

# LUKS On-Disk Format Specification

## Version 1.0

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## Document History

This document version is the final standard for the LUKS on-disk-format Version 1.0.

Document history:

Version	Changes
1.0	more clear distinction between raw data and string data by adding a byte[] data type for LUKS magic, salt- and checksum data.

## 1 Overview

LUKS is short for "Linux Unified Key Setup". It has initially been developed to remedy the unpleasantness a user experienced, when he upgrade his Linux user space software, and noticed that suddenly his cryptographic storage was unaccessible. The reason for this to happen was, a unstandardised way to read, process and set up encryption keys, and if the user was unlucky, he upgraded to an incompatible version.

LUKS has been invented to standardise key setup. But the project became bigger as anticipated, because standards creation involves decision making, which in turn demands for a justification of these decision. An overspring of this effort can be found as TKS1 [Fru04], a design model for secure key processing from entropy-weak sources<sup>1</sup>.

LUKS is the proof-of-concept implementation for TKS1. Therefore, the structure of LUKS follows the design rationals closely, as established in [Fru04]. Additionally to the security provided by the TKS1 model, LUKS gives the user the ability to associate more than one password with an encrypted partition. Any of these passwords can be changed or revoked in a secure manner.

This document specifies the structure, syntax and semantic of the partition header and the key material. The LUKS design can be used with any cipher or cipher mode, but for compatibility reasons, LUKS standarises cipher names and cipher modes.

While the reference implementation is using dm-crypt, Linux' kernel facility for bulk data encryption, it's not tied to it in any particular way.

A rough overall disk layout follows:

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<sup>1</sup>such as a user password

LUKS phdr	KM1	KM2	...	KM8	bulk data
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A LUKS partition starts with the LUKS partition header, and is followed by key material (labelled KM1, KM2 ... KM8 in figure). After the key material, the bulk data is located, which is encrypted by the master key. The phdr contains information about the used cipher, cipher mode, the key length, a uuid and a master key checksum.

Also, the phdr contains information about the key slots. Every active key slot stores an encrypted copy of the master key and is locked by an individual password. The user may choose as many password as keyslots. To access a partition, the user has to supply only one of these passwords.

If a password is changed, the old copy of the master key encrypted by the old password must be destroyed. Peter Gutmann has shown in [Gut96], how data destruction shall be done to maximise the chance, that no traces are left on the disk. Usually the master key comprises only 16 or 32 bytes. This small amount of data can easily be remapped as a whole to a reserved area. This action is taken by modern hard disk firmware, when a sector is likely to become unreadable due to mechanical wear. The original sectors become unaccessible and any traces of key data can't be purged if necessary.

To counter this problem, LUKS uses the anti-forensic information splitter to artificially inflate the volume of the key, as with a bigger data set the probability that the whole data set is remapped drops exponentially.

The inflated encrypted master key is stored in the key material section. These sections are labelled as "KMx" in the figure above.

## 2 Prerequisites

### 2.1 Block encryption system

Instead of using cipher implementations like AES or Twofish internally, LUKS reuses the block encryption facility used for the bulk data. The following syntax will be used in the pseudocode:

```
enc-data = encrypt(cipher-name, cipher-mode, key, original,
                  original-length)
original = decrypt(cipher-name, cipher-mode, key, enc-data,
                  original-length)
```

If the encryption primitive requires a certain block size, incomplete blocks are padded with zero. The zeros are stripped upon decryptions.<sup>2</sup>

### 2.2 Cryptographic hash

A cryptographic hash is necessary for the following two prerequisites. In PBKDF2 a pseudo-random function is needed, and for AFsplitting a diffusion function is needed. The pseudo-random function needs to be parameterisable, therefore the hash function will be used in a HMAC setup [BCK97].

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<sup>2</sup>These primitives are also used for key material en/decryption. The key material is always aligned to sector boundaries. If the block size of the underlying encryption primitive is larger than one sector, the pseudocode of section 4.1 has to be changed respectively.

The following syntaxes may omit the *hash-spec* parameter, because the following pseudo code will not need a great variation of this parameter. The parameter can be obtained from the partition header and will not change, once initialised.

## 2.3 PBKDF2

LUKS needs to process password from entropy-weak sources like keyboard input. PKCS #5's password based key derive function, PBKDF2, has been defined for the purpose to enhance the security properties of entropy-weak password, see [Kal97]. Therefore, LUKS depends on a working implementation of PBKDF2. LUKS uses SHA1 per default as the pseudorandom function, PRF, but any other hash function can be put in place by setting the *hash-spec* field. In the flow charts, the following syntax will be used:

```
result = PBKDF2(password,  
                salt,  
                iteration-count,  
                derived-key-length)
```

Please notice, that the result of this function depends on the current setting of *hash-spec* but the parameter has been omitted, because there is no great variance of it. Think of *hash-spec* as sort of environment variable.

## 2.4 AF-Splitter

LUKS uses anti-forensic information splitting as specified in [Fru04]. The underlying diffusion function shall be SHA1 for the reference implementation, but can be changed exactly as described in the remarks above. A C reference implementation using SHA1 is available from [Fru05].

```
splitted-material = AFsplit(unsplitted-material, length, stripes)  
unsplitted-material = AFmerge(splitted-material, length, stripes)
```

Please notice, that the result of AFsplit, *splitted-material*, is *stripes*-times as large as the original, that's *length \* stripes* bytes. Please notice, that the *length* parameter is the length of the original content and not the length of the splitted-material array.

# 3 The partition header

## 3.1 Version 1

The LUKS partition header, phdr, has the layout as described in Figure 1. It starts at sector 0 of the partition. LUKS uses 3 primitive data types in its header,

- unsigned integer, 16 bit, stored in big endian
- unsigned integer, 32 bit, stored in big endian

start offset	field name	length	data type	description
0	magic	6	byte[]	magic for LUKS partition header, see LUKS_MAGIC
6	version	2	uint16_t	LUKS version
8	cipher-name	32	char[]	cipher name specification
40	cipher-mode	32	char[]	cipher mode specification
72	hash-spec	64	char[]	hash specification
104	payload-offset	4	uint32_t	start offset of the bulk data (in sectors)
108	key-bytes	4	uint32_t	number of key bytes
112	mk-digest	20	byte[]	master key checksum from PBKDF2
132	mk-digest-salt	32	byte[]	salt parameter for master key PBKDF2
164	mk-digest-iter	4	uint32_t	iterations parameter for master key PBKDF2
168	uuid	40	char[]	UUID of the partition
208	key-slot-1	48	key slot	key slot 1
256	key-slot-2	48	key slot	key slot 2
...	...	...	...	...
544	key-slot-8	48	key slot	key slot 8
592	total phdr size			

Figure 1: PHDR layout

- char[], a string stored as null terminated sequence of 8-bit characters<sup>3</sup>
- byte[], a sequence of bytes, treated as binary.

Further, there is an aggregated data type *key slot*, which elements are described in Figure 2

A reference definition as C struct for phdr is available in the appendix.

### 3.2 Forward compatibility

LUKS' forward compatibility will center around the on-disk format. Future versions are required to be able to correctly interpret older phdr versions. Future versions are not required to be able to generate old versions of the phdr.

A LUKS implementation encountering a newer phdr version should not try to interpret it, and return an error. Of course, an error should be returned, if the phdr's magic is not present.

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<sup>3</sup>also known as C string

offset	field name	length	data type	description
0	active	4	uint32_t	state of keyslot, enabled/disabled
4	iterations	4	uint32_t	iteration parameter for PBKDF2
8	salt	32	byte[]	salt parameter for PBKDF2
40	key-material-offset	4	uint32_t	start sector of key material
44	stripes	4	uint32_t	number of anti-forensic stripes

Figure 2: key slot layout

## 4 LUKS operations

### 4.1 Initialisation

The initialisation process takes a couple of parameters. First and most important, the master key. This key is used for the bulk data. The user will want to create this key from a random source, as the overcoming of entropy weak keys is one of LUKS' main objectives. For the following remarks, the pseudo code is available as Figure 3

Further, the user specifies the cipher setup details, which are stored in *cipher-name* and *cipher-mode* fields. Although no LUKS operation manipulates these two strings, it is likely that the LUKS implementation will have to convert it into something suitable for the underlying cipher system, as the interface is not likely to be as ideal as described in section 2.1.

The overall disk layout depends on the length of the key material sections following the phdr. While the phdr is always constant in size, the key material section size depends on the length of the master key and the number of stripes used by the anti-forensic information splitter. The exact disk layout is generated by computing the size for the phdr and a key material section in sectors rounded up. Then the disk is filled sector-wise by phdr first, and following key material section 1 till key material section 8. After the eight key material section, the bulk data starts.

After determining the exact key layout and boundaries between phdr, key material and bulk data, the key material locations are written into the key slot entries in the phdr. The information about the bulk data start is written into the *payload-offset* field of the phdr.

The master key is checksummed, so a correct master key can be detected. To future-proof the checksumming, a hash is not only applied once but multiple times. In fact, the PBKDF2 primitive is reused. The master key is feed into the PBKDF2 process as if it were a user password. After the iterative hashing, the random chosen salt, the iteration count and result are stored in the phdr.

Although everything is correctly initialised up to this point, the initialisation process should not stop here. Without an active key slot the partition is useless. At least one key slot should be activated from the master key still in memory.

```

masterKeyLength = defined by user
masterKey = read from random source with length masterKeyLength

phdr.magic = LUKS_MAGIC
phdr.version = 1
phdr.cipher-name = as supplied by user
phdr.cipher-mode = as supplied by user

phdr.key-bytes = masterKey
phdr.mk-digest-salt = read from random, length: LUKS_SALT_SIZE
phdr.mk-digest-iteration-count = LUKS_MKD_ITER or user input

phdr.mk-digest = PBKDF2(masterKey,
                        phdr.mk-digest-salt,
                        phdr.mk-digest-iteration-count,
                        LUKS_DIGEST_SIZE)
stripes = LUKS_STRIPES or user defined

// integer divisions, result rounded down:
baseOffset = (size of phdr)/SECTOR_SIZE + 1
keyMaterialSectors = (stripes * masterKeyLength)/SECTOR_SIZE + 1

for each keyslot in phdr as ks {
    ks.active = LUKS_KEY_DISABLED
    ks.stripes = stripes
    ks.key-material-offset = baseOffset
    baseOffset = baseOffset + keyMaterialSectors
}

phdr.payload-offset = baseOffset
phdr.uuid = generate uuid

write phdr to disk

```

Figure 3: Pseudo code for partition initialisation

## 4.2 Adding new passwords

To add a password to a LUKS partition, one has to possess an unencrypted copy of the master key. Either this is, because the initialisation process is still in progress, or the user has supplied a correct password for an existing key slot, which master key could therefore be recovered. This operation is sketched in Figure 4.

Assuming we have a good copy of the master key in memory, the next step is to fetch a salt from a random source, and the choice of a password iteration count<sup>4</sup>. This information is written into a free, that's disabled, key slot of the `phdr`.

The user password is entered and processed by PBKDF2. The master key is then splitted by the `AFsplitter` into a number of stripes. The number of stripes is determined by the `stripes` field already stored in the key slot. The split result is written into the key material section, but encrypted. The encryption uses the same cipher setup as the bulk data (cipher type, cipher mode, ...), but while for the bulk data the master key is used, the key material section is keyed by the result of the PBKDF2.

## 4.3 Master key recovery

To access the payload bulk data, the master key has to be recovered. For a pseudo code of the following remarks, see Figure 5.

First, the user supplies a password. Then the password is processed by PBKDF2 for every active key slot individually and an attempt is made to recover the master key. The recovery is successful, when a master key candidate correctly checksums against the master key checksum stored in the `phdr`. Before this can happen, the master key candidate is read from storage, decrypted and after decryption processed by the anti-forensic information splitter in reverse gear, that's `AFmerge`.

When the checksumming of the master key succeeds for one key slot, the partition is successfully opened.

## 4.4 Password revocation

The key material section is wiped according to Peter Gutmann's data erasure principals [Gut96]. To wipe the sectors containing the key material, start from the sector as recorded in key slot's `key-material-offset` field, and proceed for `phdr.key-bytes * ks.stripes` bytes.

## 4.5 Password changing

The password changing is a synthetic operating of "master key recovery", "new password adding", and "old password revocation".

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<sup>4</sup>The iteration count should be determined by benchmarking.

```

masterKey = must be available, either because it's still in
            memory from initialisation or because it's been
            recovered by a correct password
masterKeyLength = phdr.key-bytes

emptyKeySlotIndex = find inactive key slot index in phdr by
                    scanning the keyslot.active field for
                    LUKS_KEY_DISABLED.

keyslot ks = phdr.keyslots[emptyKeySlotIndex]

PBKDF2-IterationsPerSecond = benchmark system
ks.iteration-count = PBKDF2-IterationsPerSecond *
                    intendedPasswordCheckingTime (in seconds)

ks.salt = read from random source, length LUKS_SALT_SIZE

splittedKey = AFsplit(masterKey,          // source
                     masterKeyLength,    // source length
                     ks.stripes)         // multiplication factor

splittedKeyLength = masterKeyLength * ks.stripes

pwd = read password from user input
pwd-PBKDF2ed = PBKDF2(password,
                     ks.salt,
                     ks.iteration-count
                     masterKeyLength)    // key size is the same
                                         // as for the bulk data

encryptedKey = encrypt(phdr.cipher-name, // cipher name
                     phdr.cipher-mode,  // cipher mode
                     pwd-PBKDF2ed,      // key
                     splittedKey,       // content
                     splittedKeyLength) // content length

write to partition(encryptedKey,          // source
                  ks.key-material-offset, // sector number
                  splittedKeyLength       // length in bytes

ks.active = LUKS_KEY_ACTIVE           // mark key as active in phdr

update keyslot ks in phdr

```

Figure 4: Pseudo code for key creation



```

read phdr from disk
check for correct LUKS_MAGIC and compatible version number

masterKeyLength = phdr.key-bytes
pwd = read password from user input

for each active keyslot in phdr do as ks {
    pwd-PBKDF2ed = PBKDF2(pwd,
                          ks.salt,
                          ks.iteration-count,
                          masterKeyLength)
    read from partition(encryptedKey,          // destination
                       ks.key-material-offset, // sector number
                       masterKeyLength * ks.stripes) // number of bytes

    splittedKey = decrypt(phdr.cipherSpec, // cipher spec.
                        pwd-PBKDF2ed,      // key
                        encryptedKey,       // content
                        encrypted)          // content length

    masterKeyCandidate = AFmerge(splittedKey,
                                masterkeyLength,
                                ks.stripes)

    MKCandidate-PBKDF2ed = PBKDF2(masterKeyCandidate,
                                phdr.mk-digest-salt,
                                phdr.mk-digest-iter,
                                LUKS_DIGEST_SIZE)
    if equal(MKCandidate-PBKDF2ed, phdr.mk-digest) {
        break loop and return masterKeyCandidate as
        correct master key
    }
}
return error, password doesn't match any keyslot

```

Figure 5: Pseudo code for master key recovery

## 5 Constants

All strings and characters are to be encoded in ASCII.

Symbol	Value	Description
LUKS_MAGIC	{'L','U','K','S', 0xBA, 0xBE }	partition header starts with magic
LUKS_DIGESTSIZE	20	length of master key checksum
LUKS_SALT_SIZE	32	length of the PBKDF2 salts
LUKS_NUMKEYS	8	number of key slots
LUKS_MKD_ITER	10	number of iterations for the master key digest
LUKS_KEY_DISABLED	0x0000DEAD	magic for disabled key slot in key-block[i].active
LUKS_KEY_ENABLED	0x00AC71F3	magic for enabled key slot in key-block[i].active
LUKS_STRIPES	4000	number of stripes for AFsplit. See [Fru04] for rationale.

## References

- [BCK97] Mihir Bellare, Ran Canetti, and Hugo Krawczyk. The HMAC papers. <http://www.cs.ucsd.edu/users/mihir/papers/hmac.html>, 1996-1997.
- [Fru04] Clemens Fruhwirth. TKS1 - An anti-forensic, two level, and iterated key setup scheme. <http://clemens.endorphin.org/publications>, 2004.
- [Fru05] Clemens Fruhwirth. Fruhwirth's Cryptography Website. <http://clemens.endorphin.org/cryptography>, 2005.
- [Gut96] Peter Gutmann. Secure Deletion of Data from Magnetic and Solid-State Memory. [http://www.cs.auckland.ac.nz/~pgut001/pubs/secure\\_del.html](http://www.cs.auckland.ac.nz/~pgut001/pubs/secure_del.html), 1996.
- [Kal97] Burt Kaliski. RFC 2898; PKCS #5: Password-Based Cryptography Specification Version 2.0. <http://www.faqs.org/rfcs/rfc2898.html>, 1996-1997.

## A PHDR as C struct

```
#define LUKS_MAGIC_L          6
#define LUKS_CIPHERNAME_L    32
#define LUKS_CIPHERMODE_L    32
#define LUKS_HASHSPEC_L      32
#define UUID_STRING_L        40

struct luks_phdr {
    char          magic [LUKS_MAGIC_L];
    uint16_t      version;
    char          cipherName [LUKS_CIPHERNAME_L];
    char          cipherMode [LUKS_CIPHERMODE_L];
    char          hashSpec [LUKS_HASHSPEC_L];
    uint32_t      payloadOffset;
    uint32_t      keyBytes;
    char          mkDigest [LUKS_DIGESTSIZE];
    char          mkDigestSalt [LUKS_SALTSIZE];
    uint32_t      mkDigestIterations;
    char          uuid [UUID_STRING_L];

    struct {
        uint32_t active;

        /* parameters for PBKDF2 processing */
        uint32_t passwordIterations;
        char      passwordSalt [LUKS_SALTSIZE];

        /* parameters for AF store/load */
        uint32_t keyMaterialOffset;
        uint32_t stripes;
    } keyblock [LUKS_NUMKEYS];
};
```

## B Cipher and Hash specification registry

Even if the *cipher-name* and *cipher-mode* strings are not interpreted by any LUKS operation, they must have the same meaning for all implementations to achieve compatibility among different LUKS-based implementations. LUKS has to ensure, that the underlying cipher system can utilise the cipher name and cipher mode strings, and as these strings might not always be native to the cipher system, LUKS might need to map them into something appropriate.

Valid cipher names are listed in Table 1. Valid cipher modes are listed in Table 2.

The same applies for the *hash-spec* field. Table 3 lists valid hash specs. A compliant implementation does not have to support all cipher, cipher mode or hash specifications.

<b>cipher name</b>	<b>normative document</b>
aes	Advanced Encryption Standard - FIPS PUB 197
twofish	Twofish: A 128-Bit Block Cipher - <a href="http://www.schneier.com/paper-twofish-paper.html">http://www.schneier.com/paper-twofish-paper.html</a>
serpent	<a href="http://www.cl.cam.ac.uk/~rja14/serpent.html">http://www.cl.cam.ac.uk/~rja14/serpent.html</a>
cast5	RFC 2144
cast6	RFC 2612

Table 1: Valid cipher names

<b>mode</b>	<b>description</b>
ecb	The cipher output is used directly.
cbc-plain	The cipher is operated in CBC mode. The CBC chaining is cut every sector, and reinitialised with the sector number as initial vector (converted to 32-bit and to little-endian)
lrw-plain	<a href="http://grouper.ieee.org/groups/1619/email/pdf00017.pdf">http://grouper.ieee.org/groups/1619/email/pdf00017.pdf</a>

Table 2: Valid cipher modes

<b>hash-spec string</b>	<b>normative document</b>
sha1	RFC 3174 - US Secure Hash Algorithm 1 (SHA1)
sha256	SHA variant according to FIPS 180-2
sha512	SHA variant according to FIPS 180-2
ripemd160	<a href="http://www.esat.kuleuven.ac.be/~bosselae/ripemd160.html">http://www.esat.kuleuven.ac.be/~bosselae/ripemd160.html</a>

Table 3: Valid hash specifications