The kernel security subsystem manual

Release

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CONTENTS

CHAPTER

ONE

CREDENTIALS IN LINUX

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Overview

There are several parts to the security check performed by Linux when one object acts upon another:

1. Objects.

   Objects are things in the system that may be acted upon directly by userspace programs. Linux has a variety of actionable objects, including:

   - Tasks
   - Files/inodes
   - Sockets
   - Message queues
   - Shared memory segments
   - Semaphores
   - Keys

   As a part of the description of all these objects there is a set of credentials. What's in the set depends on the type of object.

2. Object ownership.

   Amongst the credentials of most objects, there will be a subset that indicates the ownership of that object. This is used for resource accounting and limitation (disk quotas and task rlimits for example).

   In a standard UNIX filesystem, for instance, this will be defined by the UID marked on the inode.

3. The objective context.

   Also amongst the credentials of those objects, there will be a subset that indicates the 'objective context' of that object. This may or may not be the same set as in (2) - in standard UNIX files, for instance, this is the defined by the UID and the GID marked on the inode.

   The objective context is used as part of the security calculation that is carried out when an object is acted upon.

4. Subjects.

   A subject is an object that is acting upon another object.

   Most of the objects in the system are inactive: they don't act on other objects within the system. Processes/tasks are the obvious exception: they do stuff; they access and manipulate things.

   Objects other than tasks may under some circumstances also be subjects. For instance an open file may send SIGIO to a task using the UID and EUID given to it by a task that called `fcntl(F_SETOWN)` upon it. In this case, the file struct will have a subjective context too.

5. The subjective context.

   A subject has an additional interpretation of its credentials. A subset of its credentials forms the 'subjective context'. The subjective context is used as part of the security calculation that is carried out when a subject acts.

   A Linux task, for example, has the FSUID, FSGID and the supplementary group list for when it is acting upon a file - which are quite separate from the real UID and GID that normally form the objective context of the task.

6. Actions.

   Linux has a number of actions available that a subject may perform upon an object. The set of actions available depends on the nature of the subject and the object.

   Actions include reading, writing, creating and deleting files; forking or signalling and tracing tasks.

7. Rules, access control lists and security calculations.

   When a subject acts upon an object, a security calculation is made. This involves taking the subjective context, the objective context and the action, and searching one or more sets of rules to see whether the subject is granted or denied permission to act in the desired manner on the object, given those contexts.

   There are two main sources of rules:

   (a) Discretionary access control (DAC):

      Sometimes the object will include sets of rules as part of its description. This is an 'Access Control List' or 'ACL'. A Linux file may supply more than one ACL.

      A traditional UNIX file, for example, includes a permissions mask that is an abbreviated ACL with three fixed classes of subject ('user', 'group' and 'other'), each of which may be granted certain privileges ('read', 'write' and 'execute' - whatever those map to for the object in question). UNIX file permissions do not allow the arbitrary specification of subjects, however, and so are of limited use.

      A Linux file might also sport a POSIX ACL. This is a list of rules that grants various permissions to arbitrary subjects.

   (b) Mandatory access control (MAC):

      The system as a whole may have one or more sets of rules that get applied to all subjects and objects, regardless of their source. SELinux and Smack are examples of this.

In the case of SELinux and Smack, each object is given a label as part of its credentials. When an action is requested, they take the subject label, the object label and the action and look for a rule that says that this action is either granted or denied.

Types of Credentials

The Linux kernel supports the following types of credentials:

1. Traditional UNIX credentials.

   - Real User ID
   - Real Group ID

   The UID and GID are carried by most, if not all, Linux objects, even if in some cases it has to be invented (FAT or CIFS files for example, which are derived from Windows). These (mostly) define the objective context of that object, with tasks being slightly different in some cases.

   - Effective, Saved and FS User ID
   - Effective, Saved and FS Group ID
   - Supplementary groups

   These are additional credentials used by tasks only. Usually, an EUID/EGID/GROUPS will be used as the subjective context, and real UID/GID will be used as the objective. For tasks, it should be noted that this is not always true.

2. Capabilities.

   - Set of permitted capabilities
   - Set of inheritable capabilities
   - Set of effective capabilities
   - Capability bounding set

   These are only carried by tasks. They indicate superior capabilities granted piecemeal to a task that an ordinary task wouldn't otherwise have. These are manipulated implicitly by changes to the traditional UNIX credentials, but can also be manipulated directly by the `capset()` system call.

   The permitted capabilities are those caps that the process might grant itself to its effective or permitted sets through `capset()`. This inheritable set might also be so constrained.

   The effective capabilities are the ones that a task is actually allowed to make use of itself.

   The inheritable capabilities are the ones that may get passed across `execve()`.

   The bounding set limits the capabilities that may be inherited across `execve()`, especially when a binary is executed that will execute as UID 0.

3. Secure management flags (securebits).

   These are only carried by tasks. These govern the way the above credentials are manipulated and inherited over certain operations such as execve(). They aren't used directly as objective or subjective credentials.

4. Keys and keyrings.

   These are only carried by tasks. They carry and cache security tokens that don't fit into the other standard UNIX credentials. They are for making such things as network filesystem keys available to the file accesses performed by processes, without the necessity of ordinary programs having to know about security details involved.

Keyrings are a special type of key. They carry sets of other keys and can be searched for the desired key. Each process may subscribe to a number of keyrings:

Per-thread keying Per-process keyring Per-session keyring

When a process accesses a key, if not already present, it will normally be cached on one of these keyrings for future accesses to find.

For more information on using keys, see `Documentation/security/keys/*`.

5. LSM

   The Linux Security Module allows extra controls to be placed over the operations that a task may do. Currently Linux supports several LSM options.

   Some work by labelling the objects in a system and then applying sets of rules (policies) that say what operations a task with one label may do to an object with another label.

6. AF_KEY

   This is a socket-based approach to credential management for networking stacks [RFC 2367]. It isn't discussed by this document as it doesn't interact directly with task and file credentials; rather it keeps system level credentials.

When a file is opened, part of the opening task's subjective context is recorded in the file struct created. This allows operations using that file struct to use those credentials instead of the subjective context of the task that issued the operation. An example of this would be a file opened on a network filesystem where the credentials of the opened file should be presented to the server, regardless of who is actually doing a read or a write upon it.

File Markings

Files on disk or obtained over the network may have annotations that form the objective security context of that file. Depending on the type of filesystem, this may include one or more of the following:

- UNIX UID, GID, mode;
- Windows user ID;
- Access control list;
- LSM security label;
- UNIX exec privilege escalation bits (SUID/SGID);
- File capabilities exec privilege escalation bits.

These are compared to the task's subjective security context, and certain operations allowed or disallowed as a result. In the case of execve(), the privilege escalation bits come into play, and may allow the resulting process extra privileges, based on the annotations on the executable file.

Task Credentials

In Linux, all of a task's credentials are held in (uid, gid) or through (groups, keys, LSM security) a refcounted structure of type 'struct cred'. Each task points to its credentials by a pointer called 'cred' in its task_struct.

Once a set of credentials has been prepared and committed, it may not be changed, barring the following exceptions:

1. its reference count may be changed;
2. the reference count on the group_info struct it points to may be changed;
3. the reference count on the security data it points to may be changed;

4. the reference count on any keyrings it points to may be changed;
5. any keyrings it points to may be revoked, expired or have their security attributes changed; and
6. the contents of any keyrings to which it points may be changed (the whole point of keyrings being a shared set of credentials, modifiable by anyone with appropriate access).

To alter anything in the cred struct, the copy-and-replace principle must be adhered to. First take a copy, then alter the copy and then use RCU to change the task pointer to make it point to the new copy. There are wrappers to aid with this (see below).

A task may only alter its _own_ credentials; it is no longer permitted for a task to alter another's credentials. This means the `capset()` system call is no longer permitted to take any PID other than the one of the current process. Also `keyctl_instantiate()` and `keyctl_negate()` functions no longer permit attachment to process-specific keyrings in the requesting process as the instantiating process may need to create them.

Immutable Credentials

Once a set of credentials has been made public (by calling `commit_creds()` for example), it must be considered immutable, barring two exceptions:

1. The reference count may be altered.
2. Whilst the keyring subscriptions of a set of credentials may not be changed, the keyrings subscribed to may have their contents altered.

To catch accidental credential alteration at compile time, struct task_struct has _const_ pointers to its credential sets, as does struct file. Furthermore, certain functions such as `get_cred()` and `put_cred()` operate on const pointers, thus rendering casts unnecessary, but require to temporarily ditch the const qualification to be able to alter the reference count.

Accessing Task Credentials

A task being able to alter only its own credentials permits the current process to read or replace its own credentials without the need for any form of locking – which simplifies things greatly. It can just call:

```
const struct cred *current_cred()
```

to get a pointer to its credentials structure, and it doesn't have to release it afterwards.

There are convenience wrappers for retrieving specific aspects of a task's credentials (the value is simply returned in each case):

```
uid_t current_uid(void)         Current's real UID
gid_t current_gid(void)         Current's real GID
uid_t current_euid(void)        Current's effective UID
gid_t current_egid(void)        Current's effective GID
uid_t current_fsuid(void)       Current's file access UID
gid_t current_fsgid(void)       Current's file access GID
kernel_cap_t current_cap(void)  Current's effective capabilities
void *current_security(void)    Current's LSM security pointer
struct user_struct *current_user(void)  Current's user account
```

There are also convenience wrappers for retrieving specific associated pairs of a task's credentials:

```
void current_uid_gid(uid_t *, gid_t *);
void current_euid_egid(uid_t *, gid_t *);
void current_fsuid_fsgid(uid_t *, gid_t *);
```

which return these pairs of values through their arguments after retrieving them from the current task's credentials.

In addition, there is a function for obtaining a reference on the current process's current set of credentials:

```
const struct cred *get_current_cred(void);
```

and functions for getting references to one of the credentials that don't actually live in struct cred:

```
struct user_struct *get_current_user(void);
struct group_info *get_current_groups(void);
```

which get references to the current process's user accounting structure and supplementary groups list respectively.

Once a reference has been obtained, it must be released with `put_cred()`, `free_uid()` or `put_group_info()` as appropriate.

Accessing Another Task's Credentials

Whilst a task may access its own credentials without the need for locking, the same is not true of a task wanting to access another task's credentials. It must use the RCU read lock and `rcu_dereference()`.

The `rcu_dereference()` is wrapped by:

```
const struct cred *__task_cred(struct task_struct *task);
```

This should be used inside the RCU read lock, as in the following example:

```
void foo(struct task_struct *t, struct foo_data *f)
{
        const struct cred *tcred;
        ...
        rcu_read_lock();
        tcred = __task_cred(t);
        f->uid = tcred->uid;
        f->gid = tcred->gid;
        f->groups = get_group_info(tcred->groups);
        rcu_read_unlock();
        ...
}
```

Should it be necessary to hold another task's credentials for a long period of time, and possibly to sleep whilst doing so, then the caller should get a reference on them using:

```
const struct cred *get_task_cred(struct task_struct *task);
```

This does all the RCU magic inside of it. The caller must call put_cred() on the credentials so obtained when they're finished with.

Note:

The result of `__task_cred()` should not be passed directly to `get_cred()` as this may race with `commit_cred()`.

There are a couple of convenience functions to access bits of another task's credentials, hiding the RCU magic from the caller:

```
uid_t task_uid(task)            Task's real UID
uid_t task_euid(task)           Task's effective UID
```

If the caller is holding the RCU read lock at the time anyway, then:

```
__task_cred(task)->uid
__task_cred(task)->euid
```

should be used instead. Similarly, if multiple aspects of a task's credentials need to be accessed, RCU read lock should be used, `__task_cred()` called, the result stored in a temporary pointer and then the credential aspects called from that before dropping the lock. This prevents the potentially expensive RCU magic from being invoked multiple times.

Should some other single aspect of another task's credentials need to be accessed, then this can be used:

```
task_cred_xxx(task, member)
```

where 'member' is a non-pointer member of the cred struct. For instance:

```
uid_t task_cred_xxx(task, suid);
```

will retrieve 'struct cred::suid' from the task, doing the appropriate RCU magic. This may not be used for pointer members as what they point to may disappear the moment the RCU read lock is dropped.

Altering Credentials

As previously mentioned, a task may only alter its own credentials, and may not alter those of another task. This means that it doesn't need to use any locking to alter its own credentials.

To alter the current process's credentials, a function should first prepare a new set of credentials by calling:

```
struct cred *prepare_creds(void);
```

this locks current->cred_replace_mutex and then allocates and constructs a duplicate of the current process's credentials, returning with the mutex still held if successful. It returns NULL if not successful (out of memory).

The mutex prevents `ptrace()` from altering the ptrace state of a process whilst security checks on credentials construction and changing is taking place as the ptrace state may alter the outcome, particularly in the case of `execve()`.

The new credentials set should be altered appropriately, and any security checks and hooks done. Both the current and the proposed sets of credentials are available for this purpose as current_cred() will return the current set still at this point.

When replacing the group list, the new list must be sorted before it is added to the credential, as a binary search is used to test for membership. In practice, this means `groups_sort()` should be called before `set_groups()` or `set_current_groups()`. `groups_sort)()` must not be called on a `struct group_list` which is shared as it may permute elements as part of the sorting process even if the array is already sorted.

When the credential set is ready, it should be committed to the current process by calling:

```
int commit_creds(struct cred *new);
```

This will alter various aspects of the credentials and the process, giving the LSM a chance to do likewise, then it will use `rcu_assign_pointer()` to actually commit the new credentials to `current->cred`, it will release `current->cred_replace_mutex` to allow `ptrace()` to take place, and it will notify the scheduler and others of the changes.

This function is guaranteed to return 0, so that it can be tail-called at the end of such functions as `sys_setresuid()`.

Note that this function consumes the caller's reference to the new credentials. The caller should _not_ call `put_cred()` on the new credentials afterwards.

Furthermore, once this function has been called on a new set of credentials, those credentials may _not_ be changed further.

Should the security checks fail or some other error occur after `prepare_creds()` has been called, then the following function should be invoked:

```
void abort_creds(struct cred *new);
```

This releases the lock on `current->cred_replace_mutex` that `prepare_creds()` got and then releases the new credentials.

A typical credentials alteration function would look something like this:

```
int alter_suid(uid_t suid)
{
        struct cred *new;
        int ret;

        new = prepare_creds();
        if (!new)
                return -ENOMEM;

        new->suid = suid;
        ret = security_alter_suid(new);
        if (ret < 0) {
                abort_creds(new);
                return ret;
        }

        return commit_creds(new);
}
```

Managing Credentials

There are some functions to help manage credentials:

- `void put_cred(const struct cred *cred);`

  This releases a reference to the given set of credentials. If the reference count reaches zero, the credentials will be scheduled for destruction by the RCU system.

- `const struct cred *get_cred(const struct cred *cred);`

  This gets a reference on a live set of credentials, returning a pointer to that set of credentials.

- `struct cred *get_new_cred(struct cred *cred);`

  This gets a reference on a set of credentials that is under construction and is thus still mutable, returning a pointer to that set of credentials.

Open File Credentials

When a new file is opened, a reference is obtained on the opening task's credentials and this is attached to the file struct as `f_cred` in place of `f_uid` and `f_gid`. Code that used to access `file->f_uid` and `file->f_gid` should now access `file->f_cred->fsuid` and `file->f_cred->fsgid`.

It is safe to access `f_cred` without the use of RCU or locking because the pointer will not change over the lifetime of the file struct, and nor will the contents of the cred struct pointed to, barring the exceptions listed above (see the Task Credentials section).

Overriding the VFS's Use of Credentials

Under some circumstances it is desirable to override the credentials used by the VFS, and that can be done by calling into such as `vfs_mkdir()` with a different set of credentials. This is done in the following places:

- `sys_faccessat()`.
- `do_coredump()`.
- nfs4recover.c.

CHAPTER

TWO

IMA TEMPLATE MANAGEMENT MECHANISM

Introduction

The original `ima` template is fixed length, containing the filedata hash and pathname. The filedata hash is limited to 20 bytes (md5/sha1). The pathname is a null terminated string, limited to 255 characters. To overcome these limitations and to add additional file metadata, it is necessary to extend the current version of IMA by defining additional templates. For example, information that could be possibly reported are the inode UID/GID or the LSM labels either of the inode and of the process that is accessing it.

However, the main problem to introduce this feature is that, each time a new template is defined, the functions that generate and display the measurements list would include the code for handling a new format and, thus, would significantly grow over the time.

The proposed solution solves this problem by separating the template management from the remaining IMA code. The core of this solution is the definition of two new data structures: a template descriptor, to determine which information should be included in the measurement list; a template field, to generate and display data of a given type.

Managing templates with these structures is very simple. To support a new data type, developers define the field identifier and implement two functions, init() and show(), respectively to generate and display measurement entries. Defining a new template descriptor requires specifying the template format (a string of field identifiers separated by the | character) through the `ima_template_fmt` kernel command line parameter. At boot time, IMA initializes the chosen template descriptor by translating the format into an array of template fields structures taken from the set of the supported ones.

After the initialization step, IMA will call `ima_alloc_init_template()` (new function defined within the patches for the new template management mechanism) to generate a new measurement entry by using the template descriptor chosen through the kernel configuration or through the newly introduced `ima_template` and `ima_template_fmt` kernel command line parameters. It is during this phase that the advantages of the new architecture are clearly shown: the latter function will not contain specific code to handle a given template but, instead, it simply calls the `init()` method of the template fields associated to the chosen template descriptor and store the result (pointer to allocated data and data length) in the measurement entry structure.

The same mechanism is employed to display measurements entries. The functions `ima[_ascii]_measurements_show()` retrieve, for each entry, the template descriptor used to produce that entry and call the show() method for each item of the array of template fields structures.

Supported Template Fields and Descriptors

In the following, there is the list of supported template fields (`'<identifier>': description`), that can be used to define new template descriptors by adding their identifier to the format string (support for more data types will be added later):

- ‘d’: the digest of the event (i.e. the digest of a measured file), calculated with the SHA1 or MD5 hash algorithm;

- ‘n’: the name of the event (i.e. the file name), with size up to 255 bytes;
- ‘d-ng’: the digest of the event, calculated with an arbitrary hash algorithm (field format: [<hash algo>:]digest, where the digest prefix is shown only if the hash algorithm is not SHA1 or MD5);
- ‘n-ng’: the name of the event, without size limitations;
- ‘sig’: the file signature.

Below, there is the list of defined template descriptors:

- “ima”: its format is `d|n`;
- “ima-ng” (default): its format is `d-ng|n-ng`;
- “ima-sig”: its format is `d-ng|n-ng|sig`.

Use

To specify the template descriptor to be used to generate measurement entries, currently the following methods are supported:

- select a template descriptor among those supported in the kernel configuration (`ima-ng` is the default choice);
- specify a template descriptor name from the kernel command line through the `ima_template=` parameter;
- register a new template descriptor with custom format through the kernel command line parameter `ima_template_fmt=`.

CHAPTER

THREE

KERNEL KEYS

Kernel Key Retention Service

This service allows cryptographic keys, authentication tokens, cross-domain user mappings, and similar to be cached in the kernel for the use of filesystems and other kernel services.

Keyrings are permitted; these are a special type of key that can hold links to other keys. Processes each have three standard keyring subscriptions that a kernel service can search for relevant keys.

The key service can be configured on by enabling:

"Security options"/"Enable access key retention support" (CONFIG_KEYS)

This document has the following sections:

Key Overview

In this context, keys represent units of cryptographic data, authentication tokens, keyrings, etc.. These are represented in the kernel by struct key.

Each key has a number of attributes:

- A serial number.
- A type.
- A description (for matching a key in a search).
- Access control information.
- An expiry time.
- A payload.
- State.

- Each key is issued a serial number of type key_serial_t that is unique for the lifetime of that key. All serial numbers are positive non-zero 32-bit integers.

  Userspace programs can use a key's serial numbers as a way to gain access to it, subject to permission checking.

- Each key is of a defined "type". Types must be registered inside the kernel by a kernel service (such as a filesystem) before keys of that type can be added or used. Userspace programs cannot define new types directly.

  Key types are represented in the kernel by struct key_type. This defines a number of operations that can be performed on a key of that type.

  Should a type be removed from the system, all the keys of that type will be invalidated.

- Each key has a description. This should be a printable string. The key type provides an operation to perform a match between the description on a key and a criterion string.

- Each key has an owner user ID, a group ID and a permissions mask. These are used to control what a process may do to a key from userspace, and whether a kernel service will be able to find the key.

- Each key can be set to expire at a specific time by the key type's instantiation function. Keys can also be immortal.

- Each key can have a payload. This is a quantity of data that represent the actual "key". In the case of a keyring, this is a list of keys to which the keyring links; in the case of a user-defined key, it's an arbitrary blob of data.

  Having a payload is not required; and the payload can, in fact, just be a value stored in the struct key itself.

  When a key is instantiated, the key type's instantiation function is called with a blob of data, and that then creates the key's payload in some way.

  Similarly, when userspace wants to read back the contents of the key, if permitted, another key type operation will be called to convert the key's attached payload back into a blob of data.

- Each key can be in one of a number of basic states:

  - Uninstantiated. The key exists, but does not have any data attached. Keys being requested from userspace will be in this state.
  - Instantiated. This is the normal state. The key is fully formed, and has data attached.
  - Negative. This is a relatively short-lived state. The key acts as a note saying that a previous call out to userspace failed, and acts as a throttle on key lookups. A negative key can be updated to a normal state.
  - Expired. Keys can have lifetimes set. If their lifetime is exceeded, they traverse to this state. An expired key can be updated back to a normal state.
  - Revoked. A key is put in this state by userspace action. It can't be found or operated upon (apart from by unlinking it).
  - Dead. The key's type was unregistered, and so the key is now useless.

Keys in the last three states are subject to garbage collection. See the section on "Garbage collection".

Key Service Overview

The key service provides a number of features besides keys:

- The key service defines three special key types:

  (+) "keyring"

Keyrings are special keys that contain a list of other keys. Keyring lists can be modified using various system calls. Keyrings should not be given a payload when created.

(+) “user”

A key of this type has a description and a payload that are arbitrary blobs of data. These can be created, updated and read by userspace, and aren’t intended for use by kernel services.

(+) “logon”

Like a “user” key, a “logon” key has a payload that is an arbitrary blob of data. It is intended as a place to store secrets which are accessible to the kernel but not to userspace programs.

The description can be arbitrary, but must be prefixed with a non-zero length string that describes the key “subclass”. The subclass is separated from the rest of the description by a ‘:’. “logon” keys can be created and updated from userspace, but the payload is only readable from kernel space.

- Each process subscribes to three keyrings: a thread-specific keyring, a process-specific keyring, and a session-specific keyring.

  The thread-specific keyring is discarded from the child when any sort of clone, fork, vfork or execve occurs. A new keyring is created only when required.

  The process-specific keyring is replaced with an empty one in the child on clone, fork, vfork unless CLONE_THREAD is supplied, in which case it is shared. execve also discards the process’s process keyring and creates a new one.

  The session-specific keyring is persistent across clone, fork, vfork and execve, even when the latter executes a set-UID or set-GID binary. A process can, however, replace its current session keyring with a new one by using PR_JOIN_SESSION_KEYRING. It is permitted to request an anonymous new one, or to attempt to create or join one of a specific name.

  The ownership of the thread keyring changes when the real UID and GID of the thread changes.

- Each user ID resident in the system holds two special keyrings: a user specific keyring and a default user session keyring. The default session keyring is initialised with a link to the user-specific keyring.

  When a process changes its real UID, if it used to have no session key, it will be subscribed to the default session key for the new UID.

  If a process attempts to access its session key when it doesn’t have one, it will be subscribed to the default for its current UID.

- Each user has two quotas against which the keys they own are tracked. One limits the total number of keys and keyrings, the other limits the total amount of description and payload space that can be consumed.

  The user can view information on this and other statistics through procfs files. The root user may also alter the quota limits through sysctl files (see the section “New procfs files”).

  Process-specific and thread-specific keyrings are not counted towards a user’s quota.

  If a system call that modifies a key or keyring in some way would put the user over quota, the operation is refused and error EDQUOT is returned.

- There’s a system call interface by which userspace programs can create and manipulate keys and keyrings.
- There’s a kernel interface by which services can register types and search for keys.
- There’s a way for the a search done from the kernel to call back to userspace to request a key that can’t be found in a process’s keyrings.
- An optional filesystem is available through which the key database can be viewed and manipulated.

Key Access Permissions

Keys have an owner user ID, a group access ID, and a permissions mask. The mask has up to eight bits each for possessor, user, group and other access. Only six of each set of eight bits are defined. These permissions granted are:

- View

  This permits a key or keyring's attributes to be viewed - including key type and description.

- Read

  This permits a key's payload to be viewed or a keyring's list of linked keys.

- Write

  This permits a key's payload to be instantiated or updated, or it allows a link to be added to or removed from a keyring.

- Search

  This permits keyrings to be searched and keys to be found. Searches can only recurse into nested keyrings that have search permission set.

- Link

  This permits a key or keyring to be linked to. To create a link from a keyring to a key, a process must have Write permission on the keyring and Link permission on the key.

- Set Attribute

  This permits a key's UID, GID and permissions mask to be changed.

For changing the ownership, group ID or permissions mask, being the owner of the key or having the sysadmin capability is sufficient.

SELinux Support

The security class "key" has been added to SELinux so that mandatory access controls can be applied to keys created within various contexts. This support is preliminary, and is likely to change quite significantly in the near future. Currently, all of the basic permissions explained above are provided in SELinux as well; SELinux is simply invoked after all basic permission checks have been performed.

The value of the file /proc/self/attr/keycreate influences the labeling of newly-created keys. If the contents of that file correspond to an SELinux security context, then the key will be assigned that context. Otherwise, the key will be assigned the current context of the task that invoked the key creation request. Tasks must be granted explicit permission to assign a particular context to newly-created keys, using the "create" permission in the key security class.

The default keyrings associated with users will be labeled with the default context of the user if and only if the login programs have been instrumented to properly initialize keycreate during the login process. Otherwise, they will be labeled with the context of the login program itself.

Note, however, that the default keyrings associated with the root user are labeled with the default kernel context, since they are created early in the boot process, before root has a chance to log in.

The keyrings associated with new threads are each labeled with the context of their associated thread, and both session and process keyrings are handled similarly.

New ProcFS Files

Two files have been added to procfs by which an administrator can find out about the status of the key service:

- /proc/keys

  This lists the keys that are currently viewable by the task reading the file, giving information about their type, description and permissions. It is not possible to view the payload of the key this way, though some information about it may be given.

  The only keys included in the list are those that grant View permission to the reading process whether or not it possesses them. Note that LSM security checks are still performed, and may further filter out keys that the current process is not authorised to view.

  The contents of the file look like this:

```
SERIAL   FLAGS  USAGE EXPY PERM     UID   GID   TYPE      DESCRIPTION: SUMMARY
00000001 I-----    39 perm 1f3f0000     0     0 keyring   _uid_ses.0: 1/4
00000002 I-----     2 perm 1f3f0000     0     0 keyring   _uid.0: empty
00000007 I-----     1 perm 1f3f0000     0     0 keyring   _pid.1: empty
0000018d I-----     1 perm 1f3f0000     0     0 keyring   _pid.412: empty
000004d2 I--Q--     1 perm 1f3f0000    32    -1 keyring   _uid.32: 1/4
000004d3 I--Q--     3 perm 1f3f0000    32    -1 keyring   _uid_ses.32: empty
00000892 I--QU-     1 perm 1f000000     0     0 user      metal:copper: 0
00000893 I--Q-N     1  35s 1f3f0000     0     0 user      metal:silver: 0
00000894 I--Q--     1  10h 003f0000     0     0 user      metal:gold: 0
```

  The flags are:

```
I       Instantiated
R       Revoked
D       Dead
Q       Contributes to user's quota
U       Under construction by callback to userspace
N       Negative key
```

- /proc/key-users

  This file lists the tracking data for each user that has at least one key on the system. Such data includes quota information and statistics:

```
[root@andromeda root]# cat /proc/key-users
0:     46 45/45 1/100 13/10000
29:     2 2/2 2/100 40/10000
32:     2 2/2 2/100 40/10000
38:     2 2/2 2/100 40/10000
```

  The format of each line is:

```
<UID>:                  User ID to which this applies
<usage>                 Structure refcount
<inst>/<keys>           Total number of keys and number instantiated
<keys>/<max>            Key count quota
<bytes>/<max>           Key size quota
```

Four new sysctl files have been added also for the purpose of controlling the quota limits on keys:

- /proc/sys/kernel/keys/root_maxkeys /proc/sys/kernel/keys/root_maxbytes

  These files hold the maximum number of keys that root may have and the maximum total number of bytes of data that root may have stored in those keys.

- /proc/sys/kernel/keys/maxkeys /proc/sys/kernel/keys/maxbytes

  These files hold the maximum number of keys that each non-root user may have and the maximum total number of bytes of data that each of those users may have stored in their keys.

Root may alter these by writing each new limit as a decimal number string to the appropriate file.

Userspace System Call Interface

Userspace can manipulate keys directly through three new syscalls: add_key, request_key and keyctl. The latter provides a number of functions for manipulating keys.

When referring to a key directly, userspace programs should use the key's serial number (a positive 32-bit integer). However, there are some special values available for referring to special keys and keyrings that relate to the process making the call:

```
CONSTANT                        VALUE   KEY REFERENCED
==============================  ======  ===========================
KEY_SPEC_THREAD_KEYRING         -1      thread-specific keyring
KEY_SPEC_PROCESS_KEYRING        -2      process-specific keyring
KEY_SPEC_SESSION_KEYRING        -3      session-specific keyring
KEY_SPEC_USER_KEYRING           -4      UID-specific keyring
KEY_SPEC_USER_SESSION_KEYRING   -5      UID-session keyring
KEY_SPEC_GROUP_KEYRING          -6      GID-specific keyring
KEY_SPEC_REQKEY_AUTH_KEY        -7      assumed request_key()
                                          authorisation key
```

The main syscalls are:

- Create a new key of given type, description and payload and add it to the nominated keyring:

```
key_serial_t add_key(const char *type, const char *desc,
                     const void *payload, size_t plen,
                     key_serial_t keyring);
```

  If a key of the same type and description as that proposed already exists in the keyring, this will try to update it with the given payload, or it will return error EEXIST if that function is not supported by the key type. The process must also have permission to write to the key to be able to update it. The new key will have all user permissions granted and no group or third party permissions.

  Otherwise, this will attempt to create a new key of the specified type and description, and to instantiate it with the supplied payload and attach it to the keyring. In this case, an error will be generated if the process does not have permission to write to the keyring.

  If the key type supports it, if the description is NULL or an empty string, the key type will try and generate a description from the content of the payload.

  The payload is optional, and the pointer can be NULL if not required by the type. The payload is plen in size, and plen can be zero for an empty payload.

  A new keyring can be generated by setting type "keyring", the keyring name as the description (or NULL) and setting the payload to NULL.

  User defined keys can be created by specifying type "user". It is recommended that a user defined key's description by prefixed with a type ID and a colon, such as "krb5tgt:" for a Kerberos 5 ticket granting ticket.

  Any other type must have been registered with the kernel in advance by a kernel service such as a filesystem.

  The ID of the new or updated key is returned if successful.

- Search the process's keyrings for a key, potentially calling out to userspace to create it:

```
key_serial_t request_key(const char *type, const char *description,
                         const char *callout_info,
                         key_serial_t dest_keyring);
```

  This function searches all the process's keyrings in the order thread, process, session for a matching key. This works very much like KEYCTL_SEARCH, including the optional attachment of the discovered key to a keyring.

If a key cannot be found, and if callout_info is not NULL, then /sbin/request-key will be invoked in an attempt to obtain a key. The callout_info string will be passed as an argument to the program.

See also Documentation/security/keys/request-key.rst.

The keyctl syscall functions are:

- Map a special key ID to a real key ID for this process:

```
key_serial_t keyctl(KEYCTL_GET_KEYRING_ID, key_serial_t id,
                    int create);
```

The special key specified by "id" is looked up (with the key being created if necessary) and the ID of the key or keyring thus found is returned if it exists.

If the key does not yet exist, the key will be created if "create" is non-zero; and the error ENOKEY will be returned if "create" is zero.

- Replace the session keyring this process subscribes to with a new one:

```
key_serial_t keyctl(KEYCTL_JOIN_SESSION_KEYRING, const char *name);
```

If name is NULL, an anonymous keyring is created attached to the process as its session keyring, displacing the old session keyring.

If name is not NULL, if a keyring of that name exists, the process attempts to attach it as the session keyring, returning an error if that is not permitted; otherwise a new keyring of that name is created and attached as the session keyring.

To attach to a named keyring, the keyring must have search permission for the process's ownership.

The ID of the new session keyring is returned if successful.

- Update the specified key:

```
long keyctl(KEYCTL_UPDATE, key_serial_t key, const void *payload,
            size_t plen);
```

This will try to update the specified key with the given payload, or it will return error EOPNOTSUPP if that function is not supported by the key type. The process must also have permission to write to the key to be able to update it.

The payload is of length plen, and may be absent or empty as for add_key().

- Revoke a key:

```
long keyctl(KEYCTL_REVOKE, key_serial_t key);
```

This makes a key unavailable for further operations. Further attempts to use the key will be met with error EKEYREVOKED, and the key will no longer be findable.

- Change the ownership of a key:

```
long keyctl(KEYCTL_CHOWN, key_serial_t key, uid_t uid, gid_t gid);
```

This function permits a key's owner and group ID to be changed. Either one of uid or gid can be set to -1 to suppress that change.

Only the superuser can change a key's owner to something other than the key's current owner. Similarly, only the superuser can change a key's group ID to something other than the calling process's group ID or one of its group list members.

- Change the permissions mask on a key:

```
long keyctl(KEYCTL_SETPERM, key_serial_t key, key_perm_t perm);
```

This function permits the owner of a key or the superuser to change the permissions mask on a key.

Only bits the available bits are permitted; if any other bits are set, error EINVAL will be returned.

- Describe a key:

```
long keyctl(KEYCTL_DESCRIBE, key_serial_t key, char *buffer,
            size_t buflen);
```

This function returns a summary of the key's attributes (but not its payload data) as a string in the buffer provided.

Unless there's an error, it always returns the amount of data it could produce, even if that's too big for the buffer, but it won't copy more than requested to userspace. If the buffer pointer is NULL then no copy will take place.

A process must have view permission on the key for this function to be successful.

If successful, a string is placed in the buffer in the following format:

```
<type>;<uid>;<gid>;<perm>;<description>
```

Where type and description are strings, uid and gid are decimal, and perm is hexadecimal. A NUL character is included at the end of the string if the buffer is sufficiently big.

This can be parsed with:

```
sscanf(buffer, "%[^;];%d;%d;%o;%s", type, &uid, &gid, &mode, desc);
```

- Clear out a keyring:

```
long keyctl(KEYCTL_CLEAR, key_serial_t keyring);
```

This function clears the list of keys attached to a keyring. The calling process must have write permission on the keyring, and it must be a keyring (or else error ENOTDIR will result).

This function can also be used to clear special kernel keyrings if they are appropriately marked if the user has CAP_SYS_ADMIN capability. The DNS resolver cache keyring is an example of this.

- Link a key into a keyring:

```
long keyctl(KEYCTL_LINK, key_serial_t keyring, key_serial_t key);
```

This function creates a link from the keyring to the key. The process must have write permission on the keyring and must have link permission on the key.

Should the keyring not be a keyring, error ENOTDIR will result; and if the keyring is full, error ENFILE will result.

The link procedure checks the nesting of the keyrings, returning ELOOP if it appears too deep or EDEADLK if the link would introduce a cycle.

Any links within the keyring to keys that match the new key in terms of type and description will be discarded from the keyring as the new one is added.

- Unlink a key or keyring from another keyring:

```
long keyctl(KEYCTL_UNLINK, key_serial_t keyring, key_serial_t key);
```

This function looks through the keyring for the first link to the specified key, and removes it if found. Subsequent links to that key are ignored. The process must have write permission on the keyring.

If the keyring is not a keyring, error ENOTDIR will result; and if the key is not present, error ENOENT will be the result.

- Search a keyring tree for a key:

```
key_serial_t keyctl(KEYCTL_SEARCH, key_serial_t keyring,
                    const char *type, const char *description,
                    key_serial_t dest_keyring);
```

This searches the keyring tree headed by the specified keyring until a key is found that matches the type and description criteria. Each keyring is checked for keys before recursion into its children occurs.

The process must have search permission on the top level keyring, or else error EACCES will result. Only keyrings that the process has search permission on will be recursed into, and only keys and keyrings for which a process has search permission can be matched. If the specified keyring is not a keyring, ENOTDIR will result.

If the search succeeds, the function will attempt to link the found key into the destination keyring if one is supplied (non-zero ID). All the constraints applicable to KEYCTL_LINK apply in this case too.

Error ENOKEY, EKEYREVOKED or EKEYEXPIRED will be returned if the search fails. On success, the resulting key ID will be returned.

- Read the payload data from a key:

```
long keyctl(KEYCTL_READ, key_serial_t keyring, char *buffer,
            size_t buflen);
```

This function attempts to read the payload data from the specified key into the buffer. The process must have read permission on the key to succeed.

The returned data will be processed for presentation by the key type. For instance, a keyring will return an array of key_serial_t entries representing the IDs of all the keys to which it is subscribed. The user defined key type will return its data as is. If a key type does not implement this function, error EOPNOTSUPP will result.

If the specified buffer is too small, then the size of the buffer required will be returned. Note that in this case, the contents of the buffer may have been overwritten in some undefined way.

Otherwise, on success, the function will return the amount of data copied into the buffer.

- Instantiate a partially constructed key:

```
long keyctl(KEYCTL_INSTANTIATE, key_serial_t key,
            const void *payload, size_t plen,
            key_serial_t keyring);
long keyctl(KEYCTL_INSTANTIATE_IOV, key_serial_t key,
            const struct iovec *payload_iov, unsigned ioc,
            key_serial_t keyring);
```

If the kernel calls back to userspace to complete the instantiation of a key, userspace should use this call to supply data for the key before the invoked process returns, or else the key will be marked negative automatically.

The process must have write access on the key to be able to instantiate it, and the key must be uninstantiated.

If a keyring is specified (non-zero), the key will also be linked into that keyring, however all the constraints applying in KEYCTL_LINK apply in this case too.

The payload and plen arguments describe the payload data as for add_key().

The payload_iov and ioc arguments describe the payload data in an iovec array instead of a single buffer.

- Negatively instantiate a partially constructed key:

```
long keyctl(KEYCTL_NEGATE, key_serial_t key,
            unsigned timeout, key_serial_t keyring);
long keyctl(KEYCTL_REJECT, key_serial_t key,
            unsigned timeout, unsigned error, key_serial_t keyring);
```

If the kernel calls back to userspace to complete the instantiation of a key, userspace should use this call mark the key as negative before the invoked process returns if it is unable to fulfill the request.

The process must have write access on the key to be able to instantiate it, and the key must be uninstantiated.

If a keyring is specified (non-zero), the key will also be linked into that keyring, however all the constraints applying in KEYCTL_LINK apply in this case too.

If the key is rejected, future searches for it will return the specified error code until the rejected key expires. Negating the key is the same as rejecting the key with ENOKEY as the error code.

- Set the default request-key destination keyring:

```
long keyctl(KEYCTL_SET_REQKEY_KEYRING, int reqkey_defl);
```

This sets the default keyring to which implicitly requested keys will be attached for this thread. reqkey_defl should be one of these constants:

CONSTANT	VALUE	NEW DEFAULT KEYRING
KEY_REQKEY_DEFL_NO_CHANGE	-1	No change
KEY_REQKEY_DEFL_DEFAULT	0	Default[1]
KEY_REQKEY_DEFL_THREAD_KEYRING	1	Thread keyring
KEY_REQKEY_DEFL_PROCESS_KEYRING	2	Process keyring
KEY_REQKEY_DEFL_SESSION_KEYRING	3	Session keyring
KEY_REQKEY_DEFL_USER_KEYRING	4	User keyring
KEY_REQKEY_DEFL_USER_SESSION_KEYRING	5	User session keyring
KEY_REQKEY_DEFL_GROUP_KEYRING	6	Group keyring

The old default will be returned if successful and error EINVAL will be returned if reqkey_defl is not one of the above values.

The default keyring can be overridden by the keyring indicated to the request_key() system call.

Note that this setting is inherited across fork/exec.

[1] The default is: the thread keyring if there is one, otherwise the process keyring if there is one, otherwise the session keyring if there is one, otherwise the user default session keyring.

- Set the timeout on a key:

```
long keyctl(KEYCTL_SET_TIMEOUT, key_serial_t key, unsigned timeout);
```

This sets or clears the timeout on a key. The timeout can be 0 to clear the timeout or a number of seconds to set the expiry time that far into the future.

The process must have attribute modification access on a key to set its timeout. Timeouts may not be set with this function on negative, revoked or expired keys.

- Assume the authority granted to instantiate a key:

```
long keyctl(KEYCTL_ASSUME_AUTHORITY, key_serial_t key);
```

This assumes or divests the authority required to instantiate the specified key. Authority can only be assumed if the thread has the authorisation key associated with the specified key in its keyrings somewhere.

Once authority is assumed, searches for keys will also search the requester's keyrings using the requester's security label, UID, GID and groups.

If the requested authority is unavailable, error EPERM will be returned, likewise if the authority has been revoked because the target key is already instantiated.

If the specified key is 0, then any assumed authority will be divested.

The assumed authoritative key is inherited across fork and exec.

- Get the LSM security context attached to a key:

```
long keyctl(KEYCTL_GET_SECURITY, key_serial_t key, char *buffer,
            size_t buflen)
```

This function returns a string that represents the LSM security context attached to a key in the buffer provided.

Unless there's an error, it always returns the amount of data it could produce, even if that's too big for the buffer, but it won't copy more than requested to userspace. If the buffer pointer is NULL then no copy will take place.

A NUL character is included at the end of the string if the buffer is sufficiently big. This is included in the returned count. If no LSM is in force then an empty string will be returned.

A process must have view permission on the key for this function to be successful.

- Install the calling process's session keyring on its parent:

```
long keyctl(KEYCTL_SESSION_TO_PARENT);
```

This functions attempts to install the calling process's session keyring on to the calling process's parent, replacing the parent's current session keyring.

The calling process must have the same ownership as its parent, the keyring must have the same ownership as the calling process, the calling process must have LINK permission on the keyring and the active LSM module mustn't deny permission, otherwise error EPERM will be returned.

Error ENOMEM will be returned if there was insufficient memory to complete the operation, otherwise 0 will be returned to indicate success.

The keyring will be replaced next time the parent process leaves the kernel and resumes executing userspace.

- Invalidate a key:

```
long keyctl(KEYCTL_INVALIDATE, key_serial_t key);
```

This function marks a key as being invalidated and then wakes up the garbage collector. The garbage collector immediately removes invalidated keys from all keyrings and deletes the key when its reference count reaches zero.

Keys that are marked invalidated become invisible to normal key operations immediately, though they are still visible in /proc/keys until deleted (they're marked with an 'i' flag).

A process must have search permission on the key for this function to be successful.

- Compute a Diffie-Hellman shared secret or public key:

```
long keyctl(KEYCTL_DH_COMPUTE, struct keyctl_dh_params *params,
            char *buffer, size_t buflen, struct keyctl_kdf_params *kdf);
```

The params struct contains serial numbers for three keys:

```
- The prime, p, known to both parties
- The local private key
- The base integer, which is either a shared generator or the
  remote public key
```

The value computed is:

```
result = base ^ private (mod prime)
```

If the base is the shared generator, the result is the local public key. If the base is the remote public key, the result is the shared secret.

If the parameter kdf is NULL, the following applies:

  - The buffer length must be at least the length of the prime, or zero.

- If the buffer length is nonzero, the length of the result is returned when it is successfully calculated and copied in to the buffer. When the buffer length is zero, the minimum required buffer length is returned.

The kdf parameter allows the caller to apply a key derivation function (KDF) on the Diffie-Hellman computation where only the result of the KDF is returned to the caller. The KDF is characterized with struct keyctl_kdf_params as follows:

- `char *hashname` specifies the NUL terminated string identifying the hash used from the kernel crypto API and applied for the KDF operation. The KDF implemenation complies with SP800-56A as well as with SP800-108 (the counter KDF).
- `char *otherinfo` specifies the OtherInfo data as documented in SP800-56A section 5.8.1.2. The length of the buffer is given with otherinfolen. The format of OtherInfo is defined by the caller. The otherinfo pointer may be NULL if no OtherInfo shall be used.

This function will return error EOPNOTSUPP if the key type is not supported, error ENOKEY if the key could not be found, or error EACCES if the key is not readable by the caller. In addition, the function will return EMSGSIZE when the parameter kdf is non-NULL and either the buffer length or the OtherInfo length exceeds the allowed length.

- Restrict keyring linkage:

```
long keyctl(KEYCTL_RESTRICT_KEYRING, key_serial_t keyring,
            const char *type, const char *restriction);
```

An existing keyring can restrict linkage of additional keys by evaluating the contents of the key according to a restriction scheme.

“keyring” is the key ID for an existing keyring to apply a restriction to. It may be empty or may already have keys linked. Existing linked keys will remain in the keyring even if the new restriction would reject them.

“type” is a registered key type.

“restriction” is a string describing how key linkage is to be restricted. The format varies depending on the key type, and the string is passed to the lookup_restriction() function for the requested type. It may specify a method and relevant data for the restriction such as signature verification or constraints on key payload. If the requested key type is later unregistered, no keys may be added to the keyring after the key type is removed.

To apply a keyring restriction the process must have Set Attribute permission and the keyring must not be previously restricted.

One application of restricted keyrings is to verify X.509 certificate chains or individual certificate signatures using the asymmetric key type. See Documentation/crypto/asymmetric-keys.txt for specific restrictions applicable to the asymmetric key type.

Kernel Services

The kernel services for key management are fairly simple to deal with. They can be broken down into two areas: keys and key types.

Dealing with keys is fairly straightforward. Firstly, the kernel service registers its type, then it searches for a key of that type. It should retain the key as long as it has need of it, and then it should release it. For a filesystem or device file, a search would probably be performed during the open call, and the key released upon close. How to deal with conflicting keys due to two different users opening the same file is left to the filesystem author to solve.

To access the key manager, the following header must be #included:

```
<linux/key.h>
```

Specific key types should have a header file under include/keys/ that should be used to access that type. For keys of type "user", for example, that would be:

```
<keys/user-type.h>
```

Note that there are two different types of pointers to keys that may be encountered:

- struct key *

  This simply points to the key structure itself. Key structures will be at least four-byte aligned.

- key_ref_t

  This is equivalent to a `struct key *`, but the least significant bit is set if the caller "possesses" the key. By "possession" it is meant that the calling processes has a searchable link to the key from one of its keyrings. There are three functions for dealing with these:

```
key_ref_t make_key_ref(const struct key *key, bool possession);

struct key *key_ref_to_ptr(const key_ref_t key_ref);

bool is_key_possessed(const key_ref_t key_ref);
```

  The first function constructs a key reference from a key pointer and possession information (which must be true or false).

  The second function retrieves the key pointer from a reference and the third retrieves the possession flag.

When accessing a key's payload contents, certain precautions must be taken to prevent access vs modification races. See the section "Notes on accessing payload contents" for more information.

- To search for a key, call:

```
struct key *request_key(const struct key_type *type,
                        const char *description,
                        const char *callout_info);
```

  This is used to request a key or keyring with a description that matches the description specified according to the key type's match_preparse() method. This permits approximate matching to occur. If callout_string is not NULL, then /sbin/request-key will be invoked in an attempt to obtain the key from userspace. In that case, callout_string will be passed as an argument to the program.

  Should the function fail error ENOKEY, EKEYEXPIRED or EKEYREVOKED will be returned.

  If successful, the key will have been attached to the default keyring for implicitly obtained request-key keys, as set by KEYCTL_SET_REQKEY_KEYRING.

  See also Documentation/security/keys/request-key.rst.

- To search for a key, passing auxiliary data to the upcaller, call:

```
struct key *request_key_with_auxdata(const struct key_type *type,
                                     const char *description,
                                     const void *callout_info,
                                     size_t callout_len,
                                     void *aux);
```

  This is identical to request_key(), except that the auxiliary data is passed to the key_type->request_key() op if it exists, and the callout_info is a blob of length callout_len, if given (the length may be 0).

- A key can be requested asynchronously by calling one of:

```
struct key *request_key_async(const struct key_type *type,
                              const char *description,
```

```
                                const void *callout_info,
                                size_t callout_len);
```

or:

```
struct key *request_key_async_with_auxdata(const struct key_type *type,
                                           const char *description,
                                           const char *callout_info,
                                           size_t callout_len,
                                           void *aux);
```

which are asynchronous equivalents of request_key() and request_key_with_auxdata() respectively.

These two functions return with the key potentially still under construction. To wait for construction completion, the following should be called:

```
int wait_for_key_construction(struct key *key, bool intr);
```

The function will wait for the key to finish being constructed and then invokes key_validate() to return an appropriate value to indicate the state of the key (0 indicates the key is usable).

If intr is true, then the wait can be interrupted by a signal, in which case error ERESTARTSYS will be returned.

- When it is no longer required, the key should be released using:

```
void key_put(struct key *key);
```

Or:

```
void key_ref_put(key_ref_t key_ref);
```

These can be called from interrupt context. If CONFIG_KEYS is not set then the argument will not be parsed.

- Extra references can be made to a key by calling one of the following functions:

```
struct key *__key_get(struct key *key);
struct key *key_get(struct key *key);
```

Keys so references will need to be disposed of by calling key_put() when they've been finished with. The key pointer passed in will be returned.

In the case of key_get(), if the pointer is NULL or CONFIG_KEYS is not set then the key will not be dereferenced and no increment will take place.

- A key's serial number can be obtained by calling:

```
key_serial_t key_serial(struct key *key);
```

If key is NULL or if CONFIG_KEYS is not set then 0 will be returned (in the latter case without parsing the argument).

- If a keyring was found in the search, this can be further searched by:

```
key_ref_t keyring_search(key_ref_t keyring_ref,
                         const struct key_type *type,
                         const char *description)
```

This searches the keyring tree specified for a matching key. Error ENOKEY is returned upon failure (use IS_ERR/PTR_ERR to determine). If successful, the returned key will need to be released.

The possession attribute from the keyring reference is used to control access through the permissions mask and is propagated to the returned key reference pointer if successful.

- A keyring can be created by:

```
struct key *keyring_alloc(const char *description, uid_t uid, gid_t gid,
                          const struct cred *cred,
                          key_perm_t perm,
                          struct key_restriction *restrict_link,
                          unsigned long flags,
                          struct key *dest);
```

This creates a keyring with the given attributes and returns it. If dest is not NULL, the new keyring will be linked into the keyring to which it points. No permission checks are made upon the destination keyring.

Error EDQUOT can be returned if the keyring would overload the quota (pass KEY_ALLOC_NOT_IN_QUOTA in flags if the keyring shouldn't be accounted towards the user's quota). Error ENOMEM can also be returned.

If restrict_link is not NULL, it should point to a structure that contains the function that will be called each time an attempt is made to link a key into the new keyring. The structure may also contain a key pointer and an associated key type. The function is called to check whether a key may be added into the keyring or not. The key type is used by the garbage collector to clean up function or data pointers in this structure if the given key type is unregistered. Callers of key_create_or_update() within the kernel can pass KEY_ALLOC_BYPASS_RESTRICTION to suppress the check. An example of using this is to manage rings of cryptographic keys that are set up when the kernel boots where userspace is also permitted to add keys - provided they can be verified by a key the kernel already has.

When called, the restriction function will be passed the keyring being added to, the key type, the payload of the key being added, and data to be used in the restriction check. Note that when a new key is being created, this is called between payload preparsing and actual key creation. The function should return 0 to allow the link or an error to reject it.

A convenience function, restrict_link_reject, exists to always return -EPERM to in this case.

- To check the validity of a key, this function can be called:

```
int validate_key(struct key *key);
```

This checks that the key in question hasn't expired or and hasn't been revoked. Should the key be invalid, error EKEYEXPIRED or EKEYREVOKED will be returned. If the key is NULL or if CONFIG_KEYS is not set then 0 will be returned (in the latter case without parsing the argument).

- To register a key type, the following function should be called:

```
int register_key_type(struct key_type *type);
```

This will return error EEXIST if a type of the same name is already present.

- To unregister a key type, call:

```
void unregister_key_type(struct key_type *type);
```

Under some circumstances, it may be desirable to deal with a bundle of keys. The facility provides access to the keyring type for managing such a bundle:

```
struct key_type key_type_keyring;
```

This can be used with a function such as request_key() to find a specific keyring in a process's keyrings. A keyring thus found can then be searched with keyring_search(). Note that it is not possible to use request_key() to search a specific keyring, so using keyrings in this way is of limited utility.

Notes On Accessing Payload Contents

The simplest payload is just data stored in key->payload directly. In this case, there's no need to indulge in RCU or locking when accessing the payload.

More complex payload contents must be allocated and pointers to them set in the key->payload.data[] array. One of the following ways must be selected to access the data:

1. Unmodifiable key type.

   If the key type does not have a modify method, then the key's payload can be accessed without any form of locking, provided that it's known to be instantiated (uninstantiated keys cannot be "found").

2. The key's semaphore.

   The semaphore could be used to govern access to the payload and to control the payload pointer. It must be write-locked for modifications and would have to be read-locked for general access. The disadvantage of doing this is that the accessor may be required to sleep.

3. RCU.

   RCU must be used when the semaphore isn't already held; if the semaphore is held then the contents can't change under you unexpectedly as the semaphore must still be used to serialise modifications to the key. The key management code takes care of this for the key type.

   However, this means using:

```
rcu_read_lock() ... rcu_dereference() ... rcu_read_unlock()
```

   to read the pointer, and:

```
rcu_dereference() ... rcu_assign_pointer() ... call_rcu()
```

   to set the pointer and dispose of the old contents after a grace period. Note that only the key type should ever modify a key's payload.

   Furthermore, an RCU controlled payload must hold a struct rcu_head for the use of call_rcu() and, if the payload is of variable size, the length of the payload. key->datalen cannot be relied upon to be consistent with the payload just dereferenced if the key's semaphore is not held.

   Note that key->payload.data[0] has a shadow that is marked for __rcu usage. This is called key->payload.rcu_data0. The following accessors wrap the RCU calls to this element:

   (a) Set or change the first payload pointer:

```
rcu_assign_keypointer(struct key *key, void *data);
```

   (b) Read the first payload pointer with the key semaphore held:

```
[const] void *dereference_key_locked([const] struct key *key);

Note that the return value will inherit its constness from the key
parameter.  Static analysis will give an error if it things the lock
isn't held.
```

   (c) Read the first payload pointer with the RCU read lock held:

```
const void *dereference_key_rcu(const struct key *key);
```

Defining a Key Type

A kernel service may want to define its own key type. For instance, an AFS filesystem might want to define a Kerberos 5 ticket key type. To do this, it author fills in a key_type struct and registers it with the system.

Source files that implement key types should include the following header file:

```
<linux/key-type.h>
```

The structure has a number of fields, some of which are mandatory:

- `const char *name`

  The name of the key type. This is used to translate a key type name supplied by userspace into a pointer to the structure.

- `size_t def_datalen`

  This is optional - it supplies the default payload data length as contributed to the quota. If the key type's payload is always or almost always the same size, then this is a more efficient way to do things.

  The data length (and quota) on a particular key can always be changed during instantiation or update by calling:

```
int key_payload_reserve(struct key *key, size_t datalen);
```

  With the revised data length. Error EDQUOT will be returned if this is not viable.

- `int (*vet_description)(const char *description);`

  This optional method is called to vet a key description. If the key type doesn't approve of the key description, it may return an error, otherwise it should return 0.

- `int (*preparse)(struct key_preparsed_payload *prep);`

  This optional method permits the key type to attempt to parse payload before a key is created (add key) or the key semaphore is taken (update or instantiate key). The structure pointed to by prep looks like:

```
struct key_preparsed_payload {
        char            *description;
        union key_payload payload;
        const void      *data;
        size_t          datalen;
        size_t          quotalen;
        time_t          expiry;
};
```

  Before calling the method, the caller will fill in data and datalen with the payload blob parameters; quotalen will be filled in with the default quota size from the key type; expiry will be set to TIME_T_MAX and the rest will be cleared.

  If a description can be proposed from the payload contents, that should be attached as a string to the description field. This will be used for the key description if the caller of add_key() passes NULL or "".

  The method can attach anything it likes to payload. This is merely passed along to the instantiate() or update() operations. If set, the expiry time will be applied to the key if it is instantiated from this data.

  The method should return 0 if successful or a negative error code otherwise.

- `void (*free_preparse)(struct key_preparsed_payload *prep);`

  This method is only required if the preparse() method is provided, otherwise it is unused. It cleans up anything attached to the description and payload fields of the key_preparsed_payload struct as filled in by the preparse() method. It will always be called after preparse() returns successfully, even if instantiate() or update() succeed.

- `int (*instantiate)(struct key *key, struct key_preparsed_payload *prep);`

  This method is called to attach a payload to a key during construction. The payload attached need not bear any relation to the data passed to this function.

  The prep->data and prep->datalen fields will define the original payload blob. If preparse() was supplied then other fields may be filled in also.

If the amount of data attached to the key differs from the size in keytype->def_datalen, then key_payload_reserve() should be called.

This method does not have to lock the key in order to attach a payload. The fact that KEY_FLAG_INSTANTIATED is not set in key->flags prevents anything else from gaining access to the key.

It is safe to sleep in this method.

generic_key_instantiate() is provided to simply copy the data from prep->payload.data[] to key->payload.data[], with RCU-safe assignment on the first element. It will then clear prep->payload.data[] so that the free_preparse method doesn't release the data.

- `int (*update)(struct key *key, const void *data, size_t datalen);`

  If this type of key can be updated, then this method should be provided. It is called to update a key's payload from the blob of data provided.

  The prep->data and prep->datalen fields will define the original payload blob. If preparse() was supplied then other fields may be filled in also.

  key_payload_reserve() should be called if the data length might change before any changes are actually made. Note that if this succeeds, the type is committed to changing the key because it's already been altered, so all memory allocation must be done first.

  The key will have its semaphore write-locked before this method is called, but this only deters other writers; any changes to the key's payload must be made under RCU conditions, and call_rcu() must be used to dispose of the old payload.

  key_payload_reserve() should be called before the changes are made, but after all allocations and other potentially failing function calls are made.

  It is safe to sleep in this method.

- `int (*match_preparse)(struct key_match_data *match_data);`

  This method is optional. It is called when a key search is about to be performed. It is given the following structure:

```
struct key_match_data {
        bool (*cmp)(const struct key *key,
                    const struct key_match_data *match_data);
        const void      *raw_data;
        void            *preparsed;
        unsigned        lookup_type;
};
```

  On entry, raw_data will be pointing to the criteria to be used in matching a key by the caller and should not be modified. `(*cmp)()` will be pointing to the default matcher function (which does an exact description match against raw_data) and lookup_type will be set to indicate a direct lookup.

  The following lookup_type values are available:

  - KEYRING_SEARCH_LOOKUP_DIRECT - A direct lookup hashes the type and description to narrow down the search to a small number of keys.
  - KEYRING_SEARCH_LOOKUP_ITERATE - An iterative lookup walks all the keys in the keyring until one is matched. This must be used for any search that's not doing a simple direct match on the key description.

  The method may set cmp to point to a function of its choice that does some other form of match, may set lookup_type to KEYRING_SEARCH_LOOKUP_ITERATE and may attach something to the preparsed pointer for use by `(*cmp)()`. `(*cmp)()` should return true if a key matches and false otherwise.

  If preparsed is set, it may be necessary to use the match_free() method to clean it up.

  The method should return 0 if successful or a negative error code otherwise.

  It is permitted to sleep in this method, but `(*cmp)()` may not sleep as locks will be held over it.

If match_preparse() is not provided, keys of this type will be matched exactly by their description.

- `void (*match_free)(struct key_match_data *match_data);`

  This method is optional. If given, it called to clean up match_data->preparsed after a successful call to match_preparse().

- `void (*revoke)(struct key *key);`

  This method is optional. It is called to discard part of the payload data upon a key being revoked. The caller will have the key semaphore write-locked.

  It is safe to sleep in this method, though care should be taken to avoid a deadlock against the key semaphore.

- `void (*destroy)(struct key *key);`

  This method is optional. It is called to discard the payload data on a key when it is being destroyed.

  This method does not need to lock the key to access the payload; it can consider the key as being inaccessible at this time. Note that the key's type may have been changed before this function is called.

  It is not safe to sleep in this method; the caller may hold spinlocks.

- `void (*describe)(const struct key *key, struct seq_file *p);`

  This method is optional. It is called during /proc/keys reading to summarise a key's description and payload in text form.

  This method will be called with the RCU read lock held. rcu_dereference() should be used to read the payload pointer if the payload is to be accessed. key->datalen cannot be trusted to stay consistent with the contents of the payload.

  The description will not change, though the key's state may.

  It is not safe to sleep in this method; the RCU read lock is held by the caller.

- `long (*read)(const struct key *key, char __user *buffer, size_t buflen);`

  This method is optional. It is called by KEYCTL_READ to translate the key's payload into something a blob of data for userspace to deal with. Ideally, the blob should be in the same format as that passed in to the instantiate and update methods.

  If successful, the blob size that could be produced should be returned rather than the size copied.

  This method will be called with the key's semaphore read-locked. This will prevent the key's payload changing. It is not necessary to use RCU locking when accessing the key's payload. It is safe to sleep in this method, such as might happen when the userspace buffer is accessed.

- `int (*request_key)(struct key_construction *cons, const char *op, void *aux);`

  This method is optional. If provided, request_key() and friends will invoke this function rather than upcalling to /sbin/request-key to operate upon a key of this type.

  The aux parameter is as passed to request_key_async_with_auxdata() and similar or is NULL otherwise. Also passed are the construction record for the key to be operated upon and the operation type (currently only "create").

  This method is permitted to return before the upcall is complete, but the following function must be called under all circumstances to complete the instantiation process, whether or not it succeeds, whether or not there's an error:

```
void complete_request_key(struct key_construction *cons, int error);
```

  The error parameter should be 0 on success, -ve on error. The construction record is destroyed by this action and the authorisation key will be revoked. If an error is indicated, the key under construction will be negatively instantiated if it wasn't already instantiated.

If this method returns an error, that error will be returned to the caller of request_key*(). complete_request_key() must be called prior to returning.

The key under construction and the authorisation key can be found in the key_construction struct pointed to by cons:

- `struct key *key;`

  The key under construction.

- `struct key *authkey;`

  The authorisation key.

- `struct key_restriction *(*lookup_restriction)(const char *params);`

  This optional method is used to enable userspace configuration of keyring restrictions. The restriction parameter string (not including the key type name) is passed in, and this method returns a pointer to a key_restriction structure containing the relevant functions and data to evaluate each attempted key link operation. If there is no match, -EINVAL is returned.

Request-Key Callback Service

To create a new key, the kernel will attempt to execute the following command line:

```
/sbin/request-key create <key> <uid> <gid> \
        <threadring> <processring> <sessionring> <callout_info>
```

<key> is the key being constructed, and the three keyrings are the process keyrings from the process that caused the search to be issued. These are included for two reasons:

1 **There may be an authentication token in one of the keyrings that is** required to obtain the key, eg: a Kerberos Ticket-Granting Ticket.

2 The new key should probably be cached in one of these rings.

This program should set it UID and GID to those specified before attempting to access any more keys. It may then look around for a user specific process to hand the request off to (perhaps a path held in placed in another key by, for example, the KDE desktop manager).

The program (or whatever it calls) should finish construction of the key by calling KEYCTL_INSTANTIATE or KEYCTL_INSTANTIATE_IOV, which also permits it to cache the key in one of the keyrings (probably the session ring) before returning. Alternatively, the key can be marked as negative with KEYCTL_NEGATE or KEYCTL_REJECT; this also permits the key to be cached in one of the keyrings.

If it returns with the key remaining in the unconstructed state, the key will be marked as being negative, it will be added to the session keyring, and an error will be returned to the key requestor.

Supplementary information may be provided from whoever or whatever invoked this service. This will be passed as the <callout_info> parameter. If no such information was made available, then "-" will be passed as this parameter instead.

Similarly, the kernel may attempt to update an expired or a soon to expire key by executing:

```
/sbin/request-key update <key> <uid> <gid> \
        <threadring> <processring> <sessionring>
```

In this case, the program isn't required to actually attach the key to a ring; the rings are provided for reference.

Garbage Collection

Dead keys (for which the type has been removed) will be automatically unlinked from those keyrings that point to them and deleted as soon as possible by a background garbage collector.

Similarly, revoked and expired keys will be garbage collected, but only after a certain amount of time has passed. This time is set as a number of seconds in:

```
/proc/sys/kernel/keys/gc_delay
```

Encrypted keys for the eCryptfs filesystem

ECryptfs is a stacked filesystem which transparently encrypts and decrypts each file using a randomly generated File Encryption Key (FEK).

Each FEK is in turn encrypted with a File Encryption Key Encryption Key (FEFEK) either in kernel space or in user space with a daemon called 'ecryptfsd'. In the former case the operation is performed directly by the kernel CryptoAPI using a key, the FEFEK, derived from a user prompted passphrase; in the latter the FEK is encrypted by 'ecryptfsd' with the help of external libraries in order to support other mechanisms like public key cryptography, PKCS#11 and TPM based operations.

The data structure defined by eCryptfs to contain information required for the FEK decryption is called authentication token and, currently, can be stored in a kernel key of the 'user' type, inserted in the user's session specific keyring by the userspace utility 'mount.ecryptfs' shipped with the package 'ecryptfs-utils'.

The 'encrypted' key type has been extended with the introduction of the new format 'ecryptfs' in order to be used in conjunction with the eCryptfs filesystem. Encrypted keys of the newly introduced format store an authentication token in its payload with a FEFEK randomly generated by the kernel and protected by the parent master key.

In order to avoid known-plaintext attacks, the datablob obtained through commands 'keyctl print' or 'keyctl pipe' does not contain the overall authentication token, which content is well known, but only the FEFEK in encrypted form.

The eCryptfs filesystem may really benefit from using encrypted keys in that the required key can be securely generated by an Administrator and provided at boot time after the unsealing of a 'trusted' key in order to perform the mount in a controlled environment. Another advantage is that the key is not exposed to threats of malicious software, because it is available in clear form only at kernel level.

Usage:

```
keyctl add encrypted name "new ecryptfs key-type:master-key-name keylen" ring
keyctl add encrypted name "load hex_blob" ring
keyctl update keyid "update key-type:master-key-name"
```

Where:

```
name:= '<16 hexadecimal characters>'
key-type:= 'trusted' | 'user'
keylen:= 64
```

Example of encrypted key usage with the eCryptfs filesystem:

Create an encrypted key "1000100010001000" of length 64 bytes with format 'ecryptfs' and save it using a previously loaded user key "test":

```
$ keyctl add encrypted 1000100010001000 "new ecryptfs user:test 64" @u
19184530

$ keyctl print 19184530
ecryptfs user:test 64 490045d4bfe48c99f0d465fbbbb79e7500da954178e2de0697
dd85091f5450a0511219e9f7cd70dcd498038181466f78ac8d4c19504fcc72402bfc41c2
f253a41b7507ccaa4b2b03fff19a69d1cc0b16e71746473f023a95488b6edfd86f7fdd40
9d292e4bacded1258880122dd553a661

$ keyctl pipe 19184530 > ecryptfs.blob
```

Mount an eCryptfs filesystem using the created encrypted key “1000100010001000” into the ‘/secret’ directory:

```
$ mount -i -t ecryptfs -oecryptfs_sig=1000100010001000,\
  ecryptfs_cipher=aes,ecryptfs_key_bytes=32 /secret /secret
```

Key Request Service

The key request service is part of the key retention service (refer to Documentation/security/keys/core.rst). This document explains more fully how the requesting algorithm works.

The process starts by either the kernel requesting a service by calling `request_key*()`:

```
struct key *request_key(const struct key_type *type,
                        const char *description,
                        const char *callout_info);
```

or:

```
struct key *request_key_with_auxdata(const struct key_type *type,
                                     const char *description,
                                     const char *callout_info,
                                     size_t callout_len,
                                     void *aux);
```

or:

```
struct key *request_key_async(const struct key_type *type,
                              const char *description,
                              const char *callout_info,
                              size_t callout_len);
```

or:

```
struct key *request_key_async_with_auxdata(const struct key_type *type,
                                           const char *description,
                                           const char *callout_info,
                                           size_t callout_len,
                                           void *aux);
```

Or by userspace invoking the request_key system call:

```
key_serial_t request_key(const char *type,
                         const char *description,
                         const char *callout_info,
                         key_serial_t dest_keyring);
```

The main difference between the access points is that the in-kernel interface does not need to link the key to a keyring to prevent it from being immediately destroyed. The kernel interface returns a pointer directly to the key, and it’s up to the caller to destroy the key.

The request_key*_with_auxdata() calls are like the in-kernel request_key*() calls, except that they permit auxiliary data to be passed to the upcaller (the default is NULL). This is only useful for those key types that define their own upcall mechanism rather than using /sbin/request-key.

The two async in-kernel calls may return keys that are still in the process of being constructed. The two non-async ones will wait for construction to complete first.

The userspace interface links the key to a keyring associated with the process to prevent the key from going away, and returns the serial number of the key to the caller.

The following example assumes that the key types involved don’t define their own upcall mechanisms. If they do, then those should be substituted for the forking and execution of /sbin/request-key.

The Process

A request proceeds in the following manner:

1. Process A calls request_key() [the userspace syscall calls the kernel interface].
2. request_key() searches the process's subscribed keyrings to see if there's a suitable key there. If there is, it returns the key. If there isn't, and callout_info is not set, an error is returned. Otherwise the process proceeds to the next step.
3. request_key() sees that A doesn't have the desired key yet, so it creates two things:
   (a) An uninstantiated key U of requested type and description.
   (b) An authorisation key V that refers to key U and notes that process A is the context in which key U should be instantiated and secured, and from which associated key requests may be satisfied.
4. request_key() then forks and executes /sbin/request-key with a new session keyring that contains a link to auth key V.
5. /sbin/request-key assumes the authority associated with key U.
6. /sbin/request-key execs an appropriate program to perform the actual instantiation.
7. The program may want to access another key from A's context (say a Kerberos TGT key). It just requests the appropriate key, and the keyring search notes that the session keyring has auth key V in its bottom level.

   This will permit it to then search the keyrings of process A with the UID, GID, groups and security info of process A as if it was process A, and come up with key W.
8. The program then does what it must to get the data with which to instantiate key U, using key W as a reference (perhaps it contacts a Kerberos server using the TGT) and then instantiates key U.
9. Upon instantiating key U, auth key V is automatically revoked so that it may not be used again.
10. The program then exits 0 and request_key() deletes key V and returns key U to the caller.

This also extends further. If key W (step 7 above) didn't exist, key W would be created uninstantiated, another auth key (X) would be created (as per step 3) and another copy of /sbin/request-key spawned (as per step 4); but the context specified by auth key X will still be process A, as it was in auth key V.

This is because process A's keyrings can't simply be attached to /sbin/request-key at the appropriate places because (a) execve will discard two of them, and (b) it requires the same UID/GID/Groups all the way through.

Negative Instantiation And Rejection

Rather than instantiating a key, it is possible for the possessor of an authorisation key to negatively instantiate a key that's under construction. This is a short duration placeholder that causes any attempt at re-requesting the key whilst it exists to fail with error ENOKEY if negated or the specified error if rejected.

This is provided to prevent excessive repeated spawning of /sbin/request-key processes for a key that will never be obtainable.

Should the /sbin/request-key process exit anything other than 0 or die on a signal, the key under construction will be automatically negatively instantiated for a short amount of time.

The Search Algorithm

A search of any particular keyring proceeds in the following fashion:

1. When the key management code searches for a key (keyring_search_aux) it firstly calls key_permission(SEARCH) on the keyring it's starting with, if this denies permission, it doesn't search further.

2. It considers all the non-keyring keys within that keyring and, if any key matches the criteria specified, calls key_permission(SEARCH) on it to see if the key is allowed to be found. If it is, that key is returned; if not, the search continues, and the error code is retained if of higher priority than the one currently set.
3. It then considers all the keyring-type keys in the keyring it's currently searching. It calls key_permission(SEARCH) on each keyring, and if this grants permission, it recurses, executing steps (2) and (3) on that keyring.

The process stops immediately a valid key is found with permission granted to use it. Any error from a previous match attempt is discarded and the key is returned.

When search_process_keyrings() is invoked, it performs the following searches until one succeeds:

1. If extant, the process's thread keyring is searched.
2. If extant, the process's process keyring is searched.
3. The process's session keyring is searched.
4. If the process has assumed the authority associated with a request_key() authorisation key then:
   (a) If extant, the calling process's thread keyring is searched.
   (b) If extant, the calling process's process keyring is searched.
   (c) The calling process's session keyring is searched.

The moment one succeeds, all pending errors are discarded and the found key is returned.

Only if all these fail does the whole thing fail with the highest priority error. Note that several errors may have come from LSM.

The error priority is:

```
EKEYREVOKED > EKEYEXPIRED > ENOKEY
```

EACCES/EPERM are only returned on a direct search of a specific keyring where the basal keyring does not grant Search permission.

Trusted and Encrypted Keys

Trusted and Encrypted Keys are two new key types added to the existing kernel key ring service. Both of these new types are variable length symmetric keys, and in both cases all keys are created in the kernel, and user space sees, stores, and loads only encrypted blobs. Trusted Keys require the availability of a Trusted Platform Module (TPM) chip for greater security, while Encrypted Keys can be used on any system. All user level blobs, are displayed and loaded in hex ascii for convenience, and are integrity verified.

Trusted Keys use a TPM both to generate and to seal the keys. Keys are sealed under a 2048 bit RSA key in the TPM, and optionally sealed to specified PCR (integrity measurement) values, and only unsealed by the TPM, if PCRs and blob integrity verifications match. A loaded Trusted Key can be updated with new (future) PCR values, so keys are easily migrated to new pcr values, such as when the kernel and initramfs are updated. The same key can have many saved blobs under different PCR values, so multiple boots are easily supported.

By default, trusted keys are sealed under the SRK, which has the default authorization value (20 zeros). This can be set at takeownership time with the trouser's utility: "tpm_takeownership -u -z".

Usage:

```
keyctl add trusted name "new keylen [options]" ring
keyctl add trusted name "load hex_blob [pcrlock=pcrnum]" ring
keyctl update key "update [options]"
keyctl print keyid
```

```
options:
   keyhandle=    ascii hex value of sealing key default 0x40000000 (SRK)
   keyauth=      ascii hex auth for sealing key default 0x00...i
                 (40 ascii zeros)
   blobauth=     ascii hex auth for sealed data default 0x00...
                 (40 ascii zeros)
   pcrinfo=      ascii hex of PCR_INFO or PCR_INFO_LONG (no default)
   pcrlock=      pcr number to be extended to "lock" blob
   migratable=   0|1 indicating permission to reseal to new PCR values,
                 default 1 (resealing allowed)
   hash=         hash algorithm name as a string. For TPM 1.x the only
                 allowed value is sha1. For TPM 2.x the allowed values
                 are sha1, sha256, sha384, sha512 and sm3-256.
   policydigest= digest for the authorization policy. must be calculated
                 with the same hash algorithm as specified by the 'hash='
                 option.
   policyhandle= handle to an authorization policy session that defines the
                 same policy and with the same hash algorithm as was used to
                 seal the key.
```

“keyctl print” returns an ascii hex copy of the sealed key, which is in standard TPM_STORED_DATA format. The key length for new keys are always in bytes. Trusted Keys can be 32 - 128 bytes (256 - 1024 bits), the upper limit is to fit within the 2048 bit SRK (RSA) keylength, with all necessary structure/padding.

Encrypted keys do not depend on a TPM, and are faster, as they use AES for encryption/decryption. New keys are created from kernel generated random numbers, and are encrypted/decrypted using a specified ‘master’ key. The ‘master’ key can either be a trusted-key or user-key type. The main disadvantage of encrypted keys is that if they are not rooted in a trusted key, they are only as secure as the user key encrypting them. The master user key should therefore be loaded in as secure a way as possible, preferably early in boot.

The decrypted portion of encrypted keys can contain either a simple symmetric key or a more complex structure. The format of the more complex structure is application specific, which is identified by ‘format’.

Usage:

```
keyctl add encrypted name "new [format] key-type:master-key-name keylen"
    ring
keyctl add encrypted name "load hex_blob" ring
keyctl update keyid "update key-type:master-key-name"
```

Where:

```
format:= 'default | ecryptfs'
key-type:= 'trusted' | 'user'
```

Examples of trusted and encrypted key usage:

Create and save a trusted key named “kmk” of length 32 bytes:

```
$ keyctl add trusted kmk "new 32" @u
440502848

$ keyctl show
Session Keyring
       -3 --alswrv    500   500  keyring: _ses
 97833714 --alswrv    500    -1   \_ keyring: _uid.500
440502848 --alswrv    500   500       \_ trusted: kmk

$ keyctl print 440502848
0101000000000000000001005d01b7e3f4a6be5709930f3b70a743cbb42e0cc95e18e915
3f60da455bbf1144ad12e4f92b452f966929f6105fd29ca28e4d4d5a031d068478bacb0b
27351119f822911b0a11ba3d3498ba6a32e50dac7f32894dd890eb9ad578e4e292c83722
a52e56a097e6a68b3f56f7a52ece0cdccba1eb62cad7d817f6dc58898b3ac15f36026fec
```

```
d568bd4a706cb60bb37be6d8f1240661199d640b66fb0fe3b079f97f450b9ef9c22c6d5d
dd379f0facd1cd020281dfa3c70ba21a3fa6fc2471dc6d13ecf8298b946f65345faa5ef0
f1f8fff03ad0acb083725535636addb08d73dedb9832da198081e5deae84bfaf0409c22b
e4a8aea2b607ec96931e6f4d4fe563ba

$ keyctl pipe 440502848 > kmk.blob
```

Load a trusted key from the saved blob:

```
$ keyctl add trusted kmk "load `cat kmk.blob`" @u
268728824

$ keyctl print 268728824
0101000000000000000001005d01b7e3f4a6be5709930f3b70a743cbb42e0cc95e18e915
3f60da455bbf1144ad12e4f92b452f966929f6105fd29ca28e4d4d5a031d068478bacb0b
27351119f822911b0a11ba3d3498ba6a32e50dac7f32894dd890eb9ad578e4e292c83722
a52e56a097e6a68b3f56f7a52ece0cdccba1eb62cad7d817f6dc58898b3ac15f36026fec
d568bd4a706cb60bb37be6d8f1240661199d640b66fb0fe3b079f97f450b9ef9c22c6d5d
dd379f0facd1cd020281dfa3c70ba21a3fa6fc2471dc6d13ecf8298b946f65345faa5ef0
f1f8fff03ad0acb083725535636addb08d73dedb9832da198081e5deae84bfaf0409c22b
e4a8aea2b607ec96931e6f4d4fe563ba
```

Reseal a trusted key under new pcr values:

```
$ keyctl update 268728824 "update pcrinfo=`cat pcr.blob`"
$ keyctl print 268728824
010100000000002c0002800093c35a09b70fff26e7a98ae786c641e678ec6ffb6b46d805
77c8a6377aed9d3219c6dfec4b23ffe3000001005d37d472ac8a44023fbb3d18583a4f73
d3a076c0858f6f1dcaa39ea0f119911ff03f5406df4f7f27f41da8d7194f45c9f4e00f2e
df449f266253aa3f52e55c53de147773e00f0f9aca86c64d94c95382265968c354c5eab4
9638c5ae99c89de1e0997242edfb0b501744e11ff9762dfd951cffd93227cc513384e7e6
e782c29435c7ec2edafaa2f4c1fe6e7a781b59549ff5296371b42133777dcc5b8b971610
94bc67ede19e43ddb9dc2baacad374a36feaf0314d700af0a65c164b7082401740e489c9
7ef6a24defe4846104209bf0c3eced7fa1a672ed5b125fc9d8cd88b476a658a4434644ef
df8ae9a178e9f83ba9f08d10fa47e4226b98b0702f06b3b8
```

The initial consumer of trusted keys is EVM, which at boot time needs a high quality symmetric key for HMAC protection of file metadata. The use of a trusted key provides strong guarantees that the EVM key has not been compromised by a user level problem, and when sealed to specific boot PCR values, protects against boot and offline attacks. Create and save an encrypted key “evm” using the above trusted key “kmk”:

option 1: omitting ‘format’:

```
$ keyctl add encrypted evm "new trusted:kmk 32" @u
159771175
```

option 2: explicitly defining ‘format’ as ‘default’:

```
$ keyctl add encrypted evm "new default trusted:kmk 32" @u
159771175

$ keyctl print 159771175
default trusted:kmk 32 2375725ad57798846a9bbd240de8906f006e66c03af53b1b3
82dbbc55be2a44616e4959430436dc4f2a7a9659aa60bb4652aeb2120f149ed197c564e0
24717c64 5972dcb82ab2dde83376d82b2e3c09ffc

$ keyctl pipe 159771175 > evm.blob
```

Load an encrypted key “evm” from saved blob:

```
$ keyctl add encrypted evm "load `cat evm.blob`" @u
831684262
```

```
$ keyctl print 831684262
default trusted:kmk 32 2375725ad57798846a9bbd240de8906f006e66c03af53b1b3
82dbbc55be2a44616e4959430436dc4f2a7a9659aa60bb4652aeb2120f149ed197c564e0
24717c64 5972dcb82ab2dde83376d82b2e3c09ffc
```

Other uses for trusted and encrypted keys, such as for disk and file encryption are anticipated. In particular the new format 'ecryptfs' has been defined in in order to use encrypted keys to mount an eCryptfs filesystem. More details about the usage can be found in the file `Documentation/security/keys/ecryptfs.rst`.

CHAPTER

FOUR

LINUX SECURITY MODULE DEVELOPMENT

Based on https://lkml.org/lkml/2007/10/26/215, a new LSM is accepted into the kernel when its intent (a description of what it tries to protect against and in what cases one would expect to use it) has been appropriately documented in `Documentation/security/LSM.rst`. This allows an LSM's code to be easily compared to its goals, and so that end users and distros can make a more informed decision about which LSMs suit their requirements.

For extensive documentation on the available LSM hook interfaces, please see `include/linux/lsm_hooks.h`.

CHAPTER

FIVE

SCTP LSM SUPPORT

For security module support, three SCTP specific hooks have been implemented:

```
security_sctp_assoc_request()
security_sctp_bind_connect()
security_sctp_sk_clone()
```

Also the following security hook has been utilised:

```
security_inet_conn_established()
```

The usage of these hooks are described below with the SELinux implementation described in `Documentation/security/SELinux-sctp.rst`

security_sctp_assoc_request()

Passes the @ep and @chunk->skb of the association INIT packet to the security module. Returns 0 on success, error on failure.

```
@ep - pointer to sctp endpoint structure.
@skb - pointer to skbuff of association packet.
```

security_sctp_bind_connect()

Passes one or more ipv4/ipv6 addresses to the security module for validation based on the `@optname` that will result in either a bind or connect service as shown in the permission check tables below. Returns 0 on success, error on failure.

```
  @sk      - Pointer to sock structure.
  @optname - Name of the option to validate.
  @address - One or more ipv4 / ipv6 addresses.
  @addrlen - The total length of address(s). This is calculated on each
             ipv4 or ipv6 address using sizeof(struct sockaddr_in) or
             sizeof(struct sockaddr_in6).

------------------------------------------------------------------
|                      BIND Type Checks                          |
|       @optname              |         @address contains        |
|-----------------------------|----------------------------------|
| SCTP_SOCKOPT_BINDX_ADD      | One or more ipv4 / ipv6 addresses |
| SCTP_PRIMARY_ADDR           | Single ipv4 or ipv6 address       |
| SCTP_SET_PEER_PRIMARY_ADDR | Single ipv4 or ipv6 address       |
------------------------------------------------------------------


------------------------------------------------------------------
```

```
|                    CONNECT Type Checks                              |
|       @optname             |         @address contains            |
|----------------------------|--------------------------------------|
| SCTP_SOCKOPT_CONNECTX      | One or more ipv4 / ipv6 addresses |
| SCTP_PARAM_ADD_IP          | One or more ipv4 / ipv6 addresses |
| SCTP_SENDMSG_CONNECT       | Single ipv4 or ipv6 address       |
| SCTP_PARAM_SET_PRIMARY     | Single ipv4 or ipv6 address       |
-------------------------------------------------------------------
```

A summary of the @optname entries is as follows:

```
SCTP_SOCKOPT_BINDX_ADD - Allows additional bind addresses to be
                         associated after (optionally) calling
                         bind(3).
                         sctp_bindx(3) adds a set of bind
                         addresses on a socket.

SCTP_SOCKOPT_CONNECTX - Allows the allocation of multiple
                        addresses for reaching a peer
                        (multi-homed).
                        sctp_connectx(3) initiates a connection
                        on an SCTP socket using multiple
                        destination addresses.

SCTP_SENDMSG_CONNECT  - Initiate a connection that is generated by a
                        sendmsg(2) or sctp_sendmsg(3) on a new asociation.

SCTP_PRIMARY_ADDR     - Set local primary address.

SCTP_SET_PEER_PRIMARY_ADDR - Request peer sets address as
                             association primary.

SCTP_PARAM_ADD_IP          - These are used when Dynamic Address
SCTP_PARAM_SET_PRIMARY     - Reconfiguration is enabled as explained below.
```

To support Dynamic Address Reconfiguration the following parameters must be enabled on both endpoints (or use the appropriate **setsockopt**(2)):

```
/proc/sys/net/sctp/addip_enable
/proc/sys/net/sctp/addip_noauth_enable
```

then the following *_PARAM_*'s are sent to the peer in an ASCONF chunk when the corresponding @optname's are present:

```
      @optname                     ASCONF Parameter
     ----------                   ------------------
SCTP_SOCKOPT_BINDX_ADD     ->   SCTP_PARAM_ADD_IP
SCTP_SET_PEER_PRIMARY_ADDR ->   SCTP_PARAM_SET_PRIMARY
```

security_sctp_sk_clone()

Called whenever a new socket is created by **accept**(2) (i.e. a TCP style socket) or when a socket is 'peeled off' e.g userspace calls **sctp_peeloff**(3).

```
@ep - pointer to current sctp endpoint structure.
@sk - pointer to current sock structure.
@sk - pointer to new sock structure.
```

security_inet_conn_established()

Called when a COOKIE ACK is received:

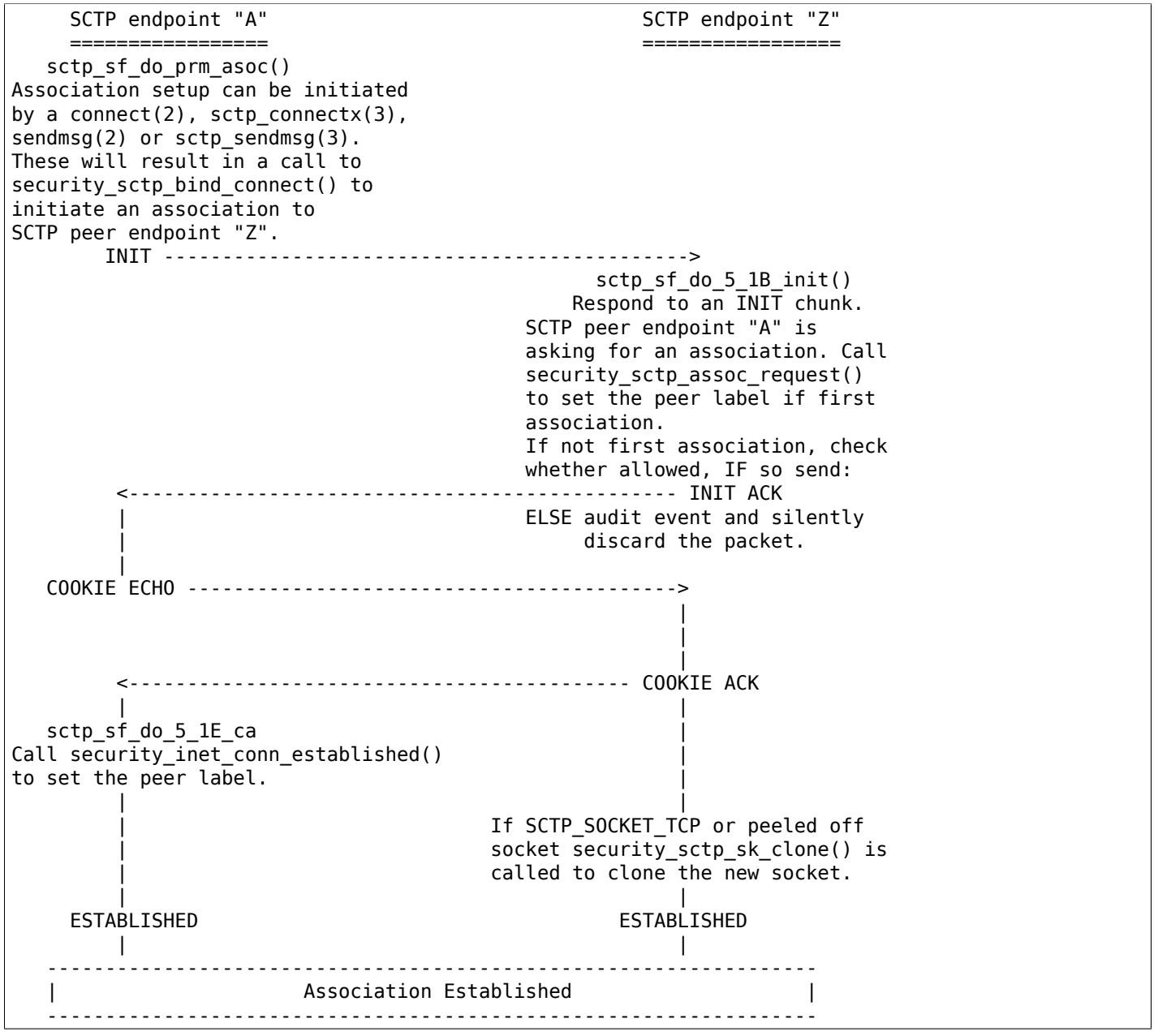
```
@sk  - pointer to sock structure.
@skb - pointer to skbuff of the COOKIE ACK packet.
```

CHAPTER

SIX

SECURITY HOOKS USED FOR ASSOCIATION ESTABLISHMENT

The following diagram shows the use of security_sctp_bind_connect(), security_sctp_assoc_request(), security_inet_conn_established() when establishing an association.



CHAPTER

SEVEN

SCTP SELINUX SUPPORT

CHAPTER

EIGHT

SECURITY HOOKS

Documentation/security/LSM-sctp.rst describes the following SCTP security hooks with the SELinux specifics expanded below:

```
security_sctp_assoc_request()
security_sctp_bind_connect()
security_sctp_sk_clone()
security_inet_conn_established()
```

security_sctp_assoc_request()

Passes the @ep and @chunk->skb of the association INIT packet to the security module. Returns 0 on success, error on failure.

```
@ep - pointer to sctp endpoint structure.
@skb - pointer to skbuff of association packet.
```

The security module performs the following operations: IF this is the first association on @ep->base.sk, then set the peer sid to that in @skb. This will ensure there is only one peer sid assigned to @ep->base.sk that may support multiple associations.

ELSE validate the @ep->base.sk peer_sid against the @skb peer sid to determine whether the association should be allowed or denied.

Set the sctp @ep sid to socket's sid (from ep->base.sk) with MLS portion taken from @skb peer sid. This will be used by SCTP TCP style sockets and peeled off connections as they cause a new socket to be generated.

If IP security options are configured (CIPSO/CALIPSO), then the ip options are set on the socket.

security_sctp_bind_connect()

Checks permissions required for ipv4/ipv6 addresses based on the @optname as follows:

```
-------------------------------------------------------------------
|                    BIND Permission Checks                       |
|       @optname              |         @address contains         |
|-----------------------------|-----------------------------------|
| SCTP_SOCKOPT_BINDX_ADD      | One or more ipv4 / ipv6 addresses |
| SCTP_PRIMARY_ADDR           | Single ipv4 or ipv6 address       |
| SCTP_SET_PEER_PRIMARY_ADDR | Single ipv4 or ipv6 address       |
-------------------------------------------------------------------

-------------------------------------------------------------------
|                  CONNECT Permission Checks                      |
|       @optname              |         @address contains         |
```

```
|----------------------------|----------------------------------|
| SCTP_SOCKOPT_CONNECTX      | One or more ipv4 / ipv6 addresses |
| SCTP_PARAM_ADD_IP          | One or more ipv4 / ipv6 addresses |
| SCTP_SENDMSG_CONNECT       | Single ipv4 or ipv6 address       |
| SCTP_PARAM_SET_PRIMARY     | Single ipv4 or ipv6 address       |
-------------------------------------------------------------------
```

`Documentation/security/LSM-sctp.rst` gives a summary of the `@optname` entries and also describes ASCONF chunk processing when Dynamic Address Reconfiguration is enabled.

security_sctp_sk_clone()

Called whenever a new socket is created by **accept**(2) (i.e. a TCP style socket) or when a socket is 'peeled off' e.g userspace calls **sctp_peeloff**(3). `security_sctp_sk_clone()` will set the new sockets sid and peer sid to that contained in the `@ep sid` and `@ep peer sid` respectively.

```
@ep - pointer to current sctp endpoint structure.
@sk - pointer to current sock structure.
@sk - pointer to new sock structure.
```

security_inet_conn_established()

Called when a COOKIE ACK is received where it sets the connection's peer sid to that in `@skb`:

```
@sk  - pointer to sock structure.
@skb - pointer to skbuff of the COOKIE ACK packet.
```

CHAPTER

NINE

POLICY STATEMENTS

The following class and permissions to support SCTP are available within the kernel:

```
class sctp_socket inherits socket { node_bind }
```

whenever the following policy capability is enabled:

```
policycap extended_socket_class;
```

SELinux SCTP support adds the `name_connect` permission for connecting to a specific port type and the `association` permission that is explained in the section below.

If userspace tools have been updated, SCTP will support the `portcon` statement as shown in the following example:

```
portcon sctp 1024-1036 system_u:object_r:sctp_ports_t:s0
```

CHAPTER

TEN

SCTP PEER LABELING

An SCTP socket will only have one peer label assigned to it. This will be assigned during the establishment of the first association. Any further associations on this socket will have their packet peer label compared to the sockets peer label, and only if they are different will the `association` permission be validated. This is validated by checking the socket peer sid against the received packets peer sid to determine whether the association should be allowed or denied.

NOTES:

1. If peer labeling is not enabled, then the peer context will always be `SECINITSID_UNLABELED` (`unlabeled_t` in Reference Policy).
2. As SCTP can support more than one transport address per endpoint (multi-homing) on a single socket, it is possible to configure policy and NetLabel to provide different peer labels for each of these. As the socket peer label is determined by the first associations transport address, it is recommended that all peer labels are consistent.
3. **getpeercon**(3) may be used by userspace to retrieve the sockets peer context.
4. While not SCTP specific, be aware when using NetLabel that if a label is assigned to a specific interface, and that interface 'goes down', then the NetLabel service will remove the entry. Therefore ensure that the network startup scripts call **netlabelctl**(8) to set the required label (see **netlabel-config**(8) helper script for details).
5. The NetLabel SCTP peer labeling rules apply as discussed in the following set of posts tagged "netlabel" at: http://www.paul-moore.com/blog/t.
6. CIPSO is only supported for IPv4 addressing: `socket(AF_INET, ...)` CALIPSO is only supported for IPv6 addressing: `socket(AF_INET6, ...)`

   Note the following when testing CIPSO/CALIPSO:

   (a) CIPSO will send an ICMP packet if an SCTP packet cannot be delivered because of an invalid label.

   (b) CALIPSO does not send an ICMP packet, just silently discards it.
7. IPSEC is not supported as RFC 3554 - sctp/ipsec support has not been implemented in userspace (**racoon**(8) or **ipsec_pluto**(8)), although the kernel supports SCTP/IPSEC.

CHAPTER

ELEVEN

KERNEL SELF-PROTECTION

Kernel self-protection is the design and implementation of systems and structures within the Linux kernel to protect against security flaws in the kernel itself. This covers a wide range of issues, including removing entire classes of bugs, blocking security flaw exploitation methods, and actively detecting attack attempts. Not all topics are explored in this document, but it should serve as a reasonable starting point and answer any frequently asked questions. (Patches welcome, of course!)

In the worst-case scenario, we assume an unprivileged local attacker has arbitrary read and write access to the kernel's memory. In many cases, bugs being exploited will not provide this level of access, but with systems in place that defend against the worst case we'll cover the more limited cases as well. A higher bar, and one that should still be kept in mind, is protecting the kernel against a _privileged_ local attacker, since the root user has access to a vastly increased attack surface. (Especially when they have the ability to load arbitrary kernel modules.)

The goals for successful self-protection systems would be that they are effective, on by default, require no opt-in by developers, have no performance impact, do not impede kernel debugging, and have tests. It is uncommon that all these goals can be met, but it is worth explicitly mentioning them, since these aspects need to be explored, dealt with, and/or accepted.

Attack Surface Reduction

The most fundamental defense against security exploits is to reduce the areas of the kernel that can be used to redirect execution. This ranges from limiting the exposed APIs available to userspace, making in-kernel APIs hard to use incorrectly, minimizing the areas of writable kernel memory, etc.

Strict kernel memory permissions

When all of kernel memory is writable, it becomes trivial for attacks to redirect execution flow. To reduce the availability of these targets the kernel needs to protect its memory with a tight set of permissions.

Executable code and read-only data must not be writable

Any areas of the kernel with executable memory must not be writable. While this obviously includes the kernel text itself, we must consider all additional places too: kernel modules, JIT memory, etc. (There are temporary exceptions to this rule to support things like instruction alternatives, breakpoints, kprobes, etc. If these must exist in a kernel, they are implemented in a way where the memory is temporarily made writable during the update, and then returned to the original permissions.)

In support of this are `CONFIG_STRICT_KERNEL_RWX` and `CONFIG_STRICT_MODULE_RWX`, which seek to make sure that code is not writable, data is not executable, and read-only data is neither writable nor executable.

Most architectures have these options on by default and not user selectable. For some architectures like arm that wish to have these be selectable, the architecture Kconfig can select ARCH_OPTIONAL_KERNEL_RWX to enable a Kconfig prompt.

CONFIG_ARCH_OPTIONAL_KERNEL_RWX_DEFAULT determines the default setting when ARCH_OPTIONAL_KERNEL_RWX is enabled.

Function pointers and sensitive variables must not be writable

Vast areas of kernel memory contain function pointers that are looked up by the kernel and used to continue execution (e.g. descriptor/vector tables, file/network/etc operation structures, etc). The number of these variables must be reduced to an absolute minimum.

Many such variables can be made read-only by setting them "const" so that they live in the .rodata section instead of the .data section of the kernel, gaining the protection of the kernel's strict memory permissions as described above.

For variables that are initialized once at `__init` time, these can be marked with the (new and under development) `__ro_after_init` attribute.

What remains are variables that are updated rarely (e.g. GDT). These will need another infrastructure (similar to the temporary exceptions made to kernel code mentioned above) that allow them to spend the rest of their lifetime read-only. (For example, when being updated, only the CPU thread performing the update would be given uninterruptible write access to the memory.)

Segregation of kernel memory from userspace memory

The kernel must never execute userspace memory. The kernel must also never access userspace memory without explicit expectation to do so. These rules can be enforced either by support of hardware-based restrictions (x86's SMEP/SMAP, ARM's PXN/PAN) or via emulation (ARM's Memory Domains). By blocking userspace memory in this way, execution and data parsing cannot be passed to trivially-controlled userspace memory, forcing attacks to operate entirely in kernel memory.

Reduced access to syscalls

One trivial way to eliminate many syscalls for 64-bit systems is building without CONFIG_COMPAT. However, this is rarely a feasible scenario.

The "seccomp" system provides an opt-in feature made available to userspace, which provides a way to reduce the number of kernel entry points available to a running process. This limits the breadth of kernel code that can be reached, possibly reducing the availability of a given bug to an attack.

An area of improvement would be creating viable ways to keep access to things like compat, user namespaces, BPF creation, and perf limited only to trusted processes. This would keep the scope of kernel entry points restricted to the more regular set of normally available to unprivileged userspace.

Restricting access to kernel modules

The kernel should never allow an unprivileged user the ability to load specific kernel modules, since that would provide a facility to unexpectedly extend the available attack surface. (The on-demand loading of modules via their predefined subsystems, e.g. MODULE_ALIAS_*, is considered "expected" here, though additional consideration should be given even to these.) For example, loading a filesystem module via an unprivileged socket API is nonsense: only the root or physically local user should trigger filesystem module loading. (And even this can be up for debate in some scenarios.)

To protect against even privileged users, systems may need to either disable module loading entirely (e.g. monolithic kernel builds or modules_disabled sysctl), or provide signed modules (e.g. CONFIG_MODULE_SIG_FORCE, or dm-crypt with LoadPin), to keep from having root load arbitrary kernel code via the module loader interface.

Memory integrity

There are many memory structures in the kernel that are regularly abused to gain execution control during an attack, By far the most commonly understood is that of the stack buffer overflow in which the return address stored on the stack is overwritten. Many other examples of this kind of attack exist, and protections exist to defend against them.

Stack buffer overflow

The classic stack buffer overflow involves writing past the expected end of a variable stored on the stack, ultimately writing a controlled value to the stack frame's stored return address. The most widely used defense is the presence of a stack canary between the stack variables and the return address (`CONFIG_STACKPROTECTOR`), which is verified just before the function returns. Other defenses include things like shadow stacks.

Stack depth overflow

A less well understood attack is using a bug that triggers the kernel to consume stack memory with deep function calls or large stack allocations. With this attack it is possible to write beyond the end of the kernel's preallocated stack space and into sensitive structures. Two important changes need to be made for better protections: moving the sensitive thread_info structure elsewhere, and adding a faulting memory hole at the bottom of the stack to catch these overflows.

Heap memory integrity

The structures used to track heap free lists can be sanity-checked during allocation and freeing to make sure they aren't being used to manipulate other memory areas.

Counter integrity

Many places in the kernel use atomic counters to track object references or perform similar lifetime management. When these counters can be made to wrap (over or under) this traditionally exposes a use-after-free flaw. By trapping atomic wrapping, this class of bug vanishes.

Size calculation overflow detection

Similar to counter overflow, integer overflows (usually size calculations) need to be detected at runtime to kill this class of bug, which traditionally leads to being able to write past the end of kernel buffers.

Probabilistic defenses

While many protections can be considered deterministic (e.g. read-only memory cannot be written to), some protections provide only statistical defense, in that an attack must gather enough information about a running system to overcome the defense. While not perfect, these do provide meaningful defenses.

Canaries, blinding, and other secrets

It should be noted that things like the stack canary discussed earlier are technically statistical defenses, since they rely on a secret value, and such values may become discoverable through an information exposure flaw.

Blinding literal values for things like JITs, where the executable contents may be partially under the control of userspace, need a similar secret value.

It is critical that the secret values used must be separate (e.g. different canary per stack) and high entropy (e.g. is the RNG actually working?) in order to maximize their success.

Kernel Address Space Layout Randomization (KASLR)

Since the location of kernel memory is almost always instrumental in mounting a successful attack, making the location non-deterministic raises the difficulty of an exploit. (Note that this in turn makes the value of information exposures higher, since they may be used to discover desired memory locations.)

Text and module base

By relocating the physical and virtual base address of the kernel at boot-time (`CONFIG_RANDOMIZE_BASE`), attacks needing kernel code will be frustrated. Additionally, offsetting the module loading base address means that even systems that load the same set of modules in the same order every boot will not share a common base address with the rest of the kernel text.

Stack base

If the base address of the kernel stack is not the same between processes, or even not the same between syscalls, targets on or beyond the stack become more difficult to locate.

Dynamic memory base

Much of the kernel's dynamic memory (e.g. kmalloc, vmalloc, etc) ends up being relatively deterministic in layout due to the order of early-boot initializations. If the base address of these areas is not the same between boots, targeting them is frustrated, requiring an information exposure specific to the region.

Structure layout

By performing a per-build randomization of the layout of sensitive structures, attacks must either be tuned to known kernel builds or expose enough kernel memory to determine structure layouts before manipulating them.

Preventing Information Exposures

Since the locations of sensitive structures are the primary target for attacks, it is important to defend against exposure of both kernel memory addresses and kernel memory contents (since they may contain kernel addresses or other sensitive things like canary values).

Kernel addresses

Printing kernel addresses to userspace leaks sensitive information about the kernel memory layout. Care should be exercised when using any printk specifier that prints the raw address, currently %px, %p[ad], (and %p[sSb] in certain circumstances [*]). Any file written to using one of these specifiers should be readable only by privileged processes.

Kernels 4.14 and older printed the raw address using %p. As of 4.15-rc1 addresses printed with the specifier %p are hashed before printing.

[*] If KALLSYMS is enabled and symbol lookup fails, the raw address is printed. If KALLSYMS is not enabled the raw address is printed.

Unique identifiers

Kernel memory addresses must never be used as identifiers exposed to userspace. Instead, use an atomic counter, an idr, or similar unique identifier.

Memory initialization

Memory copied to userspace must always be fully initialized. If not explicitly memset(), this will require changes to the compiler to make sure structure holes are cleared.

Memory poisoning

When releasing memory, it is best to poison the contents (clear stack on syscall return, wipe heap memory on a free), to avoid reuse attacks that rely on the old contents of memory. This frustrates many uninitialized variable attacks, stack content exposures, heap content exposures, and use-after-free attacks.

Destination tracking

To help kill classes of bugs that result in kernel addresses being written to userspace, the destination of writes needs to be tracked. If the buffer is destined for userspace (e.g. seq_file backed `/proc` files), it should automatically censor sensitive values.

CHAPTER

TWELVE

TRUSTED PLATFORM MODULE DOCUMENTATION

Virtual TPM Proxy Driver for Linux Containers

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This document describes the virtual Trusted Platform Module (vTPM) proxy device driver for Linux containers.

Introduction

The goal of this work is to provide TPM functionality to each Linux container. This allows programs to interact with a TPM in a container the same way they interact with a TPM on the physical system. Each container gets its own unique, emulated, software TPM.

Design

To make an emulated software TPM available to each container, the container management stack needs to create a device pair consisting of a client TPM character device `/dev/tpmX` (with X=0,1,2...) and a 'server side' file descriptor. The former is moved into the container by creating a character device with the appropriate major and minor numbers while the file descriptor is passed to the TPM emulator. Software inside the container can then send TPM commands using the character device and the emulator will receive the commands via the file descriptor and use it for sending back responses.

To support this, the virtual TPM proxy driver provides a device `/dev/vtpmx` that is used to create device pairs using an ioctl. The ioctl takes as an input flags for configuring the device. The flags for example indicate whether TPM 1.2 or TPM 2 functionality is supported by the TPM emulator. The result of the ioctl are the file descriptor for the 'server side' as well as the major and minor numbers of the character device that was created. Besides that the number of the TPM character device is returned. If for example `/dev/tpm10` was created, the number (`dev_num`) 10 is returned.

Once the device has been created, the driver will immediately try to talk to the TPM. All commands from the driver can be read from the file descriptor returned by the ioctl. The commands should be responded to immediately.

UAPI

enum **vtpm_proxy_flags**
    flags for the proxy TPM

Constants

VTPM_PROXY_FLAG_TPM2 the proxy TPM uses TPM 2.0 protocol

struct **vtpm_proxy_new_dev**
parameter structure for the VTPM_PROXY_IOC_NEW_DEV ioctl

Definition

```
struct vtpm_proxy_new_dev {
  __u32 flags;
  __u32 tpm_num;
  __u32 fd;
  __u32 major;
  __u32 minor;
};
```

Members

flags flags for the proxy TPM

tpm_num index of the TPM device

fd the file descriptor used by the proxy TPM

major the major number of the TPM device

minor the minor number of the TPM device

long **vtpmx_ioc_new_dev**(struct file * *file*, unsigned int *ioctl*, unsigned long *arg*)
handler for the VTPM_PROXY_IOC_NEW_DEV ioctl

Parameters

struct file * file /dev/vtpmx

unsigned int ioctl the ioctl number

unsigned long arg pointer to the struct vtpmx_proxy_new_dev

Description

Creates an anonymous file that is used by the process acting as a TPM to communicate with the client processes. The function will also add a new TPM device through which data is proxied to this TPM acting process. The caller will be provided with a file descriptor to communicate with the clients and major and minor numbers for the TPM device.

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