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A Deployment Profile for DKIM2 via Milter Interface
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Abstract

This document defines a deployment profile for DomainKeys Identified Mail v2 (DKIM2) that is implementable via the existing milter interface without modifications to Mail Transfer Agent (MTA) core software. It identifies a mandatory core profile (DKIM2-core) covering envelope binding, chain of custody, header accountability, replay prevention and DSN authentication and an optional extended profile (DKIM2-extended) covering body recipes and Message-Instance headers. The separation is motivated by deployment realism: the core profile addresses the primary threat models identified in the DKIM2 motivation document and is deployable incrementally across heterogeneous infrastructure, including small operators, universities and research institutions, using the same milter-based deployment model that has proven effective for DKIM1 and ARC.

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1. Introduction

DomainKeys Identified Mail v2 (DKIM2) addresses significant limitations of DKIM1 [RFC6376] and the experimental ARC protocol [RFC8617], including DKIM replay attacks, backscatter from unauthorized use of envelope senders and the absence of cryptographic binding between message signatures and SMTP envelope parameters.

The core technical contribution of DKIM2 - binding the MAIL FROM and RCPT TO values of each SMTP transaction to the message signature at every hop - is a genuine improvement over both DKIM1 and ARC and is sufficient to address the primary threat models identified in [I-D.ietf-dkim-dkim2-motivation].

However, the current specification also includes a body recipe mechanism that allows intermediaries to describe modifications made to the message body in sufficient detail to reconstruct previous versions. This mechanism introduces significant architectural complexity: it requires stateful militer implementations with persistent shared storage, JSON parsing in the delivery critical path and software modifications across the entire ecosystem of intermediaries. The body recipe mechanism also raises data protection concerns under GDPR and equivalent frameworks that have not yet been addressed in the specification.

This document proposes a structured separation of DKIM2 functionality into two profiles:

- * DKIM2-core: a mandatory profile implementing envelope binding, chain of custody, header accountability, replay prevention and DSN authentication. DKIM2-core is fully implementable via the militer interface without MTA core modifications, using header formats already familiar to the ecosystem through ARC deployment. Critically, DKIM2-core requires no persistent state between SMTP sessions - all information needed for signing and verification is available within the current session and the message headers themselves. State management is only required for body recipe generation, which belongs exclusively to DKIM2-extended.

- * DKIM2-extended: an optional profile adding body recipe generation and verification via Message-Instance headers and JSON-encoded recipes. DKIM2-extended may require stateful milter implementations or MTA core integration and is appropriate for operators who require full body accountability and are willing to accept the associated architectural cost.

This separation is consistent with the DKIM working group charter [DKIM-CHARTER], which states that "the working group will prefer a result that is incremental to the deployed ecosystem" and that "proposed solutions are expected to be robust in terms of interoperability and scalability".

The approach taken in this document is explicitly constructive: it does not propose to replace DKIM2 but to define a deployment path that allows the ecosystem to adopt the core benefits of DKIM2 incrementally, without requiring simultaneous changes to every node in the delivery chain.

1.1. Relationship to DKIM2 Specifications

This document is a deployment profile, not a competing specification. It references and depends on [I-D.clayton-dkim2-spec] and [I-D.ietf-dkim-dkim2-header] for the underlying mechanisms. Where this document proposes alternative encoding formats - specifically for envelope binding fields - these are offered as contributions to the ongoing design discussion in the working group.

1.2. Motivation

The Internet email infrastructure is not composed solely of large providers with dedicated engineering teams. A substantial portion of email is handled by operators of all sizes outside the largest commercial providers: small ISPs, universities and research institutions, regional hosting providers, non-profit organizations and small businesses. What these operators have in common is not small scale per se - a university may handle millions of messages per day - but limited engineering resources dedicated to mail infrastructure. Their administrators depend on the milter interface for incremental deployment of new authentication features precisely because it allows them to adopt new protocols without modifying MTA core software, waiting for upstream vendor releases or dedicating engineering cycles to core system changes. Every authentication protocol that has achieved broad adoption - SPF, DKIM1, DMARC and to a limited extent ARC - has been deployable via this model. DKIM2 as currently specified breaks this pattern.

Furthermore, the body recipe mechanism encounters a fundamental operational obstacle: the nodes most likely to make substantial body modifications - security gateways, DLP systems, URL rewriting proxies, antivirus engines - are precisely the nodes least likely to implement recipe generation. These nodes will systematically produce null recipes, which provide no additional accountability over incremental body hash chaining. The overhead of the recipe infrastructure is therefore paid by the entire ecosystem while the benefit accrues only to the minority of cases where all intermediaries cooperate fully.

The pragmatic approach to body integrity documented in [RFC6376] Appendix B - using relaxed canonicalization to tolerate common benign transformations rather than requiring intermediaries to declare or reconstruct them - has proven effective in practice and has contributed to the broad adoption of DKIM1. It should be noted however that relaxed canonicalization does not address all categories of involuntary body transformation: base64 line-width re-encoding, for example, breaks both simple and relaxed canonicalization equally. DKIM2-core preserves the relaxed canonicalization approach for body integrity while adding the cryptographic envelope binding and header accountability that DKIM1 lacks. The body recipe mechanism of DKIM2-extended represents a deliberate departure from this model toward deterministic reconstruction - a departure whose operational cost and deployment implications are addressed in Section 4.

1.3. Design Philosophy

This document is guided by three principles that reflect the deployment realities described in Section 1.2.

Additive, not transformative - every mechanism defined in DKIM2-core adds new header fields or new signed content to existing messages. Nothing in DKIM2-core requires existing software to change its core behavior. A legacy node that does not implement DKIM2 passes DKIM2 headers through without interpreting them, exactly as it handles any unrecognized header field today. This is the same property that allowed SPF, DKIM1, DMARC and ARC to be deployed incrementally across a heterogeneous ecosystem without flag-day transitions.

Milter-first - the milter interface is the deployment mechanism that has enabled incremental adoption of every successful email authentication protocol. DKIM2-core is designed so that every mandatory feature is implementable as a milter without MTA core modifications. This is not a constraint imposed from outside - it is a deliberate architectural choice that maximizes the probability of adoption across the full range of operators described in Section 1.2, from large providers to small ISPs and universities.

Stateless by design - DKIM2-core requires no persistent state between SMTP sessions. All information needed for signing and verification is available within the current session and the message headers themselves. This eliminates the need for shared storage between milter instances, reduces operational complexity and removes a category of failure modes that stateful implementations introduce. State management is only required for body recipe generation, which belongs exclusively to DKIM2-extended.

These three principles together define the boundary between DKIM2-core and DKIM2-extended. Any mechanism that requires MTA core modifications, persistent inter-session state, or content parsing beyond what the milter interface provides belongs in DKIM2-extended. Any mechanism that can be implemented additively, via milter and statelessly belongs in DKIM2-core.

2. Terminology and Definitions

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

This document uses terminology from [RFC5598] (Internet Mail Architecture) and inherits definitions from [I-D.clayton-dkim2-spec]. The following additional terms are defined for use in this document.

DKIM2-core: The mandatory deployment profile defined in this document. DKIM2-core implements envelope binding, chain of custody, header accountability, replay prevention and DSN authentication. It is fully implementable via the milter interface without MTA core modifications and requires no persistent state between SMTP sessions.

DKIM2-extended: The optional deployment profile defined in this document. DKIM2-extended adds body recipe generation and verification via Message-Instance headers and JSON-encoded recipes. It may require stateful milter implementations with persistent shared storage or MTA core integration.

Milter-capable node: An MTA deployment that implements DKIM2-core functionality via the milter interface. A milter-capable node requires no modifications to the MTA core software.

Legacy node: A node in the delivery chain that does not implement DKIM2 in any form. Legacy nodes pass DKIM2 headers through the delivery chain without interpreting them, exactly as they handle unrecognized header fields today.

Transparent relay: A node that adds only trace headers (Received:, Return-Path:) and makes no other modifications to the message. Transparent relays do not need to participate in DKIM2 signing or verification. Note however that in practice many nominally transparent relays introduce involuntary body transformations - base64 re-encoding at different line widths, MIME reassembly by antivirus engines, whitespace normalization - that affect body hash values.

Reviser: A node that makes intentional modifications to message headers or body. A Reviser MUST declare its modifications using DKIM2-Mod headers (DKIM2-core) or Message-Instance recipes (DKIM2-extended) and MUST add a new DKIM2 signature covering the modified message.

Inbound milter: The milter instance responsible for verifying incoming DKIM2 signatures during the SMTP session. The inbound milter operates at EndOfBody and has access to the complete envelope state accumulated during the session via MailFromRequest and RcptToRequest callbacks.

Outbound milter: The milter instance responsible for generating DKIM2-Mod headers and adding DKIM2 signatures to outgoing messages. The outbound milter is positioned last in the milter chain, after all other milters that may modify the message and signs the final state of the message.

DKIM2-Mod header: A signed header field added by a Reviser to declare a modification made to an existing header field. DKIM2-Mod headers carry an instance index (i=) aligned with the DKIM2-Signature hop number, a sequence index (seq=) for multiple modifications to the same field at the same hop and an optional frame index (fr=) to split values longer than 998 characters per [RFC5322].

Envelope binding: The cryptographic binding of SMTP MAIL FROM and RCPT TO values to the DKIM2 signature at each hop, implemented via DKIM2-Sig-mf and DKIM2-Sig-rt header fields. Envelope binding prevents DKIM replay attacks by making it impossible to reuse a valid signature for a different recipient without breaking the chain.

Chain of custody: The verifiable record of all entities that have handled a message, established by the sequence of DKIM2 signatures and envelope bindings from originator to final recipient. Each hop in the chain signs the current state of the message and references the previous hop's signature.

Null recipe: A Message-Instance declaration that a modification was made to the message body but that the previous state cannot be reconstructed. Null recipes are only relevant in DKIM2-extended. In DKIM2-core, body modifications are declared implicitly through a changed bh= value with attribution to the signing hop.

Relaxed domain match: The algorithm defined in [I-D.clayton-dkim2-spec] Section 11.3 for matching the signing domain (d=) against the MAIL FROM domain, allowing subaddress schemes used for bounce handling. Labels are removed from the left side of the MAIL FROM domain until a match is found or no labels remain.

This document inherits definitions from [I-D.clayton-dkim2-spec] and [I-D.ietf-dkim-dkim2-header]. Where terms are used without definition in this document, the definitions in those documents apply.

3. DKIM2-core: Mandatory Profile

DKIM2-core is the mandatory deployment profile. All nodes that wish to participate in DKIM2 MUST implement DKIM2-core. Nodes that implement only DKIM2-core are fully interoperable with nodes that implement DKIM2-extended.

The militer interface is an integration point, not a replacement for MTA functionality. DKIM2-core uses the militer interface to observe, verify and sign messages as they flow through the MTA's normal processing pipeline. Functions that belong to the MTA - transaction management, BCC splitting, queue handling, routing - remain with the MTA. The militer does not substitute for these functions and is not designed to do so. This separation of concerns is what makes militer-based deployment non-invasive and compatible with existing MTA infrastructure.

3.1. Envelope Binding

Envelope binding is the primary technical contribution of DKIM2 over DKIM1 and ARC. By cryptographically binding the SMTP MAIL FROM and RCPT TO values to the message signature at every hop, DKIM2-core makes it impossible to replay a valid signature for a different recipient or sender without breaking the chain.

Envelope binding is implemented via two new signed header fields: DKIM2-Sig-mf (carrying the MAIL FROM value) and DKIM2-Sig-rt (carrying the RCPT TO values). These fields use the indexed header pattern already deployed at scale in ARC, where ARC-Seal, ARC-Message-Signature and ARC-Authentication-Results use i= instance

numbers to build a verifiable chain across multiple hops. Every milter that implements ARC already parses and generates headers with `i=` indexing. DKIM2-Sig-mf and DKIM2-Sig-rt are a natural extension of this existing pattern, requiring no new parsing infrastructure.

3.1.1. Envelope Binding Format

The DKIM2-Sig-mf field carries exactly one address - the SMTP MAIL FROM value. The DKIM2-Sig-rt field carries one or more RCPT TO values, using one header per address.

Both fields use the `i=` instance indexing convention already established by ARC [RFC8617], where ARC-Seal, ARC-Message-Signature and ARC-Authentication-Results use the same `i=` numbering to build a verifiable chain across multiple hops. Implementers familiar with ARC will recognize this pattern immediately. Major email providers including Google and Microsoft implement ARC natively in their infrastructure and ARC milter implementations are deployed across the ecosystem. DKIM2-Sig-mf and DKIM2-Sig-rt extend this existing pattern to carry envelope values, requiring no new parsing concepts beyond what ARC implementations already handle.

```
DKIM2-Sig-mf: i=1; addr=bounce@mailchimp.com
DKIM2-Sig-rt: i=1; v=1; addr=dest1@esempio.com
DKIM2-Sig-rt: i=1; v=2; addr=dest2@esempio.com
DKIM2-Sig-rt: i=1; v=3; addr="john;doe"@rare.com
```

One header per address, including recipients with quoted local parts. The `v=` tag provides a sequence number that distinguishes multiple DKIM2-Sig-rt headers at the same hop. DKIM2-Sig-mf always carries exactly one address and does not require `v=`.

This format handles all RFC5321 local part cases including quoted local parts containing special characters - within a single header value there is no separator ambiguity regardless of the characters present in the local part. The format copies exactly the ARC instance indexing pattern, requires no new parsing logic beyond what ARC implementations already provide and produces output directly inspectable in mail logs and headers without decoding tools.

The design avoids the parsing complexity that arises when envelope addresses with display names, quoted local parts, or multiple addresses are embedded in more complex header formats. DKIM2-Sig-rt carries only the bare RFC5321 addr-spec - the envelope address without display name - one per header. This is the natural format for SMTP envelope values, which by definition do not carry display names. It avoids the parsing complexity of RFC5322 address-list syntax, which includes display names, group syntax and other constructs that are irrelevant for envelope binding purposes.

This format could produce more bytes than the JSON+base64 encoding currently specified in [I-D.clayton-dkim2-spec] for messages with very many recipients. For the common case of messages with a small number of recipients - which represents the substantial majority of real-world email traffic - the size difference is negligible or absent. It remains directly human-readable without decoding tools, has a parsing complexity of $O(1)$ per header rather than $O(n)$ on the full recipient list and allows individual recipient membership verification without deserializing the complete list.

It is worth noting that quoted local parts containing special characters such as semicolons are permitted by [RFC5321] but are not observed in practice in real-world email infrastructure. The format handles them correctly without any special-casing.

3.1.2. Relationship to Existing From:/To: Headers

The DKIM2-Sig-mf and DKIM2-Sig-rt fields carry the SMTP envelope values, which may differ significantly from the RFC5322 From:, To: and Cc: header fields. This distinction is particularly important in two scenarios:

Programmatic and bulk email - the envelope sender is typically a bounce handling address such as bounce-12345@mail.mailchimp.com and the envelope recipients are individual subscriber addresses that may not appear in the message headers at all. Using RFC5322 headers to infer envelope values would fail for this common case.

Group syntax and empty groups - RFC5322 permits constructs such as To: Empty Group:; where the To: header carries no actual recipient addresses. The envelope RCPT TO values are the only reliable source of recipient information in these cases.

Using existing RFC5322 headers to infer envelope values, as has been proposed in some alternatives, would require parsers to handle these edge cases correctly and would fail for programmatic email where no correspondence between envelope and headers exists. DKIM2-Sig-mf and DKIM2-Sig-rt carry the envelope values explicitly and independently of the IMF headers, eliminating this ambiguity.

It is also worth noting that the support for multiple rt= values - rather than a single recipient per message - was motivated by a specific operational requirement from a large mailbox provider whose anti-fraud system relies on verifying consistency between envelope recipients and To:/Cc: header fields to detect messages fraudulently presented as sent to multiple recipients but actually sent to only one. This use case requires that all RCPT TO values for a given SMTP transaction be visible in the signed envelope binding.

3.1.3. Relaxed Domain Match

The relaxed domain match algorithm defined in [I-D.clayton-dkim2-spec] Section 11.3 is retained unchanged. The signing domain (d=) must match the domain of the DKIM2-Sig-mf address via relaxed domain match, allowing subaddress schemes used for bounce handling such as bounce-12345@mail.mailchimp.com to match d=mailchimp.com.

3.1.4. BCC Recipients

BCC recipients require separate SMTP transactions - one per BCC recipient - to prevent disclosure of BCC addresses to other recipients, consistent with [RFC5322] Section 3.6.3. This is already best practice for correct BCC semantics independent of DKIM2. The DKIM2-Sig-rt field for each separate transaction carries only the address of that specific BCC recipient.

Operators that need to communicate BCC status from the MUA to the signing system MAY use a submission-phase header convention such as X-BCC: which the outbound milter reads and strips before external transmission. This allows the milter to identify which RCPT TO addresses are BCC and generate separate transactions accordingly, without requiring MTA core modifications.

Including multiple BCC recipients in a single SMTP transaction with all addresses listed in DKIM2-Sig-rt would reveal BCC recipient addresses in the signed headers, which are visible to all recipients of the message and to any archiving system that receives it. This directly violates the privacy requirement of BCC as defined in [RFC5322] Section 3.6.3 and MUST NOT be done.

It should be noted that the current DKIM2 specification mandates that BCC recipients MUST NOT be revealed to other recipients but provides no mechanism by which the signing system can distinguish BCC recipients from To: and Cc: recipients at the SMTP level. The SMTP envelope does not carry the BCC distinction explicitly - all recipients appear as RCPT TO regardless of their role. BCC recipients can only be identified by comparing the RCPT TO list against the To: and Cc: header fields, which requires content parsing that MTAs traditionally avoid. The X-BCC submission header convention described above addresses this gap for deployments where the MUA and MTA can be configured to cooperate. The working group should consider defining a normative mechanism for this purpose.

3.1.5. Formal Syntax

The following ABNF defines the header fields introduced by this document. Rules are imported from [RFC5234] and [RFC5321] as noted.

```

; DKIM2-Sig-mf header field
; Carries exactly one SMTP MAIL FROM address
dkim2-sig-mf      = "DKIM2-Sig-mf:" SP dkim2-mf-params CRLF
dkim2-mf-params   = dkim2-hop-index ";" SP dkim2-addr

; DKIM2-Sig-rt header field
; Carries exactly one SMTP RCPT TO address per header
; Multiple recipients use multiple headers with incrementing v=
dkim2-sig-rt      = "DKIM2-Sig-rt:" SP dkim2-rt-params CRLF
dkim2-rt-params   = dkim2-hop-index ";" SP
                    dkim2-rcpt-index ";" SP
                    dkim2-addr

; DKIM2-Mod header field
; Declares a modification made to an existing header field
dkim2-mod         = "DKIM2-Mod:" SP dkim2-mod-params CRLF
dkim2-mod-params  = dkim2-hop-index ";" SP
                    dkim2-mod-seq ";" SP
                    dkim2-field-tag
                    [ ";" SP dkim2-fr-tag ]
                    ";" SP dkim2-mod-value

dkim2-field-tag   = "field=" header-field-name
dkim2-fr-tag      = "fr=" 1*DIGIT
                    ; OPTIONAL - absent when value fits in single header

dkim2-mod-value   = *(VCHAR / WSP)
dkim2-del-tag     = "del=" dkim2-mod-value
                    ; MUST appear last in header
dkim2-new-tag     = "new=" dkim2-mod-value

```

```
        ; MUST appear last in header

; del= and new= MUST be on separate header lines
; Presence rules per complete operation:
;   del= only -> removal
;   new= only -> addition
;   del= + new= -> modification

; DKIM2-Intended-MailFrom header field
; Internal interoperability header between list manager and MTA
; MUST be removed before external transmission
; Note: intentionally not using X- prefix per [RFC6648]
dkim2-intended-mf = "DKIM2-Intended-MailFrom:" SP addr-spec CRLF

; Shared index rules
dkim2-hop-index   = "i=" 1*DIGIT
                  ; hop sequence number, starts at 1
dkim2-rcpt-index  = "v=" 1*DIGIT
                  ; recipient sequence number for DKIM2-Sig-rt
                  ; starts at 1, increments per recipient at same hop
dkim2-mod-seq     = "seq=" 1*DIGIT
                  ; modification sequence number for DKIM2-Mod

; Address rule
dkim2-addr        = "addr=" addr-spec
                  ; addr-spec as defined in [RFC5321] Section 4.1.2
                  ; including quoted local parts

; Header field name
header-field-name = 1*( ALPHA / DIGIT / "-" )
                  ; as defined in [RFC5322] Section 2.2

; Supporting rules
tag-list          = tag-spec *( ";" tag-spec ) [ ";" ]
tag-spec          = tag-name "=" tag-value
tag-name          = ALPHA *( ALPHA / DIGIT / "_" )
tag-value         = *( %x21-3A / %x3C-7E )
                  ; printable ASCII except semicolon

domain-name       = sub-domain *("." sub-domain)
sub-domain        = 1*( ALPHA / DIGIT / "-" )
selector-name     = 1*( ALPHA / DIGIT / "-" / "_" )
base64string      = 1*( ALPHA / DIGIT / "+" / "/" / "=" )
                  ; standard base64 alphabet per [RFC4648]

; Core rules imported from [RFC5234]
ALPHA             = %x41-5A / %x61-7A
DIGIT             = %x30-39
```

```

SP           = %x20
CRLF        = %x0D %x0A
VCHAR       = %x21-7E
WSP         = SP / %x09

```

3.1.6. DKIM2-Signature Envelope Tags

```

; DKIM2-Signature envelope tags
; These tags appear within the DKIM2-Signature header field
; as defined in [I-D.clayton-dkim2-spec]

dkim2-sig-tag-i = %x69 "=" 1*DIGIT
; i= hop sequence number
; MUST start at 1 and increment by 1 at each signing hop
; gaps in sequence MUST be treated as making the message unsigned

dkim2-sig-tag-v = %x76 "=" 1*DIGIT
; v= value sequence number
; used in DKIM2-Sig-rt to distinguish
; multiple recipients at the same hop
; MUST start at 1 and increment by 1

dkim2-sig-tag-d = %x64 "=" domain-name
; d= signing domain

dkim2-sig-tag-s = %x73 "=" selector-name
; s= selector

dkim2-sig-tag-bh = %x62 %x68 "=" base64string
; bh= body hash

dkim2-sig-tag-b = %x62 "=" base64string
; b= signature value

; Tag-value list structure
tag-list      = tag-spec *( ";" tag-spec ) [ ";" ]
tag-spec     = tag-name "=" tag-value
tag-name     = ALPHA *( ALPHA / DIGIT / "_" )
tag-value    = *( %x21-3A / %x3C-7E )

```

3.2. Chain of Custody

Each hop in the delivery chain MUST add a DKIM2-Signature header field signing the current state of the message. The chain of custody is established by the sequence of signatures and envelope bindings from originator to final recipient.

3.2.1. Signature Content

The DKIM2-Signature at each hop covers:

- * All DKIM2-Sig-mf and DKIM2-Sig-rt headers with the current i= value
- * All DKIM2-Mod headers with i= values less than or equal to the current hop
- * All previous DKIM2-Signature headers
- * The incomplete current DKIM2-Signature header with the signature value absent

3.2.2. Body Hash

Each hop MUST calculate and include a body hash (bh=) of the current message body using the canonicalization algorithm specified in the signature. The bh= value changes whenever the body is modified, providing implicit notification that a modification occurred and attribution of that modification to the signing hop.

No body recipe or reconstruction is required or expected in DKIM2-core. The change in bh= value between hops, combined with the identity of the signing domain at the modifying hop, provides sufficient accountability for delivery decisions.

3.2.3. Sequence Numbering

DKIM2-Signature headers are numbered sequentially starting at i=1. Gaps in the sequence MUST be treated as making the message unsigned. The maximum sequence number is 50 as defined in [I-D.ietf-dkim-dkim2-header].

3.2.4. Signed Header Set

The DKIM2 signature at each hop covers a specific set of header fields. The signed header set MUST include:

- * All DKIM2-Sig-mf headers with i= value equal to the current hop
- * All DKIM2-Sig-rt headers with i= value equal to the current hop
- * All DKIM2-Mod headers with i= value less than or equal to the current hop. DKIM2-Mod headers are subject to the same canonicalization rules as other signed headers per [RFC6376] Section 3.4. The del= and new= values are canonicalized as header

field values - line endings are normalized and folding whitespace is handled per the canonicalization algorithm specified in the signature.

- * All previous DKIM2-Signature headers with i= value less than the current hop
- * The incomplete current DKIM2-Signature header with the b= value set to empty or a placeholder as defined in [I-D.clayton-dkim2-spec]

The signed header set does NOT include Received: headers, Return-Path:, or other trace headers added during transport. These headers are explicitly excluded because they are added by every relay and their inclusion would make signatures fragile in a way that provides no security benefit.

Header fields not listed above MAY be included in the signed header set at the discretion of the signer. Signers SHOULD include headers that have security relevance for the message - From:, To:, Subject:, Date: - and SHOULD declare their inclusion or exclusion consistently across all messages.

The b= value is calculated over the signed header set using the canonicalization algorithm specified in the signature, following the same procedure defined in [RFC6376] Section 3.7 with the modifications for DKIM2 header ordering defined in [I-D.clayton-dkim2-spec].

3.3. Header Accountability

When a Reviser modifies, removes, or adds a header field, it MUST declare the change by adding one or more DKIM2-Mod headers before signing. These headers MUST be included in the signed header set of the modifying hop and all subsequent hops, making the declaration cryptographically bound to the chain.

3.3.1. Modification Cases

Modification - header existed and its value was changed. del= and new= on separate headers with same i= and seq=:

```
DKIM2-Mod: i=2; seq=1; field=Subject; del="Original subject text"
DKIM2-Mod: i=2; seq=1; field=Subject; new="Modified subject text"
```

Removal - header existed and was removed. Only del=:

```
DKIM2-Mod: i=2; seq=1; field=Subject; del="Removed subject text"
```

Addition - header did not exist and was added. Only new=:

```
DKIM2-Mod: i=2; seq=1; field=List-Id; new=<lista@esempio.com>
```

Note that new= is technically redundant for additions since the added value is already visible in the message headers. It is declared explicitly to provide an unambiguous cryptographic binding between the modification declaration and the hop signature, particularly in cases where multiple headers of the same type exist in the message.

3.3.2. Multiple Modifications

Multiple instances of the same field, each with its own seq=:

```
DKIM2-Mod: i=2; seq=1; field=X-EVALUATION; del="pippo"
DKIM2-Mod: i=2; seq=1; field=X-EVALUATION; new="paperino"
DKIM2-Mod: i=2; seq=2; field=X-EVALUATION; del="pluto"
DKIM2-Mod: i=2; seq=2; field=X-EVALUATION; new="paperone"
```

Successive hops use their own i=:

```
DKIM2-Mod: i=2; seq=1; field=Subject; del="Value before hop 2"
DKIM2-Mod: i=2; seq=1; field=Subject; new="Value after hop 2"
DKIM2-Mod: i=3; seq=1; field=Subject; del="Value after hop 2"
DKIM2-Mod: i=3; seq=1; field=Subject; new="Value after hop 3"
```

The del= and new= tags MUST appear last in the DKIM2-Mod header field value. All other tags (i=, seq=, field=, fr=) MUST precede them.

3.3.3. Long Values

For values that exceed practical inline length, implementations MAY use the optional fr= tag to split across multiple headers with incrementing fr= values. fr= is independent for del= and new=:

```
DKIM2-Mod: i=2; seq=1; field=X-Microsoft-Antispam; fr=1; del="first part..."
DKIM2-Mod: i=2; seq=1; field=X-Microsoft-Antispam; fr=2; del="...second part..."
DKIM2-Mod: i=2; seq=1; field=X-Microsoft-Antispam; fr=3; del="...third part"
DKIM2-Mod: i=2; seq=1; field=X-Microsoft-Antispam; new="new value"
```

fr= absent means value is complete in that single header. When fr= is present, headers with same i=, seq=, field= and same tag type (del= or new=) are concatenated in fr= order.

Implementations that do not support fr= MUST treat a fragmented declaration as a null declaration for that field.

Fragments MUST be concatenated without any intervening whitespace or separators. The reconstructed value is the exact concatenation of the fragment values in fr= order.

3.3.4. Relationship to Existing Conventions

DKIM2-Mod headers formalize and cryptographically bind the informal X-Original- convention already widely deployed in the ecosystem. Systems using X-Original-From, X-Original-Subject and similar headers preserve previous header values across intermediary modifications - the same semantic goal as the del= tag in DKIM2-Mod. The key difference is that DKIM2-Mod declarations are included in the signed header set and cryptographically bound to the chain of custody, making them verifiable rather than merely informational.

This pattern is already practiced informally in the ecosystem - for example, Google Groups preserves the original sender address in an X-Original-Sender header alongside its own Sender: field. DKIM2-Mod formalizes this existing convention by making the declaration cryptographically signed and part of the verifiable chain of custody, rather than an informational annotation with no authentication binding.

3.4. Replay Prevention

Replay prevention is a direct consequence of envelope binding. Since DKIM2-Sig-mf and DKIM2-Sig-rt are cryptographically signed at every hop and contain the actual SMTP envelope values, it is impossible to reuse a valid signature for a different recipient without breaking the chain. An attacker who attempts to replay a message to a recipient not listed in DKIM2-Sig-rt will produce a mismatch between the signed rt= value and the actual RCPT TO of the new transaction, which MUST be rejected by a conformant verifier.

Mailing list redistribution is not a replay attack. When a mailing list receives a message and redistributes it to subscribers, it adds its own DKIM2 signature with its own mf= and rt= values, explicitly declaring the redistribution. The chain of custody shows the original sender, the mailing list and the final recipient as distinct entities in the chain.

3.5. DSN and Bounce Authentication

DKIM2-core provides the infrastructure for authenticated Delivery Status Notifications (DSNs) that prevent backscatter to innocent sender domains.

3.5.1. Verification During SMTP Session

DKIM2-core verification is performed during the SMTP session at two distinct points:

During RCPT TO - the inbound milter MAY perform local policy checks based on the envelope sender and recipient, for example checking against local allowlists or denylists. No DKIM2-specific verification is possible at this stage because the message headers, including DKIM2 signatures, have not yet been received.

At EndOfBody - full signature verification is performed when the complete message and accumulated envelope state are available. The inbound milter verifies the DKIM2 signature chain, the envelope binding in DKIM2-Sig-mf and DKIM2-Sig-rt and the consistency of DKIM2-Mod declarations with the signed header set. The milter then returns one of the following to instruct the MTA:

- * SMFIS_CONTINUE - the message is correctly signed and the chain is valid; the MTA proceeds with delivery
- * SMFIS_REJECT - the signature is invalid, the chain is broken, or the envelope binding does not match; the MTA issues a 5xx rejection to the connected peer
- * SMFIS_TEMPFAIL - a transient error occurred, for example a DNS timeout during key lookup; the MTA issues a 4xx temporary failure to the connected peer

When the milter returns SMFIS_REJECT, the MTA issues a 5xx rejection directed at the connected peer - the system currently delivering the message over the active SMTP connection. This rejection is never directed at the original envelope sender. This is the fundamental mechanism that prevents backscatter: no DSN is ever generated toward an address that was not the source of the current SMTP session.

3.5.2. Reject Propagation and Backscatter Prevention

When a DKIM2-core node rejects a message with 5xx during the SMTP session, the connected peer - the previous hop in the delivery chain - receives the rejection and is responsible for propagating it back toward the original sender. Each hop manages its own rejection toward its direct peer. The rejection propagates back along the authenticated chain hop by hop without generating backscatter at any point.

A node that accepts a message with an invalid or missing DKIM2 signature and subsequently generates a DSN to the original envelope sender violates a MUST NOT in the protocol and produces backscatter. During the transition period, nodes MAY accept messages with invalid or missing DKIM2 signatures as a matter of local policy while adoption is incomplete. Nodes that do so MUST NOT generate DSNs to the original envelope sender - they MUST either discard silently or generate DSNs only to the connected peer.

3.5.3. Authenticated DSN Generation

A node that has accepted a DKIM2-signed message and needs to generate a DSN does not need to possess a signing key aligned with the rt= value of the incoming signature. It needs only to sign the DSN with a key authorized for its own domain and direct it to the connected peer that delivered the original message. The DSN propagates back along the chain via the same hop-by-hop rejection mechanism described in Section 3.5.2.

3.5.4. Transition Period Behavior

During the transition period when DKIM2-capable and legacy nodes coexist, a receiver that gets a message without a valid DKIM2 signature cannot perform DKIM2-specific verification - envelope binding, chain of custody validation and authenticated DSN generation toward the connected peer are not available. The receiver falls back to pre-DKIM2 behavior: verify DKIM1 signatures if present, apply DMARC policy if configured and generate DSNs as today - including the backscatter risk that DKIM2 was designed to eliminate. Backscatter prevention is only fully effective when all intermediate nodes participate in DKIM2. A single legacy node in the chain breaks authenticated DSN propagation for downstream receivers. This is a known limitation of the transition period addressed in Section 5.

3.6. Cryptographic Algorithms

DKIM2-core mandates support for RSA-SHA256 and Ed25519-SHA256 signing algorithms as defined in [I-D.clayton-dkim2-spec]. Verifiers MUST implement both algorithms. Signers SHOULD implement both algorithms and MAY sign a message with multiple algorithms simultaneously - for example RSA-SHA256 for compatibility with legacy verifiers and Ed25519-SHA256 for efficiency. Additional signing algorithms, including post-quantum algorithms, MAY be defined in future documents and added to the set of supported algorithms without requiring changes to this profile. The DKIM2-core architecture does not publish the hash value separately from the signature, which permits use of signing algorithms that incorporate their own hash function.

For body hash calculation, DKIM2-core supports both relaxed and strict canonicalization as defined in [RFC6376] Section 3.4. The choice of canonicalization algorithm is indicated in the signature and is a per-hop decision.

The choice between relaxed and strict canonicalization for body hashing reflects a fundamental tradeoff documented in [RFC6376] Appendix B. Relaxed canonicalization tolerates common benign transformations made by intermediate systems - whitespace normalization, line ending conversion, quoted-printable to 8bit transcoding - at the cost of reduced sensitivity to intentional modifications. Strict canonicalization detects all byte-level changes but is more sensitive to involuntary transformations. DKIM2-core implementations that include legacy infrastructure in their deployment path SHOULD use relaxed canonicalization for body hashing to maximize chain continuity.

3.7. Milter Implementation

DKIM2-core is designed to be implementable via the milter interface without modifications to MTA core software. This section describes the recommended deployment patterns.

3.7.1. Two-Milter Pattern

The recommended implementation uses two milter instances:

Inbound milter - runs on the receiving MTA. Operates at two points in the SMTP session:

- * During RCPT TO: MAY perform local policy checks based on the envelope sender and recipient - for example checking against local allowlists or denylists. No DKIM2-specific verification is possible at this stage because the message headers, including DKIM2 signatures, have not yet been received.
- * At EndOfBody: performs full DKIM2 verification with access to the complete message and accumulated envelope state from MailFromRequest and RcptToRequest callbacks. The milter verifies the DKIM2 signature chain, the envelope binding in DKIM2-Sig-mf and DKIM2-Sig-rt and the consistency of DKIM2-Mod declarations with the signed header set. The milter returns SMFIS_REJECT to instruct the MTA to issue a 5xx rejection, SMFIS_TEMPFAIL for transient errors, or SMFIS_CONTINUE to accept.

The inbound milter requires no persistent state between sessions - all information needed for verification is available within the current SMTP session.

Outbound milter - runs on the transmitting MTA, positioned last in the milter chain after all other milters that may modify the message. Operates at EndOfBody with access to:

- * The complete message in its final state after all other milters
- * Envelope values accumulated via MailFromRequest and RcptToRequest callbacks
- * All DKIM2-Mod headers added by modifying entities earlier in the chain

Constructs DKIM2-Sig-mf and DKIM2-Sig-rt from envelope values, validates the formal correctness of any DKIM2-Mod headers present and adds the DKIM2 signature covering the final state of the message. Requires no persistent state between sessions.

The inbound milter is inactive on outbound traffic and the outbound milter is inactive on inbound traffic - this is standard milter behavior already implemented and deployed.

The two milter instances do not need to run on the same server. Each hop in the delivery chain signs independently with its own key. The inbound milter of hop N and the outbound milter of hop N+1 have no need to communicate - the chain of custody is established through the signed headers in the message itself.

3.7.2. Responsibility for Declaring Modifications

A fundamental principle of DKIM2-core is that every entity that modifies a message MUST declare its modifications via DKIM2-Mod headers at the time of modification. This responsibility belongs to the entity that makes the modification, not to the signing milter.

This principle has an important architectural consequence: the outbound milter does not need to reconstruct what was changed by comparing the current message with a previously cached version. It trusts that modifications have already been declared by whoever made them and signs the message as presented. This eliminates the need for stateful milter implementations with persistent shared storage in the DKIM2-core profile.

Implementations that delegate modification declaration to the signing milter rather than to the modifying entity - requiring the milter to infer changes by comparing with a cached copy - are technically possible but architecturally unsound. They couple the signing infrastructure to the modification logic in ways that create operational fragility and are incompatible with the stateless deployment model described here.

3.7.3. Mailing List Managers Delegating to an MTA

When a mailing list manager such as Mailman or Sympa passes messages to a local MTA for transmission, the recommended pattern is:

- * The list manager modifies the message - adding List-* headers, modifying Subject, appending footer
- * The list manager adds DKIM2-Mod headers declaring each modification it made
- * The list manager adds a DKIM2-Intended-MailFrom header carrying the MAIL FROM value it intends the MTA to use for transmission
- * The list manager submits the message to the local MTA
- * The outbound milter on the MTA reads DKIM2-Intended-MailFrom, removes it before external transmission, constructs DKIM2-Sig-mf and DKIM2-Sig-rt from the envelope values and signs the message
- * The DKIM2-Intended-MailFrom header is an internal interoperability convention between the list manager and the local MTA. It MUST be removed by the outbound milter before transmission. It MUST NOT appear in messages transmitted to external recipients. This pattern is consistent with existing conventions such as X-BCC handling.
- * List managers that cannot be modified to add DKIM2-Mod headers MAY rely on the outbound milter to detect undeclared modifications by comparing the signed headers against the incoming DKIM2 signature. However this approach requires stateful milter operation and is therefore classified as DKIM2-extended behavior. It is NOT part of the DKIM2-core profile.

Implementations MUST validate that the domain in DKIM2-Intended-MailFrom is authorized for the authenticated submitter on the submission channel. Accepting DKIM2-Intended-MailFrom values from unauthenticated or unauthorized submitters creates a signature authority escalation risk in multi-tenant environments.

The name DKIM2-Intended-MailFrom is suggested as a convention for interoperability between list manager software and milter implementations from different vendors. Operators who control both the list manager and the milter MAY use any internal header name they find convenient, provided that the header is removed before external transmission. The suggested name is provided only to facilitate interoperability in heterogeneous deployments where the list manager and the milter are from different vendors.

3.7.4. Mailing List Managers with Integrated SMTP

Some mailing list managers - including mlmmj and similar lightweight implementations - open SMTP connections directly without passing through a local MTA. These implementations act as their own MTA for the purpose of message transmission and MUST implement DKIM2-core signing directly, without relying on an external milter.

Such implementations MUST:

- * Declare all modifications made to the message via DKIM2-Mod headers before signing
- * Construct DKIM2-Sig-mf from the MAIL FROM value used in the SMTP transaction
- * Construct DKIM2-Sig-rt from the RCPT TO values used in the SMTP transaction
- * Sign the message with a key authorized for the signing domain

Alternatively, these implementations MAY be configured to relay through a local MTA that carries an outbound milter, delegating signing responsibility to that MTA. This is the RECOMMENDED approach for operators who wish to minimize the scope of DKIM2-core implementation.

3.7.5. Hop Counting and Multiple Hops Within the Same Administrative Domain

When a message passes through multiple MTAs within the same administrative domain - for example, a receiving MTA that passes to a list manager that passes to a transmitting MTA - each SMTP transaction that adds a new DKIM2 signature constitutes a new hop with an incremented `i=` value.

Operators MAY choose not to add a DKIM2 signature at intermediate hops within their own administrative domain if the intermediate hop does not modify the message and does not need to be independently

attributed in the chain of custody. Transparent internal relays that add only Received: headers do not need to participate in DKIM2 signing.

However, any hop that modifies the message - including the list manager hop - MUST be represented in the chain of custody with its own DKIM2 signature, regardless of whether it is within the same administrative domain as adjacent hops.

3.7.6. Confirmation of Milter-Based Implementability

The feasibility of implementing DKIM2-core via the milter interface without MTA core modifications has been confirmed by multiple participants in the working group discussion.

Murray Kucherawy, co-chair of the DKIM working group, confirmed publicly on the working group mailing list that core MTA modifications are not necessary to add DKIM2 support via milter - consistent with the deployment model used for DKIM1, SPF, DMARC and ARC.

G.W. Haywood, maintainer of Sendmail::PMilter - a Perl milter implementation supporting both Sendmail and Postfix - noted that milter protocol version 6 already provides the necessary primitives: adding, deleting and modifying headers and replacing the message body. He assessed that implementing DKIM2 via milter would not be a significant implementation effort once the specification stabilizes and expressed intent to implement DKIM2 support. John Levine subsequently confirmed on the working group list that the primary difference from existing DKIM in terms of milter implementation is access to envelope addresses - and that SMFIC_MAIL and SMFIC_RCPT callbacks already provide these in the milter protocol. He characterized the milter-based implementation of DKIM2 as a Small Matter Of Programming. G.W. Haywood concurred with this assessment.

A working milter implementation of DKIM2 in Perl using Sendmail::PMilter has been published by Bron Gondwana, co-author of the DKIM2 specification, in the working group interoperability repository at <https://github.com/dkim2wg/interop/>. This implementation demonstrates that the milter interface provides the primitives necessary for DKIM2 implementation - including Message-Instance generation and outbound signing - without MTA core modifications. The existence of this implementation confirms the milter-based deployment model described in this document, independently of whether the full DKIM2-extended profile or only DKIM2-core is implemented.

These confirmations from active MTA implementers are consistent with the DKIM2-core design principle described in this document: all mandatory functionality is expressible within the existing milter interface without requiring changes to MTA core software.

4. DKIM2-extended: Optional Profile

4.1. Overview and Scope

DKIM2-extended is a superset of DKIM2-core. A node that implements DKIM2-extended implements all of DKIM2-core plus the body recipe mechanism described in this section. DKIM2-extended is not a separate protocol - it is an additional layer of functionality built on top of the mandatory core profile.

The body recipe mechanism allows intermediaries to describe modifications made to the message body in sufficient detail to allow reconstruction of previous versions. This capability has forensic value for operators who need to investigate message handling after the fact, audit modification chains, or satisfy compliance requirements that mandate retention of original message content.

However, the body recipe mechanism is not required for the primary operational objectives identified in the DKIM working group charter: replay prevention, backscatter mitigation and modification attribution. These objectives are fully satisfied by DKIM2-core. The working group charter states that "the working group will prefer a result that is incremental to the deployed ecosystem" and that "proposed solutions are expected to be robust in terms of interoperability and scalability." DKIM2-extended should be evaluated against these criteria by operators considering deployment.

Operators who do not require forensic body reconstruction SHOULD implement DKIM2-core only. Operators who require body accountability for compliance or forensic purposes MAY implement DKIM2-extended, subject to the operational considerations described in this section.

4.2. Body Recipes and Message-Instance Headers

The body recipe mechanism is described in detail in [I-D.clayton-dkim2-spec]. This section summarizes the mechanism and identifies operational considerations relevant to deployment decisions.

A Message-Instance header is added by each hop that modifies the message body. It contains a JSON-encoded recipe - a structured description of the modifications made - encoded in base64. The recipe provides sufficient information for a verifier to reconstruct the previous version of the message body from the current version by applying the recipe in reverse.

A null recipe declares that a modification was made but that the previous state cannot or should not be reconstructed. Null recipes are discussed further in Section 4.5.

An alternative approach of storing the original message content in the MIME preamble or epilogue area has been discussed in the working group. This approach has two significant limitations identified during discussion: first, a substantial fraction of modern email - particularly bulk and transactional mail - is sent as single-part HTML without MIME boundaries, making preamble and epilogue areas unavailable; second, the use of these areas for structured signed content has not been tested and their behavior across the heterogeneous ecosystem of MTA and filtering software is unknown. The approach requires extensive testing before it could be considered for standardization.

4.3. Computational and Traffic Overhead

Operators considering DKIM2-extended deployment should be aware of the following overhead costs:

JSON parsing in the delivery critical path - Message-Instance headers contain base64-encoded JSON that must be decoded and parsed at every verifying hop. JSON parsing introduces a dependency on a JSON library in the MTA or milter critical path. While JSON libraries are available in all languages, their presence in the delivery path introduces attack surface that does not exist in DKIM1 or DKIM2-core. Section 4.4 addresses the security implications.

Traffic overhead - every message that transits DKIM2-extended-aware nodes accumulates Message-Instance headers with base64-encoded JSON recipes, additional DKIM2-Signature headers and potentially substantial body recipe content. These headers travel in the message to all recipients, including those on servers that do not implement DKIM2 at all. The overhead is not optional - it is imposed on the entire ecosystem by nodes that implement DKIM2-extended, regardless of whether downstream infrastructure can use it.

Stateful milter requirement - unlike DKIM2-core, which is stateless by design, DKIM2-extended requires the signing milter to have access to the message state before and after modifications in order to

calculate body recipes. This requires either a stateful militer implementation with persistent shared storage accessible to both the inbound and outbound militer instances, or MTA core modifications that provide equivalent capability. This is a significant architectural difference from DKIM2-core and from all previous email authentication protocols.

4.3.1. Recipe Size Limits and Computational Overhead

The JSON recipe format introduces complexity dimensions that must be explicitly bounded to prevent denial of service attacks. Unlike DKIM1 and ARC whose computational cost is bounded and predictable, DKIM2-extended recipe processing has a cost that depends on recipe complexity - a parameter controlled by the sender or any intermediary in the delivery chain.

The following limits **MUST** be enforced by all DKIM2-extended implementations:

Maximum recipe object count - implementations **MUST** enforce a maximum limit on the number of top-level objects in a recipe. During the development of this specification, a limit of 50 top-level objects was proposed as a DoS mitigation measure. This value has not been formally validated and implementations **MAY** choose a different limit based on their operational experience. The need for any such limit is itself evidence of the attack surface introduced by the recipe mechanism.

Maximum nesting depth - the current specification does not define a maximum JSON nesting depth. Implementations **MUST** enforce a maximum nesting depth of 8 levels. This is sufficient for any legitimate MIME structure - real-world messages rarely exceed 4-5 levels of MIME nesting - while preventing attacks that use artificially deep nesting to exhaust parser stack space or trigger pathological behavior in JSON libraries.

Maximum recipe size in bytes - implementations **MUST** enforce a maximum size for individual recipes and for the total accumulated Message-Instance header content in a message. Until normative limits are defined in [I-D.clayton-dkim2-spec], implementations **SHOULD** enforce a maximum individual recipe size of 64KB and a maximum total Message-Instance header size of 256KB. These values are conservative estimates pending operational data from deployments.

Maximum header line count - operators with MTA configurations that enforce limits on header count or total header size MUST be aware that accumulated Message-Instance headers across multiple hops can exceed these limits, causing silent truncation that will break recipe chain verification downstream.

The one concrete data point currently available is from an implementation demonstrated during the development of this specification: a message of six lines of plain text with a footer added produces a compact recipe. However, messages containing base64-encoded attachments require recipe content that describes base64 line-width re-alignment, which can produce Message-Instance headers substantially larger than the modified content itself. At the time of writing, no quantitative analysis of overhead across representative message types has been produced. Operators should evaluate this overhead against their specific traffic profiles before committing to DKIM2-extended deployment.

It is worth noting that all four limits defined above are operationally motivated values derived from implementation experience rather than from principled bounds inherent in the protocol design. DKIM1 and ARC require no equivalent limits because their tag-value structure has bounded complexity by design: a tag-value list of N items has exactly N items, no recursive structures and no parser state beyond the current position in the list. The fact that DKIM2-extended requires explicit limits to prevent denial of service attacks is evidence that the recipe format introduces complexity that cannot be bounded by the protocol design itself. This is a qualitative difference from all previous email authentication protocols and should be evaluated as such by operators and implementers.

Beyond CPU cycles, the requirement to reassemble fragmented Base64-encoded JSON buffers forces MTAs to move from a zero-copy or stream-oriented header processing model to a buffered model, significantly increasing the per-connection memory footprint and the pressure on memory allocation subsystems at scale. DKIM1, ARC and DKIM2-core tag-value headers can be processed in a streaming fashion with constant memory per header - each tag is read, processed and discarded. DKIM2-extended recipe processing requires accumulating the complete recipe content before any verification can begin.

At tens of thousands of transactions per second, even a modest increase in per-message processing time - one millisecond of additional JSON parsing - translates to hundreds of core-seconds per second of additional load. On a server processing 50,000 messages per second, one additional millisecond per message requires 50 additional CPU cores dedicated exclusively to recipe processing.

Containerized architectures support horizontal scaling to absorb this load, but scaling has latency. An attacker who sends a burst of messages with complex recipes can saturate the processing pool before the autoscaler responds. Operators running on-premise infrastructure without horizontal scaling - including universities, regional ISPs and small businesses, precisely the operators for whom milter-based deployment is most important - have no autoscaling fallback.

The fundamental issue is that DKIM2-extended introduces a protocol component whose computational cost is controlled by potentially adversarial input - the recipe content - rather than being bounded by the protocol design itself. DKIM1 and ARC do not have this property.

4.4. Security Considerations for Body Recipes

The body recipe mechanism introduces security considerations beyond those of DKIM2-core. Three categories of concern are relevant to deployment decisions:

JSON parsing attack surface - recipe processing introduces a JSON parser in the delivery critical path that processes untrusted external input. This creates attack surface that does not exist in DKIM2-core or DKIM1. The need for explicit resource limits, discussed in Section 4.3.1, is evidence that this attack surface is real.

Recipe chain integrity - a malicious intermediary can construct a recipe that presents a clean original message to verifiers while delivering modified content to recipients. This attack is feasible for any compromised node in the chain.

Recipe stripping - operators may strip recipe content for operational or compliance reasons, removing information that downstream verifiers depend on.

These concerns are addressed in detail with normative requirements in Section 7.3.

4.5. The Null Recipe and Its Implications

A null recipe declares that a modification was made to the message body but that the previous state cannot be reconstructed. Null recipes are the correct response for several categories of intermediary that are common in real-world deployment:

- * Security gateways that rewrite URLs - the original URLs may be sensitive and should not be reconstructed

- * Antivirus gateways that remove malicious attachments - the removed content should not be preserved or transmitted
- * DLP systems that redact sensitive content - reconstruction would defeat the purpose of the redaction
- * Legacy MTAs that perform 7bit/8bit conversion - the conversion may not be perfectly reversible
- * Mailing list managers that strip attachments or filter content - software such as Mailman and Sympa supports configurable MIME type removal as an active deployment option. When a list policy removes attachments based on type or size, the list manager MUST use a null recipe because the removed content should not be reconstructed downstream. This is a currently deployed scenario, not a legacy or transitional case.
- * Any intermediary that makes modifications it cannot or should not describe in a recipe

These categories collectively represent a substantial fraction of real-world email infrastructure. When any of these nodes is present in the delivery chain, the result is a null recipe at that hop - which provides no additional body accountability beyond the bh= change already available in DKIM2-core. If null recipes are acceptable at the nodes most likely to make substantial body modifications, the incremental benefit of DKIM2-extended over DKIM2-core for body accountability is limited to the cases where all intermediaries cooperate fully - which is the minority of real-world delivery paths.

This is not a criticism of the body recipe mechanism. It is an accurate characterization of the deployment landscape that operators need to understand before committing to DKIM2-extended infrastructure.

It is worth noting that [RFC6376] Appendix B already addressed the fragility of body signatures in DKIM1 through a pragmatic approach: relaxed canonicalization tolerates common benign transformations - whitespace normalization, line ending differences, quoted-printable to 8bit conversion - without requiring intermediaries to declare or reconstruct those changes. DKIM2's strict canonicalization and body recipe mechanism represent a deliberate departure from this pragmatism in favor of a deterministic reconstruction model. The null recipe outcome is the price of that departure: cases that relaxed canonicalization would have handled silently become explicit failures in the DKIM2-extended model. Operators should evaluate whether the forensic value of body reconstruction justifies this tradeoff for their specific deployment scenario.

The systematic use of null recipes by security gateways is not a theoretical concern - it has been confirmed empirically by a major gateway vendor participating in this working group. Philip Guenther of Proofpoint, whose products perform substantial alteration of message headers and bodies under customer security policies, has stated explicitly on the working group list that reversibility of those changes is "the opposite of a goal" for their customers and that their products will use the null recipe mechanism "when necessary" - and will not follow the specification at all if null recipes are not available as an option.

This confirmation from a major in-path gateway vendor illustrates the structural limitation of the body recipe mechanism: the nodes most likely to make substantial body modifications - security gateways, DLP systems, antivirus engines - are by design and by customer requirement the nodes that will systematically produce null recipes. The forensic value of body reconstruction is therefore unavailable precisely at the hops where attribution would matter most.

4.6. Privacy Considerations for Body Recipes

Body recipes raise data protection concerns that operators in GDPR and equivalent jurisdictions must evaluate before deployment. These concerns are addressed in detail in Section 6. A summary relevant to the deployment decision is provided here.

Body recipes create structured, recoverable representations of previous message content that travel in the message to all downstream recipients and archiving systems. For most recipe types - range references, line counts - the privacy implications are limited. However for recipes that contain literal text from the original message, or for the specific cases of DLP redaction and URL rewriting, the recipe mechanism may cause personal data or sensitive content to circulate in a form that was not intended by the operator that originally processed it.

Operators subject to GDPR should evaluate whether body recipe generation and transmission is consistent with their data minimization obligations under Article 5 and whether their use of null recipes for sensitive content modifications is sufficient to meet their compliance requirements.

5. Transition and Interoperability

5.1. Overview

The deployment of DKIM2 will occur incrementally across a heterogeneous ecosystem that includes DKIM2-core nodes, DKIM2-extended nodes, DKIM1-only nodes and legacy nodes that implement no cryptographic authentication. This section describes the expected behavior of each node type in the presence of the others and identifies the properties that are and are not achievable during the transition period.

5.2. Node Types and Behaviors

DKIM2-core node - implements envelope binding, chain of custody, header accountability, replay prevention and DSN authentication as defined in Section 3. Adds DKIM2-Sig-mf, DKIM2-Sig-rt, DKIM2-Mod and DKIM2-Signature headers. Verifies incoming DKIM2 signatures. Passes DKIM2-extended headers through without interpreting them.

DKIM2-extended node - implements all of DKIM2-core plus body recipe generation and verification as defined in Section 4. Adds Message-Instance headers with JSON-encoded recipes in addition to all DKIM2-core headers.

DKIM1-only node - implements DKIM1 [RFC6376] but not DKIM2. Passes DKIM2 headers through as unrecognized header fields. Does not add DKIM2 signatures. Does not break DKIM2 chains - it simply does not extend them.

ARC node - implements ARC [RFC8617]. ARC and DKIM2-core address overlapping problems with different mechanisms. DKIM2-core is a functional superset of ARC - it provides the same modification attribution and trust chain capabilities plus cryptographic envelope binding. During the transition period, nodes that implement ARC but not DKIM2-core continue to provide ARC chains independently of the DKIM2 chain. The two chains coexist without conflict but do not bridge each other - a gap in the DKIM2 chain caused by a non-participating node remains a gap regardless of whether that node implements ARC.

Legacy node - implements no cryptographic authentication. Passes all authentication headers through without interpreting them. Does not add signatures. Does not break chains but does not extend them.

5.3. Chain Continuity and Legacy Nodes

A legacy node in the delivery chain does not break the DKIM2 signature chain, it simply passes existing signatures through without adding new ones. A downstream receiver that encounters a message with a valid DKIM2 chain ending at a hop before the legacy node can verify the chain up to that point and apply local policy for the unsigned segment.

A legacy node that makes modifications to the message - adding or changing headers, modifying the body, rewriting URLs - represents a more significant gap in the chain of custody than a transparent relay. Such modifications are not declared via DKIM2-Mod headers and cannot be attributed to any signing domain. A downstream receiver that encounters a changed bh= value or unexpected header differences between two consecutive DKIM2 signatures can identify that a modification occurred in the gap but cannot determine what was changed or by whom. Receivers that apply strict chain of custody policies SHOULD treat gaps containing undeclared modifications with additional suspicion, even if the signatures on either side of the gap are individually valid.

This is a known limitation of the transition period. The properties achievable end-to-end depend on the composition of the delivery path:

Replay prevention - fully effective only when every hop adds a DKIM2 signature with envelope binding. A legacy node between the originator and the final recipient means that the rt= value at the last signed hop does not necessarily reflect the actual final recipient.

Backscatter prevention - fully effective only when every hop participates in DKIM2. A single legacy node breaks authenticated DSN propagation for all downstream receivers. During the transition period, receivers that encounter messages with broken DKIM2 chains MUST fall back to current DKIM1 behavior: apply local policy, generate DSNs as today.

Chain of custody - provides attribution for all hops that participate in DKIM2. Legacy hops are visible as gaps in the i= sequence. A gap in the sequence does not invalidate the chain - it identifies the segment where accountability is absent.

Header accountability - fully effective for all hops that implement DKIM2-core. Modifications made by legacy nodes are not declared but are detectable as changes in the signed header set between consecutive DKIM2 signatures.

5.4. Coexistence with DKIM1

DKIM2 reuses DKIM1 DNS key infrastructure. A domain that has DKIM1 keys deployed does not need to make DNS changes to support DKIM2 signing by an ESP or MTA acting on its behalf. This is a deliberate design decision in [I-D.clayton-dkim2-spec] that significantly reduces the barrier to adoption for domain owners.

During the transition period, messages MAY carry both DKIM1 and DKIM2 signatures. Receivers that implement only DKIM1 will verify the DKIM1 signature and ignore the DKIM2 headers. Receivers that implement DKIM2 will verify the DKIM2 chain and MAY also verify the DKIM1 signature for compatibility with existing policy frameworks such as DMARC.

5.5. Coexistence with ARC

ARC [RFC8617] and DKIM2-core address overlapping problems with different mechanisms. ARC provides a trust chain for mailing list redistribution by recording the authentication state of a message as it passes through intermediaries. DKIM2-core is a functional superset of ARC - it provides the same modification attribution and trust chain capabilities plus cryptographic envelope binding that ARC lacks.

During the transition period, nodes that implement ARC but not DKIM2-core continue to provide ARC chains independently of the DKIM2 chain. The two chains coexist without conflict but do not bridge each other - a gap in the DKIM2 chain caused by a non-participating node remains a gap regardless of whether that node implements ARC. ARC does not compensate for the absence of DKIM2 participation.

Operators that have deployed ARC should not remove it during the DKIM2 transition period. ARC continues to provide value for receivers that evaluate ARC chains as part of their local policy, independently of DKIM2 adoption status.

The limited adoption of ARC after six years of availability - approximately 10,000 signing domains compared to 9.5 million DKIM1 records as reported in [I-D.adams-arc-experiment-conclusion] - is informative for DKIM2 deployment expectations. ARC is militer-deployable and architecturally simpler than DKIM2-extended. Its adoption trajectory suggests that even militer-deployable protocols face significant ecosystem inertia. This reinforces the importance of the DKIM2-core profile: reducing deployment complexity to the minimum necessary to achieve the primary objectives of the protocol maximizes the probability of meaningful adoption.

DKIM2-core enables a model of trust based on cryptographic chain of custody rather than direct domain alignment - a model that major providers already implement empirically through ARC evaluation. The approach taken in DKIM2-core is consistent with and builds upon experimental work already deployed in production.

[I-D.chuang-replay-resistant-arc] proposes extending ARC with explicit envelope binding via `dara=` and `darn=` tags in the ARC-Seal, signing SMTP recipients at each hop and declaring the forwarding path. This protocol has been implemented in production by Google on Google Groups infrastructure, as evidenced by headers observed in real message flows. DKIM2-core formalizes and extends this approach with stronger cryptographic binding and a complete chain of custody model.

5.6. Incremental Deployment Path

The recommended incremental deployment path for operators adopting DKIM2-core is:

Phase 1 - outbound signing only: deploy the outbound militer to add DKIM2-Sig-mf, DKIM2-Sig-rt and DKIM2-Signature headers to outgoing messages. No inbound verification. This establishes the operator's presence in the DKIM2 ecosystem and allows downstream receivers to begin building chain of custody records.

Phase 2 - inbound verification: deploy the inbound militer to verify incoming DKIM2 signatures and record results in Authentication-Results headers. Apply local policy based on verification results. This phase can be implemented in monitoring-only mode initially - logging verification results without affecting delivery - to assess the impact before enforcing policy.

Phase 3 - policy enforcement: begin rejecting messages that fail DKIM2 verification according to local policy. This phase requires confidence that the majority of expected senders have deployed DKIM2 outbound signing.

Phase 4 - mailing list and intermediary participation: update mailing list managers and other intermediaries to add DKIM2-Mod headers for their modifications and to pass the DKIM2-Intended-MailFrom convention to the outbound milter. This phase completes the chain of custody for messages that transit these systems.

DKIM2-extended MAY be added at any phase by operators who require body accountability, subject to the operational considerations described in Section 4.

5.7. The DMARC p=reject Mailing List Problem

The DMARC p=reject mailing list problem is a known limitation of the current email authentication ecosystem that predates DKIM2. It arises from the interaction between DMARC's domain alignment requirement and the routing changes introduced by mailing list redistribution.

The mechanism of failure: DMARC requires that at least one of SPF or DKIM provide a pass with domain alignment to the RFC5322 From: header. When a message passes through a mailing list two failure modes are possible depending on how the list handles the From: header.

Case A - list without From: rewriting: when a mailing list redistributes a message without modifying the From: header, SPF fails because the list server IP is not in the original sender's SPF record and DKIM alignment fails because the list's signing domain differs from the From: domain. The following Authentication-Results header was observed on a message from itb.it that transited Google Groups and was delivered to a Microsoft Exchange recipient:

```
dmARC=fail header.from=itb.it
dkim=pass header.d=googlegroups.com
spf=pass smtp.mailfrom=googlegroups.com
arc=pass
```

The message body was plain text with no modifications. DMARC failed purely on alignment grounds - not because the body was modified. Microsoft delivered the message via ARC override. Body recipes cannot fix this failure - even with full body reconstruction, the signing domain googlegroups.com is not aligned with the From: domain itb.it.

Case B - list with From: rewriting: when a mailing list replaces the From: header with its own domain, DMARC passes because the list's signing domain is now aligned with the new From: domain. The following Authentication-Results header was observed on a message from vittorio.moccia@gmail.com that transited a mailing list on itb.it and was delivered to a Microsoft Exchange recipient:

```
dkim=pass header.d=itb.it
dkim=pass header.from=itb.it
spf=pass smtp.mailfrom=itb.it
arc=pass
```

DMARC passed completely. But the original sender's identity was destroyed - the recipient sees "Lista Utenti utenti@itb.it" instead of the original author. This is the architectural hack that makes DMARC work today for mailing lists - and it is unsound because it destroys sender identity to achieve alignment.

Body recipes do not resolve this problem. In Case A, DMARC fails on domain alignment - a problem in the header and envelope layer that body reconstruction cannot address. In Case B, DMARC passes only because the From: header was replaced - a header modification that has nothing to do with body integrity. In neither case does body reconstruction affect the DMARC outcome.

DKIM2-core offers a third path that neither Case A nor Case B provides today. A mailing list implementing DKIM2-core can:

- * Retain the original From: header - preserving the original sender's identity
- * Declare the addition of List-* headers and any Subject: modifications via DKIM2-Mod headers
- * Sign with its own DKIM2 key, cryptographically binding the envelope and the chain of custody
- * Provide receivers with a verifiable record that the list handled the message and what modifications were made

This allows receivers that evaluate DKIM2 chain of custody - as Microsoft already does empirically with ARC - to make an informed trust decision without requiring From: rewriting or body reconstruction. DKIM2-core provides the cryptographic substrate necessary for a future DMARC2 or an evolved DMARC policy evaluation that recognizes transitive trust through a verified Chain of Custody.

This allows receivers that evaluate DKIM2 chain of custody - as Microsoft and Google already do empirically with ARC - to make an informed trust decision without requiring From: rewriting or body reconstruction. Critically, it achieves this without requiring new DNS records or SMTP capabilities.

By utilizing the i= and rt= fields, DKIM2-core establishes a verifiable cryptographic link between the original message and the modified version distributed by the list. Trust is derived from the verifiable path of the message rather than from an obsolete and hidden body state. This approach maintains the "What You See Is What Was Authenticated" principle, which is abandoned by the body reconstruction mechanism.

DKIM2-core provides the cryptographic substrate necessary for a future DMARC2 or an evolved DMARC policy evaluation that recognizes transitive trust through a verified Chain of Custody. The empirical evidence from current ARC deployment demonstrates that the trust model is sound and already accepted by major providers in practice.

Ultimately, DKIM2-core restores DMARC interoperability with mailing lists by authenticating the modification path, whereas DKIM2-extended fails to address the root cause of misalignment while introducing significant privacy and security overhead.

6. Privacy Considerations

This section addresses privacy implications of DKIM2-core and DKIM2-extended in accordance with [RFC6973], which provides guidance on privacy considerations in Internet protocol design.

6.1. DKIM2-core Privacy Properties

DKIM2-core adds the following information to messages in transit:

DKIM2-Sig-mf and DKIM2-Sig-rt headers - these fields carry the SMTP envelope values, which may include email addresses not present in the RFC5322 headers. In the common case of direct delivery, these values are already implicit in the message routing. For mailing list redistribution, the rt= value at each hop reveals the address of the individual subscriber receiving that copy of the message. This is not new information - the SMTP envelope already contains this information - but it is now carried in a signed header field that persists in the message and may be archived by downstream systems.

DKIM2-Mod headers - these fields carry previous values of modified header fields. For header modifications that involve personal data - for example a From: header that is rewritten by a mailing list - the

original value is preserved in a signed header that travels with the message. Operators that modify headers containing personal data should be aware that the original values will be visible to all downstream recipients and archiving systems.

This pattern is already practiced informally in the ecosystem - for example, Google Groups preserves the original sender address in an X-Original-Sender header alongside its own Sender: field. DKIM2-Mod formalizes this existing convention by making the declaration cryptographically signed and part of the verifiable chain of custody, rather than an informational annotation with no authentication binding.

Authentication-Results headers - these fields record the outcome of DKIM2 verification at each hop. They do not contain message content or personal data beyond what is already present in the message headers.

The privacy impact of DKIM2-core is limited and proportionate to its functional objectives. The additional data carried in DKIM2-core headers is necessary for the envelope binding and chain of custody mechanisms and does not represent a material increase in the personal data surface of the message beyond what is already present in the SMTP transaction.

6.2. DKIM2-extended Privacy Considerations

DKIM2-extended raises privacy concerns that are qualitatively different from those of standard email processing. Email messages already transit through systems that read, analyze and archive them - existing data protection frameworks address this reality. What DKIM2-extended adds is the systematic creation of structured, cryptographically signed records of previous versions of message content that did not previously exist as discrete data objects. A standard email message represents the current state of a communication. A message with body recipes represents both the current state and a signed history of previous states distributed to every downstream recipient and archiving system in cryptographically immutable form.

This distinction is relevant to data protection law in the ways described below.

6.2.1. The Null Recipe Mechanism

The null recipe is the primary technical instrument available to intermediaries for managing privacy risk in DKIM2-extended deployments. An intermediary that modifies message content may declare null rather than generating a content-bearing recipe, signalling that a modification occurred and who made it without creating any structured record of the previous content.

The null recipe preserves the core accountability property of DKIM2 - the modification is declared and attributed - while avoiding the creation of personal data records that would otherwise travel with the message to all downstream recipients and archiving systems. It is the correct response in any situation where generating a content-bearing recipe would conflict with data protection obligations or organizational security policy.

The current specification does not provide normative guidance on when intermediaries are obligated to use null recipes. This document addresses that gap for specific deployment scenarios in the sections that follow.

6.2.2. Data Minimization

GDPR Article 5(1)(c) requires that personal data be adequate, relevant and limited to what is necessary for the purposes for which it is processed. The primary operational objectives of DKIM2 - replay prevention, backscatter mitigation, modification attribution - are achievable without body recipes as argued in Section 4.5. Body recipe data collection may therefore not meet the necessity test under Article 5(1)(c).

The specific minimization problem of body recipes is not that personal data is processed - it is that body recipes create a new category of structured data that did not previously exist: recoverable representations of previous message content, distributed in signed form to all downstream systems. This is qualitatively different from the processing that occurs in standard email transit and raises minimization questions that do not arise for DKIM2-core.

This is not a definitive legal assessment. Operators subject to GDPR should seek legal advice on whether their specific use of body recipes is consistent with their data minimization obligations.

6.2.3. Data Retention

GDPR Article 5(1)(e) requires that personal data be kept in a form that permits identification of data subjects for no longer than necessary. Body recipes travel in the message and may be archived by any system that receives or intercepts it - including the final recipient's mail store, compliance archiving systems and, in some jurisdictions, systems operated under lawful interception or judicial oversight obligations. Unlike the message body itself, body recipes embedded in signed headers cannot be selectively removed without invalidating the signature chain. This creates a retention problem that has no clean technical resolution: the data persists in signed form in every copy of the message held by any system that archived it, regardless of the originating organization's retention policy.

Furthermore, intermediaries that implement DKIM2-extended may find that the body recipe itself constitutes an audit trail of modifications - and in many jurisdictions, audit records are subject to mandatory retention obligations that may exceed the retention period applicable to the communication content itself. An intermediary may therefore find itself obligated to retain recipe content as an audit record for extended periods, regardless of its normal data retention policy. This obligation did not exist before DKIM2-extended because no structured modification record was created during transit.

Operators should evaluate whether their archiving systems can handle recipe content consistently with applicable obligations under [GDPR] Article 5(1)(e) and any sector-specific retention requirements in their jurisdiction.

6.2.4. DLP Systems and Body Recipes

A Data Loss Prevention system that redacts sensitive content does so precisely because that data must not circulate. A body recipe that allows reconstruction of the content before redaction creates a structured record of the very data the DLP system was designed to protect - a structural contradiction between the purpose of the system and what DKIM2-extended asks it to generate.

Operators deploying DLP systems in conjunction with DKIM2-extended MUST use null recipes as described in Section 6.2.1 for all modifications that involve redaction of sensitive content.

6.2.5. Antivirus Gateways and Body Recipes

When an antivirus gateway removes a malicious attachment, the removed content should be eliminated, not preserved. A content-bearing recipe for such a removal creates a structured record of content that should not exist downstream.

Operators deploying antivirus gateways in conjunction with DKIM2-extended MUST use null recipes as described in Section 6.2.1 for all modifications that involve removal of malicious or suspicious content.

6.2.6. URL Rewriting and Body Recipes

Security gateways that rewrite URLs generate recipes containing the original URLs, which may reveal sensitive communication content or internal infrastructure details not intended for downstream exposure.

Operators who cannot expose original URLs in recipe content MUST use null recipes as described in Section 6.2.1.

6.2.7. Compliance with Data Subject Rights

GDPR Articles 16 and 17 grant data subjects the right to rectification of inaccurate personal data and the right to erasure. Body recipes create structural conflicts with both rights that manifest differently depending on the stage of the message lifecycle. In addition to GDPR, operators must consider Directive 2002/58/EC (ePrivacy Directive) [ePrivacy], which mandates the confidentiality of communications. By creating structured, cryptographically signed records of previous body states that are durably embedded in the message itself, DKIM2-extended converts transient communication content into a verifiable content history that travels with the message to every downstream system. This conversion raises questions about the applicability of mere conduit exemptions under Article 12 of the e-Commerce Directive and its successor provisions, which condition that exemption on the intermediary not modifying the information transmitted. Generating a body recipe may be considered a form of content processing that goes beyond mere transport, potentially requiring an explicit legal basis for the creation and retention of such records at intermediate hops.

The erasure problem - the null recipe described in Section 6.2.1 is a preventive instrument: if applied consistently before personal data enters the recipe, no erasure conflict arises. However it is not a remedial instrument. Once a content-bearing recipe has been generated and distributed, the Right to Erasure under Article 17 GDPR becomes technically unenforceable: the organization that generated

the recipe can delete its own copy, but the recipe exists in cryptographically signed form in every downstream copy of the message. GDPR Article 17 imposes an obligation on the controller to erase data - but it provides no mechanism to compel deletion from systems in other administrative domains, other jurisdictions, or operated by parties who are not data controllers under the same legal framework.

Furthermore, an intermediary that generated a recipe may itself face conflicting obligations: the erasure request requires deletion, but audit trail or documentary evidence obligations - contractual, regulatory, or legal - may require retention of records of modifications made. These two obligations cannot be simultaneously fulfilled. This conflict is not a gap in the legal framework - it is a structural consequence of DKIM2-extended creating cryptographically immutable records at transit nodes.

The rectification problem - the rectification conflict is structurally irresolvable and arises specifically when the message is in archival state. During transit the message exists transiently and the problem does not arise. The problem emerges when the message is archived - by any system at any point in the delivery chain - with a recipe containing inaccurate personal data.

At that point three obligations come into direct conflict. First, GDPR Article 16 requires that the inaccurate personal data be corrected. Second, correcting the value in the recipe invalidates the cryptographic signature of the hop that generated it, which cascades through all subsequent signatures in the chain. Third, if the archive is used as certified documentary evidence - for compliance, audit, or legal purposes - its integrity must be preserved. Modifying it to fulfill the rectification request destroys its evidentiary value. Not modifying it violates the data subject's right.

This three-way conflict between data subject rights, cryptographic integrity and documentary evidence obligations has no technical resolution within the current DKIM2-extended architecture. It does not arise in standard email archiving, where an organization can modify or delete its own archives without affecting cryptographic chains, because standard email archives do not carry immutable signed records of previous content versions.

Joint controllership - an intermediary that generates body recipes is no longer merely transporting the message - it is creating a new structured record of personal data by determining what previous content to include in the recipe and ensuring its persistence through cryptographic binding. This may constitute joint controllership

under GDPR Article 26, with associated obligations including the potential requirement for a Data Protection Impact Assessment under Article 35. Operators should evaluate whether their recipe generation activities trigger these obligations.

6.2.8. Privacy Review Recommendation

At the time of writing, [I-D.clayton-dkim2-spec] does not include a Privacy Considerations section and the Security Considerations section is marked TBA. Subsequent versions may address some of the concerns raised here following discussion on the ietf-dkim mailing list initiated in March 2026.

For a specification intended to become an IETF Standards Track document, privacy and security considerations are required per [RFC3552] (BCP 72). This document provides suggested privacy considerations text based on [RFC6973] for consideration by the working group as a contribution to the base specification.

Note on [RFC6973]: this is an IAB document rather than an IETF document. However IAB documents on protocol design are explicitly relevant to IETF Standards Track work - the IAB and IETF coordinate on architectural and privacy matters as part of the overall Internet standards process. The privacy considerations in this document are consistent with both [RFC6973] and the security considerations requirements of [RFC3552].

6.2.9. Architectural Conclusion

The privacy considerations described in this section lead to a clear architectural conclusion: DKIM2-extended MUST remain optional and loosely coupled to DKIM2-core. This is not merely a deployment preference - it is a requirement derived from data protection principles.

An operator subject to [GDPR] and [ePrivacy] who activates DKIM2-extended takes on explicit data processing obligations for the personal data contained in body recipes, including obligations that may not arise under standard email processing - among them the creation of audit-trail records at transit nodes, potential joint controllership under GDPR Article 26 and questions about mere conduit exemptions under the e-Commerce Directive. An operator who implements only DKIM2-core has no such obligations beyond those that exist today for standard email processing. The optional nature of DKIM2-extended is therefore not a technical convenience but a legal necessity for a significant portion of the global email infrastructure.

DKIM2-core and DKIM2-extended are designed to coexist cleanly: a DKIM2-core-only node passes Message-Instance headers through as opaque signed content without interpreting them and a DKIM2-extended node adds full body recipe functionality on top of the core. Activating DKIM2-extended adds capabilities; not activating it does not degrade the core functionality in any way. This clean separation is the architectural property that makes DKIM2 deployable across jurisdictions with different data protection requirements.

7. Security Considerations

7.1. Security Properties of DKIM2-core

Replay prevention - a valid DKIM2 signature cannot be reused for a different recipient without breaking the chain. The cryptographic binding of RCPT TO values in DKIM2-Sig-rt to the signature at every hop makes replay attacks detectable by any conformant verifier.

Sender accountability - the signing domain at each hop is cryptographically bound to the message and the envelope. A receiver can establish a verifiable chain of custody from originator to final recipient, identifying every entity that handled the message and declared its modifications.

Backscatter prevention - DSN generation is authenticated through the chain of custody. A receiver that rejects a message during the SMTP session directs the rejection to the connected peer, never to the envelope sender. This prevents backscatter to innocent sender domains.

Header integrity - modifications to header fields are declared via DKIM2-Mod headers and are covered by the signature of the modifying hop. Undeclared header modifications are detectable as inconsistencies between the signed header set and the declared modifications.

Body integrity - the bh= value at each hop provides a hash of the current message body. Changes in bh= between consecutive signatures identify hops where body modifications occurred and attribute them to the signing domain. Full body reconstruction is not provided in DKIM2-core and is not required for the primary security objectives.

7.2. Security Limitations of DKIM2-core

Legacy node gap - a legacy node in the delivery chain does not extend the DKIM2 chain. Modifications made by legacy nodes are not declared and cannot be attributed. The gap is visible as a discontinuity in the `i=` sequence but the content of the gap is unknown. Receivers must apply local policy for messages with gaps in the chain.

Key compromise - compromise of a signing key allows an attacker to generate valid signatures for that domain. Key rotation procedures as defined in [RFC6376] apply to DKIM2 keys. The `i=` sequence provides some mitigation - an attacker who generates a forged signature must insert it into a plausible position in the chain.

DNS security - DKIM2 inherits the DNS security properties of DKIM1. Key publication relies on DNS, which is subject to cache poisoning and other attacks unless DNSSEC is deployed. Operators SHOULD deploy DNSSEC for their signing domains.

Relaxed domain match - the relaxed domain match algorithm for `mf=` allows subaddress schemes used for bounce handling. Operators should be aware that this algorithm permits signatures from subdomains of the MAIL FROM domain, which may be exploitable if subdomain delegation is not carefully controlled.

7.3. Security Considerations for DKIM2-extended

DKIM2-extended introduces additional attack surface beyond DKIM2-core. Operators considering DKIM2-extended deployment should evaluate the following.

7.3.1. JSON Parsing Attack Surface

Message-Instance headers contain base64-encoded JSON that must be decoded and parsed at every verifying hop. JSON parsers process untrusted external input in the delivery critical path and are subject to algorithmic complexity attacks that cause excessive CPU consumption, memory exhaustion through deeply nested structures, parser inconsistency across implementations and buffer overflows in poorly implemented parsers.

A specific concern is Type Confusion: differences in JSON parser implementations regarding duplicate keys and numerical precision can cause a recipe to be interpreted differently by intermediaries and final recipients. An attacker could craft a recipe that validates correctly at intermediate hops - where the signature is verified - but is interpreted differently at the final recipient, causing signature validation to succeed on a message body that differs from

what the signer intended. This attack exploits parser inconsistency rather than cryptographic weakness and cannot be mitigated by stronger signing algorithms.

The JSON recipe syntax also exhibits semantic ambiguity: the same construct - an empty array [] - is used in different contexts with different meanings. In backward-looking recipes it declares that a header field was added by the current hop and had no previous value. In forward-looking recipe proposals discussed in the working group, the same construct declares that a header field should be ignored during verification of a future message. This dual meaning requires implementations to determine the correct interpretation from context, introducing a category of parser confusion that does not exist in the tag-value formats used by DKIM1 and DKIM2-core.

The need to define explicit limits on object count, nesting depth and total recipe size - as discussed in Section 4.3.1 - demonstrates that this attack surface has been recognized. Operators **MUST** ensure that their JSON parsing implementation enforces strict resource limits on input size, nesting depth and object count appropriate to their operational environment. Implementations **SHOULD** use a JSON parser that strictly conforms to [RFC8259] and rejects input that is ambiguous under that specification - in particular, implementations **MUST** reject JSON objects with duplicate keys rather than silently selecting one value. Sandboxing the JSON parser from the MTA delivery process is **RECOMMENDED** where operationally feasible.

7.3.2. Recipe Chain Integrity

A malicious intermediary that controls a node in the delivery chain can construct a recipe that presents a clean original message to the verifier while the delivered content is malicious. This attack requires control of a node in the chain and the ability to generate a valid signature for that node's domain, but is feasible for a compromised or malicious intermediary. Verifiers **MUST** validate the complete recipe chain from originator to final recipient and **MUST NOT** rely on individual recipes in isolation.

7.3.3. Semantic Gap Between Verification and Visualization

DKIM2-extended introduces a structural discrepancy between the reconstructed body - the previous state that is cryptographically verified - and the transferred body - the modified state that is rendered to the end user. This creates a semantic gap that undermines the fundamental premise of email authentication: that the content being displayed is the content that was authenticated.

When a receiver applies a body recipe to validate a DKIM signature on a version of the message that is no longer present, a verification pass result is semantically ambiguous. The user is presented with a verified status - a positive Authentication-Results header or a trust indicator in a mail client - but the content displayed does not correspond to the cryptographically covered data.

This gap is a vector for social engineering. A compromised intermediary can craft modifications that are functionally malicious while providing a valid reconstruction recipe that produces a clean original. The receiver's verification passes on the ghost version; the user sees and acts on the malicious version.

There is no standardized mechanism to communicate a "reconstructed authentication" state to human recipients without creating UI confusion or warning fatigue. The DKIM2-extended body recipe mechanism therefore constitutes a departure from the "What You See Is What Was Signed" principle. It should be treated as a specialized tool for automated forensic processing rather than a general-purpose body integrity mechanism for end-user trust decisions.

This concern is distinct from but related to the Recipe Injection attack described in Section 7.3.4. Recipe Injection exploits the gap to authenticate a stolen message. The semantic gap concern exists even without malicious intent - any legitimate body modification creates a divergence between what was authenticated and what is displayed.

7.3.4. Attribution of Change vs. Verification of State

It has been argued that body recipes provide attribution for modifications. However, attribution of a state change is not equivalent to verification of the previous state. In mixed environments (DKIM1/DKIM2), an intermediary can provide a cryptographically consistent recipe for a state that never existed, effectively signing a fabrication. As long as the fabrication is consistent with a previously obtained DKIM1 signature, the mechanisms described in the DKIM2-extended profile validate the lie as truth.

The attack proceeds as follows: a malicious intermediary in possession of a stolen DKIM1-signed message receives a legitimate but unsigned message. It provides a signed recipe that, when applied to the legitimate message, reconstructs the stolen DKIM1 message. The intermediary's DKIM2 signature validates the recipe's integrity. The recipe validates the stolen message's DKIM1 signature. The receiver sees a valid chain and believes the trusted domain sent the stolen message in the current delivery.

DKIM2-core avoids this entirely. An intermediary declares what it received and what it changed - attestation of flow, not reconstruction of state. There is no recipe mechanism that can be used as a payload injector because there is no mechanism for claiming what the previous state was.

DKIM2-core provides a stateless chain of custody over message headers and body content as transmitted. This property is well-suited to general Internet mail flow across administrative boundaries.

DKIM2-extended introduces stateful body reconstruction across those same boundaries, with the verification limitations described above. Implementers SHOULD carefully evaluate the operational, security and legal implications of deploying DKIM2-extended before adoption and MUST NOT treat a passing DKIM2-extended verification result as equivalent to verification of the reconstructed prior message state.

7.3.5. Null Recipe Ambiguity

A null recipe declares that a modification was made but provides no information about the nature or extent of the modification. A malicious intermediary can use a null recipe to conceal arbitrary body modifications while remaining nominally compliant with the protocol. Receivers that rely on body recipe verification for security decisions MUST treat null recipes as untrusted modifications equivalent to a complete body replacement.

7.3.6. Recipe Stripping

An intermediary that strips body recipe content from a message removes information that downstream verifiers depend on. The specification does not currently define how receivers should handle messages with stripped or truncated recipes. Implementations MUST handle this case gracefully without crashing or producing incorrect verification results. Stripped recipes SHOULD be treated as null recipes for the purpose of verification policy.

7.3.7. Stateful Militer Attack Surface

The persistent shared storage required by stateful DKIM2-extended militer implementations is an additional attack surface. Compromise of the shared storage allows an attacker to manipulate cached message state and cause the militer to generate incorrect recipes or signatures. Operators MUST apply appropriate access controls to stateful militer storage and MUST monitor for unexpected modifications.

7.4. Cryptographic Agility

DKIM2-core mandates support for RSA-SHA256 and Ed25519-SHA256. The architecture does not publish the hash value separately from the signature, which permits future adoption of post-quantum signing algorithms that incorporate their own hash function. Operators should monitor the development of post-quantum algorithm standards and be prepared to add support for new algorithms as they are standardized.

The use of both RSA-SHA256 and Ed25519-SHA256 in parallel is RECOMMENDED during the transition period to provide cryptographic agility. Ed25519 signatures are significantly shorter than RSA signatures and impose lower computational overhead at scale.

7.5. Timestamp Handling

DKIM2 signatures include a timestamp. Receivers SHOULD reject signatures with timestamps significantly in the future, which may indicate replay of pre-generated signatures. The acceptable clock skew is implementation-defined. Operators should balance two competing concerns: a tight skew window reduces the window for pre-generated replay attacks but may cause legitimate rejections due to clock synchronization differences between sending and receiving systems; a loose skew window accommodates clock differences but increases the window available for replay attacks. NTP-synchronized infrastructure typically maintains clock accuracy within seconds, making a skew window of a few minutes sufficient for most deployments.

Signatures with timestamps significantly in the past MAY be treated with additional suspicion as potential replays, subject to local policy. The appropriate age threshold depends on the deployment context - mailing list redistribution may legitimately introduce delays of hours or days and operators with mailing list traffic in their delivery paths should configure age thresholds accordingly. This is consistent with operational experience from DKIM1 deployments, where signature expiry timestamps are often set generously or ignored precisely because legitimate redistribution paths introduce unpredictable delays.

8. IANA Considerations

This document requests the registration of the following header fields in the Permanent Message Header Field Registry maintained by IANA in accordance with [RFC3864].

8.1. DKIM2-Sig-mf

- * Header field name: DKIM2-Sig-mf
- * Applicable protocol: mail
- * Status: standard
- * Author/Change controller: IETF
- * Specification document: this document, Section 3.1
- * Related information: carries the SMTP MAIL FROM value bound to a DKIM2 signature at a specific hop, indexed by i=

8.2. DKIM2-Sig-rt

- * Header field name: DKIM2-Sig-rt
- * Applicable protocol: mail
- * Status: standard
- * Author/Change controller: IETF
- * Specification document: this document, Section 3.1
- * Related information: carries exactly one SMTP RCPT TO address per header, bound to a DKIM2 signature at a specific hop. Multiple recipients use multiple headers with incrementing v= sequence index. Indexed by i= for hop and v= for recipient sequence.

8.3. DKIM2-Mod

- * Header field name: DKIM2-Mod
- * Applicable protocol: mail
- * Status: standard
- * Author/Change controller: IETF
- * Specification document: this document, Section 3.3
- * Related information: declares a modification made to a header field by a Reviser node, using:
 - field= - identifies the modified header field name

- del= - previous value, present for removals and modifications
- new= - new value, present for additions and modifications
- fr= - optional frame index for splitting long values across multiple headers
- i= - hop index
- seq= - field instance index
- del= and new= MUST appear on separate header lines and MUST be last in the header field value

8.4. DKIM2-Intended-MailFrom

- * Header field name: DKIM2-Intended-MailFrom
- * Applicable protocol: mail
- * Status: informational
- * Author/Change controller: IETF
- * Specification document: this document, Section 3.7.3
- * Related information: internal interoperability header used by mailing list managers to communicate the intended MAIL FROM value to the outbound signing milter. MUST be removed before external transmission. MUST NOT appear in messages delivered to external recipients.

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Appendix A. Implementation Notes (Informative)

A.1. DKIM2-Mod Header Representation

A DKIM2-Mod header declaration maps directly to a simple flat data structure. The following Go example illustrates a complete representation:

```
// HeaderMod represents a single DKIM2-Mod header declaration
type HeaderMod struct {
    HopIndex    int    // i= tag: hop sequence number
    SeqIndex    int    // seq= tag: field instance index
    FrameIndex  int    // fr= tag: fragment index, 0 if not fragmented
    FieldName   string // field= tag: name of the modified header field
    DelValue    string // del= tag: previous value, empty if addition
    NewValue    string // new= tag: new value, empty if removal
}

// ModChain accumulates all DKIM2-Mod declarations for a message
// at a single hop
type ModChain []HeaderMod

// ModificationType returns the type of modification
func (m HeaderMod) ModificationType() string {
    switch {
    case m.DelValue != "" && m.NewValue != "":
        return "modification"
    case m.DelValue != "":
        return "removal"
    case m.NewValue != "":
        return "addition"
    default:
        return "invalid"
    }
}
```

All fields are primitive types. No JSON parser, no base64 decoder, no recursive structures. The complete state for a hop can be built by iterating the message headers once in $O(n)$ time with $O(1)$ memory per header.

A.2. Comparison: DKIM2-Mod vs JSON Header Recipe Encoding

The current DKIM2 specification encodes header modifications as JSON inside the Message-Instance header. The following is a real example from a working implementation demonstrated during the development of this specification. The `r=` field decoded from base64 contains:

```
{
  "h": {
    "content-transfer-encoding": [],
    "content-type": [],
    "list-help": [],
    "list-id": [],
    "list-owner": [],
    "list-post": [],
    "list-subscribe": [],
    "list-unsubscribe": [],
    "precedence": [],
    "subject": ["s= format 23:26:28"]
  },
  "b": [[1,1]]
}
```

This structure is not directly readable in mail logs - it requires base64 decoding followed by JSON parsing before any field can be inspected. The equivalent declaration using DKIM2-Mod headers:

```
DKIM2-Mod: i=2; seq=1; field=Subject; del="s= format 23:26:28"
DKIM2-Mod: i=2; seq=1; field=List-Id; new="dkim2.mailman.dkim2.com"
DKIM2-Mod: i=2; seq=1; field=List-Help; new="mailto:dkim2-request@mailman.dkim2.com"
DKIM2-Mod: i=2; seq=1; field=Precedence; new="list"
```

The Go data structures required for each approach illustrate the implementation complexity difference:

```
// DKIM2-Mod - flat structure, no JSON dependency
type HeaderMod struct {
    HopIndex    int    // i=
    SeqIndex    int    // seq=
    FrameIndex  int    // fr= optional
    FieldName   string // field=
    DelValue    string // del= empty if addition
    NewValue    string // new= empty if removal
}

// JSON recipe - requires recursive structure and runtime type assertion
type HeaderRecipe struct {
    Headers map[string][]interface{} `json:"h"`
    Body    []int `json:"b"`
}

// Processing requires:
// 1. Accumulate complete base64 value across folded lines
// 2. Decode base64 into buffer
// 3. Unmarshal JSON into map with interface{} values
// 4. Type-assert each value to determine if string or empty
// 5. Apply resource limits before processing
```

The DKIM2-Mod approach requires only the tag-value parser already present in every DKIM1 and ARC implementation. The JSON recipe approach requires base64 decoding, JSON unmarshaling with dynamic type handling and resource limit enforcement as discussed in Sections 4.3.1 and 7.3.

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