Network Working Group
Internet-Draft
Intended status: Standards Track
Expires: June 13, 2008

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December 11, 2007

DNSSEC Hashed Authenticated Denial of Existence
draft-ietf-dnsext-nsec3-13

Status of this Memo

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Abstract

The Domain Name System Security Extensions (DNSSEC) introduced the NSEC resource record (RR) for authenticated denial of existence. This document introduces an alternative resource record, NSEC3, which similarly provides authenticated denial of existence. However, it also provides measures against zone enumeration and permits gradual

expansion of delegation-centric zones.

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1. Introduction

1.1. Rationale

The DNS Security Extensions included the NSEC RR to provide authenticated denial of existence. Though the NSEC RR meets the requirements for authenticated denial of existence, it introduces a side-effect in that the contents of a zone can be enumerated. This property introduces undesired policy issues.

The enumeration is enabled by the set of NSEC records that exists inside a signed zone. An NSEC record lists two names that are ordered canonically, in order to show that nothing exists between the two names. The complete set of NSEC records lists all the names in a zone. It is trivial to enumerate the content of a zone by querying for names that do not exist.

An enumerated zone can be used, for example, as a source of probable e-mail addresses for spam, or as a key for multiple WHOIS queries to reveal registrant data which many registries may have legal obligations to protect. Many registries therefore prohibit copying of their zone data; however, the use of NSEC RRs renders these policies unenforceable.

A second problem is that the cost to cryptographically secure delegations to unsigned zones is high, relative to the perceived security benefit, in two cases: large, delegation-centric zones, and zones where insecure delegations will be updated rapidly. In these cases, the costs of maintaining the NSEC RR chain may be extremely high and use of the "Opt-Out" convention may be more appropriate (for these unsecured zones).

This document presents the NSEC3 Resource Record which can be used as an alternative to NSEC to mitigate these issues.

Earlier work to address these issues include [I-D.jas-dnsext-no], [RFC4956] and [I-D.laurie-dnsext-nsec2v2].

1.2. Reserved Words

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 [RFC2119].

1.3. Terminology

The reader is assumed to be familiar with the basic DNS and DNSSEC concepts described in [RFC1034], [RFC1035], [RFC4033], [RFC4034],

[RFC4035] and subsequent RFCs that update them: [RFC2136], [RFC2181] and [RFC2308].

The following terminology is used throughout this document:

Zone enumeration: the practice of discovering the full content of a zone via successive queries. Zone enumeration was non-trivial prior to the introduction of DNSSEC.

Original owner name: the owner name corresponding to a hashed owner name.

Hashed owner name: the owner name created after applying the hash function to an owner name.

Hash order: the order in which hashed owner names are arranged according to their numerical value, treating the leftmost (lowest numbered) octet as the most significant octet. Note that this order is the same as the canonical DNS name order specified in [RFC4034] when the hashed owner names are in base32 encoded with Extended Hex Alphabet [RFC4648].

Empty non-terminal: a domain name that owns no resource records, but has one or more subdomains that do.

Delegation: an NS RRSet with a name different from the current zone apex (non-zone-apex), signifying a delegation to a child zone.

Secure delegation: a name containing a delegation (NS RRSet), and a signed DS RRSet, signifying a delegation to a signed child zone.

Insecure delegation: a name containing a delegation (NS RRSet), but lacking a DS RRSet, signifying a delegation to an unsigned child zone.

Opt-Out NSEC3 resource record: an NSEC3 resource record which has the Opt-Out flag set to 1.

Opt-Out zone: a zone with at least one Opt-Out NSEC3 RR.

Closest encloser: the longest existing ancestor of a name. See also section 3.3.1 of [RFC4592].

Closest provable encloser: the longest ancestor of a name that can be proven to exist. Note that this is only different from the closest encloser in an Opt-Out zone.

Next closer name: the name one label longer than the closest provable encloser of a name.

Base32: the "Base 32 Encoding with Extended Hex Alphabet" as specified in [RFC4648]. Note that trailing padding characters ("=") are not used in the NSEC3 specification.

To cover: An NSEC3 RR is said to "cover" a name if the hash of the name or "next closer" name falls between the owner name and the next hashed owner name of the NSEC3. In other words, if it proves the nonexistence of the name, either directly or by proving the nonexistence of an ancestor of the name.

To match: An NSEC3 RR is said to "match" a name if the owner name of the NSEC3 RR is the same as the hashed owner name of that name.

2. Backwards Compatibility

This specification describes a protocol change that is not generally backwards compatible with [RFC4033], [RFC4034] and [RFC4035]. In particular, security-aware resolvers that are unaware of this specification (NSEC3-unaware resolvers) may fail to validate the responses introduced by this document.

In order to aid deployment, this specification uses a signaling technique to prevent NSEC3-unaware resolvers from attempting to validate responses from NSEC3-signed zones.

This specification allocates two new DNSKEY algorithm identifiers for this purpose. Algorithm XX, DSA-NSEC3-SHA1 [### RFC-editor update required, temporarily, XX=131] is an alias for algorithm 3, DSA. Algorithm YY, RSASHA1-NSEC3-SHA1 [### RFC-editor update required, temporarily, YY=133] is an alias for algorithm 5, RSASHA1. These are not new algorithms, they are additional identifiers for the existing algorithms.

Zones signed according to this specification MUST only use these algorithm identifiers for their DNSKEY RRs. Because these new identifiers will be unknown algorithms to existing, NSEC3-unaware resolvers, those resolvers will then treat responses from the NSEC3 signed zone as insecure, as detailed in [RFC4035], section 5.2.

These algorithm identifiers are used with the NSEC3 hash algorithm SHA1. Using other NSEC3 hash algorithms requires allocation of a new alias (see Section 12.1.3).

Security aware resolvers that are aware of this specification MUST

recognize the new algorithm identifiers and treat them as equivalent to the algorithms that they alias.

A methodology for transitioning from a DNSSEC signed zone to a zone signed using NSEC3 is discussed in Section 10.4.

3. The NSEC3 Resource Record

The NSEC3 Resource Record (RR) provides authenticated denial of existence for DNS Resource Record Sets.

The NSEC3 RR lists RR types present at the original owner name of the NSEC3 RR. It includes the next hashed owner name in the hash order of the zone. The complete set of NSEC3 RRs in a zone indicates which RRSets exist for the original owner name of the RR and form a chain of hashed owner names in the zone. This information is used to provide authenticated denial of existence for DNS data. To provide protection against zone enumeration, the owner names used in the NSEC3 RR are cryptographic hashes of the original owner name prepended as a single label to the name of the zone. The NSEC3 RR indicates which hash function is used to construct the hash, which salt is used, and how many iterations of the hash function are performed over the original owner name. The hashing technique is described fully in Section 5.

Hashed owner names of unsigned delegations may be excluded from the chain. An NSEC3 RR whose span covers the hash of an owner name or "next closer" name of an unsigned delegation is referred to as an Opt-Out NSEC3 RR and is indicated by the presence of a flag.

The owner name for the NSEC3 RR is the base32 encoding of the hashed owner name prepended as a single label to the name of the zone.

The type value for the NSEC3 RR is NN. [### RFC-editor update required, the examples assume NN=50]

The NSEC3 RR RDATA format is class independent and is described below.

The class MUST be the same as the class of the original owner name.

The NSEC3 RR SHOULD have the same TTL value as the SOA minimum TTL field. This is in the spirit of negative caching [RFC2308].

3.1. RDATA Fields

3.1.1. Hash Algorithm

The Hash Algorithm field identifies the cryptographic hash algorithm used to construct the hash-value.

The values for this field are defined in the NSEC3 hash algorithm registry, described in Section 11.

3.1.2. Flags

The Flags field contains 8 one-bit flags that can be used to indicate different processing. All undefined flags must be zero. The only flag defined by this specification is the Opt-Out flag.

3.1.2.1. Opt-Out Flag

If the Opt-Out flag is set, the NSEC3 record covers zero or more unsigned delegations.

If the Opt-Out flag is clear, the NSEC3 record covers zero unsigned delegations.

The Opt-Out Flag indicates whether this NSEC3 RR may cover unsigned delegations. It is the least significant bit in the Flags field. See Section 6 for details about the use of this flag.

3.1.3. Iterations

The Iterations field defines the number of additional times the hash function has been performed. More iterations result in greater resiliency of the hash value against dictionary attacks, but at a higher computational cost for both the server and resolver. See Section 5 for details of the use of this field, and Section 10.3 for limitations on the value.

3.1.4. Salt Length

The Salt Length field defines the length of the Salt field in octets, ranging in value from 0 to 255.

3.1.5. Salt

The Salt field is appended to the original owner name before hashing in order to defend against pre-calculated dictionary attacks. See Section 5 for details on how the salt is used.

3.1.6. Hash Length

The Hash Length field defines the length of the Next Hashed Owner Name field, ranging in value from 1 to 255 octets.

3.1.7. Next Hashed Owner Name

The Next Hashed Owner Name field contains the next hashed owner name in hash order. This value is in binary format. Given the ordered set of all hashed owner names, the Next Hashed Owner Name field contains the hash of an owner name that immediately follows the owner name of the given NSEC3 RR. The value of the Next Hashed Owner Name field in the last NSEC3 RR in the zone is the same as the hashed owner name of the first NSEC3 RR in the zone in hash order. Note that, unlike the owner name of the NSEC3 RR, the value of this field does not contain the appended zone name.

3.1.8. Type Bit Maps

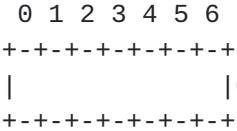
The Type Bit Maps field identifies the RRSet types which exist at the original owner name of the NSEC3 RR.

3.2. NSEC3 RDATA Wire Format

The RDATA of the NSEC3 RR is as shown below:

Hash Algorithm is a single octet.

Flags field is a single octet, the Opt-Out flag is the least significant bit, as shown below:



Iterations is represented as a 16-bit unsigned integer, with the most significant bit first.

Salt Length is represented as an unsigned octet. Salt Length represents the length of the Salt field in octets. If the value is zero, the following Salt field is omitted.

Salt, if present, is encoded as a sequence of binary octets. The length of this field is determined by the preceding Salt Length field.

Hash Length is represented as an unsigned octet. Hash Length represents the length of the Next Hashed Owner Name field in octets.

The next hashed owner name is not base32 encoded, unlike the owner name of the NSEC3 RR. It is the unmodified binary hash value. It does not include the name of the containing zone. The length of this field is determined by the preceding Hash Length field.

3.2.1. Type Bit Maps Encoding

The encoding of the Type Bit Maps field is the same as that used by the NSEC RR, described in [RFC4034]. It is explained and clarified here for clarity.

The RR type space is split into 256 window blocks, each representing the low-order 8 bits of the 16-bit RR type space. Each block that has at least one active RR type is encoded using a single octet window number (from 0 to 255), a single octet bitmap length (from 1 to 32) indicating the number of octets used for the bitmap of the window block, and up to 32 octets (256 bits) of bitmap.

Blocks are present in the NSEC3 RR RDATA in increasing numerical order.

```
Type Bit Maps Field = ( Window Block # | Bitmap Length | Bitmap )+
```

where "|" denotes concatenation.

Each bitmap encodes the low-order 8 bits of RR types within the window block, in network bit order. The first bit is bit 0. For window block 0, bit 1 corresponds to RR type 1 (A), bit 2 corresponds to RR type 2 (NS), and so forth. For window block 1, bit 1 corresponds to RR type 257, bit 2 to RR type 258. If a bit is set to 1, it indicates that an RRSet of that type is present for the original owner name of the NSEC3 RR. If a bit is set to 0, it indicates that no RRSet of that type is present for the original owner name of the NSEC3 RR.

Since bit 0 in window block 0 refers to the non-existing RR type 0, it MUST be set to 0. After verification, the validator MUST ignore the value of bit 0 in window block 0.

Bits representing Meta-TYPEs or QTYPEs as specified in [RFC2929] (section 3.1) or within the range reserved for assignment only to QTYPEs and Meta-TYPEs MUST be set to 0, since they do not appear in zone data. If encountered, they must be ignored upon reading.

Blocks with no types present MUST NOT be included. Trailing zero octets in the bitmap MUST be omitted. The length of the bitmap of each block is determined by the type code with the largest numerical value, within that block, among the set of RR types present at the original owner name of the NSEC3 RR. Trailing octets not specified MUST be interpreted as zero octets.

3.3. Presentation Format

The presentation format of the RDATA portion is as follows:

- The Hash Algorithm field is represented as an unsigned decimal integer. The value has a maximum of 255.

- The Flags field is represented as an unsigned decimal integer. The value has a maximum of 255.

- The Iterations field is represented as an unsigned decimal integer. The value is between 0 and 65535, inclusive.

- The Salt Length field is not represented.

- The Salt field is represented as a sequence of case-insensitive hexadecimal digits. Whitespace is not allowed within the sequence. The Salt field is represented as "-" (without the quotes) when the Salt Length field has value 0.

- The Hash Length field is not represented.

- The Next Hashed Owner Name field is represented as an unpadded sequence of case-insensitive base32 digits, without whitespace.

- The Type Bit Maps field is represented as a sequence of RR type mnemonics. When the mnemonic is not known, the TYPE representation as described in [RFC3597] (section 5) MUST be used.

4. The NSEC3PARAM Record

The NSEC3PARAM RR contains the NSEC3 parameters (hash algorithm, flags, iterations and salt) needed by authoritative servers to calculate hashed owner names. The presence of an NSEC3PARAM RR at a zone apex indicates that the specified parameters may be used by authoritative servers to choose an appropriate set of NSEC3 RRs for negative responses. The NSEC3PARAM RR is not used by validators or resolvers.

If an NSEC3PARAM RR is present at the apex of a zone with a Flags field value of zero, then there MUST be an NSEC3 RR using the same hash algorithm, iterations and salt parameters present at every hashed owner name in the zone. That is, the zone MUST contain a complete set of NSEC3 RRs with the same hash algorithm, iterations and salt parameters.

The owner name for the NSEC3PARAM RR is the name of the zone apex.

The type value for the NSEC3PARAM RR is MM. [### RFC-editor update required, the examples assume MM=51]

The NSEC3PARAM RR RDATA format is class independent and is described below.

The class MUST be the same as the NSEC3 RRs to which this RR refers.

4.1. RDATA Fields

The RDATA for this RR mirrors the first four fields in the NSEC3 RR.

4.1.1. Hash Algorithm

The Hash Algorithm field identifies the cryptographic hash algorithm used to construct the hash-value.

The acceptable values are the same as the corresponding field in the NSEC3 RR.

4.1.2. Flag Fields

The Opt-Out flag is not used and is set to zero.

All other flags are reserved for future use, and must be zero.

NSEC3PARAM RRs with a Flags field value other than zero MUST be ignored.

4.1.3. Iterations

The Iterations field defines the number of additional times the hash is performed.

Its acceptable values are the same as the corresponding field in the NSEC3 RR.

4.1.4. Salt Length

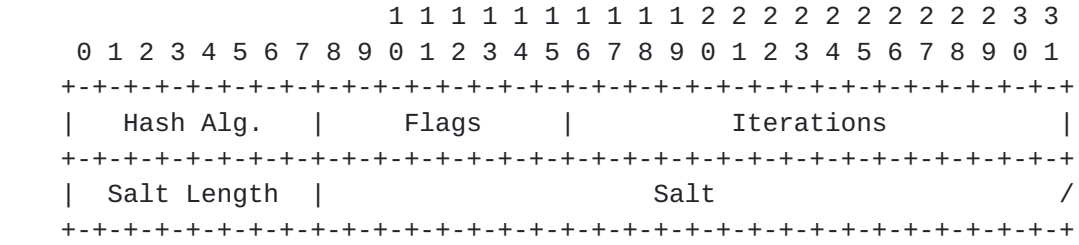
The Salt Length field defines the length of the salt in octets, ranging in value from 0 to 255.

4.1.5. Salt

The Salt field is appended to the original owner name before hashing.

4.2. NSEC3PARAM RDATA Wire Format

The RDATA of the NSEC3PARAM RR is as shown below:



Hash Algorithm is a single octet.

Flags field is a single octet.

Iterations is represented as a 16-bit unsigned integer, with the most significant bit first.

Salt Length is represented as an unsigned octet. Salt Length represents the length of the following Salt field in octets. If the value is zero, the Salt field is omitted.

Salt, if present, is encoded as a sequence of binary octets. The length of this field is determined by the preceding Salt Length field.

4.3. Presentation Format

The presentation format of the RDATA portion is as follows:

- The Hash Algorithm field is represented as an unsigned decimal integer. The value has a maximum of 255.

- The Flags field is represented as an unsigned decimal integer. The value has a maximum value of 255.

- The Iterations field is represented as an unsigned decimal integer. The value is between 0 and 65535, inclusive.

- The Salt Length field is not represented.

- The Salt field is represented as a sequence of case-insensitive hexadecimal digits. Whitespace is not allowed within the sequence. This field is represented as "-" (without the quotes) when the Salt Length field is zero.

5. Calculation of the Hash

The hash calculation uses three of the NSEC3 RDATA fields: Hash Algorithm, Salt, and Iterations.

Define H(x) to be the hash of x using the Hash Algorithm selected by the NSEC3 RR, k to be the number of Iterations, and || to indicate concatenation. Then define:

IH(salt, x, 0) = H(x || salt), and

IH(salt, x, k) = H(IH(salt, x, k-1) || salt), if k > 0

Then the calculated hash of an owner name is

IH(salt, owner name, iterations),

where the owner name is in the canonical form, defined as:

The wire format of the owner name where:

1. The owner name is fully expanded (no DNS name compression) and fully qualified;

2. All uppercase US-ASCII letters are replaced by the corresponding lowercase US-ASCII letters;

3. If the owner name is a wildcard name, the owner name is in its original unexpanded form, including the "*" label (no wildcard substitution);

This form is as defined in section 6.2 of [RFC4034].

The method to calculate the Hash is based on [RFC2898].

6. Opt-Out

In this specification, as in [RFC4033], [RFC4034] and [RFC4035], NS RRSets at delegation points are not signed and may be accompanied by a DS RRSet. With the Opt-Out bit clear, the security status of the child zone is determined by the presence or absence of this DS RRSet, cryptographically proven by the signed NSEC3 RR at the hashed owner name of the delegation. Setting the Opt-Out flag modifies this by allowing insecure delegations to exist within the signed zone without a corresponding NSEC3 RR at the hashed owner name of the delegation.

An Opt-Out NSEC3 RR is said to cover a delegation if the hash of the owner name or "next closer" name of the delegation is between the owner name of the NSEC3 RR and the next hashed owner name.

An Opt-Out NSEC3 RR does not assert the existence or non-existence of the insecure delegations that it may cover. This allows for the addition or removal of these delegations without recalculating or re-signing RRs in the NSEC3 RR chain. However, Opt-Out NSEC3 RRs do assert the (non)existence of other, authoritative RRSets.

An Opt-Out NSEC3 RR MAY have the same original owner name as an insecure delegation. In this case, the delegation is proven insecure by the lack of a DS bit in the type map and the signed NSEC3 RR does assert the existence of the delegation.

Zones using Opt-Out MAY contain a mixture of Opt-Out NSEC3 RRs and non-Opt-Out NSEC3 RRs. If an NSEC3 RR is not Opt-Out, there MUST NOT be any hashed owner names of insecure delegations (nor any other RRs) between it and the name indicated by the next hashed owner name in the NSEC3 RDATA. If it is Opt-Out, it MUST only cover hashed owner names or hashed "next closer" names of insecure delegations.

The effects of the Opt-Out flag on signing, serving, and validating responses are covered in following sections.

7. Authoritative Server Considerations

7.1. Zone Signing

Zones using NSEC3 must satisfy the following properties:

- Each owner name within the zone that owns authoritative RRSets MUST have a corresponding NSEC3 RR. Owner names that correspond to unsigned delegations MAY have a corresponding NSEC3 RR. However, if there is not a corresponding NSEC3 RR, there MUST be an Opt-Out NSEC3 RR that covers the "next closer" name to the delegation. Other non-authoritative RRs are not represented by NSEC3 RRs.

- Each empty non-terminal MUST have a corresponding NSEC3 RR, unless the empty non-terminal is only derived from an insecure delegation covered by an Opt-Out NSEC3 RR.

- The TTL value for any NSEC3 RR SHOULD be the same as the minimum TTL value field in the zone SOA RR.

- The Type Bit Maps field of every NSEC3 RR in a signed zone MUST indicate the presence of all types present at the original owner name, except for the types solely contributed by an NSEC3 RR itself. Note that this means that the NSEC3 type itself will never be present in the Type Bit Maps.

The following steps describe a method of proper construction of NSEC3 RRs. This is not the only such possible method.

1. Select the hash algorithm and the values for salt and iterations.

2. For each unique original owner name in the zone add an NSEC3 RR.

    * If Opt-Out is being used, owner names of unsigned delegations MAY be excluded.

    * The owner name of the NSEC3 RR is the hash of the original owner name, prepended as a single label to the zone name.

    * The Next Hashed Owner Name field is left blank for the moment.

    * If Opt-Out is being used, set the Opt-Out bit to one.

    * For collision detection purposes, optionally keep track of the original owner name with the NSEC3 RR.

    * Additionally, for collision detection purposes, optionally create an additional NSEC3 RR corresponding to the original owner name with the asterisk label prepended (i.e., as if a wildcard existed as a child of this owner name) and keep track of this original owner name. Mark this NSEC3 RR as temporary.

3. For each RRSet at the original owner name, set the corresponding bit in the Type Bit Maps field.

4. If the difference in number of labels between the apex and the original owner name is greater than 1, additional NSEC3 RRs need to be added for every empty non-terminal between the apex and the original owner name. This process may generate NSEC3 RRs with duplicate hashed owner names. Optionally, for collision detection, track the original owner names of these NSEC3 RRs and create temporary NSEC3 RRs for wildcard collisions in a similar fashion to step 1.

5. Sort the set of NSEC3 RRs into hash order.

6. Combine NSEC3 RRs with identical hashed owner names by replacing them with a single NSEC3 RR with the Type Bit Maps field consisting of the union of the types represented by the set of NSEC3 RRs. If the original owner name was tracked, then collisions may be detected when combining, as all of the matching NSEC3 RRs should have the same original owner name. Discard any possible temporary NSEC3 RRs.

7. In each NSEC3 RR, insert the next hashed owner name by using the value of the next NSEC3 RR in hash order. The next hashed owner name of the last NSEC3 RR in the zone contains the value of the hashed owner name of the first NSEC3 RR in the hash order.

8. Finally, add an NSEC3PARAM RR with the same Hash Algorithm, Iterations and Salt fields to the zone apex.

If a hash collision is detected, then a new salt has to be chosen and the signing process restarted.

7.2. Zone Serving

This specification modifies DNSSEC-enabled DNS responses generated by authoritative servers. In particular, it replaces the use of NSEC RRs in such responses with NSEC3 RRs.

In the following response cases, the NSEC RRs dictated by DNSSEC [RFC4035] are replaced with NSEC3 RRs that prove the same facts. Responses that would not contain NSEC RRs are unchanged by this specification.

When returning responses containing multiple NSEC3 RRs, all of the NSEC3 RRs MUST use the same hash algorithm, iteration, and salt values. The Flags field value MUST be either zero or one.

7.2.1. Closest Encloser Proof

For many NSEC3 responses a proof of the closest encloser is required. This is a proof that some ancestor of the QNAME is the closest encloser of QNAME.

This proof consists of (up to) two different NSEC3 RRs:

- An NSEC3 RR that matches the closest (provable) encloser.
- An NSEC3 RR that covers the "next closer" name to the closest encloser.

The first NSEC3 RR essentially proposes a possible closest encloser, and proves that the particular encloser does, in fact, exist. The second NSEC3 RR proves that the possible closest encloser is the closest, and proves that QNAME (and any ancestors between QNAME and the closest encloser) do not exist.

These NSEC3 RRs are collectively referred to as the "closest encloser proof" in the subsequent descriptions.

For example, the closest encloser proof for the nonexistent "alpha.beta.gamma.example." owner name might prove that "gamma.example." is the closest encloser. This response would contain the NSEC3 RR that matches "gamma.example.", and would also contain the NSEC3 RR that covers "beta.gamma.example." (which is the "next closer" name.)

It is possible, when using Opt-Out (Section 6), to not be able to prove the actual closest encloser because it is, or is part of an insecure delegation covered by an Opt-Out span. In this case, instead of proving the actual closest encloser, the closest provable encloser is used. That is, the closest enclosing authoritative name is used instead. In this case, the set of NSEC3 RRs used for this proof is referred to as the "closest provable encloser proof."

7.2.2. Name Error Responses

To prove the nonexistence of QNAME a closest encloser proof and an NSEC3 RR covering the (nonexistent) wildcard RR at the closest encloser MUST be included in the response. This collection of (up to) three NSEC3 RRs proves both that QNAME does not exist and that a wildcard that could have matched QNAME also does not exist.

For example, if "gamma.example." is the closest provable encloser to QNAME, then a NSEC3 RR covering "*.gamma.example." is included in the authority section of the response.

7.2.3. No Data Responses, QTYPE is not DS

The server MUST include the NSEC3 RR that matches QNAME. This NSEC3 RR MUST NOT have the bits corresponding to either the QTYPE or CNAME set in its Type Bit Maps field.

7.2.4. No Data Responses, QTYPE is DS

If there is an NSEC3 RR that matches QNAME, the server MUST return it in the response. The bits corresponding with DS and CNAME MUST NOT be set in the Type Bit Maps field of this NSEC3 RR.

If no NSEC3 RR matches QNAME, the server MUST return a closest provable encloser proof for QNAME. The NSEC3 RR that covers the "next closer" name MUST have the Opt-Out bit set (note that this is true by definition - if the Opt-Out bit is not set, something has gone wrong).

If a server is authoritative for both sides of a zone cut at QNAME, the server MUST return the proof from the parent side of the zone cut.

7.2.5. Wildcard No Data Responses

If there is a wildcard match for QNAME, but QTYPE is not present at that name, the response MUST include a closest encloser proof for QNAME and MUST include the NSEC3 RR that matches the wildcard. This combination proves both that QNAME itself does not exist and that a wildcard that matches QNAME does exist. Note that the closest encloser to QNAME MUST be the immediate ancestor of the wildcard RR (if this is not the case, then something has gone wrong).

7.2.6. Wildcard Answer Responses

If there is a wildcard match for QNAME and QTYPE, then, in addition to the expanded wildcard RRSet returned in the answer section of the response, proof that the wildcard match was valid must be returned.

This proof is accomplished by proving that both QNAME does not exist, and that the closest encloser of the QNAME and the immediate ancestor of the wildcard are the same (i.e., the correct wildcard matched).

To this end, the NSEC3 RR that covers the "next closer" name of the immediate ancestor of the wildcard MUST be returned. It is not necessary to return an NSEC3 RR that matches the closest encloser, as the existence of this closest encloser is proven by the presence of the expanded wildcard in the response.

7.2.7. Referrals to Unsigned Subzones

If there is an NSEC3 RR that matches the delegation name, then that NSEC3 RR MUST be included in the response. The DS bit in the type bit maps of the NSEC3 RR MUST NOT be set.

If the zone is Opt-Out, then there may not be an NSEC3 RR corresponding to the delegation. In this case, the closest provable encloser proof MUST be included in the response. The included NSEC3 RR that covers the "next closer" name for the delegation MUST have the Opt-Out flag set to one. (Note that this will be the case unless something has gone wrong).

7.2.8. Responding to Queries for NSEC3 Owner Names

The owner names of NSEC3 RRs are not represented in the NSEC3 RR chain like other owner names. As a result, each NSEC3 owner name is covered by another NSEC3 RR, effectively negating the existence of the NSEC3 RR. This is a paradox, since the existence of an NSEC3 RR can be proven by its RRSIG RRSet.

If the following conditions are all true:

o The QNAME equals the owner name of an existing NSEC3 RR, and

o No RR types exist at the QNAME, nor at any descendant of QNAME.

Then the response MUST be constructed as a Name Error response (Section 7.2.2). Or, in other words, the authoritative name server will act, as if the owner name of the NSEC3 RR did not exist.

Note that NSEC3 RRs are returned as a result of an AXFR or IXFR query.

7.2.9. Server Response to a Run-time Collision

If the hash of a non-existing QNAME collides with the owner name of an existing NSEC3 RR, then the server will be unable to return a response that proves that QNAME does not exist. In this case, the server MUST return a response with an RCODE of 2 (server failure).

Note that with the hash algorithm specified in this document, SHA-1, such collisions are highly unlikely.

7.3. Secondary Servers

Secondary servers (and perhaps other entities) need to reliably determine which NSEC3 parameters (i.e., hash, salt and iterations)

are present at every hashed owner name, in order to be able to choose an appropriate set of NSEC3 RRs for negative responses. This is indicated by an NSEC3PARAM RR present at the zone apex.

If there are multiple NSEC3PARAM RRs present, there are multiple valid NSEC3 chains present. The server must choose one of them, but may use any criteria to do so.

7.4. Zones Using Unknown Hash Algorithms

Zones that are signed according to this specification, but are using an unrecognized NSEC3 hash algorithm value, cannot be effectively served. Such zones SHOULD be rejected when loading. Servers SHOULD respond with RCODE=2 (server failure) responses when handling queries that would fall under such zones.

7.5. Dynamic Update

A zone signed using NSEC3 may accept dynamic updates [RFC2136]. However, NSEC3 introduces some special considerations for dynamic updates.

Adding and removing names in a zone MUST account for the creation or removal of empty non-terminals.

- When removing a name with a corresponding NSEC3 RR, any NSEC3 RRs corresponding to empty non-terminals created by that name MUST be removed. Note that more than one name may be asserting the existence of a particular empty non-terminal.

- When adding a name that requires adding an NSEC3 RR, NSEC3 RRs MUST also be added for any empty non-terminals that are created. That is, if there is not an existing NSEC3 RR matching an empty non-terminal, it must be created and added.

The presence of Opt-Out in a zone means that some additions or delegations of names will not require changes to the NSEC3 RRs in a zone.

- When removing a delegation RRSet, if that delegation does not have a matching NSEC3 RR, then it was opted out. In this case, nothing further needs to be done.

- When adding a delegation RRSet, if the "next closer" name of the delegation is covered by an existing Opt-Out NSEC3 RR, then the delegation MAY be added without modifying the NSEC3 RRs in the zone.

The presence of Opt-Out in a zone means that when adding or removing NSEC3 RRs, the value of the Opt-Out flag that should be set in new or modified NSEC3 RRs is ambiguous. Servers SHOULD follow this set of basic rules to resolve the ambiguity.

The central concept to these rules is that the state of the Opt-Out flag of the covering NSEC3 RR is preserved.

- When removing an NSEC3 RR, the value of the Opt-Out flag for the previous NSEC3 RR (the one whose next hashed owner name is modified) should not be changed.

- When adding an NSEC3 RR, the value of the Opt-Out flag is set to the value of the Opt-Out flag of the NSEC3 RR that previously covered the owner name of the NSEC3 RR. That is, the now previous NSEC3 RR.

If the zone in question is consistent with its use of the Opt-Out flag (that is, all NSEC3 RRs in the zone have the same value for the flag) then these rules will retain that consistency. If the zone is not consistent in the use of the flag (i.e., a partially Opt-Out zone), then these rules will not retain the same pattern of use of the Opt-Out flag.

For zones that partially use the Opt-Out flag, if there is a logical pattern for that use, the pattern could be maintained by using a local policy on the server.

8. Validator Considerations

8.1. Responses with Unknown Hash Types

A validator MUST ignore NSEC3 RRs with unknown hash types. The practical result of this is that responses containing only such NSEC3 RRs will generally be considered bogus.

8.2. Verifying NSEC3 RRs

A validator MUST ignore NSEC3 RRs with a Flag fields value other than zero or one.

A validator MAY treat a response as bogus if the response contains NSEC3 RRs that contain different values for hash algorithm, iterations, or salt from each other for that zone.

8.3. Closest Encloser Proof

In order to verify a closest encloser proof, the validator MUST find the longest name, X, such that

- X is an ancestor of QNAME that is matched by an NSEC3 RR present in the response. This is a candidate for the closest encloser. And:

- The name one label longer than X (but still an ancestor of--or equal to--QNAME) is covered by an NSEC3 RR present in the response.

One possible algorithm for verifying this proof is as follows:

1. Set SNAME=QNAME. Clear the flag.

2. Check whether SNAME exists:

    * If there is no NSEC3 RR in the response that matches SNAME (i.e., an NSEC3 RR whose owner name is the same as the hash of SNAME, prepended as a single label to the zone name), clear the flag.

    * If there is an NSEC3 RR in the response that covers SNAME, set the flag.

    * If there is a matching NSEC3 RR in the response and the flag was set, then the proof is complete, and SNAME is the closest encloser.

    * If there is a matching NSEC3 RR in the response, but the flag is not set, then the response is bogus.

3. Truncate SNAME by one label from the left, go to step 2.

Once the closest encloser has been discovered, the validator MUST check that the NSEC3 RR that has the closest encloser as the original owner name is from the proper zone. The DNAME type bit must not be set and the NS type bit may only be set if the SOA type bit is set. If this is not the case, it would be an indication that an attacker is using them to falsely deny the existence of RRs for which the server is not authoritative.

In the following descriptions, the phrase "a closest (provable) encloser proof for X" means that the algorithm above (or an equivalent algorithm) proves that X does not exist by proving that an ancestor of X is its closest encloser.

8.4. Validating Name Error Responses

A validator MUST verify that there is a closest encloser proof for QNAME present in the response and that there is an NSEC3 RR that covers the wildcard at the closest encloser (i.e., the name formed by prepending the asterisk label to the closest encloser.)

8.5. Validating No Data Responses, QTYPE is not DS

The validator MUST verify that an NSEC3 RR that matches QNAME is present and that both the QTYPE and the CNAME type are not set in its Type Bit Maps field.

Note that this test also covers the case where the NSEC3 RR exists because it corresponds to an empty non-terminal, in which case the NSEC3 RR will have an empty Type Bit Maps field.

8.6. Validating No Data Responses, QTYPE is DS

If there is an NSEC3 RR that matches QNAME present in the response, then that NSEC3 RR MUST NOT have the bits corresponding to DS and CNAME set in its Type Bit Maps field.

If there is no such NSEC3 RR, then the validator MUST verify that a closest provable encloser proof for QNAME is present in the response, and that the NSEC3 RR that covers the "next closer" name has the Opt-Out bit set.

8.7. Validating Wildcard No Data Responses

The validator MUST verify a closest encloser proof for QNAME and MUST find an NSEC3 RR present in the response that matches the wildcard name generated by prepending the asterisk label to the closest encloser. Furthermore, the bits corresponding to both QTYPE and CNAME MUST NOT be set in the wildcard matching NSEC3 RR.

8.8. Validating Wildcard Answer Responses

The verified wildcard answer RRSet in the response provides the validator with a (candidate) closest encloser for QNAME. This closest encloser is the immediate ancestor to the generating wildcard.

Validators MUST verify that there is an NSEC3 RR that covers the "next closer" name to QNAME present in the response. This proves that QNAME itself did not exist and that the correct wildcard was used to generate the response.

8.9. Validating Referrals to Unsigned Subzones

The delegation name in a referral is the owner name of the NS RRSet present in the authority section of the referral response.

If there is an NSEC3 RR present in the response that matches the delegation name, then the validator MUST ensure that the NS bit is set and that the DS bit is not set in the Type Bit Maps field of the NSEC3 RR. The validator MUST also ensure that the NSEC3 RR is from the correct (i.e., parent) zone. This is done by ensuring that the SOA bit is not set in the Type Bit Maps field of this NSEC3 RR.

Note that the presence of an NS bit implies the absence of a DNAME bit, so there is no need to check for the DNAME bit in the Type Bit Maps field of the NSEC3 RR.

If there is no NSEC3 RR present that matches the delegation name, then the validator MUST verify a closest provable encloser proof for the delegation name. The validator MUST verify that the Opt-Out bit is set in the NSEC3 RR that covers the "next closer" name to the delegation name.

9. Resolver Considerations

9.1. NSEC3 Resource Record Caching

Caching resolvers MUST be able to retrieve the appropriate NSEC3 RRs when returning responses that contain them. In DNSSEC [RFC4035], in many cases it is possible to find the correct NSEC RR to return in a response by name (e.g., when returning a referral, the NSEC RR will always have the same owner name as the delegation.) With this specification, that will not be true, nor will a cache be able to calculate the name(s) of the appropriate NSEC3 RR(s). Implementations may need to use new methods for caching and retrieving NSEC3 RRs.

9.2. Use of the AD Bit

The AD bit, as defined by [RFC4035], MUST NOT be set when returning a response containing a closest (provable) encloser proof in which the NSEC3 RR that covers the "next closer" name has the Opt-Out bit set.

This rule is based on what this closest encloser proof actually proves: names that would be covered by the Opt-Out NSEC3 RR may or may not exist as insecure delegations. As such, not all the data in responses containing such closest encloser proofs will have been cryptographically verified, so the AD bit cannot be set.

10. Special Considerations

10.1. Domain Name Length Restrictions

Zones signed using this specification have additional domain name length restrictions imposed upon them. In particular, zones with names that, when converted into hashed owner names, exceed the 255 octet length limit imposed by [RFC1035] cannot use this specification.

The actual maximum length of a domain name in a particular zone depends on both the length of the zone name (versus the whole domain name) and the particular hash function used.

As an example, SHA-1 produces a hash of 160 bits. The base-32 encoding of 160 bits results in 32 characters. The 32 characters are prepended to the name of the zone as a single label, which includes a length field of a single octet. The maximum length of the zone name, when using SHA-1, is 222 octets (255 - 33).

10.2. DNAME at the Zone Apex

The DNAME specification [RFC2672] section 3 has a 'no-descendants' limitation. If a DNAME RR is present at node N, there MUST be no data at any descendant of N.

If N is the apex of the zone, there will be NSEC3 and RRSIG types present at descendants of N. This specification updates the DNAME specification to allow NSEC3 and RRSIG types at descendants of the apex regardless of the existence of DNAME at the apex.

10.3. Iterations

Setting the number of iterations used allows the zone owner to choose the cost of computing a hash, and so the cost of generating a dictionary. Note that this is distinct from the effect of salt, which prevents the use of a single precomputed dictionary for all time.

Obviously the number of iterations also affects the zone owner's cost of signing and serving the zone as well as the validator's cost of verifying responses from the zone. We therefore impose an upper limit on the number of iterations. We base this on the number of iterations that approximates the cost of verifying an RRSet.

The limits, therefore, are based on the size of the smallest zone signing key, rounded up to the nearest table value (or rounded down if the key is larger than the largest table value.)

A zone owner MUST NOT use a value higher than shown in the table below for iterations for the given key size. A resolver MAY treat a response with a higher value as insecure, after the validator has verified that the signature over the NSEC3 RR is correct.

Key Size	Iterations
1024	150
2048	500
4096	2,500

This table is based on an approximation of the ratio between the cost of an SHA-1 calculation and the cost of an RSA verification for keys of size 1024 bits (150 to 1), 2048 bits (500 to 1) and 4096 bits (2500 to 1).

The ratio between SHA-1 calculation and DSA verification is higher (1500 to 1 for keys of size 1024). A higher iteration count degrades performance, while DSA verification is already more expensive than RSA for the same key size. Therefore the values in the table MUST be used independent of the key algorithm.

10.4. Transitioning a Signed Zone from NSEC to NSEC3

When transitioning an already signed and trusted zone to this specification, care must be taken to prevent client validation failures during the process.

The basic procedure is as follows:

1. Transition all DNSKEYs to DNSKEYs using the algorithm aliases described in Section 2. The actual method for safely and securely changing the DNSKEY RRSet of the zone is outside the scope of this specification. However, the end result MUST be that all DS RRs in the parent use the specified algorithm aliases.

   After this transition is complete, all NSEC3-unaware clients will treat the zone as insecure. At this point, the authoritative server still returns negative and wildcard responses that contain NSEC RRs.

2. Add signed NSEC3 RRs to the zone, either incrementally or all at once. If adding incrementally, then the last RRSet added MUST be the NSEC3PARAM RRSet.

3. Upon the addition of the NSEC3PARAM RRSet, the server switches to serving negative and wildcard responses with NSEC3 RRs according to this specification.

4. Remove the NSEC RRs either incrementally or all at once.

10.5. Transitioning a Signed Zone From NSEC3 to NSEC

To safely transition back to a DNSSEC [RFC4035] signed zone, simply reverse the procedure above:

1. Add NSEC RRs incrementally or all at once.

2. Remove the NSEC3PARAM RRSet. This will signal the server to use the NSEC RRs for negative and wildcard responses.

3. Remove the NSEC3 RRs either incrementally or all at once.

4. Transition all of the DNSKEYs to DNSSEC algorithm identifiers. After this transition is complete, all NSEC3-unaware clients will treat the zone as secure.

11. IANA Considerations

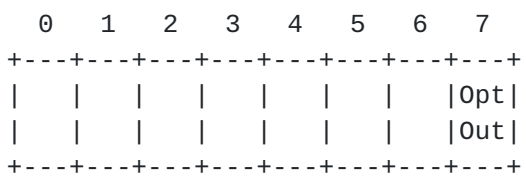
Although the NSEC3 and NSEC3PARAM RR formats include a hash algorithm parameter, this document does not define a particular mechanism for safely transitioning from one NSEC3 hash algorithm to another. When specifying a new hash algorithm for use with NSEC3, a transition mechanism MUST also be defined.

This document updates the IANA registry "DOMAIN NAME SYSTEM PARAMETERS" [http://www.iana.org/assignments/dns-parameters] in sub-registry "TYPES", by defining two new types. Section 3 defines the NSEC3 RR type NN, (value 50 suggested). Section 4 defines the NSEC3PARAM RR type MM (value 51 suggested).

This document updates the IANA registry "DNS SECURITY ALGORITHM NUMBERS - per [RFC4035]" http://www.iana.org/assignments/dns-sec-alg-numbers]. Section 2 defines the aliases DSA-NSEC3-SHA1 (XX) and RSASHA1-NSEC3-SHA1 (YY) for respectively existing registrations DSA and RSASHA1 in combination with NSEC3 hash algorithm SHA1.

Since these algorithm numbers are aliases for existing DNSKEY algorithm numbers, the flags that exist for the original algorithm are valid for the alias algorithm.

This document creates a new IANA registry for NSEC3 flags. This registry should be named "DNSSEC NSEC3 Flags". The initial contents of this registry are:

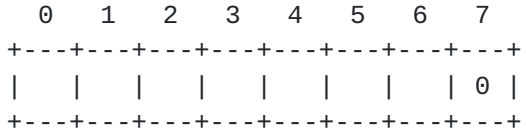


bit 7 is the Opt-Out flag.

bits 0 - 6 are available for assignment.

Assignment of additional NSEC3 Flags in this registry requires IETF Standards Action [RFC2434].

This document creates a new IANA registry for NSEC3PARAM flags. This registry should be named "DNSSEC NSEC3PARAM Flags". The initial contents of this registry are:



bit 7 is reserved and must be 0.

bits 0 - 6 are available for assignment.

Assignment of additional NSEC3PARAM Flags in this registry requires IETF Standards Action [RFC2434].

Finally, this document creates a new IANA registry for NSEC3 hash algorithms. This registry should be named "DNSSEC NSEC3 Hash Algorithms". The initial contents of this registry are:

0 is Reserved

1 is SHA-1.

2-255 Available for assignment

Assignment of additional NSEC3 hash algorithms in this registry requires IETF Standards Action [RFC2434].

12. Security Considerations

12.1. Hashing Considerations

12.1.1. Dictionary Attacks

The NSEC3 RRs are still susceptible to dictionary attacks (i.e. the attacker retrieves all the NSEC3 RRs, then calculates the hashes of all likely domain names, comparing against the hashes found in the NSEC3 RRs, and thus enumerating the zone). These are substantially more expensive than enumerating the original NSEC RRs would have been, and in any case, such an attack could also be used directly against the name server itself by performing queries for all likely names, though this would obviously be more detectable. The expense of this off-line attack can be chosen by setting the number of iterations in the NSEC3 RR.

Zones are also susceptible to a pre-calculated dictionary attack -- that is, a list of hashes for all likely names is computed once, then NSEC3 RR is scanned periodically and compared against the precomputed hashes. This attack is prevented by changing the salt on a regular basis.

The salt SHOULD be at least 64 bits long and unpredictable, so that an attacker cannot anticipate the value of the salt and compute the next set of dictionaries before the zone is published.

12.1.2. Collisions

Hash collisions between QNAME and the owner name of an NSEC3 RR may occur. When they do, it will be impossible to prove the non-existence of the colliding QNAME. However, with SHA-1, this is highly unlikely (on the order of 1 in 2^160). Note that DNSSEC already relies on the presumption that a cryptographic hash function is second pre-image resistant, since these hash functions are used for generating and validating signatures and DS RRs.

12.1.3. Transitioning to a New Hash Algorithm

Although the NSEC3 and NSEC3PARAM RR formats include a hash algorithm parameter, this document does not define a particular mechanism for safely transitioning from one NSEC3 hash algorithm to another. When specifying a new hash algorithm for use with NSEC3, a transition mechanism MUST also be defined. It is possible that the only practical and palatable transition mechanisms may require an intermediate transition to an insecure state, or to a state that uses NSEC records instead of NSEC3.

12.1.4. Using High Iteration Values

Since validators should treat responses containing NSEC3 RRs with high iteration values as insecure, presence of just one signed NSEC3 RR with a high iteration value in a zone provides attackers with a possible downgrade attack.

The attack is simply to remove any existing NSEC3 RRs from a response, and replace or add a single (or multiple) NSEC3 RR that uses a high iterations value to the response. Validators will then be forced to treat the response as insecure. This attack would be effective only when all of following conditions are met:

- There is at least one signed NSEC3 RR that uses a high iterations value present in the zone.

- The attacker has access to one or more of these NSEC3 RRs. This is trivially true when the NSEC3 RRs with high iterations values are being returned in typical responses, but may also be true if the attacker can access the zone via AXFR or IXFR queries, or any other methodology.

Using a high number of iterations also introduces an additional denial-of-service opportunity against servers, since servers must calculate several hashes per negative or wildcard response.

12.2. Opt-Out Considerations

The Opt-Out Flag (O) allows for unsigned names, in the form of delegations to unsigned zones, to exist within an otherwise signed zone. All unsigned names are, by definition, insecure, and their validity or existence cannot be cryptographically proven.

In general:

- Resource records with unsigned names (whether existing or not) suffer from the same vulnerabilities as RRs in an unsigned zone. These vulnerabilities are described in more detail in [RFC3833] (note in particular sections 2.3, "Name Chaining" and 2.6, "Authenticated Denial of Domain Names").

- Resource records with signed names have the same security whether or not Opt-Out is used.

Note that with or without Opt-Out, an insecure delegation may be undetectably altered by an attacker. Because of this, the primary difference in security when using Opt-Out is the loss of the ability to prove the existence or nonexistence of an insecure delegation

within the span of an Opt-Out NSEC3 RR.

In particular, this means that a malicious entity may be able to insert or delete RRs with unsigned names. These RRs are normally NS RRs, but this also includes signed wildcard expansions (while the wildcard RR itself is signed, its expanded name is an unsigned name).

Note that being able to add a delegation is functionally equivalent to being able to add any RR type: an attacker merely has to forge a delegation to name server under his/her control and place whatever RRs needed at the subzone apex.

While in particular cases, this issue may not present a significant security problem, in general it should not be lightly dismissed. Therefore, it is strongly RECOMMENDED that Opt-Out be used sparingly. In particular, zone signing tools SHOULD NOT default to using Opt-Out, and MAY choose to not support Opt-Out at all.

12.3. Other Considerations

Walking the NSEC3 RRs will reveal the total number of RRs in the zone (plus empty non-terminals), and also what types there are. This could be mitigated by adding dummy entries, but certainly an upper limit can always be found.

13. References

13.1. Normative References

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[RFC2672] Crawford, M., "Non-Terminal DNS Name Redirection", RFC 2672, August 1999.

[RFC2898] Kaliski, B., "PKCS #5: Password-Based Cryptography Specification Version 2.0", RFC 2898, September 2000.

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[RFC4592] Lewis, E., "The Role of Wildcards in the Domain Name

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Appendix A. Example Zone

This is a zone showing its NSEC3 RRs. They can also be used as test vectors for the hash algorithm.

The overall TTL and class are specified in the SOA RR, and are subsequently omitted for clarity.

The zone is preceded by a list that contains the hashes of the original ownernames.

```
; H(example)       = 0p9mhaveqvm6t7vbl5lop2u3t2rp3tom
; H(a.example)     = 35mthgpgcu1qg68fab165klnsnk3dpvl
; H(ai.example)    = gjeqe526plbf1g8mklp59enfd789njgi
; H(ns1.example)   = 2t7b4g4vsa5smi47k61mv5bv1a22bojr
; H(ns2.example)   = q04jkcevqvmu85r014c7dkba38o0ji5r
; H(w.example)     = k8udemvp1j2f7eg6jebps17vp3n8i58h
; H(*.w.example)   = r53bq7cc2uvmubfu5ocmm6pers9tk9en
; H(x.w.example)   = b4um86eghhds6nea196smvmlo4ors995
; H(y.w.example)   = ji6neoaepv8b5o6k4ev33abha8ht9fgc
; H(x.y.w.example) = 2vptu5timamqttgl4luu9kg21e0aor3s
; H(xx.example)    = t644ebqk9bibcna874givr6joj62mlhv
; H(2t7b4g4vsa5smi47k61mv5bv1a22bojr.example)
;                  = kohar7mbb8dc2ce8a9qvl8hon4k53uhi
example. 3600  IN SOA  ns1.example. bugs.x.w.example. 1 3600 300 (
                       3600000 3600 )
               RRSIG   SOA 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
                       hNIkW1xzn+c+9P3W7PUVVptI72xEmOtn+eqQ
                       ux0BE7Pfc6ikx4m7ivOVWETjbwHjqfY0X5G+
                       rynLZNqsbLm40Q== )
               NS      ns1.example.
               NS      ns2.example.
               RRSIG   NS 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
                       D9+iBwcbeKL5+TorTfYn4/pLr2lSFwyGYCyM
                       gfq4TpFaZpxrCJPLxHbKjdkR18jAt7+SR7B5
                       JpiZcff2Cj2B0w== )
               MX      1 xx.example.
               RRSIG   MX 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
```

```
                        jsGuTpXTTrZHzUKnViUpJ8YyGNpDd6n/sy2g
                        HnSC0nj2jPxTC5VENLo3GxSpCSA5DlAz57p+
                        RllUJk3DWktkjw== )
                DNSKEY  256 3 133 (
                        AQO0gEmbZUL6xbD/xQczHbnwYnf+jQjwz/sU
                        5k44rHTt0Ty+3aOdYoome9TjGMhwkkGby1TL
                        ExXT48OGGdbfIme5 )
                DNSKEY  257 3 133 (
                        AQOnsGyJvywVjYmiLbh0EwIRuWYcDiB/8blX
                        cpkoxtpe19Oicv6Zko+8brVsTMeMOpcUeGB1
                        zsYKWJ7BvR2894hX )
                RRSIG   DNSKEY 133 1 3600 20150420235959 (
                        20051021000000 22088 example.
                        Xpo9ptByXb8M1JR1i0KuRmKGc/YeOLcc6Ptn
                        RJOx6ADLSL2mU6AYX5tAJRMTKTXk6waLIaxu
                        liqUBOkCjLUZMw== )
                NSEC3PARAM 1 0 12 aabbccdd
                RRSIG   NSEC3PARAM 133 1 3600 20150420235959 (
                        20051021000000 62827 example.
                        pwUfI8cF9JJn5dTWI24nJy92HYrRPtPgHtgi
                        jAlKx9QELe68pLKuGU/8Sf87kyV7yMXJYVhf
                        HIB8wmHllsqM+g== )
0p9mhaveqvm6t7vbl5lop2u3t2rp3tom.example. NSEC3 1 1 12 aabbccdd (
                        2t7b4g4vsa5smi47k61mv5bv1a22bojr MX DNSKEY NS
                        SOA NSEC3PARAM RRSIG )
                RRSIG   NSEC3 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        rn2tv99+9StXbc7JaEnjT1+8I8f2vVOMOIbF
                        xzlrn94lQLxEOYxQR4SrxDRP4/fC54Jui0Ix
                        4eI9tMfaTVgehQ== )
2t7b4g4vsa5smi47k61mv5bv1a22bojr.example. A 192.0.2.127
                RRSIG   A 133 2 3600 20150420235959 20051021000000 (
                        62827 example.
                        GtJTFlvT5eYaK3rNUPQjpCKoIefvWZxQrDxU
                        jYsmoIWdLOVOuD5ZSDDQA3anDctOHdA/XbXn
                        o2uyWso1OzVlgg== )
                NSEC3   1 1 12 aabbccdd (
                        2vptu5timamqttgl4luu9kg21e0aor3s A RRSIG )
                RRSIG   NSEC3 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        fJER1Z3nGoN0HmZm99lqNLSpIf7jLXTMoGm2
                        k4gIwlc0R4DztJp6Sq37OV6XnGdre4MfgRpB
                        mAcgpPWC5A5eiw== )
2vptu5timamqttgl4luu9kg21e0aor3s.example. NSEC3 1 1 12 aabbccdd (
                        35mthgpgcu1qg68fab165klnsnk3dpvl MX RRSIG )
                RRSIG   NSEC3 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        os2mHXmu3bsaWu0XzT1R61fHL1a3LvyQ6bKq
```

```
                        oKokSyJ0ch0jBqEdxP2BqUe0WW0ja19fQGCG
                        8Bc+L9MbAeYsrw== )
   35mthgpgcu1qg68fab165klnsnk3dpvl.example. NSEC3 1 1 12 aabbccdd (
                        b4um86eghhds6nea196smvmlo4ors995 NS DS RRSIG )
                RRSIG   NSEC3 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        QrjOpXVIvodCw0O8uPMNA+yEeS/o3KKkEIPX
                        r5DoEShq2hymAsRTc/t9BvRKpcSTExyc5m3T
                        vYN3GgN0W/0WHQ== )
   a.example.   NS      ns1.a.example.
                NS      ns2.a.example.
                DS      58470 5 1 (
                        3079F1593EBAD6DC121E202A8B766A6A4837206C )
                RRSIG   DS 133 2 3600 20150420235959 20051021000000 (
                        62827 example.
                        qxw4j5LNe70UDu121YqAaqQjyjYbdKNd/4bE
                        nH0kjQswuiGs9EuArCBhcWocWQDBku+A4HMH
                        JdLqJr5p4JctLg== )
   ns1.a.example. A     192.0.2.5
   ns2.a.example. A     192.0.2.6
   ai.example.  A       192.0.2.9
                RRSIG   A 133 2 3600 20150420235959 20051021000000 (
                        62827 example.
                        qfXAvKr5o3Jixy5KXnVMEhABo3DDHYSR5+Ag
                        lVxWCExWGMokdkafjW8Hb54+GrOFp/xmDoj5
                        BXfXAqURwLqznA== )
                HINFO   "KLH-10" "ITS"
                RRSIG   HINFO 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        BuDv+No06VEcIsEnvBdjdKm6kxQGrhOgKEKb
                        Gsb8DJRjY7Lia+YG2//s6OlOIfxPmLlLiYpA
                        i3q2sEjTJhocGQ== )
                AAAA    2001:db8:0:0:0:0:f00:baa9
                RRSIG   AAAA 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        m65zc0A16Xbx3jYb0t5vPwMzE2xS15mKh76M
                        hSuKfiFVhBFcQ9IilEM0pXnLzt3ozrM/3X0x
                        2ruyuN0zC+PABA== )
   b4um86eghhds6nea196smvmlo4ors995.example. NSEC3 1 1 12 aabbccdd (
                        gjeqe526plbf1g8mklp59enfd789njgi MX RRSIG )
                RRSIG   NSEC3 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        GWDmUk8Sv0dxy/UZFol4Ss7Wz3wBiongcnVy
                        strNODWwdnoO9z6pDh8JLk58ExfEgXm79i4b
                        Ma6C/s/bkk1LvA== )
   c.example.   NS      ns1.c.example.
                NS      ns2.c.example.
   ns1.c.example. A     192.0.2.7
```

```
   ns2.c.example. A       192.0.2.8
   gjeqe526plbf1g8mklp59enfd789njgi.example. NSEC3 1 1 12 aabbccdd (
                          ji6neoaepv8b5o6k4ev33abha8ht9fgc HINFO A AAAA
                          RRSIG )
                  RRSIG   NSEC3 133 2 3600 20150420235959 (
                          20051021000000 62827 example.
                          DCkJyHQSgA9HNA2AQUENLfmAdAqQ4iIcuqZV
                          pF2x/i1UyWIBuV25iESs4hhwRVIU5uMZaBGE
                          lNwi0H6f66BpOA== )
   ji6neoaepv8b5o6k4ev33abha8ht9fgc.example. NSEC3 1 1 12 aabbccdd (
                          k8udemvp1j2f7eg6jebps17vp3n8i58h )
                  RRSIG   NSEC3 133 2 3600 20150420235959 (
                          20051021000000 62827 example.
                          fvKWkD3lXNLyUn0/gN+i3Z8301oRujSFFrJy
                          SfAPS2Q1bw1Q5eQoy7IE+ZtUVO15ha6C9cUh
                          CArJyEk247MADA== )
   k8udemvp1j2f7eg6jebps17vp3n8i58h.example. NSEC3 1 1 12 aabbccdd (
                          kohar7mbb8dc2ce8a9qvl8hon4k53uhi )
                  RRSIG   NSEC3 133 2 3600 20150420235959 (
                          20051021000000 62827 example.
                          IKJfInxfypsDiXKgT6HDvCPEIBu9lZCc0CWl
                          c46+Gj/Jrg1NBkSJkKMjCERp1HT8tKU+zYp5
                          Kyio/cddEaa5Gg== )
   kohar7mbb8dc2ce8a9qvl8hon4k53uhi.example. NSEC3 1 1 12 aabbccdd (
                          q04jkcevqvmu85r014c7dkba38o0ji5r A RRSIG )
                  RRSIG   NSEC3 133 2 3600 20150420235959 (
                          20051021000000 62827 example.
                          j+XRmZBLAu/s0Ah49x7SChH2VsXAMD3nJE0m
                          UEjzrjFxkdjhdIAFNlvPMn8gy6mIVe5eNc3r
                          4+2KaJUEJhyUEQ== )
   ns1.example.   A       192.0.2.1
                  RRSIG   A 133 2 3600 20150420235959 20051021000000 (
                          62827 example.
                          ratEKfeWD/pJJHO/XqEINvOp3so7pn9Pphxn
                          fRiCOVsa527M/ucRcQqGYCF0CN4jAXhW+6BS
                          ZzT0om+VdioRmg== )
   ns2.example.   A       192.0.2.2
                  RRSIG   A 133 2 3600 20150420235959 20051021000000 (
                          62827 example.
                          mW/DJMbQyD5y5C+a70vWyIWZyQ+Xg1zzkWHX
                          w3jfqmePgpdJnMrpGOcRIpy5irCFWiCwTp2o
                          cPT+k0ccpxtkLQ== )
   q04jkcevqvmu85r014c7dkba38o0ji5r.example. NSEC3 1 1 12 aabbccdd (
                          r53bq7cc2uvmubfu5ocmm6pers9tk9en A RRSIG )
                  RRSIG   NSEC3 133 2 3600 20150420235959 (
                          20051021000000 62827 example.
                          ktIfH8VRjEKYPB0Qf4EdTuSlYn4DVSRRaGWc
                          kVGmKzreEU5zs97CL8OQSa6C0JZX2yMBXijC
```

```
                        Wu6EvgCXrflgiQ== )
   r53bq7cc2uvmubfu5ocmm6pers9tk9en.example. NSEC3 1 1 12 aabbccdd (
                        t644ebqk9bibcna874givr6joj62mlhv MX RRSIG )
                RRSIG   NSEC3 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        SzeyaiFOy9dFO1RKHAK4uVCb5GF4rNnxFMXu
                        6hpM44cmLcDgshlnG1CwkkcihfKOiPIBWd7I
                        bGhsbhqrBrn5Dg== )
   t644ebqk9bibcna874givr6joj62mlhv.example. NSEC3 1 1 12 aabbccdd (
                        0p9mhaveqvm6t7vbl5lop2u3t2rp3tom HINFO A AAAA
                        RRSIG )
                RRSIG   NSEC3 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        hkULY2VaEg8lvI0cf+YkUB0rvOORGMGJnfms
                        h2OecPBYfI9XGUBvqgIyNpNpK3nIFoW/VNO+
                        3H+6P1NzivDmog== )
   *.w.example.   MX      1 ai.example.
                RRSIG   MX 133 2 3600 20150420235959 20051021000000 (
                        62827 example.
                        DnT0Y6dRBM8f3v8HdKmZUsGVkXh+b+htujCR
                        c423x6c8erEMGVnxcrmcrZ53qGXcMYJ+TDkq
                        a7Xfz/f9xzvSTw== )
   x.w.example.   MX      1 xx.example.
                RRSIG   MX 133 3 3600 20150420235959 20051021000000 (
                        62827 example.
                        BLSDMos8kYR7+2U7iwwdqdhU82hzq0s57xtw
                        F08tWU/d19jrNO6LdWfBL/FJ8zL8ZpEjhh6b
                        8cj0f5yQOUyShw== )
   x.y.w.example. MX      1 xx.example.
                RRSIG   MX 133 4 3600 20150420235959 20051021000000 (
                        62827 example.
                        GPzELyUCxrnyep8uMcqthUXjTqYBmgeaveb9
                        2vQgzUyPLLamNN/YqMHr6tGQNxeMAhclxUSQ
                        eoCggUBVhFfB1Q== )
   xx.example.    A       192.0.2.10
                RRSIG   A 133 2 3600 20150420235959 20051021000000 (
                        62827 example.
                        Sz+fPqY8II1VDq+dY48Q40dq1aoBR2RAuhKg
                        QNKXEYcULtJo/hxxfEAkJSNBKU5QnHpnnT9L
                        jqaSdob7ZhdxHg== )
                HINFO   "KLH-10" "TOPS-20"
                RRSIG   HINFO 133 2 3600 20150420235959 (
                        20051021000000 62827 example.
                        YJFwmD0By0NpGEvO1nE1ZTH10XrmpKnVuAEI
                        cAxLLHyPs3qyGQdDEG7sQX5+PfiOGZrNmZef
                        8NgQhW8kGEgN1Q== )
                AAAA    2001:db8:0:0:0:0:f00:baaa
                RRSIG   AAAA 133 2 3600 20150420235959 (
```

```
                        20051021000000 62827 example.
                        VAJBlXoTOScrIM6yPlDsd9o05v39qIzFnemR
                        2vgw1s4l8maJVWi9IHEg8oiypJvGwSCP1nFs
                        EOlXyNFQJ0fWGA== )
```

Appendix B. Example Responses

The examples in this section show response messages using the signed zone example in Appendix A.

B.1. Name Error

An authoritative name error. The NSEC3 RRs prove that the name does not exist and that there is no wildcard RR that should have been expanded.

```
;; Header: QR AA DO RCODE=3
;;
;; Question
a.c.x.w.example.         IN A

;; Answer
;; (empty)

;; Authority

example.       SOA     ns1.example. bugs.x.w.example. 1 3600 300 (
                       3600000 3600 )
example.       RRSIG   SOA 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
                       hNIkW1xzn+c+9P3W7PUVVptI72xEmOtn+eqQ
                       ux0BE7Pfc6ikx4m7ivOVWETjbwHjqfY0X5G+
                       rynLZNqsbLm40Q== )

;; NSEC3 RR that covers the "next closer" name (c.x.w.example)
;; H(c.x.w.example) = 0va5bpr2ou0vk0lbqeeljri88laipsfh

0p9mhaveqvm6t7vbl5lop2u3t2rp3tom.example. NSEC3 1 1 12 aabbccdd (
                       2t7b4g4vsa5smi47k61mv5bv1a22bojr MX DNSKEY NS
                       SOA NSEC3PARAM RRSIG )
0p9mhaveqvm6t7vbl5lop2u3t2rp3tom.example. RRSIG NSEC3 133 2 3600 (
                       20150420235959 20051021000000 62827 example.
                       rn2tv99+9StXbc7JaEnjT1+8I8f2vVOMOIbF
                       xzlrn94lQLxEOYxQR4SrxDRP4/fC54Jui0Ix
                       4eI9tMfaTVgehQ== )

;; NSEC3 RR that matches the closest encloser (x.w.example)
```

```
;; H(x.w.example) = b4um86eghhds6nea196smvmlo4ors995

b4um86eghhds6nea196smvmlo4ors995.example. NSEC3 1 1 12 aabbccdd (
                        gjeqe526plbf1g8mklp59enfd789njgi MX RRSIG )
b4um86eghhds6nea196smvmlo4ors995.example. RRSIG NSEC3 133 2 3600 (
                        20150420235959 20051021000000 62827 example.
                        GWDmUk8Sv0dxy/UZFol4Ss7Wz3wBiongcnVy
                        strNODWwdnoO9z6pDh8JLk58ExfEgXm79i4b
                        Ma6C/s/bkk1LvA== )

;; NSEC3 RR that covers wildcard at the closest encloser (*.x.w.example)
;; H(*.x.w.example) = 92pqneegtaue7pjatc3l3qnk738c6v5m

35mthgpgcu1qg68fab165klnsnk3dpvl.example. NSEC3 1 1 12 aabbccdd (
                        b4um86eghhds6nea196smvmlo4ors995 NS DS RRSIG )
35mthgpgcu1qg68fab165klnsnk3dpvl.example. RRSIG NSEC3 133 2 3600 (
                        20150420235959 20051021000000 62827 example.
                        QrjOpXVIvodCw0O8uPMNA+yEeS/o3KKkEIPX
                        r5DoEShq2hymAsRTc/t9BvRKpcSTExyc5m3T
                        vYN3GgN0W/0WHQ== )

;; Additional
;; (empty)
```

The query returned three NSEC3 RRs that prove that the requested data does not exist and that no wildcard expansion applies. The negative response is authenticated by verifying the NSEC3 RRs. The corresponding RRSIGs indicate that the NSEC3 RRs are signed by an "example" DNSKEY of algorithm 133 and with key tag 62827. The resolver needs the corresponding DNSKEY RR in order to authenticate this answer.

One of the owner names of the NSEC3 RRs matches the closest encloser. One of the NSEC3 RRs prove that there exists no longer name. One of the NSEC3 RRs prove that there exists no wildcard RRSets that should have been expanded. The closest encloser can be found by applying the algorithm in section Section 8.3.

In the above example, the name 'x.w.example' hashes to 'b4um86eghhds6nea196smvmlo4ors995'. This indicates that this might be the closest encloser. To prove that 'c.x.w.example' and '*.x.w.example' do not exist, these names are hashed to, respectively, '0va5bpr2ou0vk0lbqeeljri88laipsfh' and '92pqneegtaue7pjatc3l3qnk738c6v5m'. The first and last NSEC3 RRs prove that these hashed owner names do not exist.

B.2. No Data Error

A "no data" response. The NSEC3 RR proves that the name exists and that the requested RR type does not.

```
;; Header: QR AA DO RCODE=0
;;
;; Question
ns1.example.        IN MX

;; Answer
;; (empty)

;; Authority
example.       SOA     ns1.example. bugs.x.w.example. 1 3600 300 (
                       3600000 3600 )
example.       RRSIG   SOA 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
                       hNIkW1xzn+c+9P3W7PUVVptI72xEmOtn+eqQ
                       ux0BE7Pfc6ikx4m7ivOVWETjbwHjqfY0X5G+
                       rynLZNqsbLm40Q== )

;; NSEC3 RR matches the QNAME and shows that the MX type bit is not set.

2t7b4g4vsa5smi47k61mv5bv1a22bojr.example. NSEC3 1 1 12 aabbccdd (
                       2vptu5timamqttgl4luu9kg21e0aor3s A RRSIG )
2t7b4g4vsa5smi47k61mv5bv1a22bojr.example. RRSIG NSEC3 133 2 3600 (
                       20150420235959 20051021000000 62827 example.
                       fJER1Z3nGoN0HmZm99lqNLSpIf7jLXTMoGm2
                       k4gIwlc0R4DztJp6Sq37OV6XnGdre4MfgRpB
                       mAcgpPWC5A5eiw== )
;; Additional
;; (empty)
```

The query returned an NSEC3 RR that proves that the requested name exists ("ns1.example." hashes to "2t7b4g4vsa5smi47k61mv5bv1a22bojr"), but the requested RR type does not exist (type MX is absent in the type code list of the NSEC3 RR), and was not a CNAME (type CNAME is also absent in the type code list of the NSEC3 RR.)

B.2.1. No Data Error, Empty Non-Terminal

A "no data" response because of an empty non-terminal. The NSEC3 RR proves that the name exists and that the requested RR type does not.

```
;; Header: QR AA DO RCODE=0
;;
;; Question
y.w.example.        IN A

;; Answer
;; (empty)

;; Authority
example.       SOA     ns1.example. bugs.x.w.example. 1 3600 300 (
                       3600000 3600 )
example.       RRSIG   SOA 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
                       hNIkW1xzn+c+9P3W7PUVVptI72xEmOtn+eqQ
                       ux0BE7Pfc6ikx4m7ivOVWETjbwHjqfY0X5G+
                       rynLZNqsbLm40Q== )

;; NSEC3 RR matches the QNAME and shows that the A type bit is not set.

ji6neoaepv8b5o6k4ev33abha8ht9fgc.example. NSEC3 1 1 12 aabbccdd (
                       k8udemvp1j2f7eg6jebps17vp3n8i58h )
ji6neoaepv8b5o6k4ev33abha8ht9fgc.example. RRSIG NSEC3 133 2 3600 (
                       20150420235959 20051021000000 62827 example.
                       fvKWkD3lXNLyUn0/gN+i3Z8301oRujSFFrJy
                       SfAPS2Q1bw1Q5eQoy7IE+ZtUVO15ha6C9cUh
                       CArJyEk247MADA== )

;; Additional
;; (empty)
```

The query returned an NSEC3 RR that proves that the requested name exists ("y.w.example." hashes to "ji6neoaepv8b5o6k4ev33abha8ht9fgc"), but the requested RR type does not exist (Type A is absent in the Type Bit Maps field of the NSEC3 RR). Note that, unlike an empty non-terminal proof using NSECs, this is identical to a No Data Error. This example is solely mentioned to be complete.

B.3. Referral to an Opt-Out Unsigned Zone

The NSEC3 RRs prove that nothing for this delegation was signed. There is no proof that the unsigned delegation exists.

```
;; Header: QR DO RCODE=0
;;
;; Question
mc.c.example.       IN MX

;; Answer
;; (empty)

;; Authority
c.example.     NS      ns1.c.example.
               NS      ns2.c.example.

;; NSEC3 RR that covers the "next closer" name (c.example)
;; H(c.example) = 4g6p9u5gvfshp30pqecj98b3maqbn1ck

35mthgpgcu1qg68fab165klnsnk3dpvl.example. NSEC3 1 1 12 aabbccdd (
                        b4um86eghhds6nea196smvmlo4ors995 NS DS RRSIG )
35mthgpgcu1qg68fab165klnsnk3dpvl.example. RRSIG NSEC3 133 2 3600 (
                        20150420235959 20051021000000 62827 example.
                        QrjOpXVIvodCw0O8uPMNA+yEeS/o3KKkEIPX
                        r5DoEShq2hymAsRTc/t9BvRKpcSTExyc5m3T
                        vYN3GgN0W/0WHQ== )

;; NSEC3 RR that matches the closest encloser (example)
;; H(example) = 0p9mhaveqvm6t7vbl5lop2u3t2rp3tom

0p9mhaveqvm6t7vbl5lop2u3t2rp3tom.example. NSEC3 1 1 12 aabbccdd (
                        2t7b4g4vsa5smi47k61mv5bv1a22bojr MX DNSKEY NS
                        SOA NSEC3PARAM RRSIG )
0p9mhaveqvm6t7vbl5lop2u3t2rp3tom.example. RRSIG NSEC3 133 2 3600 (
                        20150420235959 20051021000000 62827 example.
                        rn2tv99+9StXbc7JaEnjT1+8I8f2vVOMOIbF
                        xzlrn94lQLxEOYxQR4SrxDRP4/fC54Jui0Ix
                        4eI9tMfaTVgehQ== )

;; Additional
ns1.c.example. A       192.0.2.7
ns2.c.example. A       192.0.2.8
```

The query returned a referral to the unsigned "c.example." zone. The response contains the closest provable encloser of "c.example" to be "example", since the hash of "c.example" ("4g6p9u5gvfshp30pqecj98b3maqbn1ck") is covered by the first NSEC3 RR and its Opt-Out bit is set.

B.4. Wildcard Expansion

A query that was answered with a response containing a wildcard expansion. The label count in the RRSIG RRSet in the answer section indicates that a wildcard RRSet was expanded to produce this response, and the NSEC3 RR proves that no "next closer" name exists in the zone.

```
   ;; Header: QR AA DO RCODE=0
   ;;
   ;; Question
   a.z.w.example. IN MX

   ;; Answer
   a.z.w.example. MX      1 ai.example.
   a.z.w.example. RRSIG   MX 133 2 3600 20150420235959 20051021000000 (
                          62827 example.
                          DnT0Y6dRBM8f3v8HdKmZUsGVkXh+b+htujCR
                          c423x6c8erEMGVnxcrmcrZ53qGXcMYJ+TDkq
                          a7Xfz/f9xzvSTw== )

   ;; Authority
   example.       NS      ns1.example.
   example.       NS      ns2.example.
   example.       RRSIG   NS 133 1 3600 20150420235959 20051021000000 (
                          62827 example.
                          D9+iBwcbeKL5+TorTfYn4/pLr2lSFwyGYCyM
                          gfq4TpFaZpxrCJPLxHbKjdkR18jAt7+SR7B5
                          JpiZcff2Cj2B0w== )

   ;; NSEC3 RR that covers the "next closer" name (z.w.example)
   ;; H(z.w.example) = qlu7gtfaeh0ek0c05ksfhdpbcgglbe03

   q04jkcevqvmu85r014c7dkba38o0ji5r.example. NSEC3 1 1 12 aabbccdd (
                          r53bq7cc2uvmubfu5ocmm6pers9tk9en A RRSIG )
   q04jkcevqvmu85r014c7dkba38o0ji5r.example. RRSIG NSEC3 133 2 3600 (
                          20150420235959 20051021000000 62827 example.
                          ktIfH8VRjEKYPB0Qf4EdTuSlYn4DVSRRaGWc
                          kVGmKzreEU5zs97CL8OQSa6C0JZX2yMBXijC
                          Wu6EvgCXrflgiQ== )

   ;; Additional
   ai.example.    A       192.0.2.9
   ai.example.    RRSIG   A 133 2 3600 20150420235959 20051021000000 (
                          62827 example.
                          qfXAvKr5o3Jixy5KXnVMEhABo3DDHYSR5+Ag
                          lVxWCExWGMokdkafjW8Hb54+GrOFp/xmDoj5
                          BXfXAqURwLqznA== )
   ai.example.    AAAA    2001:db8:0:0:0:0:f00:baa9
   ai.example.    RRSIG   AAAA 133 2 3600 20150420235959 (
                          20051021000000 62827 example.
                          m65zc0A16Xbx3jYb0t5vPwMzE2xS15mKh76M
                          hSuKfiFVhBFcQ9IilEM0pXnLzt3ozrM/3X0x
                          2ruyuN0zC+PABA== )
```

The query returned an answer that was produced as a result of wildcard expansion. The answer section contains a wildcard RRSet expanded as it would be in a traditional DNS response. The RRSIG Labels field value of 2 indicates that the answer is the result of wildcard expansion, as the "a.z.w.example" name contains 4 labels. This also shows that "w.example" exists, so there is no need for an NSEC3 RR that matches the closest encloser.

The NSEC3 RR proves that no closer match could have been used to answer this query.

B.5. Wildcard No Data Error

A "no data" response for a name covered by a wildcard. The NSEC3 RRs prove that the matching wildcard name does not have any RRs of the requested type and that no closer match exists in the zone.

```
;; Header: QR AA DO RCODE=0
;;
;; Question
a.z.w.example.      IN AAAA

;; Answer
;; (empty)

;; Authority
example.       SOA     ns1.example. bugs.x.w.example. 1 3600 300 (
                       3600000 3600 )
example.       RRSIG   SOA 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
                       hNIkW1xzn+c+9P3W7PUVVptI72xEmOtn+eqQ
                       ux0BE7Pfc6ikx4m7ivOVWETjbwHjqfY0X5G+
                       rynLZNqsbLm40Q== )

;; NSEC3 RR that matches the closest encloser (w.example)
;; H(w.example) = k8udemvp1j2f7eg6jebps17vp3n8i58h

k8udemvp1j2f7eg6jebps17vp3n8i58h.example. NSEC3 1 1 12 aabbccdd (
                       kohar7mbb8dc2ce8a9qvl8hon4k53uhi )
k8udemvp1j2f7eg6jebps17vp3n8i58h.example. RRSIG NSEC3 133 2 3600 (
                       20150420235959 20051021000000 62827 example.
                       IKJfInxfypsDiXKgT6HDvCPEIBu9lZCc0CWl
                       c46+Gj/Jrg1NBkSJkKMjCERp1HT8tKU+zYp5
                       Kyio/cddEaa5Gg== )

;; NSEC3 RR that covers the "next closer" name (z.w.example)
;; H(z.w.example) = qlu7gtfaeh0ek0c05ksfhdpbcgglbe03
```

```
q04jkcevqvmu85r014c7dkba38o0ji5r.example. NSEC3 1 1 12 aabbccdd (
                        r53bq7cc2uvmubfu5ocmm6pers9tk9en A RRSIG )
q04jkcevqvmu85r014c7dkba38o0ji5r.example. RRSIG NSEC3 133 2 3600 (
                        20150420235959 20051021000000 62827 example.
                        ktIfH8VRjEKYPB0Qf4EdTuSlYn4DVSRRaGWc
                        kVGmKzreEU5zs97CL8OQSa6C0JZX2yMBXijC
                        Wu6EvgCXrflgiQ== )

;; NSEC3 RR that matches a wildcard at the closest encloser.
;; H(*.w.example) = r53bq7cc2uvmubfu5ocmm6pers9tk9en

r53bq7cc2uvmubfu5ocmm6pers9tk9en.example. NSEC3 1 1 12 aabbccdd (
                        t644ebqk9bibcna874givr6joj62mlhv MX RRSIG )
r53bq7cc2uvmubfu5ocmm6pers9tk9en.example. RRSIG NSEC3 133 2 3600 (
                        20150420235959 20051021000000 62827 example.
                        SzeyaiFOy9dFO1RKHAK4uVCb5GF4rNnxFMXu
                        6hpM44cmLcDgshlnG1CwkkcihfKOiPIBWd7I
                        bGhsbhqrBrn5Dg== )

;; Additional
;; (empty)
```

The query returned the NSEC3 RRs that prove that the requested data does not exist and no wildcard RR applies.

B.6. DS Child Zone No Data Error

A "no data" response for a QTYPE=DS query that was mistakenly sent to a name server for the child zone.

```
;; Header: QR AA DO RCODE=0
;;
;; Question
example.            IN DS

;; Answer
;; (empty)

;; Authority
example.       SOA     ns1.example. bugs.x.w.example. 1 3600 300 (
                       3600000 3600 )
example.       RRSIG   SOA 133 1 3600 20150420235959 20051021000000 (
                       62827 example.
                       hNIkW1xzn+c+9P3W7PUVVptI72xEmOtn+eqQ
                       ux0BE7Pfc6ikx4m7ivOVWETjbwHjqfY0X5G+
                       rynLZNqsbLm40Q== )

;; NSEC3 RR matches the QNAME and shows that the DS type bit is not set.

0p9mhaveqvm6t7vbl5lop2u3t2rp3tom.example. NSEC3 1 1 12 aabbccdd (
                       2t7b4g4vsa5smi47k61mv5bv1a22bojr MX DNSKEY NS
                       SOA NSEC3PARAM RRSIG )
0p9mhaveqvm6t7vbl5lop2u3t2rp3tom.example. RRSIG NSEC3 133 2 3600 (
                       20150420235959 20051021000000 62827 example.
                       rn2tv99+9StXbc7JaEnjT1+8I8f2vVOMOIbF
                       xzlrn94lQLxEOYxQR4SrxDRP4/fC54Jui0Ix
                       4eI9tMfaTVgehQ== )

;; Additional
;; (empty)
```

The query returned an NSEC3 RR showing that the requested was answered by the server authoritative for the zone "example". The NSEC3 RR indicates the presence of an SOA RR, showing that this NSEC3 RR is from the apex of the child, not from the zone cut of the parent. Queries for the "example" DS RRSet should be sent to the parent servers (which are in this case the root servers).

Appendix C. Special Considerations

The following paragraphs clarify specific behavior and explain special considerations for implementations.

C.1. Salting

Augmenting original owner names with salt before hashing increases the cost of a dictionary of pre-generated hash-values. For every bit

of salt, the cost of a precomputed dictionary doubles (because there must be an entry for each word combined with each possible salt value). The NSEC3 RR can use a maximum of 2040 bits (255 octets) of salt, multiplying the cost by 2^2040. This means that an attacker must, in practice, recompute the dictionary each time the salt is changed.

Including a salt, regardless of size, does not affect the cost of constructing NSEC3 RRs. It does increase the size of the NSEC3 RR.

There MUST be at least one complete set of NSEC3 RRs for the zone using the same salt value.

The salt SHOULD be changed periodically to prevent pre-computation using a single salt. It is RECOMMENDED that the salt be changed for every re-signing.

Note that this could cause a resolver to see RRs with different salt values for the same zone. This is harmless, since each RR stands alone (that is, it denies the set of owner names whose hashes, using the salt in the NSEC3 RR, fall between the two hashes in the NSEC3 RR) - it is only the server that needs a complete set of NSEC3 RRs with the same salt in order to be able to answer every possible query.

There is no prohibition with having NSEC3 RRs with different salts within the same zone. However, in order for authoritative servers to be able to consistently find covering NSEC3 RRs, the authoritative server MUST choose a single set of parameters (algorithm, salt, and iterations) to use when selecting NSEC3 RRs.

C.2. Hash Collision

Hash collisions occur when different messages have the same hash value. The expected number of domain names needed to give a 1 in 2 chance of a single collision is about 2^(n/2) for a hash of length n bits (i.e. 2^80 for SHA-1). Though this probability is extremely low, the following paragraphs deal with avoiding collisions and assessing possible damage in the event of an attack using hash collisions.

C.2.1. Avoiding Hash Collisions During Generation

During generation of NSEC3 RRs, hash values are supposedly unique. In the (academic) case of a collision occurring, an alternative salt MUST be chosen and all hash values MUST be regenerated.

C.2.2. Second Preimage Requirement Analysis

A cryptographic hash function has a second-preimage resistance property. The second-preimage resistance property means that it is computationally infeasible to find another message with the same hash value as a given message, i.e. given preimage X, to find a second preimage X' != X such that hash(X) = hash(X'). The work factor for finding a second preimage is of the order of 2^160 for SHA-1. To mount an attack using an existing NSEC3 RR, an adversary needs to find a second preimage.

Assuming an adversary is capable of mounting such an extreme attack, the actual damage is that a response message can be generated which claims that a certain QNAME (i.e. the second pre-image) does exist, while in reality QNAME does not exist (a false positive), which will either cause a security aware resolver to re-query for the non-existent name, or to fail the initial query. Note that the adversary can't mount this attack on an existing name but only on a name that the adversary can't choose and does not yet exist.

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Acknowledgment

Funding for the RFC Editor function is provided by the IETF Administrative Support Activity (IASA).