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Randomness Improvements for Security Protocols
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Abstract

Randomness is a crucial ingredient for TLS and related security protocols. Weak or predictable "cryptographically-strong" pseudorandom number generators (CSPRNGs) can be abused or exploited for malicious purposes. The Dual EC random number backdoor and Debian bugs are relevant examples of this problem. An initial entropy source that seeds a CSPRNG might be weak or broken as well, which can also lead to critical and systemic security problems. This document describes a way for security protocol participants to augment their CSPRNGs using long-term private keys. This improves randomness from broken or otherwise subverted CSPRNGs.

Table of Contents

1. Introduction 2
2. Randomness Wrapper 3
3. Tag Generation 5
4. Application to TLS 5
5. Acknowledgements 5
6. IANA Considerations 6
7. Security Considerations 6
8. Comparison to RFC 6979 7
9. Normative References 7
Authors' Addresses 8

1. Introduction

Randomness is a crucial ingredient for TLS and related transport security protocols. TLS in particular uses random number generators (generally speaking, CSPRNGs) to generate several values: session IDs, ephemeral key shares, and ClientHello and ServerHello random values. CSPRNG failures such as the Debian bug described in [DebianBug] can lead to insecure TLS connections. CSPRNGs may also be intentionally weakened to cause harm [DualEC]. Initial entropy sources can also be weak or broken, and that would lead to insecurity of all CSPRNG instances seeded with them. In such cases where CSPRNGs are poorly implemented or insecure, an adversary may be able to predict its output and recover secret Diffie-Hellman key shares that protect the connection.

This document proposes an improvement to randomness generation in security protocols inspired by the "NAXOS trick" [NAXOS]. Specifically, instead of using raw randomness where needed, e.g., in generating ephemeral key shares, a party's long-term private key is mixed into the entropy pool. In the NAXOS key exchange protocol, raw

random value x is replaced by H(x, sk), where sk is the sender's private key. Unfortunately, as private keys are often isolated in HSMs, direct access to compute H(x, sk) is impossible. An alternate yet functionally equivalent construction is needed.

The approach described herein replaces the NAXOS hash with a keyed hash, or pseudorandom function (PRF), where the key is derived from a raw random value and a private key signature. Implementations SHOULD apply this technique when indirect access to a private key is available and CSPRNG randomness guarantees are dubious, or to provide stronger guarantees about possible future issues with the randomness. Roughly, the security properties provided by the proposed construction are as follows:

1. If the CSPRNG works fine, that is, in a certain adversary model the CSPRNG output is indistinguishable from a truly random sequence, then the output of the proposed construction is also indistinguishable from a truly random sequence in that adversary model.

2. An adversary Adv with full control of a (potentially broken) CSPRNG and able to observe all outputs of the proposed construction, does not obtain any non-negligible advantage in leaking the private key, modulo side channel attacks.

3. If the CSPRNG is broken or controlled by adversary Adv, the output of the proposed construction remains indistinguishable from random provided the private key remains unknown to Adv.

2. Randomness Wrapper

Let x be the output of a CSPRNG. When properly instantiated, x should be indistinguishable from a random string of x bytes. However, as previously discussed, this is not always true. To mitigate this problem, we propose an approach for wrapping the CSPRNG output with a construction that mixes secret data into a value that may be lacking randomness.

Let G(n) be an algorithm that generates n random bytes, i.e., the output of a CSPRNG. Define an augmented CSPRNG G' as follows. Let Sig(sk, m) be a function that computes a signature of message m given private key sk. Let H be a cryptographic hash function that produces output of length M. Let Extract(salt, IKM) be a randomness extraction function, e.g., HKDF-Extract [RFC5869], which accepts a salt and input keying material (IKM) parameter and produces a pseudorandom key of length L suitable for cryptographic use. Let Expand(k, info, n) be a variable-length output PRF, e.g., HKDF-Expand [RFC5869], that takes as input a pseudorandom key k of length L, info

string, and output length n, and produces output of n bytes. Finally, let tag1 be a fixed, context-dependent string, and let tag2 be a dynamically changing string.

The construction works as follows. Instead of using G(n) when randomness is needed, use G'(n), where

G'(n) = Expand(Extract(H(Sig(sk, tag1)), G(L)), tag2, n)

Functionally, this expands n random bytes from a key derived from the CSPRNG output and signature over a fixed string (tag1). See Section 3 for details about how "tag1" and "tag2" should be generated and used per invocation of the randomness wrapper. Expand() generates a string that is computationally indistinguishable from a truly random string of n bytes. Thus, the security of this construction depends upon the secrecy of H(Sig(sk, tag1)) and G(L). If the signature is leaked, then security of G'(n) reduces to the scenario wherein randomness is expanded directly from G(L).

If a private key sk is stored and used inside an HSM, then the signature calculation is implemented inside it, while all other operations (including calculation of a hash function, Extract and Expand functions) can be implemented either inside or outside the HSM.

Sig(sk, tag1) should only be computed once for the lifetime of the randomness wrapper, and MUST NOT be used or exposed beyond its role in this computation. To achieve this, tag1 may have the format that is not supported (or explicitly forbidden) by other applications using sk.

Sig MUST be a deterministic signature function, e.g., deterministic ECDSA [RFC6979], or use an independent (and completely reliable) entropy source, e.g., if Sig is implemented in an HSM with its own internal trusted entropy source for signature generation.

In systems where signature computations are expensive, Sig(sk, tag1) may be cached. In that case the relative cost of using G'(n) instead of G(n) tends to be negligible with respect to cryptographic operations in protocols such as TLS. A description of the performance experiments and their results can be found in the appendix of [SecAnalysis].

Moreover, the values of G'(n) may be precomputed and pooled. This is possible since the construction depends solely upon the CSPRNG output and private key.

3. Tag Generation

Both tags SHOULD be generated such that they never collide with another contender or owner of the private key. This can happen if, for example, one HSM with a private key is used from several servers, or if virtual machines are cloned.

To mitigate collisions, tag strings SHOULD be constructed as follows:

- tag1: Constant string bound to a specific device and protocol in use. This allows caching of Sig(sk, tag1). Device specific information may include, for example, a MAC address. To provide security in the cases of usage of CSPRNGs in virtual environments, it is RECOMMENDED to incorporate all available information specific to the process that would ensure the uniqueness of each tag1 value among different instances of virtual machines (including ones that were cloned or recovered from snapshots). It is needed to address the problem of CSPRNG state cloning (see [RY2010]). See Section 4 for example protocol information that can be used in the context of TLS 1.3.

- tag2: Non-constant string that includes a timestamp or counter. This ensures change over time even if outputs of G(L) were to repeat. It MUST be implemented such that its values never repeat. This means, in particular, that timestamp is guaranteed to change between two requests to CSPRNG (otherwise counters should be used).

4. Application to TLS

The PRF randomness wrapper can be applied to any protocol wherein a party has a long-term private key and also generates randomness. This is true of most TLS servers. Thus, to apply this construction to TLS, one simply replaces the "private" CSPRNG G(n), i.e., the CSPRNG that generates private values, such as key shares, with:

G'(n) = HKDF-Expand(HKDF-Extract(H(Sig(sk, tag1)), G(L)), tag2, n)

Moreover, we fix tag1 to protocol-specific information such as "TLS 1.3 Additional Entropy" for TLS 1.3. Older variants use similarly constructed strings.

5. Acknowledgements

We thank Liliya Akhmetzyanova for her deep involvement in the security assessment in [SecAnalysis].

6. IANA Considerations

This document makes no request to IANA.

7. Security Considerations

A security analysis was performed in [SecAnalysis]. Generally speaking, the following security theorem has been proven: if the adversary learns only one of the signature or the usual randomness generated on one particular instance, then under the security assumptions on our primitives, the wrapper construction should output randomness that is indistinguishable from a random string.

The main reason one might expect the signature to be exposed is via a side-channel attack. It is therefore prudent when implementing this construction to take into consideration the extra long-term key operation if equipment is used in a hostile environment when such considerations are necessary. Hence, it is recommended to generate a key specifically for the purposes of the defined construction and not to use it another way.

The signature in the construction as well as in the protocol itself MUST NOT use randomness from entropy sources with dubious security guarantees. Thus, the signature scheme MUST either use a reliable entropy source (independent from the CSPRNG that is being improved with the proposed construction) or be deterministic: if the signatures are probabilistic and use weak entropy, our construction does not help and the signatures are still vulnerable due to repeat randomness attacks. In such an attack, the adversary might be able to recover the long-term key used in the signature.

Under these conditions, applying this construction should never yield worse security guarantees than not applying it assuming that applying the PRF does not reduce entropy. We believe there is always merit in analyzing protocols specifically. However, this construction is generic so the analyses of many protocols will still hold even if this proposed construction is incorporated.

The proposed construction cannot provide any guarantees of security if the CSPRNG state is cloned due to the virtual machine snapshots or process forking (see [MAFS2017]). Thus tag1 SHOULD incorporate all available information about the environment, such as process attributes, virtual machine user information, etc.

8. Comparison to RFC 6979

The construction proposed herein has similarities with that of RFC 6979 [RFC6979]: both of them use private keys to seed a DRBG. Section 3.3 of RFC 6979 recommends deterministically instantiating an instance of the HMAC DRBG pseudorandom number generator, described in [SP80090A] and Annex D of [X962], using the private key sk as the entropy_input parameter and H(m) as the nonce. The construction G'(n) provided herein is similar, with such difference that a key derived from G(n) and H(Sig(sk, tag1)) is used as the entropy input and tag2 is the nonce.

However, the semantics and the security properties obtained by using these two constructions are different. The proposed construction aims to improve CSPRNG usage such that certain trusted randomness would remain even if the CSPRNG is completely broken. Using a signature scheme which requires entropy sources according to RFC 6979 is intended for different purposes and does not assume possession of any entropy source - even an unstable one. For example, if in a certain system all private key operations are performed within an HSM, then the differences will manifest as follows: the HMAC DRBG construction of RFC 6979 may be implemented inside the HSM for the sake of signature generation, while the proposed construction would assume calling the signature implemented in the HSM.

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