

Hash: A cryptographic hash function whose output length is N_h bytes long.

This section includes an initial set of ciphersuites with supported groups and hash functions. It also includes implementation details for each ciphersuite, focusing on input validation. Future documents can specify additional ciphersuites as needed, provided they meet the requirements in [Section 4.6](#).

For each ciphersuite, `contextString` is that which is computed in the `Setup` functions. Applications should take caution in using ciphersuites targeting P-256 and ristretto255. See [Section 7.2](#) for related discussion.

4.1. OPRF(ristretto255, SHA-512)

This ciphersuite uses ristretto255 [\[RFC9496\]](#) for the Group and SHA-512 for the hash function. The value of the ciphersuite identifier is "ristretto255-SHA512".

Group: ristretto255 [\[RFC9496\]](#)

Order(): Return $2^{252} + 27742317777372353535851937790883648493$ (see [\[RFC9496\]](#)).

Identity(): As defined in [\[RFC9496\]](#).

Generator(): As defined in [\[RFC9496\]](#).

HashToGroup(): Use `hash_to_ristretto255` [\[RFC9380\]](#) with `DST = "HashToGroup-" || contextString` and `expand_message = expand_message_xmd` using SHA-512.

HashToScalar(): Compute `uniform_bytes` using `expand_message = expand_message_xmd`, `DST = "HashToScalar-" || contextString`, and an output length of 64 bytes, interpret `uniform_bytes` as a 512-bit integer in little-endian order, and reduce the integer modulo `Group.Order()`.

ScalarInverse(s): Returns the multiplicative inverse of input Scalar `s mod Group.Order()`.

RandomScalar(): Implemented by returning a uniformly random Scalar in the range `[0, G.Order() - 1]`. Refer to [Section 4.7](#) for implementation guidance.

SerializeElement(A): Implemented using the `Encode` function from [Section 4.3.2](#) of [\[RFC9496\]](#); `Ne = 32`.

DeserializeElement(buf): Implemented using the `Decode` function from [Section 4.3.1](#) of [\[RFC9496\]](#). Additionally, this function validates that the resulting element is not the group identity element. If these checks fail, deserialization returns an `InputValidationError` error.

SerializeScalar(s): Implemented by outputting the little-endian, 32-byte encoding of the Scalar value with the top three bits set to zero; `Ns = 32`.

DeserializeScalar(buf): Implemented by attempting to deserialize a Scalar from a little-endian, 32-byte string. This function can fail if the input does not represent a Scalar in the range `[0, G.Order() - 1]`. Note that this means the top three bits of the input **MUST** be zero.

Hash: SHA-512; Nh = 64.

4.2. OPRF(decaf448, SHAKE-256)

This ciphersuite uses decaf448 [RFC9496] for the Group and SHAKE-256 for the hash function. The value of the ciphersuite identifier is "decaf448-SHAKE256".

Group: decaf448 [RFC9496]

Order(): Return $2^{446} -$

13818066809895115352007386748515426880336692474882178609894547503885.

Identity(): As defined in [RFC9496].

Generator(): As defined in [RFC9496].

RandomScalar(): Implemented by returning a uniformly random Scalar in the range $[0, G.Order() - 1]$. Refer to Section 4.7 for implementation guidance.

HashToGroup(): Use hash_to_decaf448 [RFC9380] with DST = "HashToGroup-" || contextString and expand_message = expand_message_xof using SHAKE-256.

HashToScalar(): Compute uniform_bytes using expand_message = expand_message_xof, DST = "HashToScalar-" || contextString, and output length 64, interpret uniform_bytes as a 512-bit integer in little-endian order, and reduce the integer modulo $G.Order()$.

ScalarInverse(s): Returns the multiplicative inverse of input Scalar $s \bmod G.Order()$.

SerializeElement(A): Implemented using the Encode function from Section 5.3.2 of [RFC9496]; Ne = 56.

DeserializeElement(buf): Implemented using the Decode function from Section 5.3.1 of [RFC9496]. Additionally, this function validates that the resulting element is not the group identity element. If these checks fail, deserialization returns an InputValidationError error.

SerializeScalar(s): Implemented by outputting the little-endian, 56-byte encoding of the Scalar value; Ns = 56.

DeserializeScalar(buf): Implemented by attempting to deserialize a Scalar from a little-endian, 56-byte string. This function can fail if the input does not represent a Scalar in the range $[0, G.Order() - 1]$.

Hash: SHAKE-256; Nh = 64.

4.3. OPRF(P-256, SHA-256)

This ciphersuite uses P-256 [NISTCurves] for the Group and SHA-256 for the hash function. The value of the ciphersuite identifier is "P256-SHA256".

Group: P-256 (secp256r1) [NISTCurves]

Order(): Return `0xffffffff00000000ffffffffffffffffbce6faada7179e84f3b9cac2fc632551`.

Identity(): As defined in [NISTCurves].

Generator(): As defined in [NISTCurves].

RandomScalar(): Implemented by returning a uniformly random Scalar in the range `[0, G.Order() - 1]`. Refer to Section 4.7 for implementation guidance.

HashToGroup(): Use `hash_to_curve` with suite `P256_XMD:SHA-256_SSWU_RO_` [RFC9380] and `DST = "HashToGroup-" | | contextString`.

HashToScalar(): Use `hash_to_field` from [RFC9380] using `L = 48`, `expand_message_xmd` with `SHA-256`, `DST = "HashToScalar-" | | contextString`, and a prime modulus equal to `Group.Order()`.

ScalarInverse(s): Returns the multiplicative inverse of input Scalar `s mod Group.Order()`.

SerializeElement(A): Implemented using the compressed Elliptic-Curve-Point-to-Octet-String method according to [SEC1]; `Ne = 33`.

DeserializeElement(buf): Implemented by attempting to deserialize a 33-byte input string to a public key using the compressed Octet-String-to-Elliptic-Curve-Point method according to [SEC1] and then performing partial public-key validation, as defined in Section 5.6.2.3.4 of [KEYAGREEMENT]. This includes checking that the coordinates of the resulting point are in the correct range, that the point is on the curve, and that the point is not the group identity element. If these checks fail, deserialization returns an `InputValidationError` error.

SerializeScalar(s): Implemented using the Field-Element-to-Octet-String conversion according to [SEC1]; `Ns = 32`.

DeserializeScalar(buf): Implemented by attempting to deserialize a Scalar from a 32-byte string using `Octet-String-to-Field-Element` from [SEC1]. This function can fail if the input does not represent a Scalar in the range `[0, G.Order() - 1]`.

Hash: SHA-256; `Nh = 32`.

4.4. OPRF(P-384, SHA-384)

This ciphersuite uses P-384 [NISTCurves] for the Group and SHA-384 for the hash function. The value of the ciphersuite identifier is "P384-SHA384".

Group: P-384 (secp384r1) [NISTCurves]

Order(): Return `0xffc7634d81f4372ddf581a0db248b0a77aecec196accc52973`.

Identity(): As defined in [NISTCurves].

Generator(): As defined in [\[NISTCurves\]](#).

RandomScalar(): Implemented by returning a uniformly random Scalar in the range $[0, G.Order() - 1]$. Refer to [Section 4.7](#) for implementation guidance.

HashToGroup(): Use `hash_to_curve` with suite `P384_XMD:SHA-384_SSWU_RO_` [\[RFC9380\]](#) and `DST = "HashToGroup-" || contextString`.

HashToScalar(): Use `hash_to_field` from [\[RFC9380\]](#) using `L = 72`, `expand_message_xmd` with `SHA-384`, `DST = "HashToScalar-" || contextString`, and a prime modulus equal to `Group.Order()`.

ScalarInverse(s): Returns the multiplicative inverse of input Scalar `s mod Group.Order()`.

SerializeElement(A): Implemented using the compressed Elliptic-Curve-Point-to-Octet-String method according to [\[SEC1\]](#); `Ne = 49`.

DeserializeElement(buf): Implemented by attempting to deserialize a 49-byte array to a public key using the compressed Octet-String-to-Elliptic-Curve-Point method according to [\[SEC1\]](#) and then performing partial public-key validation, as defined in Section 5.6.2.3.4 of [\[KEYAGREEMENT\]](#). This includes checking that the coordinates of the resulting point are in the correct range, that the point is on the curve, and that the point is not the point at infinity. Additionally, this function validates that the resulting element is not the group identity element. If these checks fail, deserialization returns an `InputValidationError` error.

SerializeScalar(s): Implemented using the Field-Element-to-Octet-String conversion according to [\[SEC1\]](#); `Ns = 48`.

DeserializeScalar(buf): Implemented by attempting to deserialize a Scalar from a 48-byte string using `Octet-String-to-Field-Element` from [\[SEC1\]](#). This function can fail if the input does not represent a Scalar in the range $[0, G.Order() - 1]$.

Hash: SHA-384; `Nh = 48`.

4.5. OPRF(P-521, SHA-512)

This ciphersuite uses P-521 [\[NISTCurves\]](#) for the Group and SHA-512 for the hash function. The value of the ciphersuite identifier is "P521-SHA512".

Group: P-521 (secp521r1) [\[NISTCurves\]](#)

Order(): Return

```
0x01fffffffffffffffffffffffffffffffffffffffffffffffffffffffffffffa51868783bf2f966b7fcc0148f709a5d0
3bb5c9b8899c47aebb6fb71e91386409.
```

Identity(): As defined in [\[NISTCurves\]](#).

Generator(): As defined in [\[NISTCurves\]](#).

- `RandomScalar()`: Implemented by returning a uniformly random Scalar in the range $[0, G.Order() - 1]$. Refer to [Section 4.7](#) for implementation guidance.
- `HashToGroup()`: Use `hash_to_curve` with suite `P521_XMD:SHA-512_SSWU_RO_` [[RFC9380](#)] and `DST = "HashToGroup-" || contextString`.
- `HashToScalar()`: Use `hash_to_field` from [[RFC9380](#)] using $L = 98$, `expand_message_xmd` with SHA-512, `DST = "HashToScalar-" || contextString`, and a prime modulus equal to `Group.Order()`.
- `ScalarInverse(s)`: Returns the multiplicative inverse of input Scalar $s \bmod Group.Order()$.
- `SerializeElement(A)`: Implemented using the compressed Elliptic-Curve-Point-to-Octet-String method according to [[SEC1](#)]; $N_e = 67$.
- `DeserializeElement(buf)`: Implemented by attempting to deserialize a 67-byte input string to a public key using the compressed Octet-String-to-Elliptic-Curve-Point method according to [[SEC1](#)] and then performing partial public-key validation, as defined in Section 5.6.2.3.4 of [[KEYAGREEMENT](#)]. This includes checking that the coordinates of the resulting point are in the correct range, that the point is on the curve, and that the point is not the point at infinity. Additionally, this function validates that the resulting element is not the group identity element. If these checks fail, deserialization returns an `InputValidationError` error.
- `SerializeScalar(s)`: Implemented using the Field-Element-to-Octet-String conversion according to [[SEC1](#)]; $N_s = 66$.
- `DeserializeScalar(buf)`: Implemented by attempting to deserialize a Scalar from a 66-byte string using `Octet-String-to-Field-Element` from [[SEC1](#)]. This function can fail if the input does not represent a Scalar in the range $[0, G.Order() - 1]$.
- Hash: SHA-512; $N_h = 64$.

4.6. Future Ciphersuites

A critical requirement of implementing the prime-order group using elliptic curves is a method to instantiate the function `HashToGroup`, which maps inputs to group elements. In the elliptic curve setting, this deterministically maps inputs (as byte arrays) to uniformly chosen points on the curve.

In the security proof of the construction, Hash is modeled as a random oracle. This implies that any instantiation of `HashToGroup` must be pre-image and collision resistant. In [Section 4](#), we give instantiations of this functionality based on the functions described in [[RFC9380](#)]. Consequently, any OPRF implementation must adhere to the implementation and security considerations discussed in [[RFC9380](#)] when instantiating the function.

The `DeserializeElement` and `DeserializeScalar` functions instantiated for a particular prime-order group corresponding to a ciphersuite **MUST** adhere to the description in [Section 2.1](#). Future ciphersuites **MUST** describe how input validation is done for `DeserializeElement` and `DeserializeScalar`.

Additionally, future ciphersuites must take care when choosing the security level of the group. See [Section 7.2.3](#) for additional details.

4.7. Random Scalar Generation

Two popular algorithms for generating a random integer uniformly distributed in the range $[0, G.Order() - 1]$ are described in the following subsections.

4.7.1. Rejection Sampling

Generate a random byte array with N_s bytes and attempt to map to a Scalar by calling `DeserializeScalar` in constant time. If it succeeds, return the result. If it fails, try again with another random byte array until the procedure succeeds. Failure to implement `DeserializeScalar` in constant time can leak information about the underlying corresponding Scalar.

As an optimization, if the group order is very close to a power of 2, it is acceptable to omit the rejection test completely. In particular, if the group order is p and there is an integer b such that $|p - 2^b|$ is less than $2^{(b/2)}$, then `RandomScalar` can simply return a uniformly random integer of at most b bits.

4.7.2. Random Number Generation Using Extra Random Bits

Generate a random byte array with $L = \text{ceil}(\text{ceil}(\log_2(G.Order())) / 2) / 8$ bytes, and interpret it as an integer; reduce the integer modulo $G.Order()$, and return the result. See [\[RFC9380\]](#), [Section 5](#) for the underlying derivation of L .

5. Application Considerations

This section describes considerations for applications, including external interface recommendations, explicit error treatment, and public input representation for the POPRF protocol variant.

5.1. Input Limits

Application inputs, expressed as `PrivateInput` or `PublicInput` values, **MUST** be smaller than $2^{16} - 1$ bytes in length. Applications that require longer inputs can use a cryptographic hash function to map these longer inputs to a fixed-length input that fits within the `PublicInput` or `PrivateInput` length bounds. Note that some cryptographic hash functions have input length restrictions themselves, but these limits are often large enough to not be a concern in practice. For example, SHA-256 has an input limit of 2^{61} bytes.

5.2. External Interface Recommendations

In [Section 3.3](#), the interface of the protocol functions allows that some inputs (and outputs) to be group Element and Scalar values. However, implementations can instead operate over Element and Scalar values internally and only expose interfaces that operate with an application-specific format of messages.

5.3. Error Considerations

Some OPRF variants specified in this document have fallible operations. For example, `Finalize` and `BlindEvaluate` can fail if any element received from the peer fails input validation. The explicit errors generated throughout this specification, along with the conditions that lead to each error, are as follows:

`VerifyError`: Verifiable OPRF proof verification failed ([Sections 3.3.2](#) and [3.3.3](#)).

`DeserializeError`: Group Element or Scalar deserialization failure ([Sections 2.1](#) and [3.3](#)).

`InputValidationError`: Validation of byte array inputs failed ([Section 4](#)).

There are other explicit errors generated in this specification; however, they occur with negligible probability in practice. We note them here for completeness.

`InvalidInputError`: OPRF Blind input produces an invalid output element ([Sections 3.3.1](#) and [3.3.3](#)).

`InverseError`: A tweaked private key is invalid, i.e., has no multiplicative inverse ([Sections 2.1](#) and [3.3](#)).

In general, the errors in this document are meant as a guide to implementors. They are not an exhaustive list of all the errors an implementation might emit. For example, implementations might run out of memory and return a corresponding error.

5.4. POPRF Public Input

Functionally, the VOPRF and POPRF variants differ in that the POPRF variant admits public input, whereas the VOPRF variant does not. Public input allows clients and servers to cryptographically bind additional data to the POPRF output. A POPRF with fixed public input is functionally equivalent to a VOPRF. However, there are differences in the underlying security assumptions made about each variant; see [Section 7.2](#) for more details.

This public input is known to both parties at the start of the protocol. It is **RECOMMENDED** that this public input be constructed with some type of higher-level domain separation to avoid cross protocol attacks or related issues. For example, protocols using this construction might ensure that the public input uses a unique, prefix-free encoding. See [\[RFC9380\]](#), [Section 10.4](#) for further discussion on constructing domain separation values.

Implementations of the POPRF may choose to not let applications control info in cases where this value is fixed or otherwise not useful to the application. In this case, the resulting protocol is functionally equivalent to the VOPRF, which does not admit public input.

6. IANA Considerations

This document has no IANA actions.

7. Security Considerations

This section discusses the security of the protocols defined in this specification, along with some suggestions and trade-offs that arise from the implementation of the protocol variants in this document. Note that the syntax of the POPRF variant is different from that of the OPRF and VOPRF variants since it admits an additional public input, but the same security considerations apply.

7.1. Security Properties

The security properties of an OPRF protocol with functionality $y = F(k, x)$ include those of a standard PRF. Specifically:

Pseudorandomness: For a random sampling of k , F is pseudorandom if the output $y = F(k, x)$ on any input x is indistinguishable from uniformly sampling any element in F 's range.

In other words, consider an adversary that picks inputs x from the domain of F and evaluates F on (k, x) (without knowledge of randomly sampled k). Then, the output distribution $F(k, x)$ is indistinguishable from the output distribution of a randomly chosen function with the same domain and range.

A consequence of showing that a function is pseudorandom is that it is necessarily nonmalleable (i.e., we cannot compute a new evaluation of F from an existing evaluation). A genuinely random function will be nonmalleable with high probability, so a pseudorandom function must be nonmalleable to maintain indistinguishability.

Unconditional input secrecy: The server does not learn anything about the client input x , even with unbounded computation.

In other words, an attacker with infinite computing power cannot recover any information about the client's private input x from an invocation of the protocol.

Essentially, input secrecy is the property that, even if the server learns the client's private input x at some point in the future, the server cannot link any particular PRF evaluation to x . This property is also known as unlinkability [DGSTV18].

Beyond client input secrecy, in the OPRF protocol, the server learns nothing about the output y of the function, nor does the client learn anything about the server's private key k .

For the VOPRF and POPRF protocol variants, there is an additional security property:

Verifiable: The client must only complete execution of the protocol if it can successfully assert that the output it computes is correct. This is taken with respect to the private key held by the server.

Any VOPRF or POPRF that satisfies the 'verifiable' security property is known as 'verifiable'. In practice, the notion of verifiability requires that the server commits to the key before the actual protocol execution takes place. Then, the client verifies that the server has used the key in the protocol using this commitment. In the following, we may also refer to this commitment as a public key.

Finally, the POPRF variant also has the following security property:

Partial obliviousness: The client and server must be able to perform the PRF on the client's private and public input. Both the client and server know the public input, but similar to the OPRF and VOPRF protocols, the server learns nothing about the client's private input or the output of the function, and the client learns nothing about the server's private key.

This property becomes useful when dealing with key management operations, such as the rotation of the server's keys. Note that partial obliviousness only applies to the POPRF variant because neither the OPRF nor VOPRF variants accept public input to the protocol.

Since the POPRF variant has a different syntax than the OPRF and VOPRF variants, i.e., $y = F(k, x, \text{info})$, the pseudorandomness property is generalized:

Pseudorandomness: For a random sampling of k , F is pseudorandom if the output $y = F(k, x, \text{info})$ on any input pairs (x, info) is indistinguishable from uniformly sampling any element in F 's range.

7.2. Security Assumptions

Below, we discuss the cryptographic security of each protocol variant from [Section 3](#), relative to the necessary cryptographic assumptions that need to be made.

7.2.1. OPRF and VOPRF Assumptions

The OPRF and VOPRF protocol variants in this document are based on [\[JKK14\]](#). In particular, the VOPRF construction is similar to the [\[JKK14\]](#) construction with the following distinguishing properties:

1. This document does not use session identifiers to differentiate different instances of the protocol.
2. This document supports batching so that multiple evaluations can happen at once whilst only constructing one DLEQ proof object. This is enabled using an established batching technique [\[DGSTV18\]](#).

The pseudorandomness and input secrecy (and verifiability) of the OPRF (and VOPRF) protocols in [JKK14] are based on the One-More Gap Computational Diffie-Hellman assumption that is computationally difficult to solve in the corresponding prime-order group. In [JKK14], these properties are proven for one instance (i.e., one key) of the VOPRF protocol and without batching. There is currently no security analysis available for the VOPRF protocol described in this document in a setting with multiple server keys or batching.

7.2.2. POPRF Assumptions

The POPRF construction in this document is based on the construction known as 3HashSDHI, given by [TCRSTW21]. The construction is identical to 3HashSDHI, except that this design can optionally perform multiple POPRF evaluations in one batch, whilst only constructing one DLEQ proof object. This is enabled using an established batching technique [DGSTV18].

Pseudorandomness, input secrecy, verifiability, and partial obliviousness of the POPRF variant is based on the assumption that the One-More Gap Strong Diffie-Hellman Inversion (SDHI) assumption from [TCRSTW21] is computationally difficult to solve in the corresponding prime-order group. Tyagi et al. [TCRSTW21] show that both the One-More Gap Computational Diffie-Hellman assumption and the One-More Gap SDHI assumption reduce to the q -DL (Discrete Log) assumption in the algebraic group model for some q number of `BlindEvaluate` queries. (The One-More Gap Computational Diffie-Hellman assumption was the hardness assumption used to evaluate the OPRF and VOPRF designs based on [JKK14], which is a predecessor to the POPRF variant in Section 3.3.3.)

7.2.3. Static Diffie-Hellman Attack and Security Limits

A side effect of the OPRF protocol variants in this document is that they allow instantiation of an oracle for constructing static Diffie-Hellman (DH) samples; see [BG04] and [Cheon06]. These attacks are meant to recover (bits of) the server private key. Best-known attacks reduce the security of the prime-order group instantiation by $\log_2(Q) / 2$ bits, where Q is the number of `BlindEvaluate` calls made by the attacker.

As a result of this class of attacks, choosing prime-order groups with a 128-bit security level instantiates an OPRF with a reduced security level of $128 - (\log_2(Q) / 2)$ bits of security. Moreover, such attacks are only possible for those certain applications where the adversary can query the OPRF directly. Applications can mitigate against this problem in a variety of ways, e.g., by rate-limiting client queries to `BlindEvaluate` or by rotating private keys. In applications where such an oracle is not made available, this security loss does not apply.

In most cases, it would require an informed and persistent attacker to launch a highly expensive attack to reduce security to anything much below 100 bits of security. Applications that admit the aforementioned oracle functionality and that cannot tolerate discrete logarithm security of lower than 128 bits are **RECOMMENDED** to choose groups that target a higher security level, such as `decaf448` (used by ciphersuite `decaf448-SHAKE256`), `P-384` (used by ciphersuite `P384-SHA384`), or `P-521` (used by ciphersuite `P521-SHA512`).

7.3. Domain Separation

Applications **SHOULD** construct input to the protocol to provide domain separation. Any system that has multiple OPRF applications should distinguish client inputs to ensure the OPRF results are separate. Guidance for constructing info can be found in [RFC9380], Section 3.1.

7.4. Timing Leaks

To ensure no information is leaked during protocol execution, all operations that use secret data **MUST** run in constant time. This includes all prime-order group operations and proof-specific operations that operate on secret data, including `GenerateProof` and `BlindEvaluate`.

8. References

8.1. Normative References

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8.2. Informative References

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Appendix A. Test Vectors

This section includes test vectors for the protocol variants specified in this document. For each ciphersuite specified in [Section 4](#), there is a set of test vectors for the protocol when running the OPRE, VOPRE, and POPRF modes. Each test vector lists the batch size for the evaluation. Each test vector value is encoded as a hexadecimal byte string. The fields of each test vector are described below.

"Input": The private client input, an opaque byte string.

"Info": The public info, an opaque byte string. Only present for POPRF test vectors.

"Blind": The blind value output by `Blind()`, a serialized Scalar of N_s bytes long.

"BlindedElement": The blinded value output by `Blind()`, a serialized Element of N_e bytes long.

"EvaluatedElement": The evaluated element output by `BlindEvaluate()`, a serialized Element of N_e bytes long.

"Proof": The serialized Proof output from `GenerateProof()` composed of two serialized Scalar values, each N_s bytes long. Only present for VOPRF and POPRF test vectors.

"ProofRandomScalar": The random Scalar r computed in `GenerateProof()`, a serialized Scalar of N_s bytes long. Only present for VOPRF and POPRF test vectors.

"Output": The protocol output, an opaque byte string of N_h bytes long.

Test vectors with batch size $B > 1$ have inputs separated by a comma ",". Applicable test vectors will have B different values for the "Input", "Blind", "BlindedElement", "EvaluationElement", and "Output" fields.

The server key material, `pkSm` and `skSm`, are listed under the mode for each ciphersuite. Both `pkSm` and `skSm` are the serialized values of `pkS` and `skS`, respectively, as used in the protocol. Each key pair is derived from a seed, denoted `Seed`, and info string, denoted `KeyInfo`, which are listed as well, using the `DeriveKeyPair` function from [Section 3.2](#).

A.1.2.1. Test Vector 1, Batch Size 1

```

Input = 00
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec4c1f
6706
BlindedElement = 863f330cc1a1259ed5a5998a23acfd37fb4351a793a5b3c090b
642ddc439b945
EvaluationElement = aa8fa048764d5623868679402ff6108d2521884fa138cd7f
9c7669a9a014267e
Proof = ddef93772692e535d1a53903db24367355cc2cc78de93b3be5a8ffcc6985
dd066d4346421d17bf5117a2a1ff0fcb2a759f58a539dfbe857a40bce4cf49ec600d
ProofRandomScalar = 222a5e897cf59db8145db8d16e597e8facb80ae7d4e26d98
81aa6f61d645fc0e
Output = b58cfbe118e0cb94d79b5fd6a6dafb98764dff49c14e1770b566e42402d
a1a7da4d8527693914139caee5bd03903af43a491351d23b430948dd50cde10d32b3
c

```

A.1.2.2. Test Vector 2, Batch Size 1

```

Input = 5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec4c1f
6706
BlindedElement = cc0b2a350101881d8a4cba4c80241d74fb7dcbfde4a61fde2f9
1443c2bf9ef0c
EvaluationElement = 60a59a57208d48aca71e9e850d22674b611f752bed48b36f
7a91b372bd7ad468
Proof = 401a0da6264f8cf45bb2f5264bc31e109155600babb3cd4e5af7d181a2c9
dc0a67154fabf031fd936051dec80b0b6ae29c9503493dde7393b722eafdf5a50b02
ProofRandomScalar = 222a5e897cf59db8145db8d16e597e8facb80ae7d4e26d98
81aa6f61d645fc0e
Output = 8a9a2f3c7f085b65933594309041fc1898d42d0858e59f90814ae90571a
6df60356f4610bf816f27afdd84f47719e480906d27ecd994985890e5f539e7ea74b
6

```


A.2.1.1. Test Vector 1, Batch Size 1

```
Input = 00
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec65fa
3833a26e9388336361686ff1f83df55046504dfecad8549ba112
BlindedElement = e0ae01c4095f08e03b19baf47ffdc19cb7d98e583160522a3c7
d6a0b2111cd93a126a46b7b41b730cd7fc943d4e28e590ed33ae475885f6c
EvaluationElement = 50ce4e60eed006e22e7027454b5a4b8319eb2bc8ced609eb
19eb3ad42fb19e06ba12d382cbe7ae342a0cad6ead0ef8f91f00bb7f0cd9c0a2
Output = 37d3f7922d9388a15b561de5829bbf654c4089ede89c0ce0f3f85bcdba0
9e382ce0ab3507e021f9e79706a1798ffeac68ebd5cf62e5eb9838c7068351d97ae3
7
```

A.2.1.2. Test Vector 2, Batch Size 1

```
Input = 5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec65fa
3833a26e9388336361686ff1f83df55046504dfecad8549ba112
BlindedElement = 86a88dc5c6331ecfcb1d9aacb50a68213803c462e377577cacc
00af28e15f0ddb2e3d716f2f39ef95f3ec1314a2c64d940a9f295d8f13bb
EvaluationElement = 162e9fa6e9d527c3cd734a31bf122a34dbd5bcb7bb23651f
1768a7a9274cc116c03b58afa6f0dede3994a60066c76370e7328e7062fd5819
Output = a2a652290055cb0f6f8637a249ee45e32ef4667db0b4c80c0a70d2a6416
4d01525cfdad5d870a694ec77972b9b6ec5d2596a5223e5336913f945101f0137f55
e
```

A.2.2. VOPRF Mode

```
Seed = a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3
3a3
KeyInfo = 74657374206b6579
skSm = e3c01519a076a326a0eb566343e9b21c115fa18e6e85577ddbe890b33104f
cc2835ddfb14a928dc3f5d79b936e17c76b99e0bf6a1680930e
pkSm = 945fc518c47695cf65217ace04b86ac5e4cbe26ca649d52854bb16c494ce0
9069d6add96b20d4b0ae311a87c9a73e3a146b525763ab2f955
```

A.2.2.1. Test Vector 1, Batch Size 1

```

Input = 00
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec65fa
3833a26e9388336361686ff1f83df55046504dfecad8549ba112
BlindedElement = 7261bbc335c664ba788f1b1a1a4cd5190cc30e787ef277665ac
1d314f8861e3ec11854ce3ddd42035d9e0f5cddde324c332d8c880abc00eb
EvaluationElement = ca1491a526c28d880806cf0fb012222392cf495657be6e4
c9d203bceffa46c86406caf8217859d3fb259077af68e5d41b3699410781f467
Proof = f84bbeee47aedf43558dae4b95b3853635a9fc1a9ea7eac9b454c64c66c4
f49cd1c72711c7ac2e06c681e16ea693d5500bbd7b56455df52f69e00b76b4126961
e1562fdbaaac40b7701065cbeece3febbfe09e00160f81775d36daed99d8a2a10be0
759e01b7ee81217203416c9db208
ProofRandomScalar = b1b748135d405ce48c6973401d9455bb8ccd18b01d0295c0
627f67661200dbf9569f73fbb3925daa043a070e5f953d80bb464ea369e5522b
Output = e2ac40b634f36cccd8262b285adff7c9dcc19cd308564a5f4e581d1a853
5773b86fa4fc9f2203c370763695c5093aea4a7aedec4488b1340ba3bf663a23098c
1

```

A.2.2.2. Test Vector 2, Batch Size 1

```

Input = 5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec65fa
3833a26e9388336361686ff1f83df55046504dfecad8549ba112
BlindedElement = 88287e553939090b888ddc15913e1807dc4757215555e1c3a79
488ef311594729c7fa74c772a732b78440b7d66d0aa35f3bb316f1d93e1b2
EvaluationElement = c00978c73e8e4ee1d447ab0d3ad1754055e72cc85c08e3a0
db170909a9c61cbff1f1e7015f289e3038b0f341faea5d7780c130106065c231
Proof = 7a2831a6b237e11ac1657d440df93bc5ce00f552e6020a99d5c956ffc4d0
7b5ade3e82ecdc257fd53d76239e733e0a1313e84ce16cc0d82734806092a693d7e8
d3c420c2cb6ccd5d0ca32514fb78e9ad0973ebdcb52eba438fc73948d76339ee7101
21d83e2fe6f001cfd551aff9f36
ProofRandomScalar = b1b748135d405ce48c6973401d9455bb8ccd18b01d0295c0
627f67661200dbf9569f73fbb3925daa043a070e5f953d80bb464ea369e5522b
Output = 862952380e07ec840d9f6e6f909c5a25d16c3dacb586d89a181b4aa7380
c959baa8c480fe8e6c64e089d68ea7aeeb5817bd524d7577905b5bab487690048c94
1

```

A.2.2.3. Test Vector 3, Batch Size 2

```

Input = 00,5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec65fa
3833a26e9388336361686ff1f83df55046504dfecad8549ba112, b1b748135d405ce
48c6973401d9455bb8ccd18b01d0295c0627f67661200dbf9569f73fbb3925daa043
a070e5f953d80bb464ea369e5522b
BlindedElement = 7261bbc335c664ba788f1b1a1a4cd5190cc30e787ef277665ac
1d314f8861e3ec11854ce3ddd42035d9e0f5cddde324c332d8c880abc00eb, 2e15f3
93c035492a1573627a3606e528c6294c767c8d43b8c691ef70a52cc7dc7d1b53fe45
8350a270abb7c231b87ba58266f89164f714d9
EvaluationElement = ca1491a526c28d880806cf0fb012222392cf495657be6e4
c9d203bceffa46c86406caf8217859d3fb259077af68e5d41b3699410781f467, 8ec
68e9871b296e81c55647ce64a04fe75d19932f1400544cd601468c60f998408bbb54
6601d4a636e8be279e558d70b95c8d4a4f61892be
Proof = 167d922f0a6ffa845eed07f8aa97b6ac746d902ecbeb18f49c009adc0521
eab1e4d275b74a2dc266b7a194c854e85e7eb54a9a36376dfc04ec7f3bd55fc9618c
3970cb548e064f8a2f06183a5702933dbc3e4c25a73438f2108ee1981c306181003c
7ea92f963ec7b4ba4f270e6d38
ProofRandomScalar = 63798726803c9451ba405f00ef3acb633ddf0c420574a2ec
6cbf28f840800e355c9fbaac10699686de2724ed22e797a00f3bd93d105a7f23
Output = e2ac40b634f36cccd8262b285adff7c9dcc19cd308564a5f4e581d1a853
5773b86fa4fc9f2203c370763695c5093aea47aedec4488b1340ba3bf663a23098c
1,862952380e07ec840d9f6e6f909c5a25d16c3dacb586d89a181b4aa7380c959baa
8c480fe8e6c64e089d68ea7aeeb5817bd524d7577905b5bab487690048c941

```

A.2.3. POPRF Mode

```

Seed = a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3a3
3a3
KeyInfo = 74657374206b6579
skSm = 792a10dcbd3ba4a52a054f6f39186623208695301e7adb9634b74709ab22d
e402990eb143fd7c67ac66be75e0609705ecea800992aac8e19
pkSm = 6c9d12723a5bbcf305522cc04b4a34d9ced2e12831826018ea7b5dcf54526
47ad262113059bf0f6e4354319951b9d513c74f29cb0eec38c1

```

A.2.3.1. Test Vector 1, Batch Size 1

```
Input = 00
Info = 7465737420696e666f
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec65fa
3833a26e9388336361686ff1f83df55046504dfecad8549ba112
BlindedElement = 161183c13c6cb33b0e4f9b7365f8c5c12d13c72f8b62d276ca0
9368d093dce9b42198276b9e9d870ac392dda53efd28d1b7e6e8c060cdc42
EvaluationElement = 06ec89dfde25bb2a6f0145ac84b91ac277b35de39ad1d6f4
02a8e46414952ce0d9ea1311a4ece283e2b01558c7078b040cfaa40dd63b3e6c
Proof = 66caee75bf2460429f620f6ad3e811d524cb8ddd848a435fc5d89af48877
abf6506ee341a0b6f67c2d76cd021e5f3d1c9abe5aa9f0dce016da746135fedba2af
41ed1d01659bfd6180d96bc1b7f320c0cb6926011ce392ecca748662564892bae665
16acaac6ca39aadf6fcc9a5af406
ProofRandomScalar = b1b748135d405ce48c6973401d9455bb8ccd18b01d0295c0
627f67661200dbf9569f73fbb3925daa043a070e5f953d80bb464ea369e5522b
Output = 4423f6dcc1740688ea201de57d76824d59cd6b859e1f9884b7eebc49b0b
971358cf9cb075df1536a8ea31bcf55c3e31c2ba9cfa8efe54448d17091daeb9924e
d
```

A.2.3.2. Test Vector 2, Batch Size 1

```
Input = 5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a5a
Info = 7465737420696e666f
Blind = 64d37aed22a27f5191de1c1d69fadb899d8862b58eb4220029e036ec65fa
3833a26e9388336361686ff1f83df55046504dfecad8549ba112
BlindedElement = 12082b6a381c6c51e85d00f2a3d828cdeab3f5cb19a10b9c014
c33826764ab7e7cfb8b4ff6f411bddb2d64e62a472af1cd816e5b712790c6
EvaluationElement = f2919b7eedc05ab807c221fce2b12c4ae9e19e6909c47845
64b690d1972d2994ca623f273afc67444d84ea40cbc58fcdab7945f321a52848
Proof = a295677c54d1bc4286330907fc2490a7de163da26f9ce03a462a452fea42
2b19ade296ba031359b3b6841e48455d20519ad01b4ac4f0b92e76d3cf16fbef0a3f
72791a8401ef2d7081d361e502e96b2c60608b9fa566f43d4611c2f161d83aabef7f
8017332b26ed1daaf80440772022
ProofRandomScalar = b1b748135d405ce48c6973401d9455bb8ccd18b01d0295c0
627f67661200dbf9569f73fbb3925daa043a070e5f953d80bb464ea369e5522b
Output = 8691905500510843902c44bdd9730ab9dc3925aa58ff9dd42765a2baf63
3126de0c3adb93bef5652f38e5827b6396e87643960163a560fc4ac9738c8de4e4a8
d
```


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Authors' Addresses

Alex Davidson

Brave Software

Email: alex.davidson92@gmail.com

Armando Faz-Hernandez

Cloudflare, Inc.

101 Townsend St

San Francisco, CA

United States of America

Email: armfazh@cloudflare.com

Nick Sullivan

Cloudflare, Inc.

101 Townsend St

San Francisco, CA

United States of America

Email: nicholas.sullivan+ietf@gmail.com

Christopher A. Wood

Cloudflare, Inc.

101 Townsend St

San Francisco, CA

United States of America

Email: caw@heapingbits.net