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Privacy Pass Architectural Framework
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Abstract

This document specifies the architectural framework for constructing secure and anonymity-preserving instantiations of the Privacy Pass protocol. It provides recommendations on how the protocol ecosystem should be constructed to ensure the privacy of clients, and the security of all participating entities.

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[1.](#) Introduction

Privacy Pass is a protocol for authorization based on anonymous-credential authentication mechanisms. Typical approaches for authorizing clients, such as through the use of long-term cookies, are not privacy-friendly since they allow servers to track clients across sessions and interactions. Privacy Pass takes a different approach: instead of presenting linkable state carrying information to servers, e.g., whether or not the client is an authorized user or has completed some prior challenge, clients present unlinkable proofs that attest to this information.

The most basic Privacy Pass protocol provides a set of cross-origin authorization tokens that protect the client's anonymity during interactions with a server. This allows clients to communicate an attestation of a previously authenticated server action, without having to reauthenticate manually. The tokens retain anonymity in the sense that the act of revealing them cannot be linked back to the session where they were initially issued.

At a high level, Privacy Pass is composed of two protocols: issuance and redemption.

The issuance protocol runs between a Client and two network functions in the Privacy Pass architecture: Attestation and Issuance. These two network functions can be implemented by the same protocol participant, but can also be implemented separately. The Issuer is responsible for issuing tokens in response to requests from Clients. The Attester is responsible for attesting properties about the Client for which tokens are issued. The Issuer needs to be trusted by the server that later redeems the token. Attestation can be performed by the Issuer or by an Attester that is trusted by the Issuer. Clients might prefer to select different Attesters, separate from the Issuer, to be able to use preferred authentication methods or improve privacy by not directly communicating with an Issuer. Depending on the attestation, Attesters can store state about a Client, such as the

number of overall tokens issued thus far. As an example of an Issuance protocol, in the original Privacy Pass protocol [PPSRV], tokens were only issued to Clients that solved CAPTCHAs. In this context, the Attester attested that some client solved a CAPTCHA and the resulting token produced by the Issuer was proof of this fact.

The redemption protocol runs between Client and Origin (server). It allows Origins to challenge Clients to present one or more tokens for authorization. Depending on the type of token, e.g., whether or not it is cross-origin or per-origin, and whether or not it can be cached, the Client either presents a previously obtained token or invokes the issuance protocol to acquire one for authorization.

The issuance and redemption protocols operate in concert as shown in the figure below.

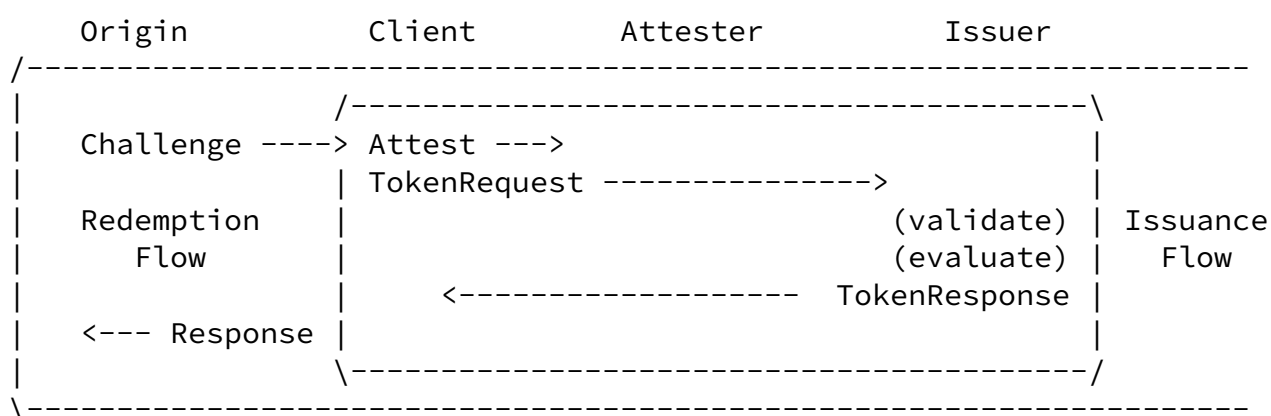


Figure 1: Privacy Pass Architectural Components

This document describes requirements for both issuance and redemption protocols. This document also describes ecosystem considerations that impact the stated privacy and security guarantees of the protocol.

2. Terminology

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.

The following terms are used throughout this document.

- * **Client:** An entity that seeks authorization to an Origin.
- * **Origin:** An entity that challenges Clients for tokens.
- * **Issuer:** An entity that issues tokens to Clients for properties attested to by the Attester.
- * **Attester:** An entity that attests to properties of Client for the purposes of token issuance.

[3.](#) Architecture

The Privacy Pass architecture consists of four logical entities -- Client, Origin, Issuer, and Attester -- that work in concert as shown in [Section 1](#) for token issuance and redemption. This section describes the purpose of token issuance and redemption and the requirements therein on the relevant participants.

[3.1.](#) Redemption Protocol

The redemption protocol is a simple challenge-response based authorization protocol between Client and Origin. Origins prompt Clients with a token challenge and, if possible, Clients present a valid token for the challenge in response. The context in which an Origin challenges a Client for a token is referred to as the redemption context. This context includes all information associated with the redemption event, such as the timestamp of the event, Client visible information (including the IP address), and the Origin name.

The challenge controls the type of token that the Origin will accept for the given resource. As described in [\[HTTP-Authentication\]](#), there are a number of ways in which the token may vary, including:

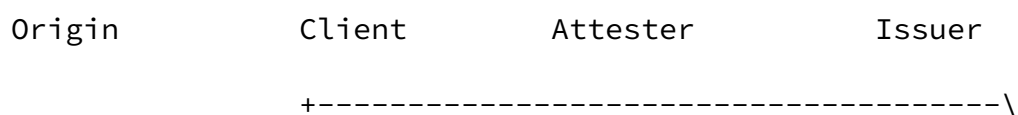
- * Issuance protocol. The token identifies the type of issuance protocol required for producing the token. Different issuance protocols have different security properties, e.g., some issuance protocols may produce tokens that are publicly verifiable, whereas others may not have this property.
- * Issuer identity. Tokens identify which issuers are trusted for a given issuance protocol.
- * Interactive or non-interactive. Tokens can either be interactive or not. An interactive token is one which requires a freshly issued token based on the challenge, whereas a non-interactive token can be issued proactively and cached for future use.
- * Per-origin or cross-origin. Tokens can be constrained to the Origin for which the challenge originated, or can be used across Origins.

Depending on the use case, Origins may need to maintain state to track redeemed tokens. For example, Origins that accept non-interactive, cross-origin tokens SHOULD track which tokens have been redeemed already, since these tokens can be issued and then spent multiple times in response to any such challenge. See [Section 6.1](#) for discussion.

Origins that admit cross-origin tokens bear some risk of allowing tokens issued for one Origin to be spent in an interaction with another Origin. If tokens protected with resources are unique to a single Origin, then said Origin MUST NOT admit cross-origin tokens for authorization.

[3.2.](#) Issuance Protocol

The issuance protocol embodies the core of Privacy Pass. It takes as input a challenge from the redemption protocol and produces a token, as shown in the figure below.



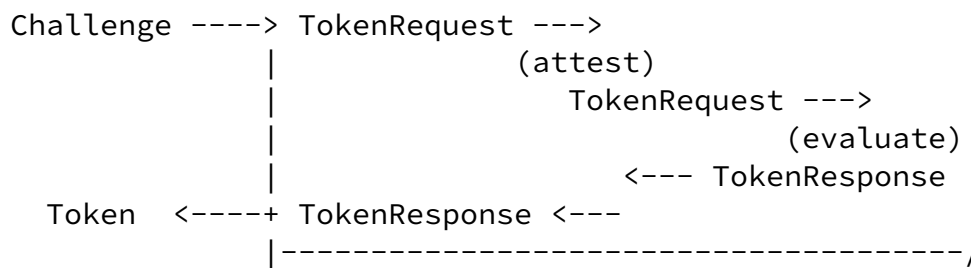


Figure 2: Issuance Overview

Clients interact with the Attester and Issuer to produce a token in response to a challenge. The context in which an Attester vouches for a Client during issuance is referred to as the attestation context. This context includes all information associated with the issuance event, such as the timestamp of the event and Client visible information, including the IP address or other information specific to the type of attestation done.

Each issuance protocol may be different, e.g., in the number and types of participants, underlying cryptographic constructions used when issuing tokens, and even privacy properties.

Clients initiate the Token issuance protocol using the challenge, a randomly generated nonce, and public key for the Issuer. The Token issuance protocol itself can be any interactive protocol between Client, Issuer, or other parties that produces a valid authenticator over the Client's input, subject to the following security requirements.

1. Unconditional input secrecy. The issuance protocol MUST NOT reveal anything about the Client's private input, including the challenge and nonce, to the Attester or Issuer. The issuance protocol can reveal the Issuer public key for the purposes of

determining which private key to use in producing the issuance protocol. A result of this property is that the redemption flow is unlinkable from the issuance flow.

2. One-more forgery security. The issuance protocol MUST NOT allow malicious Clients or Attesters (acting as Clients) to forge tokens without interacting with the Issuer directly.

3. Concurrent security. The issuance protocol MUST be safe to run concurrently with arbitrarily many Clients.

Each Issuance protocol MUST come with a detailed analysis of the privacy impacts of the protocol, why these impacts are justified, and guidelines on changes to the parametrization in [Section 7](#).

The mechanism by which clients obtain the Issuer public key is not specified. Clients may be configured with this key or they may discover it via some other form. See [[CONSISTENCY](#)].

Depending on the use case, issuance may require some form of Client anonymization service similar to an IP-hiding proxy so that Issuers cannot learn information about Clients. This can be provided by an explicit participant in the issuance protocol, or it can be provided via external means, e.g., through the use of an IP-hiding proxy service like Tor. In general, Clients SHOULD minimize or remove identifying information where possible when invoking the issuance protocol.

Issuers MUST NOT issue tokens for Clients through untrusted Attesters. This is important because the Attester's role is to vouch for trust in privacy-sensitive Client information, such as account identifiers or IP address information, to the Issuer. Tokens produced by an Issuer that admits issuance for any type of attestation cannot be relied on for any specific property. See [Section 3.2.1](#) for more details.

[3.2.1](#). Attester Role

Attestation is an important part of the issuance protocol. Attestation is the process by which an Attester bears witness to, confirms, or authenticates a Client so as to verify a property about the Client that is required for Issuance. Examples of attestation properties include, though are not limited to:

- * Capable of solving a CAPTCHA. Clients that solve CAPTCHA challenges can attest to this capability for the purposes of being ruled out as a bot or otherwise automated Client.

- * Client state. Clients can be associated with state and the

attester can attest to this state. Examples of state include the number of issuance protocol invocations, the client's geographic region, and whether the client has a valid application-layer account.

- * Trusted device. Some Clients run on trusted hardware that are capable of producing device-level attestation statements.

Each of these attestation types have different security properties. For example, attesting to having a valid account is different from attesting to be running on trusted hardware. In general, Attesters should accept a limited form of attestation formats.

Each attestation format also has an impact on the overall system privacy. For example, the number of users in possession of a single class of trusted device might be lesser than the number of users that can solve CAPTCHAs. Similarly, requiring a conjunction of attestation types could decrease the overall anonymity set size. For example, the number of Clients that have solved a CAPTCHA in the past day, have a valid account, and are running on a trusted device is lesser than the number of Clients that have solved a CAPTCHA in the past day. Attesters should not admit attestation types that result in small anonymity sets.

[3.2.2.](#) Issuer Role

Issuers MUST be uniquely identifiable by all Clients with a consistent identifier. In a web context, this identifier might be the Issuer host name. As discussed later in [Section 5](#), ecosystems that admit a large number of Issuers can lead to privacy concerns for the Clients in the ecosystem. Therefore, in practice, the number of Issuers should be bounded. The actual Issuers can be replaced with different Issuers as long as the total never exceeds these bounds. Moreover, Issuer replacements also have an effect on client anonymity that is similar to when a key rotation occurs. See [Section 5](#) for more details about maintaining privacy with multiple Issuers.

[3.2.2.1.](#) Key Management

To facilitate issuance, the Issuer MUST hold an Issuance key pair at any given time. The Issuer public key MUST be made available to all Clients in such a way that key rotations and other updates are publicly visible. The key material and protocol configuration that an Issuer uses to produce tokens corresponds to a number of different pieces of information.

- * The issuance protocol in use; and

- * The public keys that are active for the Issuer.

The way that the Issuer publishes and maintains this information impacts the effective privacy of the clients; see [Section 5](#) for more details. The fundamental requirement for key management and discovery is that Issuers must be unable to target specific clients with unique keys without detection. There are a number of ways in which this might be implemented:

- * Servers use a verifiable, tamper-free registry from which clients discover keys. Similar to related mechanisms and protocols such as Certificate Transparency [[RFC6962](#)], this may require external auditors or additional client behavior to ensure the registry state is consistent for all clients.
- * Clients use an anonymity-preserving tool such as Tor to discover keys from multiple network vantage points. This is done to ensure consistent keys to seemingly different clients.
- * Clients embed Issuer keys into software.

As above, specific mechanisms for key management and discovery are out of scope for this document.

[3.2.2.2](#). Key Rotation

Token issuance associates all issued tokens with a particular choice of key. If an Issuer issues tokens with many keys, then this may harm the anonymity of the Client. For example, they would be able to map the Client's access patterns by inspecting which key each token they possess has been issued under.

To prevent against this, Issuers MUST only use one private key for issuing tokens at any given time. Servers MAY use one or more keys for redemption to allow Issuers for seamless key rotation.

Servers may rotate keys as a means of revoking tokens issued under old or otherwise expired keys. Alternatively, Issuers may include expiration information as metadata alongside the token; See [Section 3.2.3](#) for more discussion about metadata constraints. Both techniques are equivalent since they cryptographically bind expiration to individual tokens.

Key rotations should be limited in frequency for similar reasons. See [Section 7](#) for guidelines on what frequency of key rotations are permitted.

[3.2.3.](#) Metadata

Certain instantiations of the issuance protocol may permit public or private metadata to be cryptographically bound to a token. As an example, one trivial way to include public metadata is to assign a unique issuer public key for each value of metadata, such that N keys yields $\log_2(N)$ bits of metadata. The total amount of metadata bits included in a token is the sum of public and private metadata bits. See [Section 7](#) for discussion about metadata limits.

Public metadata is that which clients can observe as part of the token issuance flow. Public metadata can either be transparent or opaque. For example, transparent public metadata is a value that the client either generates itself, or the Issuer provides during the issuance flow and the client can check for correctness. Opaque public metadata is metadata the client can see but cannot check for correctness. As an example, the opaque public metadata might be a "fraud detection signal", computed on behalf of the Issuer, during token issuance. In normal circumstances, clients cannot determine if this value is correct or otherwise a tracking vector.

Private metadata is that which clients cannot observe as part of the token issuance flow. Such instantiations may be built on the Private Metadata Bit construction from Kreuter et al. [[KLOR20](#)] or the attribute-based VOPRF from Huang et al. [[HIJK21](#)].

Metadata may also be arbitrarily long or bounded in length. The amount of permitted metadata may be determined by application or by the underlying cryptographic protocol.

[3.2.4.](#) Issuance Protocol Extensibility

The Privacy Pass protocol and ecosystem are both intended to be receptive to extensions that expand the current set of functionalities through new issuance protocols. Each issuance protocol SHOULD come with a detailed analysis of the privacy impacts of the extension, why these impacts are justified, and guidelines on changes to the parametrization in [Section 7](#). Any extension to the Privacy Pass protocol MUST adhere to the guidelines specified in

[4.](#) Deployment Considerations

Client uses Privacy Pass to separate attestation context and redemption context. Linking or combining these contexts can reveal sensitive information about the Client, including their identity or browsing history. Depending on the deployment model, separating these contexts can take different forms. The Origin, Attester, and Issuer portrayed in Figure 1 can be instantiated and deployed in a number of different ways. This section covers some expected deployment models and their corresponding security and privacy considerations. The discussion below assumes non-collusion between entities when operated by separate parties. Mechanisms for enforcing non-collusion are out of scope for this architecture.

[4.1.](#) Shared Origin, Attester, Issuer

In this model, the Origin, Attester, and Issuer are all operated by the same entity, as shown in the figure below.

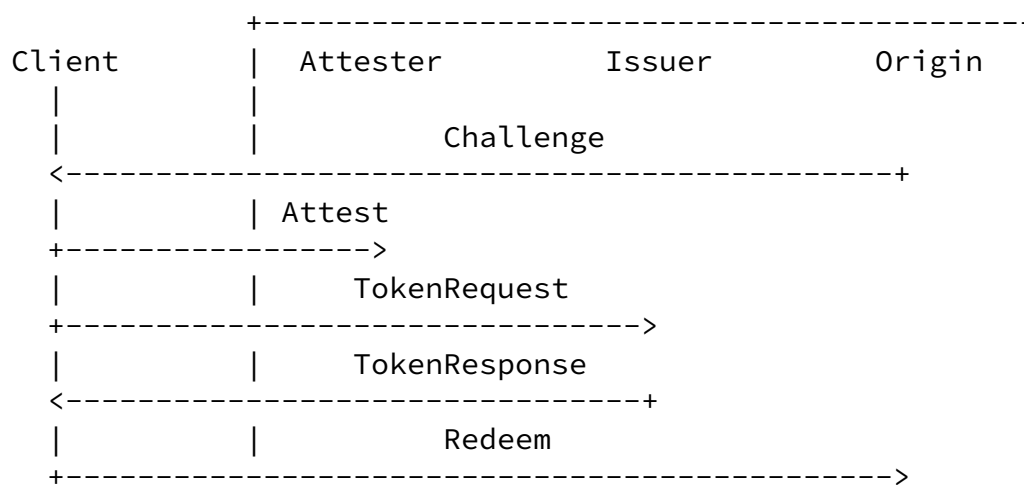


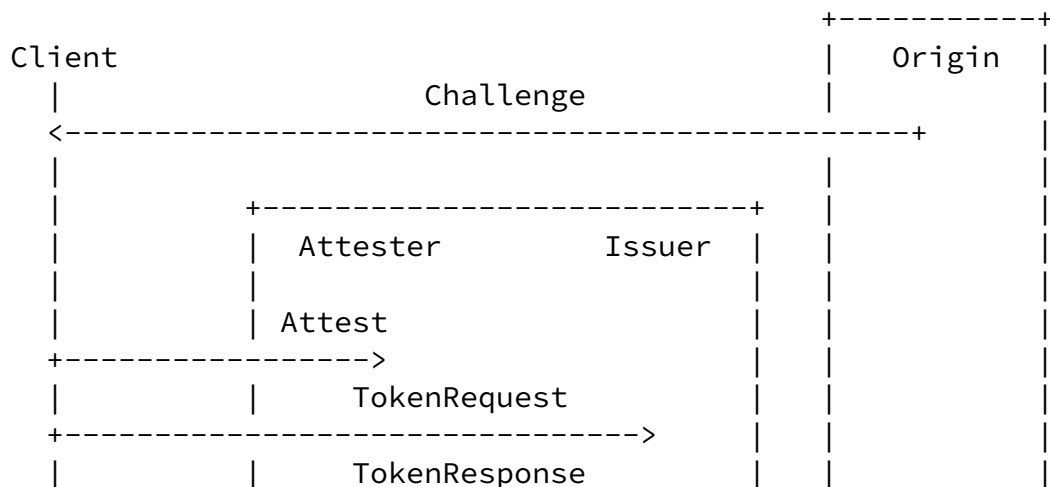
Figure 3: Shared Deployment Model

This model represents the initial deployment of Privacy Pass, as described in [PPSRV]. In this model, the Attester, Issuer, and Origin share the attestation and redemption contexts. As a result, attestation mechanisms that can uniquely identify a Client, e.g., requiring that Clients authenticate with some type of application-layer account, are not appropriate, as they could be used to learn or reconstruct a Client's browsing history.

Attestation and redemption context unlinkability requires that these events be separated over time, e.g., through the use of non-interactive tokens that can be issued without a fresh Origin challenge, or over space, e.g., through the use of an anonymizing proxy when connecting to the Origin.

[4.2.](#) Joint Attester and Issuer

In this model, the Attester and Issuer are operated by the same entity that is separate from the Origin, as shown in the figure below.



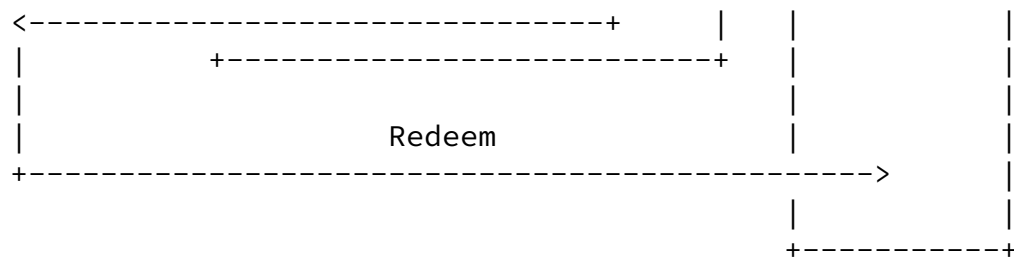


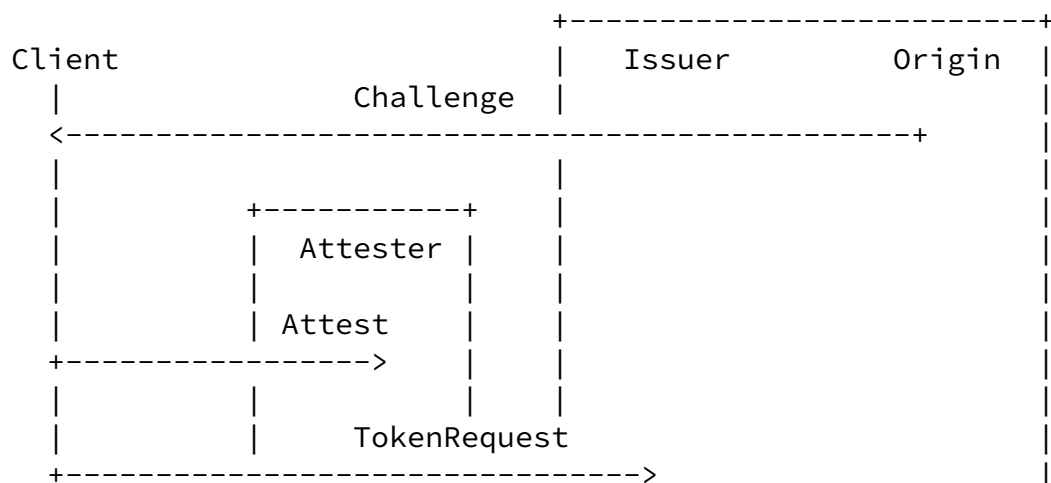
Figure 4: Joint Attester and Issuer Deployment Model

This model is useful if an Origin wants to offload attestation and issuance to a trusted entity. In this model, the Attester and Issuer share attestation context for the Client, which can be separate from the Origin's redemption context.

For certain types of issuance protocols, this model separates attestation and redemption contexts. However, Issuance protocols that require the Issuer to learn information about the Origin, such as that which is described in [rate-limited], are not appropriate since they could link attestation and redemption contexts through the Origin name.

[4.3.](#) Joint Origin and Issuer

In this model, the Origin and Issuer are operated by the same entity, separate from the Attester, as shown in the figure below.



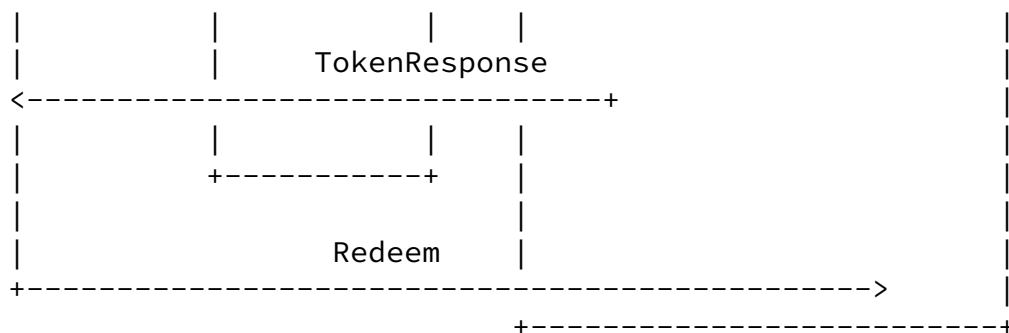


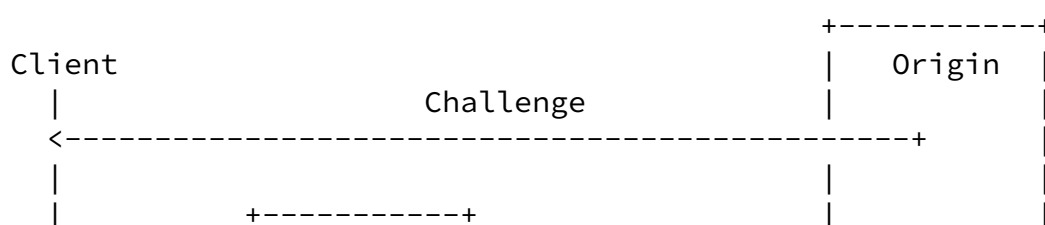
Figure 5: Joint Origin and Issuer Deployment Model

This model is useful for Origins that require Client-identifying attestation, e.g., through the use of application-layer account information, but do not otherwise want to learn information about individual Clients beyond what is observed during the token redemption, such as Client IP addresses.

In this model, attestation and redemption contexts are separate. As a result, any type of attestation is suitable in this model. Moreover, any type of token challenge is suitable assuming there is more than one Origin involved, since no single party will have access to the identifying Client information and unique Origin information. If there is only a single Origin, then per-Origin tokens are not appropriate in this model, since the Attester can learn the redemption context. (Note, however, that the Attester does not learn whether a token is per-Origin or cross-Origin.)

[4.4.](#) Split Origin, Attester, Issuer

In this model, the Origin, Attester, and Issuer are all operated by different entities, as shown in the figure below.



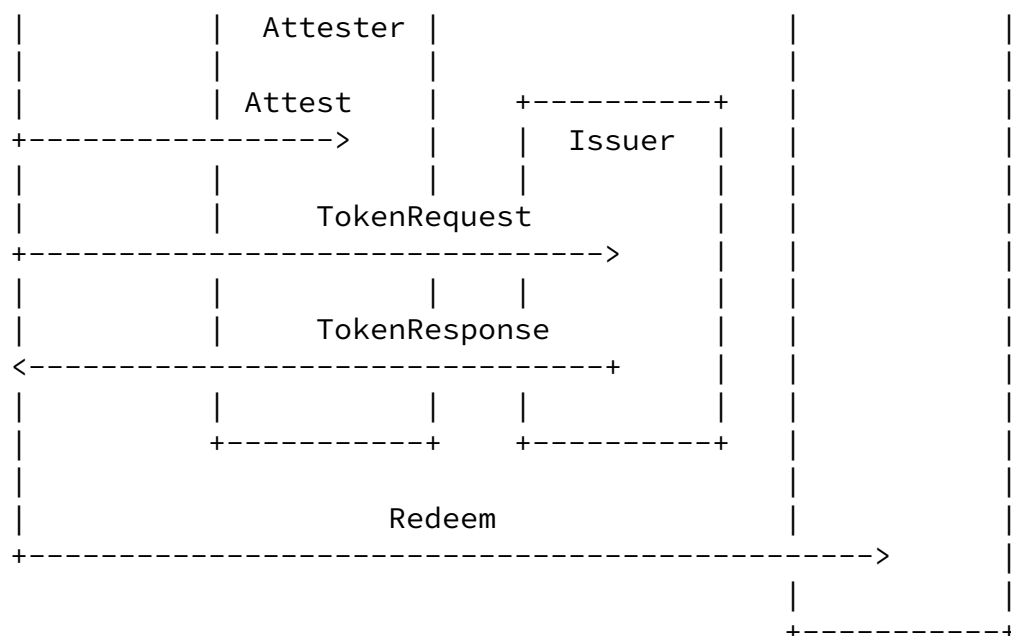


Figure 6: Split Deployment Model

This is the most general deployment model, and is necessary for some types of issuance protocols where the Attester plays a role in token issuance; see [rate-limited] for one such type of issuance protocol. In this model, the Attester, Issuer, and Origin have a separate view of the Client: the Attester sees potentially sensitive Client identifying information, such as account identifiers or IP addresses, the Issuer sees only the information necessary for Issuance, and the Origin sees token challenges, corresponding tokens, and Client source information, such as their IP address. As a result, attestation and redemption contexts are separate, and therefore any type of token challenge is suitable in this model assuming there is more than a single Origin. As in the Joint Origin and Issuer model in [Section 4.3](#), if there is only a single Origin, then per-Origin tokens are not appropriate.

5. Privacy Considerations

Client uses Private Pass to separate attestation context and redemption context. Depending on the deployment model, this can take

different forms. For example, any Client can only remain private relative to the entire space of other Clients using the protocol. Moreover, by owning tokens for a given set of keys, the Client's anonymity set shrinks to the total number of clients controlling tokens for the same keys.

In the following, we consider the possible ways that Issuers can leverage their position to try and reduce the anonymity sets that Clients belong to (or, user segregation). For each case, we provide mitigations that the Privacy Pass ecosystem must implement to prevent these actions.

[5.1.](#) Metadata Privacy Implications

Any metadata bits of information can be used to further segment the size of the Client's anonymity set. Any Issuer that wanted to track a single Client could add a single metadata bit to Client tokens. For the tracked Client it would set the bit to 1, and 0 otherwise. Adding additional bits provides an exponential increase in tracking granularity similarly to introducing more Issuers (though with more potential targeting).

For this reason, the amount of metadata used by an Issuer in creating redemption tokens must be taken into account -- together with the bits of information that Issuer's may learn about Clients otherwise. Since this metadata may be useful for practical deployments of Privacy Pass, Issuers must balance this against the reduction in Client privacy. In general, Issuers should permit no more than 32 bits of metadata, as this can uniquely identify each possible user. We discuss this more in [Section 7](#).

[5.2.](#) Issuer Key Rotation

Techniques to introduce Client "segregation" can be used to reduce Client anonymity. Such techniques are closely linked to the type of key schedule that is used by the Issuer. When an Issuer rotates their key, any Client that invokes the issuance protocol in this key cycle will be part of a group of possible clients owning valid tokens for this key. To mechanize this attack strategy, an Issuer could introduce a key rotation policy that forces Clients into small key cycles. Thus, reducing the size of the anonymity set for these Clients.

Issuers SHOULD invoke key rotation for a period of time between 1 and 12 weeks. Key rotations represent a trade-off between Client privacy and continued Issuer security. Therefore, it is still important that key rotations occur on a regular cycle to reduce the harmfulness of an Issuer key compromise.

With a large number of Clients, a minimum of one week gives a large enough window for Clients to participate in the issuance protocol and thus enjoy the anonymity guarantees of being part of a larger group. A maximum of 12 weeks limits the damage caused by a key compromise. If an Issuer realizes that a key compromise has occurred then the Issuer should generate a new key and make it available to Clients. If possible, it should invoke any revocation procedures that may apply for the old key.

[5.3.](#) Large Number of Issuers

Similarly to the Issuer rotation dynamic that is raised above, if there are a large number of Issuers, and Origins accept all of them, segregation can occur. For example, if Clients obtain tokens from many Issuers, and Origins later challenge a Client for a token from each Issuer, Origins can learn information about the Client. Each per-Issuer token that a Client holds essentially corresponds to a bit of information about the Client that Origin learn. Therefore, there is an exponential loss in anonymity relative to the number of Issuers that there are.

For example, if there are 32 Issuers, then Origins learn 32 bits of information about the Client if a valid token is presented for each one. If the distribution of Issuer trust is anything close to a uniform distribution, then this is likely to uniquely identify any Client amongst all other Internet users. Assuming a uniform distribution is clearly the worst-case scenario, and unlikely to be accurate, but it provides a stark warning against allowing too many Issuers at any one time.

In cases where clients can hold tokens for all Issuers at any given time, a strict bound SHOULD be applied to the active number of Issuers in the ecosystem. We propose that allowing no more than 4 Issuers at any one time is highly preferable (leading to a maximum of 64 possible user segregations). However, as highlighted in [Section 7](#), having a very large user base (> 5 million users), could potentially allow for larger values. Issuer replacements should only occur with the same frequency as config rotations as they can lead to similar losses in anonymity if clients still hold redemption tokens for previously active Issuers.

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In addition, we RECOMMEND that trusted registries indicate at all times which Issuers are deemed to be active. If a Client is asked to invoke any Privacy Pass exchange for an Issuer that is not declared active, then the client SHOULD refuse to retrieve the Issuer public key during the protocol.

[5.3.1.](#) Allowing More Issuers

The bounds on the numbers of Issuers that this document proposes above are very restrictive. This is because this document considers a situation where a Client could be challenged (and asked to redeem) tokens for any Issuer.

An alternative system is to ensure a robust strategy for ensuring that Clients only possess redemption tokens for a similarly small number of Issuers at any one time. This prevents a malicious verifier from being able to invoke redemptions for many Issuers since the Client would only be holding redemption tokens for a small set of Issuers. When a Client is issued tokens from a new Issuer and already has tokens from the maximum number of Issuers, it simply deletes the oldest set of redemption tokens in storage and then stores the newly acquired tokens.

For example, if Clients ensure that they only hold redemption tokens for 4 Issuers, then this increases the potential size of the anonymity sets that the Client belongs to. However, this doesn't protect Clients completely as it would if only 4 Issuers were permitted across the whole system. For example, these 4 Issuers could be different for each Client. Therefore, the selection of Issuers they possess tokens for is still revealing. Understanding this trade-off is important in deciding the effective anonymity of each Client in the system.

[5.3.1.1.](#) Redemption Partitions

Another option to allow a large number of Issuers in the ecosystem, while preventing the joining of a number of different tokens is for the Client to maintain sharded "redemption partitions". This would allow the Client to redeem the tokens it wishes to use in a particular context, while still allowing the Client to maintain a

large variety of tokens from many Issuers. Within a redemption partition, the Client limits the number of different Issuers used to a small number to maintain the privacy properties the Client requires. As long as each redemption partition maintains a strong privacy boundary with each other, the verifier will only be able to learn a number of bits of information up to the limits within that "redemption partitions".

To support this strategy, the client keeps track of a partition which contains the set of Issuers that redemptions have been attempted against. An empty redemption is returned when the limit has been hit:

```

Client(partition, issuer)                                Issuer(skS, pkS)
-----
if issuer not in partition {
    if partition.length > REDEEM_LIMIT {
        Output {}
        return
    }
    partition.push(issuer)
}
token = store[issuer.id].pop()
req = Redeem(token, info)

                                req
                                ----->

                                if (dsIdx.includes(req.data)) {
                                    raise ERR_DOUBLE_SPEND
                                }
                                resp = Verify(pkS, skS, req)
                                if resp.success {
                                    dsIdx.push(req.data)
                                }

                                resp
                                <-----
Output resp

```

6. Security Considerations

We present a number of security considerations that prevent malicious Clients from abusing the protocol.

[6.1.](#) Double-spend Protection

When applicable for non-interactive tokens, all Origins SHOULD implement a robust storage-query mechanism for checking that tokens sent by clients have not been spent before. Such tokens only need to be checked for each Origin individually. But all Origins must perform global double-spend checks to avoid clients from exploiting the possibility of spending tokens more than once against distributed token checking systems. For the same reason, the global data storage must have quick update times. While an update is occurring it may be possible for a malicious client to spend a token more than once.

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[6.2.](#) Token Exhaustion

When a Client holds tokens for an Issuer, it is possible for any verifier to invoke that client to redeem tokens for that Issuer. This can lead to an attack where a malicious verifier can force a Client to spend all of their tokens from a given Issuer. To prevent this from happening, tokens can be scoped to single Origins such that they can only be redeemed within for a single Origin.

If tokens are cross-Origin, Clients should use alternate methods to prevent many tokens from being redeemed at once. For example, if the Origin requests an excess of tokens, the Client could choose to not present any tokens for verification if a redemption had already occurred in a given time window.

[7.](#) Protocol Parameterization

This section provides a summary of the parameters used in the Privacy Pass protocol ecosystem. These parameters are informed by both privacy and security considerations that are highlighted in [Section 5](#) and [Section 6](#), respectively. These parameters are intended as a single reference point for those implementing the protocol.

Firstly, let U be the total number of Clients (or users), I be the total number of Issuers. We let M be the total number of metadata bits that are allowed to be added by any given Issuer. Assuming that

each user accept tokens from a uniform sampling of all the possible Issuers, as a worst-case analysis, this segregates Clients into a total of 2^I buckets. As such, we see an exponential reduction in the size of the anonymity set for any given user. This allows us to specify the privacy constraints of the protocol below, relative to the setting of A .

parameter	value
Minimum anonymity set size (A)	5000
Recommended key lifetime (L)	2 - 24 weeks
Recommended key rotation frequency (F)	$L/2$
Maximum additional metadata bits (M)	1
Maximum allowed Issuers (I)	$(\log_2(U/A)-1)/2$
Maximum active issuance keys	1
Maximum active redemption keys	2
Minimum cryptographic security parameter	128 bits

Table 1

[7.1.](#) Justification

We make the following assumptions in these parameter choices.

- * Inferring the identity of a user in a 5000-strong anonymity set is difficult.
- * After 2 weeks, all Clients in a system will have rotated to the new key.

In terms of additional metadata, the only concrete applications of Privacy Pass that use additional metadata require just a single bit. Therefore, we set the ceiling of permitted metadata to 1 bit for now, this may be revisited in future revisions.

The maximum choice of I is based on the equation $1/2 * U/2^{(2I)} = A$. This is derived from the fact that permitting I Issuers lead to 2^I segregations of the total user-base U . Moreover, if we permit $M = 1$, then this effectively halves the anonymity set for each Issuer, and thus we incur a factor of $2I$ in the exponent. By reducing I , we limit the possibility of performing the attacks mentioned in [Section 5](#).

We must also account for each user holding issued data for more than one possible active keys. While this may also be a vector for monitoring the access patterns of Clients, it is likely to

unavoidable that Clients hold valid issuance data for the previous key epoch. This also means that the Issuer can continue to verify redemption data for a previously used key. This makes the rotation period much smoother for Clients.

For privacy reasons, it is recommended that key epochs are chosen that limit Clients to holding issuance data for a maximum of two keys. By choosing $F = L/2$ then the minimum value of F is a week, since the minimum recommended value of L is 2 weeks. Therefore, by the initial assumption, then all users should only have access to only two keys at any given time. This reduces the anonymity set by another half at most.

Finally, the minimum security parameter size is related to the cryptographic security offered by the protocol that is run. This parameter corresponds to the number of operations that any adversary has in breaking one of the security guarantees in the Privacy Pass protocol [[I-D.ietf-privacypass-protocol](#)].

[7.2.](#) Example parameterization

Using the specification above, we can give some example parameterizations. For example, the current Privacy Pass browser extension [[PPEXT](#)] has nearly 300000 active users (from Chrome and Firefox). As a result, $\log_2(U/A)$ is approximately 6 and so the maximum value of I should be 3.

If the value of U is much bigger (e.g. 5 million) then this would permit $I = (\log_2(5000000/5000)-1)/2 \approx 4$ Issuers.

[7.3.](#) Allowing more Issuers

Using the recommendations in [Section 5.3.1](#), it is possible to tolerate larger number of Issuers if Clients in the ecosystem ensure that they only store tokens for a small number of them. In particular, if Clients limit their storage of redemption tokens to the bound implied by I , then prevents a malicious verifier from triggering redemptions for all Issuers in the ecosystem.

[8.](#) References

[8.1.](#) Normative References

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[Appendix A](#). Acknowledgements

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