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AES-GCM-SIV: Nonce Misuse-Resistant Authenticated Encryption
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Abstract

This memo specifies two authenticated encryption algorithms that are nonce misuse-resistant - that is that they do not fail catastrophically if a nonce is repeated.

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1. Introduction

The concept of "Authenticated encryption with additional data" (AEAD [RFC5116]) couples confidentiality and integrity in a single operation that is easier to use correctly. The most popular AEAD, AES-GCM [GCM], is seeing widespread use due to its attractive performance.

However, most AEADs suffer catastrophic failures of confidentiality and/or integrity when two distinct messages are encrypted with the same nonce. While the requirements for AEADs specify that the pair of (key, nonce) shall only ever be used once, and thus prohibit this, in practice this is a worry.

Nonce misuse-resistant AEADs do not suffer from this problem. For this class of AEADs, encrypting two messages with the same nonce only discloses whether the messages were equal or not. This is the minimum amount of information that a deterministic algorithm can leak in this situation.

This memo specifies two nonce misuse-resistant AEADs: "AEAD_AES_128_GCM_SIV" and "AEAD_AES_256_GCM_SIV". These AEADs are designed to be able to take advantage of existing hardware support for AES-GCM and can decrypt within 5% of the speed of AES-GCM (for multi-kilobyte messages). Encryption is, perforce, slower than AES-GCM because two passes are required. However, measurements suggest that it can still run at 2/3rds of the speed of AES-GCM.

We suggest that these AEADs be considered in any situation where nonce uniqueness cannot be guaranteed. This includes situations where there is no stateful counter or where such state cannot be guaranteed, as when multiple encryptors use the same key. As discussed in Section 9, it is RECOMMENDED to use this scheme with randomly chosen nonces.

2. Requirements Language

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL", "SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in RFC 2119 [RFC2119].

3. POLYVAL

The GCM-SIV construction is similar to GCM: the block cipher is used in counter mode to encrypt the plaintext and a polynomial authenticator is used to provide integrity. The authenticator in GCM-SIV is called POLYVAL.

POLYVAL, like GHASH, operates in a binary field of size 2^128. The field is defined by the irreducible polynomial x^128 + x^127 + x^126 + x^121 + 1. The sum of any two elements in the field is the result of XORing them. The product of any two elements is calculated using standard (binary) polynomial multiplication followed by reduction modulo the irreducible polynomial.

We define another binary operation on elements of the field: dot(a, b), where dot(a, b) = a * b * x^-128. The value of the field element x^-128 is equal to x^127 + x^124 + x^121 + x^114 + 1. The result, dot(a, b), of this multiplication is another field element.

Polynomials in this field are converted to and from 128-bit strings by taking the least-significant bit of the first byte to be the coefficient of x^0, the most-significant bit of the first byte to the coefficient of x^7 and so on, until the most-significant bit of the last byte is the coefficient of x^127.

POLYVAL takes a field element, H, and a series of field elements X_1, ..., X_s. Its result is S_s, where S is defined by the iteration S_0 = 0; S_j = dot(S_{j-1} + X_j, H), for j = 0..s

We note that POLYVAL(H, X_1, X_2, ...) is equal to ByteReverse(GHASH(ByteReverse(H) * x, ByteReverse(X_1), ByteReverse(X_2), ...)), where ByteReverse is a function that reverses the order of 16 bytes. See Appendix A for a more detailed explanation.

4. Encryption

AES-GCM-SIV encryption takes a 16- or 32-byte key-generating key, a 96-bit nonce, and variable-length plaintext & additional data byte-strings. It outputs an authenticated ciphertext that will be 16 bytes longer than the plaintext. Both encryption and decryption are only defined on inputs that are a whole number of bytes.

If the key-generating key is 16 bytes long then AES-128 is used throughout. Otherwise AES-256 is used throughout.

The first step of encryption is to generate per-nonce, record-authentication and record-encryption keys. The record-authentication key is 128-bit and the record-encryption key is either 128- (for AES-128) or 256-bit (for AES-256).

These keys are generated by encrypting a series of plaintext blocks that contain a 32-bit, little-endian counter followed by the nonce, and then discarding the second half of the resulting ciphertext. In the AES-128 case, 128 + 128 = 256 bits of key material need to be generated and, since encrypting each block yields 64 bits after discarding half, four blocks need to be encrypted. The counter values for these blocks are 0, 1, 2 and 3. For AES-256, six blocks are needed in total, with counter values 0 through 5 (inclusive).

In pseudocode form, where ++ indicates concatenation and x[:8] indicates taking only the first eight bytes from x:

```
   func derive_keys(key_generating_key, nonce) {
     record_authentication_key =
         AES(key = key_generating_key,
             block = little_endian_uint32(0) ++ nonce)[:8] ++
         AES(key = key_generating_key,
             block = little_endian_uint32(1) ++ nonce)[:8]
     record_encryption_key =
         AES(key = key_generating_key,
             block = little_endian_uint32(2) ++ nonce)[:8] ++
         AES(key = key_generating_key,
             block = little_endian_uint32(3) ++ nonce)[:8]

     if bytelen(key_generating_key) == 32 {
       record_encryption_key ++=
           AES(key = key_generating_key,
               block = little_endian_uint32(4) ++ nonce)[:8] ++
           AES(key = key_generating_key,
               block = little_endian_uint32(5) ++ nonce)[:8]
     }

     return record_authentication_key, record_encryption_key
   }
```

Define the "length block" as a 16-byte value that is the concatenation of the 64-bit, little-endian encodings of bytelen(additional_data) * 8 and bytelen(plaintext) * 8. Pad the plaintext and additional data with zeros until they are each a multiple of 16 bytes, the AES block size. Then X_1, X_2, ... (the series of field elements that are inputs to POLYVAL) are the concatenation of the padded additional data, the padded plaintext and the length block.

Calculate S_s = POLYVAL(record-authentication-key, X_1, X_2, ...). XOR the first twelve bytes of S_s with the nonce and clear the most-significant bit of the last byte. Encrypt the result with AES using the record-encryption key to produce the tag.

The encrypted plaintext is produced by using AES, with the record-encryption key, in counter mode on the unpadded plaintext. The initial counter block is the tag with the most-significant bit of the last byte set to one. The counter advances by incrementing the first 32 bits interpreted as an unsigned, little-endian integer, with overflow. The result of the encryption is the encrypted plaintext (truncated to the length of the plaintext) followed by the tag.

In pseudo-code form, the encryption process can be expressed as:

```
   func right_pad_to_multiple_of_16_bytes(input) {
```

```
    while (bytelen(input) % 16 != 0) {
      input = input ++ "\x00"
    }
    return input
  }

  func AES_CTR(key, initial_counter_block, in) {
    block = initial_counter_block

    output = ""
    while bytelen(in) > 0 {
      keystream_block = AES(key = key, block = block)
      block[0:4] = little_endian_uint32(
          read_little_endian_uint32(block[0:4]) + 1)

      todo = min(bytelen(in), bytelen(keystream_block)
      for j = 0; j < todo; j++ {
        output = output ++ (keystream_block[j] ^ in[j])
      }

      in = in[todo:]
    }

    return output
  }

  func encrypt(key_generating_key,
               nonce,
               plaintext,
               additional_data) {
    if bytelen(plaintext) > 2**36 {
      fail()
    }
    if bytelen(additional_data) > 2**36 {
      fail()
    }

    record_encryption_key, record_authentication_key =
        derive_keys(key_generating_key, nonce)

    length_block =
        little_endian_uint64(bytelen(additional_data) * 8) ++
        little_endian_uint64(bytelen(plaintext) * 8)
    padded_plaintext = right_pad_to_multiple_of_16_bytes(plaintext)
    padded_ad = right_pad_to_multiple_of_16_bytes(additional_data)
    S_s = POLYVAL(key = record_authentication_key,
                  input = padded_ad ++ padded_plaintext ++
                          length_block)
```

```
    for i = 0; i < 12; i++ {
      S_s[i] ^= nonce[i]
    }
    S_s[15] &= 0x7f
    tag = AES(key = record_encryption_key, block = S_s)

    counter_block = tag
    counter_block[15] |= 0x80
    return AES_CTR(key = record_encryption_key,
                   initial_counter_block = counter_block,
                   in = plaintext) ++
           tag
  }
```

5. Decryption

Decryption takes a 16- or 32-byte key-generating key, a 96-bit nonce, and variable-length ciphertext & additional data byte-strings. It either fails, or outputs a plaintext that is 16 bytes shorter than the ciphertext.

Firstly, the record-encryption and record-authentication keys are derived in the same manner as when encrypting.

If the ciphertext is less than 16 bytes or more than 2^36 + 16 bytes, then fail. Otherwise split the input into the encrypted plaintext and a 16-byte tag. Decrypt the encrypted plaintext with the record-encryption key in counter mode, where the initial counter block is the tag with the most-significant bit of the last byte set to one. The counter advances in the same way as for encryption.

Pad the additional data and plaintext with zeros until they are each a multiple of 16 bytes, the AES block size. Calculate the length block and X_1, X_2, ... as above and compute S_s = POLYVAL(record-authentication-key, X_1, X_2, ...). Compute the expected tag by XORing S_s and the nonce, clearing the most-significant bit of the last byte and encrypting with the record-encryption key. Compare the provided and expected tag values in constant time. If they do not match, fail. Otherwise return the plaintext.

In pseudo-code form, the decryption process can be expressed as:

```
   func decrypt(key_generating_key,
                nonce,
                ciphertext,
                additional_data) {
     if bytelen(ciphertext) < 16 || bytelen(ciphertext) > 2**36 + 16 {
       fail()
     }
     if bytelen(additional_data) > 2**36 {
       fail()
     }

     record_encryption_key, record_authentication_key =
         derive_keys(key_generating_key, nonce)

     tag = ciphertext[bytelen(ciphertext)-16:]

     counter_block = tag
     counter_block[15] |= 0x80
     plaintext = AES_CTR(key = record_encryption_key,
                         initial_counter_block = counter_block,
                         in = ciphertext[:bytelen(ciphertext)-16])

     length_block =
         little_endian_uint64(bytelen(additional_data) * 8) ++
         little_endian_uint64(bytelen(plaintext) * 8)
     padded_plaintext = right_pad_to_multiple_of_16_bytes(plaintext)
     padded_ad = right_pad_to_multiple_of_16_bytes(additional_data)
     S_s = POLYVAL(key = record_authentication_key,
                   input = padded_ad ++ padded_plaintext ++
                           length_block)
     for i = 0; i < 12; i++ {
       S_s[i] ^= nonce[i]
     }
     S_s[15] &= 0x7f
     expected_tag = AES(key = record_encryption_key, block = S_s)

     xor_sum = 0
     for i := 0; i < bytelen(expected_tag); i++ {
       xor_sum |= expected_tag[i] ^ tag[i]
     }

     if xor_sum != 0 {
       fail()
     }

     return plaintext
   }
```

6. AEADs

We define two AEADs, in the format of RFC 5116, that use AES-GCM-SIV: AEAD_AES_128_GCM_SIV and AEAD_AES_256_GCM_SIV. They differ only in the size of the AES key used.

The key input to these AEADs becomes the key-generating key. Thus AEAD_AES_128_GCM_SIV takes a 16-byte key and AEAD_AES_256_GCM_SIV takes a 32-byte key.

The parameters for AEAD_AES_128_GCM_SIV are then: K_LEN is 16, P_MAX is 2^36, A_MAX is 2^36, N_MIN and N_MAX are 12 and C_MAX is 2^36 + 16.

The parameters for AEAD_AES_256_GCM_SIV differ only in the key size: K_LEN is 32, P_MAX is 2^36, A_MAX is 2^36, N_MIN and N_MAX are 12 and C_MAX is 2^36 + 16.

7. Field operation examples

Polynomials in this document will be written as 16-byte values. For example, the sixteen bytes 01000000000000000000000000000492 would represent the polynomial x^127 + x^124 + x^121 + x^114 + 1, which is also the value of x^-128 in this field.

If a = 66e94bd4ef8a2c3b884cfa59ca342b2e and b = ff000000000000000000000000000000 then a + b = 99e94bd4ef8a2c3b884cfa59ca342b2e, a * b = 37856175e9dc9df26ebc6d6171aa0ae9 and dot(a, b) = ebe563401e7e91ea3ad6426b8140c394.

8. Worked example

Consider the encryption of the plaintext "Hello world" with the additional data "example" under key ee8e1ed9ff2540ae8f2ba9f50bc2f27c using AEAD_AES_128_GCM_SIV. The random nonce that we'll use for this example is 752abad3e0afb5f434dc4310.

In order to generate the record-authentication and record-encryption keys, a counter is combined with the nonce to form four blocks. These blocks are encrypted with key given above:

```
Counter |       Nonce                          Ciphertext
00000000752abad3e0afb5f434dc4310 -> 310728d9911f1f38c40e952ca83d093e
01000000752abad3e0afb5f434dc4310 -> 37b24316c3fab9a046ae90952daa0450
02000000752abad3e0afb5f434dc4310 -> a4c5ae624996327947920b2d2412474b
03000000752abad3e0afb5f434dc4310 -> c100be4d7e2c6edd1efef004305ab1e7
```

The latter halves of the ciphertext blocks are discarded and the remaining bytes are concatenated to form the per-record keys. Thus the record-authentication key is 310728d9911f1f3837b24316c3fab9a0 and the record-encryption key is a4c5ae6249963279c100be4d7e2c6edd.

The length block contains the encoding of the bit-lengths of the additional data and plaintext, respectively. The string "example" is seven characters, thus 56 bits (or 0x38 in hex). The string "Hello world" is 11 characters, or 88 = 0x58 bits. Thus the length block is 38000000000000005800000000000000.

The input to POLYVAL is the padded additional data, padded plaintext and then the length block. This is 6578616d706c650000000000000000004 8656c6c6f20776f726c6400000000003800000000000000580000000000000000, based on the ASCII encoding of "example" (6578616d706c65) and of "Hello world" (48656c6c6f20776f726c64).

Calling POLYVAL with the record-authentication key and the input above results in S_s = ad7fcf0b5169851662672f3c5f95138f.

Before encrypting, the nonce is XORed in and the most-significant bit of the last byte is cleared. This gives d85575d8b1c630e256bb6c2c5f95130f because that bit happened to be one previously. Encrypting with the record-encryption key gives the tag, which is 4fbcdeb7e4793f4a1d7e4faa70100af1.

In order to form the initial counter block, the most-significant bit of the last byte of the tag is set to one. That doesn't result in a change in this example. Encrypting this with the record key gives the first block of the keystream: 1551f2c1787e81deac9a99f139540ab5.

The final ciphertext is the result of XORing the plaintext with the keystream and appending the tag. That gives 5d349ead175ef6b1def6fd4fbcdeb7e4793f4a1d7e4faa70100af1.

9. Security Considerations

A detailed analysis of these schemes appears in [AES-GCM-SIV] and the remainder of this section is a summary of that paper.

The AEADs defined in this document calculate fresh AES keys for each nonce. This allows a larger number of plaintexts to be encrypted under a given key. Without this step, AES-GCM-SIV encryption would be limited by the birthday bound like other standard modes (e.g., AES-GCM, AES-CCM, AES-SIV). This means that when 2^64 blocks have been encrypted overall, the adversary has an advantage of 1/2. Thus, in order to limit the adversary's advantage to 2^-32, at most 2^48 blocks can be encrypted overall. In contrast, by deriving fresh keys

from each nonce, it is possible to encrypt a far larger number of messages and blocks with AES-GCM-SIV.

We stress that nonce-misuse resistant schemes guarantee that if a nonce repeats then the only security loss is that identical plaintexts will produce identical ciphertexts. Since this can also be a concern (as the fact that the same plaintext has been encrypted twice is revealed), we do not recommend using a fixed nonce as a policy. In addition, as we show below, better-than-birthday bounds are achieved by AES-GCM-SIV when nonces repetition is low. Finally, as shown in [BHT18], there is a great security benefit in the multi-user/multi-key setting when each particular nonce is re-used by a small number of users only. We stress that nonce-misuse resistance was never intended to be used with intentional nonce-reuse; rather, such schemes provide the best possible security in the event of nonce reuse. Due to all of the above, it is RECOMMENDED that nonces be randomly generated.

Some example usage bounds for AES-GCM-SIV are given below (for these bounds, the adversary's advantage is always below 2^-32). For up to 256 repeats of a nonce (i.e., where one can assume that nonce misuse is no more than this bound), the following message limits should be respected (this assumes a short AAD):

2^29 messages, where each plaintext is at most 1GiB

2^35 messages, where each plaintext is at most 128MiB

2^49 messages, where each plaintext is at most 1MiB

2^61 messages, where each plaintext is at most 16KiB

Suzuki et al [multibirthday] show that even if nonces are selected uniformly at random, the probability that one or more values would be repeated 256 or more times is negligible until the number of nonces reaches 2^102. (Specifically the probability is 1/((2^96)^(255)) * Binomial(q, 256), where q is the number of nonces.) Since 2^102 is vastly greater than the limit on the number of plaintexts per key given above, we don't feel that this limit on the number of repeated nonces will be a problem. This also means that selecting nonces at random is a safe practice with AES-GCM-SIV. In fact, nonces repeat far less than 256 times when randomly chosen. Thus, the bounds obtained for random nonces are as follows (as above, for these bounds the adversary's advantage is at most 2^-32):

2^32 messages, where each plaintext is at most 8GiB

2^48 messages, where each plaintext is at most 32MiB

2^64 messages, where each plaintext is at most 128KiB

For situations where, for some reason, an even higher number of nonce repeats is possible (e.g. in devices with very poor randomness), the message limits need to be reconsidered. Theorem Seven in the paper contains more details but, for up to 1,024 repeats of each nonce, the limits would be (again assuming a short AAD):

2^25 messages, where each plaintext is at most 1GiB

2^31 messages, where each plaintext is at most 128MiB

2^45 messages, where each plaintext is at most 1MiB

2^57 messages, where each plaintext is at most 16KiB

In addition to calculating fresh AES keys for each nonce, these AEADs also calculate fresh POLYVAL keys. Previous versions of GCM-SIV did not do this and, instead, used part of the AEAD's key as the POLYVAL key. Bleichenbacher pointed out that this allowed an attacker who controlled the AEAD key to force the POLYVAL key to be zero. If a user of this AEAD authenticated messages with a secret additional-data value then this would be insecure as the attacker could calculate a valid authenticator without knowing the input. This does not violate the standard properties of an AEAD as the additional data is not assumed to be confidential. However, we want these AEADs to be robust to plausible misuse and also to be drop-in replacements for AES-GCM and so derive nonce-specific POLYVAL keys to avoid this issue.

We also wish to note that the probability of successful forgery increases with the number of attempts that an attacker is permitted. If an attacker is permitted extremely large numbers of attempts then the tiny probability that any given attempt succeeds may sum to a non-trivial chance.

A security analysis of a similar scheme without nonce-based key derivation appears in [GCM-SIV] and a full analysis of the bounds when applying nonce-based key derivation appears in [key-derive]. A larger table of bounds and other information appears at [aes-gcm-siv-homepage].

The multi-user/multi-key security of AES-GCM-SIV was studied by [BHT18] who showed that security is almost like in the single user setting, as long as nonces do not repeat many times across many users. This is the case when nonces are chosen randomly.

10. IANA Considerations

IANA is requested to add two entries to the registry of AEAD algorithms: AEAD_AES_128_GCM_SIV and AEAD_AES_256_GCM_SIV, both referencing this document as their specification.

11. Acknowledgements

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12. References

12.1. Normative References

[RFC2119] Bradner, S., "Key words for use in RFCs to Indicate Requirement Levels", BCP 14, RFC 2119, DOI 10.17487/RFC2119, March 1997, <https://www.rfc-editor.org/info/rfc2119>.

12.2. Informative References

[AES-GCM-SIV] Gueron, S., Langley, A., and Y. Lindell, "AES-GCM-SIV: specification and analysis", July 2017, <https://eprint.iacr.org/2017/168>.

[aes-gcm-siv-homepage] Gueron, S., Langley, A., and Y. Lindell, "Webpage for the AES-GCM-SIV Mode of Operation", 2017, <https://cyber.biu.ac.il/aes-gcm-siv/>.

[BHT18] Bose, P., Hoang, V., and S. Tessaro, "Revisiting AES-GCM-SIV: Multi-user Security, Faster Key Derivation, and Better Bounds", Proceedings of EUROCRYPT 2018 , May 2018, <https://eprint.iacr.org/2018/136.pdf>.

[GCM] Dworkin, M., "Recommendation for Block Cipher Modes of Operation: Galois/Counter Mode (GCM) and GMAC", NIST SP-800-38D, November 2007, <http://csrc.nist.gov/publications/nistpubs/800-38D/SP-800-38D.pdf>.

[GCM-SIV] Gueron, S. and Y. Lindell, "GCM-SIV: Full Nonce Misuse-Resistant Authenticated Encryption at Under One Cycle Per Byte", Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security , 2015, <http://doi.acm.org/10.1145/2810103.2813613>.

[key-derive] Gueron, S. and Y. Lindell, "Better Bounds for Block Cipher Modes of Operation via Nonce-Based Key Derivation", Proceedings of the 24th ACM SIGSAC Conference on Computer and Communications Security , 2017, <https://doi.org/10.1145/3133956.3133992>.

[multibirthday] Suzuki, K., Tonien, D., Kurosawa, K., and K. Toyota, "Birthday Paradox for Multi-collisions", ICISC 2006: 9th International Conference, Busan, Korea, November 30 - December 1, 2006. Proceedings , 2006, <http://dx.doi.org/10.1007/11927587_5>.

[RFC5116] McGrew, D., "An Interface and Algorithms for Authenticated Encryption", RFC 5116, DOI 10.17487/RFC5116, January 2008, <https://www.rfc-editor.org/info/rfc5116>.

Appendix A. The relationship between POLYVAL and GHASH

GHASH and POLYVAL both operate in GF(2^128), although with different irreducible polynomials: POLYVAL works modulo x^128 + x^127 + x^126 + x^121 + 1 and GHASH works modulo x^128 + x^7 + x^2 + x + 1. Note that these irreducible polynomials are the "reverse" of each other.

GHASH also has a different mapping between 128-bit strings and field elements. Where as POLYVAL takes the least-significant to most-significant bits of the first byte to be the coefficients of x^0 to x^7, GHASH takes them to be the coefficients of x^7 to x^0. This continues until, for the last byte, POLYVAL takes the least-significant to most-significant bits to be the coefficients of x^120 to x^127 while GHASH takes them to be the coefficients of x^127 to x^120.

The combination of these facts means that it's possible to "convert" values between the two by reversing the order of the bytes in a 16-byte string. The differing interpretations of bit order takes care of reversing the bits within each byte and then reversing the bytes does the rest. This may have a practical benefit for implementations that wish to implement both GHASH and POLYVAL.

In order to be clear which field a given operation is performed in, let mulX_GHASH be a function that takes a 16-byte string, converts it to an element of GHASH's field using GHASH's convention, multiplies it by x and converts back to a string. Likewise, let mulX_POLYVAL be a function that converts a 16-byte string to an element of POLYVAL's field using POLYVAL's convention, multiplies it by x and converts back.

Given the 16-byte string 01000000000000000000000000000000, mulX_GHASH of that string is 00800000000000000000000000000000 and mulX_POLYVAL of that string is 02000000000000000000000000000000. As a more general example, given 9c98c04df9387ded828175a92ba652d8, mulX_GHASH of that string is 4e4c6026fc9c3ef6c140bad495d3296c and mulX_POLYVAL of it is 3931819bf271fada0503eb52574ca5f2.

Lastly, let ByteReverse be the function that takes a 16-byte string and returns a copy where the order of the bytes has been reversed.

Now GHASH and POLYVAL can be defined in terms of one another:

POLYVAL(H, X_1, ..., X_n) =
ByteReverse(GHASH(mulX_GHASH(ByteReverse(H)), ByteReverse(X_1), ..., ByteReverse(X_n)))

GHASH(H, X_1, ..., X_n) =
ByteReverse(POLYVAL(mulX_POLYVAL(ByteReverse(H)), ByteReverse(X_1), ..., ByteReverse(X_n)))

As a worked example, let H = 25629347589242761d31f826ba4b757b, X_1 = 4f4f95668c83dfb6401762bb2d01a262 and X_2 = d1a24ddd2721d006bbe45f20d3c9f362. POLYVAL(H, X_1, X_2) = f7a3b47b846119fae5b7866cf5e5b77e. If we wished to calculate this given only an implementation of GHASH then the key for GHASH would be mulX_GHASH(ByteReverse(H)) = dcbaa5dd137c188ebb21492c23c9b112. Then ByteReverse(GHASH(dcba..., ByteReverse(X_1), ByteReverse(X_2))) = f7a3b47b846119fae5b7866cf5e5b77e, as required.

In the other direction, GHASH(H, X_1, X_2) = bd9b3997046731fb96251b91f9c99d7a. If we wished to calculate this given only an implementation of POLYVAL then we would first calculate the key for POLYVAL, mulX_POLYVAL(ByteReverse(H)), which is f6ea96744df0633aec8424b18e26c54a. Then ByteReverse(POLYVAL(f6ea..., ByteReverse(X_1), ByteReverse(X_2))) = bd9b3997046731fb96251b91f9c99d7a.

Appendix B. Additional comparisons with AES-GCM

Some, non-security, properties also differ between AES-GCM and AES-GCM-SIV that are worth noting:

AES-GCM allows plaintexts to be encrypted in a streaming fashion, i.e. the beginning of the plaintext can be encrypted and transmitted before the entire message has been processed. AES-GCM-SIV requires two passes for encryption and so cannot do this.

AES-GCM allows a constant additional-data input to be precomputed in order to save per-record computation. AES-GCM-SIV varies the authenticator key based on the nonce and so does not permit this.

The performance for AES-GCM vs AES-GCM-SIV on small machines can be roughly characterised by the number of AES operations and the number of GF(2^128) multiplications needed to process a message. Let a = (bytelen(additional-data) + 15) / 16 and p = (bytelen(plaintext) + 15) / 16. Then AES-GCM requires p + 1 AES operations and p + a + 1 field multiplications.

Defined similarly, AES-GCM-SIV with AES-128 requires p + 5 AES operations and p + a + 1 field multiplications. With AES-256 that becomes p + 7 AES operations.

With large machines, the available parallelism becomes far more important and such simple performance analysis is no longer representative. For such machines, we find that decryption of AES-GCM-SIV is only about 5% slower then AES-GCM, as long as the message is at least a couple of kilobytes. Encryption tends to be about 2/3's the speed because of the additional pass required.

Appendix C. Test vectors

C.1. AEAD_AES_128_GCM_SIV

```
Plaintext (0 bytes) =
AAD (0 bytes) =
Key =                          01000000000000000000000000000000
Nonce =                        030000000000000000000000
Record authentication key = d9b360279694941ac5dbc6987ada7377
Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
POLYVAL input =             00000000000000000000000000000000
POLYVAL result =            00000000000000000000000000000000
POLYVAL result XOR nonce =  03000000000000000000000000000000
... and masked =            03000000000000000000000000000000
Tag =                       dc20e2d83f25705bb49e439eca56de25
Initial counter =           dc20e2d83f25705bb49e439eca56dea5
```

```
   Result (16 bytes) =         dc20e2d83f25705bb49e439eca56de25


   Plaintext (8 bytes) =       0100000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               00000000000000004000000000000000
   POLYVAL result =            eb93b7740962c5e49d2a90a7dc5cec74
   POLYVAL result XOR nonce =  e893b7740962c5e49d2a90a7dc5cec74
   ... and masked =            e893b7740962c5e49d2a90a7dc5cec74
   Tag =                       578782fff6013b815b287c22493a364c
   Initial counter =           578782fff6013b815b287c22493a36cc
   Result (24 bytes) =         b5d839330ac7b786578782fff6013b81
                               5b287c22493a364c


   Plaintext (12 bytes) =      010000000000000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               00000000000000006000000000000000
   POLYVAL result =            48eb6c6c5a2dbe4a1dde508fee06361b
   POLYVAL result XOR nonce =  4beb6c6c5a2dbe4a1dde508fee06361b
   ... and masked =            4beb6c6c5a2dbe4a1dde508fee06361b
   Tag =                       a4978db357391a0bc4fdec8b0d106639
   Initial counter =           a4978db357391a0bc4fdec8b0d1066b9
   Result (28 bytes) =         7323ea61d05932260047d942a4978db3
                               57391a0bc4fdec8b0d106639


   Plaintext (16 bytes) =      01000000000000000000000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               00000000000000008000000000000000
   POLYVAL result =            20806c26e3c1de019e111255708031d6
   POLYVAL result XOR nonce =  23806c26e3c1de019e111255708031d6
   ... and masked =            23806c26e3c1de019e11125570803156
```

```
   Tag =                       303aaf90f6fe21199c6068577437a0c4
   Initial counter =           303aaf90f6fe21199c6068577437a0c4
   Result (32 bytes) =         743f7c8077ab25f8624e2e948579cf77
                               303aaf90f6fe21199c6068577437a0c4


   Plaintext (32 bytes) =      01000000000000000000000000000000
                               02000000000000000000000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               00000000000000000001000000000000
   POLYVAL result =            ce6edc9a50b36d9a98986bbf6a261c3b
   POLYVAL result XOR nonce =  cd6edc9a50b36d9a98986bbf6a261c3b
   ... and masked =            cd6edc9a50b36d9a98986bbf6a261c3b
   Tag =                       1a8e45dcd4578c667cd86847bf6155ff
   Initial counter =           1a8e45dcd4578c667cd86847bf6155ff
   Result (48 bytes) =         84e07e62ba83a6585417245d7ec413a9
                               fe427d6315c09b57ce45f2e3936a9445
                               1a8e45dcd4578c667cd86847bf6155ff


   Plaintext (48 bytes) =      01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               00000000000000008001000000000000
   POLYVAL result =            81388746bc22d26b2abc3dcb15754222
   POLYVAL result XOR nonce =  82388746bc22d26b2abc3dcb15754222
   ... and masked =            82388746bc22d26b2abc3dcb15754222
   Tag =                       5e6e311dbf395d35b0fe39c2714388f8
   Initial counter =           5e6e311dbf395d35b0fe39c2714388f8
   Result (64 bytes) =         3fd24ce1f5a67b75bf2351f181a475c7
                               b800a5b4d3dcf70106b1eea82fa1d64d
                               f42bf7226122fa92e17a40eeaac1201b
                               5e6e311dbf395d35b0fe39c2714388f8
```

```
   Plaintext (64 bytes) =      01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
                               00000000000000000002000000000000
   POLYVAL result =            1e39b6d3344d348f6044f89935d1cf78
   POLYVAL result XOR nonce =  1d39b6d3344d348f6044f89935d1cf78
   ... and masked =            1d39b6d3344d348f6044f89935d1cf78
   Tag =                       8a263dd317aa88d56bdf3936dba75bb8
   Initial counter =           8a263dd317aa88d56bdf3936dba75bb8
   Result (80 bytes) =         2433668f1058190f6d43e360f4f35cd8
                               e475127cfca7028ea8ab5c20f7ab2af0
                               2516a2bdcbc08d521be37ff28c152bba
                               36697f25b4cd169c6590d1dd39566d3f
                               8a263dd317aa88d56bdf3936dba75bb8


   Plaintext (8 bytes) =       0200000000000000
   AAD (1 bytes) =             01
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               08000000000000004000000000000000
   POLYVAL result =            b26781e7e2c1376f96bec195f3709b2a
   POLYVAL result XOR nonce =  b16781e7e2c1376f96bec195f3709b2a
   ... and masked =            b16781e7e2c1376f96bec195f3709b2a
   Tag =                       3b0a1a2560969cdf790d99759abd1508
   Initial counter =           3b0a1a2560969cdf790d99759abd1588
   Result (24 bytes) =         1e6daba35669f4273b0a1a2560969cdf
                               790d99759abd1508


   Plaintext (12 bytes) =      020000000000000000000000
   AAD (1 bytes) =             01
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
```

```
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               08000000000000006000000000000000
   POLYVAL result =            111f5affb18e4cc1164a01bdc12a4145
   POLYVAL result XOR nonce =  121f5affb18e4cc1164a01bdc12a4145
   ... and masked =            121f5affb18e4cc1164a01bdc12a4145
   Tag =                       08299c5102745aaa3a0c469fad9e075a
   Initial counter =           08299c5102745aaa3a0c469fad9e07da
   Result (28 bytes) =         296c7889fd99f41917f4462008299c51
                               02745aaa3a0c469fad9e075a


   Plaintext (16 bytes) =      02000000000000000000000000000000
   AAD (1 bytes) =             01
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               08000000000000008000000000000000
   POLYVAL result =            79745ab508622c8a958543675fac4688
   POLYVAL result XOR nonce =  7a745ab508622c8a958543675fac4688
   ... and masked =            7a745ab508622c8a958543675fac4608
   Tag =                       8f8936ec039e4e4bb97ebd8c4457441f
   Initial counter =           8f8936ec039e4e4bb97ebd8c4457449f
   Result (32 bytes) =         e2b0c5da79a901c1745f700525cb335b
                               8f8936ec039e4e4bb97ebd8c4457441f


   Plaintext (32 bytes) =      02000000000000000000000000000000
                               03000000000000000000000000000000
   AAD (1 bytes) =             01
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               08000000000000000001000000000000
   POLYVAL result =            2ce7daaf7c89490822051255b12eca6b
   POLYVAL result XOR nonce =  2fe7daaf7c89490822051255b12eca6b
   ... and masked =            2fe7daaf7c89490822051255b12eca6b
   Tag =                       e6af6a7f87287da059a71684ed3498e1
   Initial counter =           e6af6a7f87287da059a71684ed3498e1
```

```
   Result (48 bytes) =         620048ef3c1e73e57e02bb8562c416a3
                               19e73e4caac8e96a1ecb2933145a1d71
                               e6af6a7f87287da059a71684ed3498e1


   Plaintext (48 bytes) =      020000000000000000000000000000000
                               030000000000000000000000000000000
                               040000000000000000000000000000000
   AAD (1 bytes) =             01
   Key =                       010000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             010000000000000000000000000000000
                               020000000000000000000000000000000
                               030000000000000000000000000000000
                               040000000000000000000000000000000
                               080000000000000080010000000000000
   POLYVAL result =            9ca987715d69c1786711dfcd22f830fc
   POLYVAL result XOR nonce =  9fa987715d69c1786711dfcd22f830fc
   ... and masked =            9fa987715d69c1786711dfcd22f8307c
   Tag =                       6a8cc3865f76897c2e4b245cf31c51f2
   Initial counter =           6a8cc3865f76897c2e4b245cf31c51f2
   Result (64 bytes) =         50c8303ea93925d64090d07bd109dfd9
                               515a5a33431019c17d93465999a8b005
                               3201d723120a8562b838cdff25bf9d1e
                               6a8cc3865f76897c2e4b245cf31c51f2


   Plaintext (64 bytes) =      020000000000000000000000000000000
                               030000000000000000000000000000000
                               040000000000000000000000000000000
                               050000000000000000000000000000000
   AAD (1 bytes) =             01
   Key =                       010000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             010000000000000000000000000000000
                               020000000000000000000000000000000
                               030000000000000000000000000000000
                               040000000000000000000000000000000
                               050000000000000000000000000000000
                               080000000000000000020000000000000
   POLYVAL result =            ffcd05d5770f34ad9267f0a59994b15a
   POLYVAL result XOR nonce =  fccd05d5770f34ad9267f0a59994b15a
   ... and masked =            fccd05d5770f34ad9267f0a59994b15a
   Tag =                       cdc46ae475563de037001ef84ae21744
```

```
   Initial counter =           cdc46ae475563de037001ef84ae217c4
   Result (80 bytes) =         2f5c64059db55ee0fb847ed513003746
                               aca4e61c711b5de2e7a77ffd02da42fe
                               ec601910d3467bb8b36ebbaebce5fba3
                               0d36c95f48a3e7980f0e7ac299332a80
                               cdc46ae475563de037001ef84ae21744


   Plaintext (4 bytes) =       02000000
   AAD (12 bytes) =            010000000000000000000000
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               60000000000000002000000000000000
   POLYVAL result =            f6ce9d3dcd68a2fd603c7ecc18fb9918
   POLYVAL result XOR nonce =  f5ce9d3dcd68a2fd603c7ecc18fb9918
   ... and masked =            f5ce9d3dcd68a2fd603c7ecc18fb9918
   Tag =                       07eb1f84fb28f8cb73de8e99e2f48a14
   Initial counter =           07eb1f84fb28f8cb73de8e99e2f48a94
   Result (20 bytes) =         a8fe3e8707eb1f84fb28f8cb73de8e99
                               e2f48a14


   Plaintext (20 bytes) =      03000000000000000000000000000000
                               04000000
   AAD (18 bytes) =            01000000000000000000000000000000
                               0200
   Key =                       01000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
                               90000000000000a000000000000000
   POLYVAL result =            4781d492cb8f926c504caa36f61008fe
   POLYVAL result XOR nonce =  4481d492cb8f926c504caa36f61008fe
   ... and masked =            4481d492cb8f926c504caa36f610087e
   Tag =                       24afc9805e976f451e6d87f6fe106514
   Initial counter =           24afc9805e976f451e6d87f6fe106594
   Result (36 bytes) =         6bb0fecf5ded9b77f902c7d5da236a43
                               91dd029724afc9805e976f451e6d87f6
                               fe106514
```

```
   Plaintext (18 bytes) =      030000000000000000000000000000000
                               0400
   AAD (20 bytes) =            010000000000000000000000000000000
                               02000000
   Key =                       010000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = d9b360279694941ac5dbc6987ada7377
   Record encryption key =     4004a0dcd862f2a57360219d2d44ef6c
   POLYVAL input =             010000000000000000000000000000000
                               020000000000000000000000000000000
                               030000000000000000000000000000000
                               040000000000000000000000000000000
                               a000000000000009000000000000000
   POLYVAL result =            75cbc23a1a10e348aeb8e384b5cc79fd
   POLYVAL result XOR nonce =  76cbc23a1a10e348aeb8e384b5cc79fd
   ... and masked =            76cbc23a1a10e348aeb8e384b5cc797d
   Tag =                       bff9b2ef00fb47920cc72a0c0f13b9fd
   Initial counter =           bff9b2ef00fb47920cc72a0c0f13b9fd
   Result (34 bytes) =         44d0aaf6fb2f1f34add5e8064e83e12a
                               2adabff9b2ef00fb47920cc72a0c0f13
                               b9fd

   Plaintext (0 bytes) =
   AAD (0 bytes) =
   Key =                       e66021d5eb8e4f4066d4adb9c33560e4
   Nonce =                     f46e44bb3da0015c94f70887
   Record authentication key = 036ee1fe2d7926af68898095e54e7b3c
   Record encryption key =     5e46482396008223b5c1d25173d87539
   POLYVAL input =             000000000000000000000000000000000
   POLYVAL result =            000000000000000000000000000000000
   POLYVAL result XOR nonce =  f46e44bb3da0015c94f7088700000000
   ... and masked =            f46e44bb3da0015c94f7088700000000
   Tag =                       a4194b79071b01a87d65f706e3949578
   Initial counter =           a4194b79071b01a87d65f706e39495f8
   Result (16 bytes) =         a4194b79071b01a87d65f706e3949578


   Plaintext (3 bytes) =       7a806c
   AAD (5 bytes) =             46bb91c3c5
   Key =                       36864200e0eaf5284d884a0e77d31646
   Nonce =                     bae8e37fc83441b16034566b
   Record authentication key = 3e28de1120b2981a0155795ca2812af6
   Record encryption key =     6d4b78b31a4c9c03d8db0f42f7507fae
   POLYVAL input =             46bb91c3c500000000000000000000000
                               7a806c000000000000000000000000000
                               280000000000000180000000000000000
   POLYVAL result =            43d9a745511dcfa21b96dd606f1d5720
   POLYVAL result XOR nonce =  f931443a99298e137ba28b0b6f1d5720
```

```
   ... and masked =            f931443a99298e137ba28b0b6f1d5720
   Tag =                       711bd85bc1e4d3e0a462e074eea428a8
   Initial counter =           711bd85bc1e4d3e0a462e074eea428a8
   Result (19 bytes) =         af60eb711bd85bc1e4d3e0a462e074ee
                               a428a8


   Plaintext (6 bytes) =       bdc66f146545
   AAD (10 bytes) =            fc880c94a95198874296
   Key =                       aedb64a6c590bc84d1a5e269e4b47801
   Nonce =                     afc0577e34699b9e671fdd4f
   Record authentication key = 43b8de9cea62330d15cccfc84a33e8c8
   Record encryption key =     8e54631607e431e095b54852868e3a27
   POLYVAL input =             fc880c94a9519887429600000000000
                               bdc66f14654500000000000000000000
                               50000000000000003000000000000000
   POLYVAL result =            26498e0d2b1ef004e808c458e8f2f515
   POLYVAL result XOR nonce =  8989d9731f776b9a8f171917e8f2f515
   ... and masked =            8989d9731f776b9a8f171917e8f2f515
   Tag =                       d6a9c45545cfc11f03ad743dba20f966
   Initial counter =           d6a9c45545cfc11f03ad743dba20f9e6
   Result (22 bytes) =         bb93a3e34d3cd6a9c45545cfc11f03ad
                               743dba20f966


   Plaintext (9 bytes) =       1177441f195495860f
   AAD (15 bytes) =            046787f3ea22c127aaf195d1894728
   Key =                       d5cc1fd161320b6920ce07787f86743b
   Nonce =                     275d1ab32f6d1f0434d8848c
   Record authentication key = 8a51df64d93eaf667c2c09bd454ce5c5
   Record encryption key =     43ab276c2b4a473918ca73f2dd85109c
   POLYVAL input =             046787f3ea22c127aaf195d189472800
                               1177441f195495860f00000000000000
                               78000000000000004800000000000000
   POLYVAL result =            63a3451c0b23345ad02bba59956517cf
   POLYVAL result XOR nonce =  44fe5faf244e2b5ee4f33ed5956517cf
   ... and masked =            44fe5faf244e2b5ee4f33ed59565174f
   Tag =                       1d02fd0cd174c84fc5dae2f60f52fd2b
   Initial counter =           1d02fd0cd174c84fc5dae2f60f52fdab
   Result (25 bytes) =         4f37281f7ad12949d01d02fd0cd174c8
                               4fc5dae2f60f52fd2b


   Plaintext (12 bytes) =      9f572c614b4745914474e7c7
   AAD (20 bytes) =            c9882e5386fd9f92ec489c8fde2be2cf
                               97e74e93
   Key =                       b3fed1473c528b8426a582995929a149
   Nonce =                     9e9ad8780c8d63d0ab4149c0
```

```
   Record authentication key = 22f50707a95dd416df069d670cb775e8
   Record encryption key =     f674a5584ee21fe97b4cebc468ab61e4
   POLYVAL input =             c9882e5386fd9f92ec489c8fde2be2cf
                               97e74e9300000000000000000000000
                               9f572c614b4745914474e7c700000000
                               a000000000000000600000000000000
   POLYVAL result =            0cca0423fba9d77fe7e2e6963b08cdd0
   POLYVAL result XOR nonce =  9250dc5bf724b4af4ca3af563b08cdd0
   ... and masked =            9250dc5bf724b4af4ca3af563b08cd50
   Tag =                       c1dc2f871fb7561da1286e655e24b7b0
   Initial counter =           c1dc2f871fb7561da1286e655e24b7b0
   Result (28 bytes) =         f54673c5ddf710c745641c8bc1dc2f87
                               1fb7561da1286e655e24b7b0


   Plaintext (15 bytes) =      0d8c8451178082355c9e940fea2f58
   AAD (25 bytes) =            2950a70d5a1db2316fd568378da107b5
                               2b0da55210cc1c1b0a
   Key =                       2d4ed87da44102952ef94b02b805249b
   Nonce =                     ac80e6f61455bfac8308a2d4
   Record authentication key = 0b00a29a83e7e95b92e3a0783b29f140
   Record encryption key =     a430c27f285aed913005975c42eed5f3
   POLYVAL input =             2950a70d5a1db2316fd568378da107b5
                               2b0da55210cc1c1b0a00000000000000
                               0d8c8451178082355c9e940fea2f5800
                               c800000000000000780000000000000
   POLYVAL result =            1086ef25247aa41009bbc40871d9b350
   POLYVAL result XOR nonce =  bc0609d3302f1bbc8ab366dc71d9b350
   ... and masked =            bc0609d3302f1bbc8ab366dc71d9b350
   Tag =                       83b3449b9f39552de99dc214a1190b0b
   Initial counter =           83b3449b9f39552de99dc214a1190b8b
   Result (31 bytes) =         c9ff545e07b88a015f05b274540aa183
                               b3449b9f39552de99dc214a1190b0b


   Plaintext (18 bytes) =      6b3db4da3d57aa94842b9803a96e07fb
                               6de7
   AAD (30 bytes) =            1860f762ebfbd08284e421702de0de18
                               baa9c9596291b08466f37de21c7f
   Key =                       bde3b2f204d1e9f8b06bc47f9745b3d1
   Nonce =                     ae06556fb6aa7890bebc18fe
   Record authentication key = 21c874a8bad3603d1c3e8784df5b3f9f
   Record encryption key =     d1c16d72651c3df504eae27129d818e8
   POLYVAL input =             1860f762ebfbd08284e421702de0de18
                               baa9c9596291b08466f37de21c7f0000
                               6b3db4da3d57aa94842b9803a96e07fb
                               6de7000000000000000000000000000
                               f000000000000009000000000000000
```

```
   POLYVAL result =            55462a5afa0da8d646481e049ef9c764
   POLYVAL result XOR nonce =  fb407f354ca7d046f8f406fa9ef9c764
   ... and masked =            fb407f354ca7d046f8f406fa9ef9c764
   Tag =                       3e377094f04709f64d7b985310a4db84
   Initial counter =           3e377094f04709f64d7b985310a4db84
   Result (34 bytes) =         6298b296e24e8cc35dce0bed484b7f30
                               d5803e377094f04709f64d7b985310a4
                               db84


   Plaintext (21 bytes) =      e42a3c02c25b64869e146d7b233987bd
                               dfc240871d
   AAD (35 bytes) =            7576f7028ec6eb5ea7e298342a94d4b2
                               02b370ef9768ec6561c4fe6b7e7296fa
                               859c21
   Key =                       f901cfe8a69615a93fdf7a98cad48179
   Nonce =                     6245709fb18853f68d833640
   Record authentication key = 3724f55f1d22ac0ab830da0b6a995d74
   Record encryption key =     75ac87b70c05db287de779006105a344
   POLYVAL input =             7576f7028ec6eb5ea7e298342a94d4b2
                               02b370ef9768ec6561c4fe6b7e7296fa
                               859c210000000000000000000000000
                               e42a3c02c25b64869e146d7b233987bd
                               dfc240871d000000000000000000000
                               180100000000000a800000000000000
   POLYVAL result =            4cbba090f03f7d1188ea55749fa6c7bd
   POLYVAL result XOR nonce =  2efed00f41b72ee7056963349fa6c7bd
   ... and masked =            2efed00f41b72ee7056963349fa6c73d
   Tag =                       2d15506c84a9edd65e13e9d24a2a6e70
   Initial counter =           2d15506c84a9edd65e13e9d24a2a6ef0
   Result (37 bytes) =         391cc328d484a4f46406181bcd62efd9
                               b3ee197d052d15506c84a9edd65e13e9
                               d24a2a6e70
```

C.2. AEAD_AES_256_GCM_SIV

```
   Plaintext (0 bytes) =
   AAD (0 bytes) =
   Key =                       010000000000000000000000000000000
                               000000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             000000000000000000000000000000000
   POLYVAL result =            000000000000000000000000000000000
   POLYVAL result XOR nonce =  030000000000000000000000000000000
   ... and masked =            030000000000000000000000000000000
```

```
   Tag =                        07f5f4169bbf55a8400cd47ea6fd400f
   Initial counter =            07f5f4169bbf55a8400cd47ea6fd408f
   Result (16 bytes) =          07f5f4169bbf55a8400cd47ea6fd400f


   Plaintext (8 bytes) =        0100000000000000
   AAD (0 bytes) =
   Key =                        0100000000000000000000000000000000
                                0000000000000000000000000000000000
   Nonce =                      030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =      b914f4742be9e1d7a2f84addbf96dec3
                                456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =              0100000000000000000000000000000000
                                0000000000000000400000000000000000
   POLYVAL result =             05230f62f0eac8aa14fe4d646b59cd41
   POLYVAL result XOR nonce =   06230f62f0eac8aa14fe4d646b59cd41
   ... and masked =             06230f62f0eac8aa14fe4d646b59cd41
   Tag =                        843122130f7364b761e0b97427e3df28
   Initial counter =            843122130f7364b761e0b97427e3dfa8
   Result (24 bytes) =          c2ef328e5c71c83b843122130f7364b7
                                61e0b97427e3df28


   Plaintext (12 bytes) =       010000000000000000000000
   AAD (0 bytes) =
   Key =                        0100000000000000000000000000000000
                                0000000000000000000000000000000000
   Nonce =                      030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =      b914f4742be9e1d7a2f84addbf96dec3
                                456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =              0100000000000000000000000000000000
                                0000000000000000600000000000000000
   POLYVAL result =             6d81a24732fd6d03ae5af544720a1c13
   POLYVAL result XOR nonce =   6e81a24732fd6d03ae5af544720a1c13
   ... and masked =             6e81a24732fd6d03ae5af544720a1c13
   Tag =                        8ca50da9ae6559e48fd10f6e5c9ca17e
   Initial counter =            8ca50da9ae6559e48fd10f6e5c9ca1fe
   Result (28 bytes) =          9aab2aeb3faa0a34aea8e2b18ca50da9
                                ae6559e48fd10f6e5c9ca17e


   Plaintext (16 bytes) =       01000000000000000000000000000000
   AAD (0 bytes) =
   Key =                        0100000000000000000000000000000000
                                0000000000000000000000000000000000
   Nonce =                      030000000000000000000000
```

```
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               00000000000000008000000000000000
   POLYVAL result =            74eee2bf7c9a165f8b25dea73db32a6d
   POLYVAL result XOR nonce =  77eee2bf7c9a165f8b25dea73db32a6d
   ... and masked =            77eee2bf7c9a165f8b25dea73db32a6d
   Tag =                       c9eac6fa700942702e90862383c6c366
   Initial counter =           c9eac6fa700942702e90862383c6c3e6
   Result (32 bytes) =         85a01b63025ba19b7fd3ddfc033b3e76
                               c9eac6fa700942702e90862383c6c366


   Plaintext (32 bytes) =      01000000000000000000000000000000
                               02000000000000000000000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               00000000000000000001000000000000
   POLYVAL result =            899b6381b3d46f0def7aa0517ba188f5
   POLYVAL result XOR nonce =  8a9b6381b3d46f0def7aa0517ba188f5
   ... and masked =            8a9b6381b3d46f0def7aa0517ba18875
   Tag =                       e819e63abcd020b006a976397632eb5d
   Initial counter =           e819e63abcd020b006a976397632ebdd
   Result (48 bytes) =         4a6a9db4c8c6549201b9edb53006cba8
                               21ec9cf850948a7c86c68ac7539d027f
                               e819e63abcd020b006a976397632eb5d


   Plaintext (48 bytes) =      01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
   AAD (0 bytes) =
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
```

```
                          03000000000000000000000000000000
                          00000000000000008001000000000000
   POLYVAL result =       c1f8593d8fc29b0c290cae1992f71f51
   POLYVAL result XOR nonce =  c2f8593d8fc29b0c290cae1992f71f51
   ... and masked =       c2f8593d8fc29b0c290cae1992f71f51
   Tag =                  790bc96880a99ba804bd12c0e6a22cc4
   Initial counter =      790bc96880a99ba804bd12c0e6a22cc4
   Result (64 bytes) =    c00d121893a9fa603f48ccc1ca3c57ce
                          7499245ea0046db16c53c7c66fe717e3
                          9cf6c748837b61f6ee3adcee17534ed5
                          790bc96880a99ba804bd12c0e6a22cc4


   Plaintext (64 bytes) = 01000000000000000000000000000000
                          02000000000000000000000000000000
                          03000000000000000000000000000000
                          04000000000000000000000000000000
   AAD (0 bytes) =
   Key =                  01000000000000000000000000000000
                          00000000000000000000000000000000
   Nonce =                030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =    b914f4742be9e1d7a2f84addbf96dec3
                          456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =        01000000000000000000000000000000
                          02000000000000000000000000000000
                          03000000000000000000000000000000
                          04000000000000000000000000000000
                          00000000000000000002000000000000
   POLYVAL result =       6ef38b06046c7c0e225efaef8e2ec4c4
   POLYVAL result XOR nonce =  6df38b06046c7c0e225efaef8e2ec4c4
   ... and masked =       6df38b06046c7c0e225efaef8e2ec444
   Tag =                  112864c269fc0d9d88c61fa47e39aa08
   Initial counter =      112864c269fc0d9d88c61fa47e39aa88
   Result (80 bytes) =    c2d5160a1f8683834910acdafc41fbb1
                          632d4a353e8b905ec9a5499ac34f96c7
                          e1049eb080883891a4db8caaa1f99dd0
                          04d80487540735234e3744512c6f90ce
                          112864c269fc0d9d88c61fa47e39aa08


   Plaintext (8 bytes) =  0200000000000000
   AAD (1 bytes) =        01
   Key =                  01000000000000000000000000000000
                          00000000000000000000000000000000
   Nonce =                030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =    b914f4742be9e1d7a2f84addbf96dec3
```

```
                              456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =            01000000000000000000000000000000
                              02000000000000000000000000000000
                              08000000000000004000000000000000
   POLYVAL result =           34e57bafe011b9b36fc6821b7ffb3354
   POLYVAL result XOR nonce = 37e57bafe011b9b36fc6821b7ffb3354
   ... and masked =           37e57bafe011b9b36fc6821b7ffb3354
   Tag =                      91213f267e3b452f02d01ae33e4ec854
   Initial counter =          91213f267e3b452f02d01ae33e4ec8d4
   Result (24 bytes) =        1de22967237a813291213f267e3b452f
                              02d01ae33e4ec854


   Plaintext (12 bytes) =     020000000000000000000000
   AAD (1 bytes) =            01
   Key =                      01000000000000000000000000000000
                              00000000000000000000000000000000
   Nonce =                    030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =    b914f4742be9e1d7a2f84addbf96dec3
                              456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =            01000000000000000000000000000000
                              02000000000000000000000000000000
                              08000000000000006000000000000000
   POLYVAL result =           5c47d68a22061c1ad5623a3b66a8e206
   POLYVAL result XOR nonce = 5f47d68a22061c1ad5623a3b66a8e206
   ... and masked =           5f47d68a22061c1ad5623a3b66a8e206
   Tag =                      c1a4a19ae800941ccdc57cc8413c277f
   Initial counter =          c1a4a19ae800941ccdc57cc8413c27ff
   Result (28 bytes) =        163d6f9cc1b346cd453a2e4cc1a4a19a
                              e800941ccdc57cc8413c277f


   Plaintext (16 bytes) =     02000000000000000000000000000000
   AAD (1 bytes) =            01
   Key =                      01000000000000000000000000000000
                              00000000000000000000000000000000
   Nonce =                    030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =    b914f4742be9e1d7a2f84addbf96dec3
                              456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =            01000000000000000000000000000000
                              02000000000000000000000000000000
                              08000000000000008000000000000000
   POLYVAL result =           452896726c616746f01d11d82911d478
   POLYVAL result XOR nonce = 462896726c616746f01d11d82911d478
   ... and masked =           462896726c616746f01d11d82911d478
   Tag =                      b292d28ff61189e8e49f3875ef91aff7
```

```
   Initial counter =           b292d28ff61189e8e49f3875ef91aff7
   Result (32 bytes) =         c91545823cc24f17dbb0e9e807d5ec17
                               b292d28ff61189e8e49f3875ef91aff7


   Plaintext (32 bytes) =      02000000000000000000000000000000
                               03000000000000000000000000000000
   AAD (1 bytes) =             01
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               08000000000000000001000000000000
   POLYVAL result =            4e58c1e341c9bb0ae34eda9509dfc90c
   POLYVAL result XOR nonce =  4d58c1e341c9bb0ae34eda9509dfc90c
   ... and masked =            4d58c1e341c9bb0ae34eda9509dfc90c
   Tag =                       aea1bad12702e1965604374aab96dbbc
   Initial counter =           aea1bad12702e1965604374aab96dbbc
   Result (48 bytes) =         07dad364bfc2b9da89116d7bef6daaaf
                               6f255510aa654f920ac81b94e8bad365
                               aea1bad12702e1965604374aab96dbbc


   Plaintext (48 bytes) =      02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
   AAD (1 bytes) =             01
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
                               08000000000000008001000000000000
   POLYVAL result =            2566a4aff9a525df9772c16d4eaf8d2a
   POLYVAL result XOR nonce =  2666a4aff9a525df9772c16d4eaf8d2a
   ... and masked =            2666a4aff9a525df9772c16d4eaf8d2a
   Tag =                       03332742b228c647173616cfd44c54eb
   Initial counter =           03332742b228c647173616cfd44c54eb
```

```
   Result (64 bytes) =         c67a1f0f567a5198aa1fcc8e3f213143
                               36f7f51ca8b1af61feac35a86416fa47
                               fbca3b5f749cdf564527f2314f42fe25
                               03332742b228c647173616cfd44c54eb


   Plaintext (64 bytes) =      02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
                               05000000000000000000000000000000
   AAD (1 bytes) =             01
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
                               05000000000000000000000000000000
                               08000000000000000002000000000000
   POLYVAL result =            da58d2f61b0a9d343b2f37fb0c519733
   POLYVAL result XOR nonce =  d958d2f61b0a9d343b2f37fb0c519733
   ... and masked =            d958d2f61b0a9d343b2f37fb0c519733
   Tag =                       5bde0285037c5de81e5b570a049b62a0
   Initial counter =           5bde0285037c5de81e5b570a049b62a0
   Result (80 bytes) =         67fd45e126bfb9a79930c43aad2d3696
                               7d3f0e4d217c1e551f59727870beefc9
                               8cb933a8fce9de887b1e40799988db1f
                               c3f91880ed405b2dd298318858467c89
                               5bde0285037c5de81e5b570a049b62a0


   Plaintext (4 bytes) =       02000000
   AAD (12 bytes) =            010000000000000000000000
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               60000000000000002000000000000000
   POLYVAL result =            6dc76ae84b88916e073a303aafde05cf
   POLYVAL result XOR nonce =  6ec76ae84b88916e073a303aafde05cf
```

```
   ... and masked =            6ec76ae84b88916e073a303aafde054f
   Tag =                       1835e517741dfddccfa07fa4661b74cf
   Initial counter =           1835e517741dfddccfa07fa4661b74cf
   Result (20 bytes) =         22b3f4cd1835e517741dfddccfa07fa4
                               661b74cf


   Plaintext (20 bytes) =      03000000000000000000000000000000
                               04000000
   AAD (18 bytes) =            01000000000000000000000000000000
                               0200
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
                               9000000000000000a000000000000000
   POLYVAL result =            973ef4fd04bd31d193816ab26f8655ca
   POLYVAL result XOR nonce =  943ef4fd04bd31d193816ab26f8655ca
   ... and masked =            943ef4fd04bd31d193816ab26f86554a
   Tag =                       b879ad976d8242acc188ab59cabfe307
   Initial counter =           b879ad976d8242acc188ab59cabfe387
   Result (36 bytes) =         43dd0163cdb48f9fe3212bf61b201976
                               067f342bb879ad976d8242acc188ab59
                               cabfe307


   Plaintext (18 bytes) =      03000000000000000000000000000000
                               0400
   AAD (20 bytes) =            01000000000000000000000000000000
                               02000000
   Key =                       01000000000000000000000000000000
                               00000000000000000000000000000000
   Nonce =                     030000000000000000000000
   Record authentication key = b5d3c529dfafac43136d2d11be284d7f
   Record encryption key =     b914f4742be9e1d7a2f84addbf96dec3
                               456e3c6c05ecc157cdbf0700fedad222
   POLYVAL input =             01000000000000000000000000000000
                               02000000000000000000000000000000
                               03000000000000000000000000000000
                               04000000000000000000000000000000
                               a000000000000009000000000000000
   POLYVAL result =            2cbb6b7ab2dbffefb797f825f826870c
```

```
   POLYVAL result XOR nonce =  2fbb6b7ab2dbffefb797f825f826870c
   ... and masked =            2fbb6b7ab2dbffefb797f825f826870c
   Tag =                       cfcdf5042112aa29685c912fc2056543
   Initial counter =           cfcdf5042112aa29685c912fc20565c3
   Result (34 bytes) =         462401724b5ce6588d5a54aae5375513
                               a075cfcdf5042112aa29685c912fc205
                               6543

   Plaintext (0 bytes) =
   AAD (0 bytes) =
   Key =                       e66021d5eb8e4f4066d4adb9c33560e4
                               f46e44bb3da0015c94f7088736864200
   Nonce =                     e0eaf5284d884a0e77d31646
   Record authentication key = e40d26f82774aa27f47b047b608b9585
   Record encryption key =     7c7c3d9a542cef53dde0e6de9b580040
                               0f82e73ec5f7ee41b7ba8dcb9ba078c3
   POLYVAL input =             00000000000000000000000000000000
   POLYVAL result =            00000000000000000000000000000000
   POLYVAL result XOR nonce =  e0eaf5284d884a0e77d3164600000000
   ... and masked =            e0eaf5284d884a0e77d3164600000000
   Tag =                       169fbb2fbf389a995f6390af22228a62
   Initial counter =           169fbb2fbf389a995f6390af22228ae2
   Result (16 bytes) =         169fbb2fbf389a995f6390af22228a62


   Plaintext (3 bytes) =       671fdd
   AAD (5 bytes) =             4fbdc66f14
   Key =                       bae8e37fc83441b16034566b7a806c46
                               bb91c3c5aedb64a6c590bc84d1a5e269
   Nonce =                     e4b47801afc0577e34699b9e
   Record authentication key = b546f5a850d0a90adfe39e95c2510fc6
   Record encryption key =     b9d1e239d62cbb5c49273ddac8838bdc
                               c53bca478a770f07087caa4e0a924a55
   POLYVAL input =             4fbdc66f14000000000000000000000000
                               671fdd0000000000000000000000000000
                               28000000000000001800000000000000
   POLYVAL result =            b91f91f96b159a7c611c05035b839e92
   POLYVAL result XOR nonce =  5dabe9f8c4d5cd0255759e9d5b839e92
   ... and masked =            5dabe9f8c4d5cd0255759e9d5b839e12
   Tag =                       93da9bb81333aee0c785b240d319719d
   Initial counter =           93da9bb81333aee0c785b240d319719d
   Result (19 bytes) =         0eaccb93da9bb81333aee0c785b240d3
                               19719d


   Plaintext (6 bytes) =       195495860f04
   AAD (10 bytes) =            6787f3ea22c127aaf195
   Key =                       6545fc880c94a95198874296d5cc1fd1
```

```
                          61320b6920ce07787f86743b275d1ab3
   Nonce =                2f6d1f0434d8848c1177441f
   Record authentication key = e156e1f9b0b07b780cbe30f259e3c8da
   Record encryption key =    6fc1c494519f944aae52fcd8b14e5b17
                          1b5a9429d3b76e430d49940c0021d612
   POLYVAL input =            6787f3ea22c127aaf195000000000000
                          195495860f040000000000000000000000
                          500000000000000030000000000000000
   POLYVAL result =           2c480ed9d236b1df24c6eec109bd40c1
   POLYVAL result XOR nonce = 032511dde6ee355335b1aade09bd40c1
   ... and masked =           032511dde6ee355335b1aade09bd4041
   Tag =                      6b62b84dc40c84636a5ec12020ec8c2c
   Initial counter =          6b62b84dc40c84636a5ec12020ec8cac
   Result (22 bytes) =        a254dad4f3f96b62b84dc40c84636a5e
                          c12020ec8c2c


   Plaintext (9 bytes) =      c9882e5386fd9f92ec
   AAD (15 bytes) =           489c8fde2be2cf97e74e932d4ed87d
   Key =                      d1894728b3fed1473c528b8426a58299
                          5929a1499e9ad8780c8d63d0ab4149c0
   Nonce =                    9f572c614b4745914474e7c7
   Record authentication key = 0533fd71f4119257361a3ff1469dd4e5
   Record encryption key =    4feba89799be8ac3684fa2bb30ade0ea
                          51390e6d87dcf3627d2ee44493853abe
   POLYVAL input =            489c8fde2be2cf97e74e932d4ed87d00
                          c9882e5386fd9f92ec00000000000000
                          780000000000000048000000000000000
   POLYVAL result =           bf160bc9ded8c63057d2c38aae552fb4
   POLYVAL result XOR nonce = 204127a8959f83a113a6244dae552fb4
   ... and masked =           204127a8959f83a113a6244dae552f34
   Tag =                      c0fd3dc6628dfe55ebb0b9fb2295c8c2
   Initial counter =          c0fd3dc6628dfe55ebb0b9fb2295c8c2
   Result (25 bytes) =        0df9e308678244c44bc0fd3dc6628dfe
                          55ebb0b9fb2295c8c2


   Plaintext (12 bytes) =     1db2316fd568378da107b52b
   AAD (20 bytes) =           0da55210cc1c1b0abde3b2f204d1e9f8
                          b06bc47f
   Key =                      a44102952ef94b02b805249bac80e6f6
                          1455bfac8308a2d40d8c845117808235
   Nonce =                    5c9e940fea2f582950a70d5a
   Record authentication key = 64779ab10ee8a280272f14cc8851b727
   Record encryption key =    25f40fc63f49d3b9016a8eeeb75846e0
                          d72ca36ddbd312b6f5ef38ad14bd2651
   POLYVAL input =            0da55210cc1c1b0abde3b2f204d1e9f8
                          b06bc47f000000000000000000000000
```

```
                              1db2316fd568378da107b52b00000000
                              a000000000000006000000000000000
   POLYVAL result =           cc86ee22c861e1fd474c84676b42739c
   POLYVAL result XOR nonce = 90187a2d224eb9d417eb893d6b42739c
   ... and masked =           90187a2d224eb9d417eb893d6b42731c
   Tag =                      404099c2587f64979f21826706d497d5
   Initial counter =          404099c2587f64979f21826706d497d5
   Result (28 bytes) =        8dbeb9f7255bf5769dd56692404099c2
                              587f64979f21826706d497d5


   Plaintext (15 bytes) =     21702de0de18baa9c9596291b08466
   AAD (25 bytes) =           f37de21c7ff901cfe8a69615a93fdf7a
                              98cad481796245709f
   Key =                      9745b3d1ae06556fb6aa7890bebc18fe
                              6b3db4da3d57aa94842b9803a96e07fb
   Nonce =                    6de71860f762ebfbd08284e4
   Record authentication key = 27c2959ed4daea3b1f52e849478de376
   Record encryption key =    307a38a5a6cf231c0a9af3b527f23a62
                              e9a6ff09aff8ae669f760153e864fc93
   POLYVAL input =            f37de21c7ff901cfe8a69615a93fdf7a
                              98cad481796245709f00000000000000
                              21702de0de18baa9c9596291b0846600
                              c800000000000000780000000000000
   POLYVAL result =           c4fa5e5b713853703bcf8e6424505fa5
   POLYVAL result XOR nonce = a91d463b865ab88beb4d0a8024505fa5
   ... and masked =           a91d463b865ab88beb4d0a8024505f25
   Tag =                      b3080d28f6ebb5d3648ce97bd5ba67fd
   Initial counter =          b3080d28f6ebb5d3648ce97bd5ba67fd
   Result (31 bytes) =        793576dfa5c0f88729a7ed3c2f1bffb3
                              080d28f6ebb5d3648ce97bd5ba67fd


   Plaintext (18 bytes) =     b202b370ef9768ec6561c4fe6b7e7296
                              fa85
   AAD (30 bytes) =           9c2159058b1f0fe91433a5bdc20e214e
                              ab7fecef4454a10ef0657df21ac7
   Key =                      b18853f68d833640e42a3c02c25b6486
                              9e146d7b233987bddfc240871d7576f7
   Nonce =                    028ec6eb5ea7e298342a94d4
   Record authentication key = 670b98154076ddb59b7a9137d0dcc0f0
   Record encryption key =    78116d78507fbe69d4a820c350f55c7c
                              b36c3c9287df0e9614b142b76a587c3f
   POLYVAL input =            9c2159058b1f0fe91433a5bdc20e214e
                              ab7fecef4454a10ef0657df21ac70000
                              b202b370ef9768ec6561c4fe6b7e7296
                              fa85000000000000000000000000000
                              f000000000000009000000000000000
```

```
   POLYVAL result =            4e4108f09f41d797dc9256f8da8d58c7
   POLYVAL result XOR nonce =  4ccfce1bc1e6350fe8b8c22cda8d58c7
   ... and masked =            4ccfce1bc1e6350fe8b8c22cda8d5847
   Tag =                       454fc2a154fea91f8363a39fec7d0a49
   Initial counter =           454fc2a154fea91f8363a39fec7d0ac9
   Result (34 bytes) =         857e16a64915a787637687db4a951963
                               5cdd454fc2a154fea91f8363a39fec7d
                               0a49


   Plaintext (21 bytes) =      ced532ce4159b035277d4dfbb7db6296
                               8b13cd4eec
   AAD (35 bytes) =            734320ccc9d9bbbb19cb81b2af4ecbc3
                               e72834321f7aa0f70b7282b4f33df23f
                               167541
   Key =                       3c535de192eaed3822a2fbbe2ca9dfc8
                               8255e14a661b8aa82cc54236093bbc23
   Nonce =                     688089e55540db1872504e1c
   Record authentication key = cb8c3aa3f8dbaeb4b28a3e86ff6625f8
   Record encryption key =     02426ce1aa3ab31313b0848469a1b5fc
                               6c9af9602600b195b04ad407026bc06d
   POLYVAL input =             734320ccc9d9bbbb19cb81b2af4ecbc3
                               e72834321f7aa0f70b7282b4f33df23f
                               16754100000000000000000000000000
                               ced532ce4159b035277d4dfbb7db6296
                               8b13cd4eec0000000000000000000000
                               18010000000000000a800000000000000
   POLYVAL result =            ffd503c7dd712eb3791b7114b17bb0cf
   POLYVAL result XOR nonce =  97558a228831f5ab0b4b3f08b17bb0cf
   ... and masked =            97558a228831f5ab0b4b3f08b17bb04f
   Tag =                       9d6c7029675b89eaf4ba1ded1a286594
   Initial counter =           9d6c7029675b89eaf4ba1ded1a286594
   Result (37 bytes) =         626660c26ea6612fb17ad91e8e767639
                               edd6c9faee9d6c7029675b89eaf4ba1d
                               ed1a286594
```

C.3. Counter wrap tests

The tests in this section use AEAD_AES_256_GCM_SIV and are crafted to test correct wrapping of the block counter.

```
   Plaintext (32 bytes) =      0000000000000000000000000000000000
                               4db923dc793ee6497c76dcc03a98e108
   AAD (0 bytes) =
   Key =                       0000000000000000000000000000000000
                               0000000000000000000000000000000000
   Nonce =                     000000000000000000000000
   Record authentication key = dc95c078a24089895275f3d86b4fb868
   Record encryption key =     779b38d15bffb63d39d6e9ae76a9b2f3
                               75d11b0e3a68c422845c7d4690fa594f
   POLYVAL input =             0000000000000000000000000000000000
                               4db923dc793ee6497c76dcc03a98e108
                               0000000000000000001000000000000000
   POLYVAL result =            7367cdb411b730128dd56e8edc0eff56
   POLYVAL result XOR nonce =  7367cdb411b730128dd56e8edc0eff56
   ... and masked =            7367cdb411b730128dd56e8edc0eff56
   Tag =                       ffffffff0000000000000000000000000
   Initial counter =           ffffffff0000000000000000000000080
   Result (48 bytes) =         f3f80f2cf0cb2dd9c5984fcda908456c
                               c537703b5ba70324a6793a7bf218d3ea
                               ffffffff0000000000000000000000000


   Plaintext (24 bytes) =      eb3640277c7ffd1303c7a542d02d3e4c
                               0000000000000000
   AAD (0 bytes) =
   Key =                       0000000000000000000000000000000000
                               0000000000000000000000000000000000
   Nonce =                     000000000000000000000000
   Record authentication key = dc95c078a24089895275f3d86b4fb868
   Record encryption key =     779b38d15bffb63d39d6e9ae76a9b2f3
                               75d11b0e3a68c422845c7d4690fa594f
   POLYVAL input =             eb3640277c7ffd1303c7a542d02d3e4c
                               0000000000000000000000000000000000
                               0000000000000000c000000000000000
   POLYVAL result =            7367cdb411b730128dd56e8edc0eff56
   POLYVAL result XOR nonce =  7367cdb411b730128dd56e8edc0eff56
   ... and masked =            7367cdb411b730128dd56e8edc0eff56
   Tag =                       ffffffff0000000000000000000000000
   Initial counter =           ffffffff0000000000000000000000080
   Result (40 bytes) =         18ce4f0b8cb4d0cac65fea8f79257b20
                               888e53e72299e56dffffffff00000000
                               0000000000000000
```

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