Linux Capabilities and Namespaces

User Namespaces

Michael Kerrisk, man7.org

February 2023

mtk@man7.org

Outline

Rev: # e2bf8f005a44

10 User Namespaces 10-1
10.1 Overview of user namespaces 10-3
10.2 Creating and joining a user namespace 10-9
10.3 User namespaces: UID and GID mappings 10-17
10.4 User namespaces, *execve()*, and user ID 0 10-31
10.5 Accessing files; file-related capabilities 10-48
10.6 Security issues 10-57
10.7 Use cases 10-64
10.8 Combining user namespaces with other namespaces 10-69

Outline

10	User Namespaces	10-1
10.1	Overview of user namespaces	10-3
10.2	Creating and joining a user namespace	10-9
10.3	User namespaces: UID and GID mappings	10-17
10.4	User namespaces, *execve()*, and user ID 0	10-31
10.5	Accessing files; file-related capabilities	10-48
10.6	Security issues	10-57
10.7	Use cases	10-64
10.8	Combining user namespaces with other namespaces	10-69

Preamble

- For even more detail than presented here, see my articles:
  - *Namespaces in operation, part 5: user namespaces*, `https://lwn.net/Articles/532593/`
  - *Namespaces in operation, part 6: more on user namespaces*, `https://lwn.net/Articles/540087/`
  - ⚠ See my notes in comments section for some updates
- And *user_namespaces(7)* man page

Introduction

- Milestone release: Linux 3.8 (Feb 2013)
  - User NSs can now be created by unprivileged users...
- Allow per-namespace mappings of UIDs and GIDs
  - I.e., process's UIDs and GIDs inside NS may be different from IDs outside NS
- Interesting use case: process may have nonzero UID outside NS, and UID of 0 inside NS
  - ⇒ Process has *root* privileges *for operations inside user NS*
    - We will learn what this means...

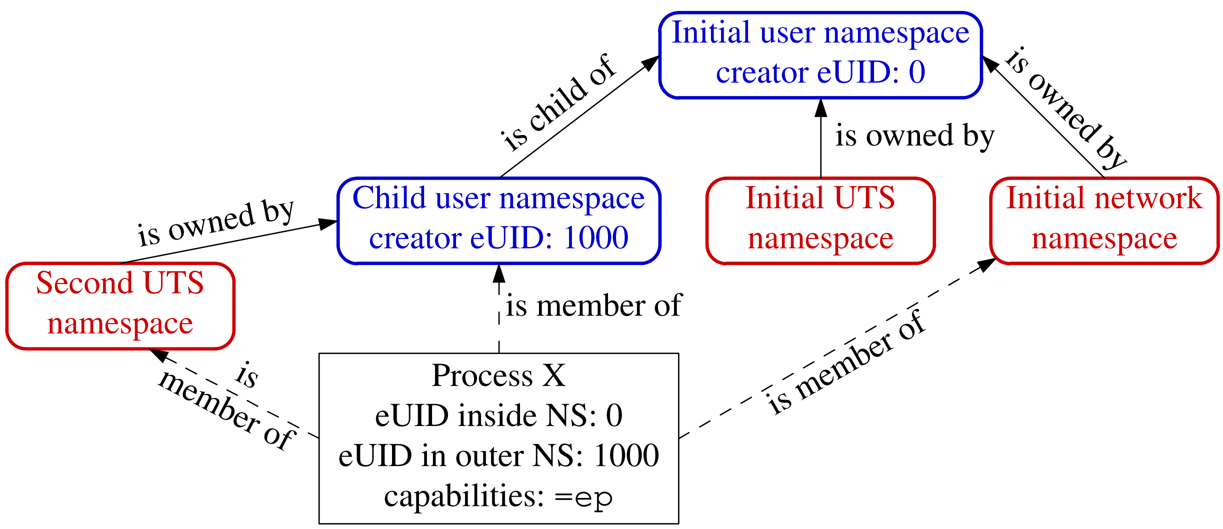
Relationships between user namespaces

- User NSs have a hierarchical relationship:
  - A user NS can have 0 or more child user NSs
  - Each user NS has parent NS, going back to initial user NS
    - Initial user NS == sole user NS that exists at boot time
  - Maximum nesting depth for user NSs is 32
    - (To prevent extremely long chains of descent, since these need to be traversed)
  - Parent of a user NS == user NS of process that created this user NS using *clone()* or *unshare()*
- Parental relationship determines some rules about operations that can be performed on a (child) user NS (later...)

“Root privileges inside a user NS”

- What does “*root* privileges in a user NS” mean?
- We’ve already seen that:
  - There are a number of NS types
  - Each NS type governs some global resource(s); e.g.:
    - UTS: hostname, NIS domain name
    - Mount: set of mounts
    - Network: IP routing tables, port numbers, `/proc/net`, ...
- What we will see is that:
  - There is an ownership relationship between user NSs and non-user NSs
    - I.e., each non-user NS is “owned” by a particular user NS
  - “*root* privileges in a user NS” == *root* privileges on (only) resources governed by non-user NSs owned by this user NS
    - And on resources associated with descendant user NSs...

User namespaces “govern” other namespace types



- Understanding this picture is our ultimate goal...

Outline

10 User Namespaces 10-1

10.1 Overview of user namespaces 10-3

10.2 Creating and joining a user namespace 10-9

10.3 User namespaces: UID and GID mappings 10-17

10.4 User namespaces, *execve()*, and user ID 0 10-31

10.5 Accessing files; file-related capabilities 10-48

10.6 Security issues 10-57

10.7 Use cases 10-64

10.8 Combining user namespaces with other namespaces 10-69

Creating and joining a user NS

- New user NS is created with `CLONE_NEWUSER` flag
  - *clone()* ⇒ child is made a member of new user NS
  - *unshare()* ⇒ caller is made a member of new user NS
- Can join an existing user NS using *setns()*
  - Process must have `CAP_SYS_ADMIN` capability in target NS
    - (The capability requirement will become clearer later)

User namespaces and capabilities

- A process gains a full set of permitted and effective capabilities in the new/target user NS when:
  - It is the child of *clone()* that creates a new user NS
  - It creates and joins a new user NS using *unshare()*
  - It joins an existing user NS using *setns()*
- But, process has no capabilities in parent/previous user NS
  - ⚠ Even if it was *root* in that NS!

Example: `namespaces/demo_userns.c`

```
./demo_userns
```

- (Very) simple user NS demonstration program
- Uses *clone()* to create child in new user NS
- Child displays its UID, GID, and capabilities

Example: namespaces/demo_userns.c

```
#define STACK_SIZE (1024 * 1024)

int main(int argc, char *argv[]) {
    char *stack = mmap(..., STACK_SIZE);    /* Allocate memory for
                                               child's stack */
    pid_t pid = clone(childFunc, stack + STACK_SIZE,
                      CLONE_NEWUSER | SIGCHLD, argv[1]);
    printf("PID of child: %ld\n", (long) pid);

    munmap(stack, STACK_SIZE);              /* Deallocate stack */

    waitpid(pid, NULL, 0);
    exit(EXIT_SUCCESS);
}
```

- Use *clone()* to create a child in a new user NS
  - Child will execute *childFunc()*, with argument *argv[1]*
- Printing PID of child is useful for some demos...
- Wait for child to terminate

Example: namespaces/demo_userns.c

```
static int childFunc(void *arg) {
    for (;;) {
        printf("eUID = %ld; eGID = %ld; ",
               (long) geteuid(), (long) getegid());

        cap_t caps = cap_get_proc();
        char *str = cap_to_text(caps, NULL);
        printf("capabilities: %s\n", str);
        cap_free(caps);
        cap_free(str);

        if (arg == NULL)
            break;
        sleep(5);
    }
    return 0;
}
```

- Display PID, effective UID + GID, and capabilities
- If *arg* (*argv[1]*) was NULL, break out of loop
- Otherwise, redisplay IDs and capabilities every 5 seconds

Example: namespaces/demo_userns.c

```
$ id -u       # Display effective UID of shell process
1000
$ id -g       # Display effective GID of shell process
1000
$ ./demo_userns
eUID = 65534; eGID = 65534; capabilities: =ep
```

Upon running the program, we'll see something like the above

- Program was run from unprivileged user account
- =ep means child process has a full set of permitted and effective capabilities
  - If *libcap* is not aware of all capability numbers supported by kernel, displayed capability sets may be more verbose

Example: namespaces/demo_userns.c

```
$ id -u       # Display effective UID of shell process
1000
$ id -g       # Display effective GID of shell process
1000
$ ./demo_userns
eUID = 65534; eGID = 65534; capabilities: =ep
```

Displayed UID and GID are "strange"

- System calls such as *geteuid()* and *getegid()* always return credentials as they appear inside user NS where caller resides
- But, no mapping has yet been defined to map IDs outside user NS to IDs inside NS
- ⇒ when a UID is unmapped, system calls return value in `/proc/sys/kernel/overflowuid`
  - Unmapped GIDs ⇒ `/proc/sys/kernel/overflowgid`
  - Default value, 65534, chosen to be same as NFS `nobody` ID

Outline

10 User Namespaces 10-1

10.1 Overview of user namespaces 10-3

10.2 Creating and joining a user namespace 10-9

10.3 User namespaces: UID and GID mappings 10-17

10.4 User namespaces, *execve()*, and user ID 0 10-31

10.5 Accessing files; file-related capabilities 10-48

10.6 Security issues 10-57

10.7 Use cases 10-64

10.8 Combining user namespaces with other namespaces 10-69

UID and GID mappings

- One of first steps after creating a user NS is to define UID and GID mapping for NS
- Mappings for a user NS are defined by writing to 2 files: `/proc/PID/uid_map` and `/proc/PID/gid_map`
  - Each process in user NS has these files; writing to files of *any* process in the user NS suffices
  - Initially, these files are empty

UID and GID mappings

- Records written to/read from `uid_map` and `gid_map` have this form:

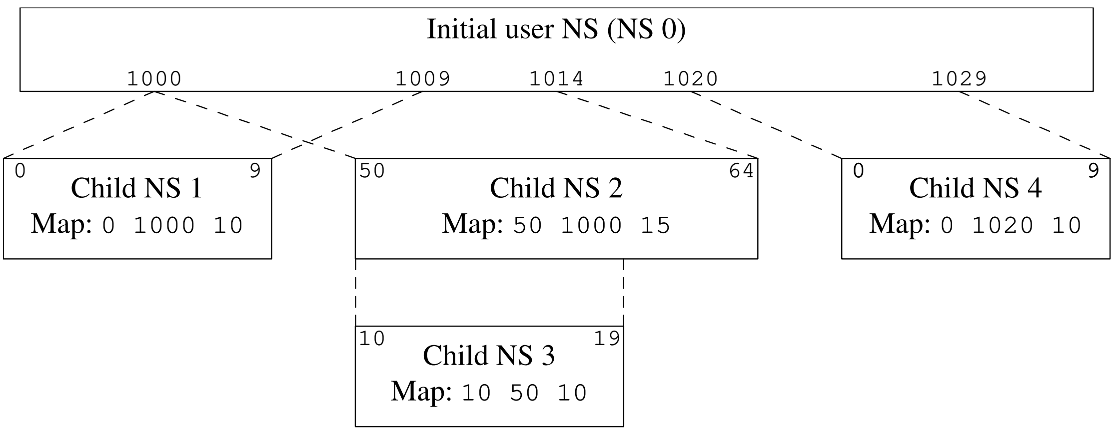
```
ID-inside-ns    ID-outside-ns    length
```

  - *ID-inside-ns* and *length* define range of IDs inside user NS that are to be mapped
  - *ID-outside-ns* defines start of corresponding mapped range in "outside" user NS
- E.g., following says that IDs 0...9 inside user NS map to IDs 1000...1009 in outside user NS

```
0     1000     10
```

- ⚠ To properly understand *ID-outside-ns*, we must first look at a picture

Understanding UID and GID maps

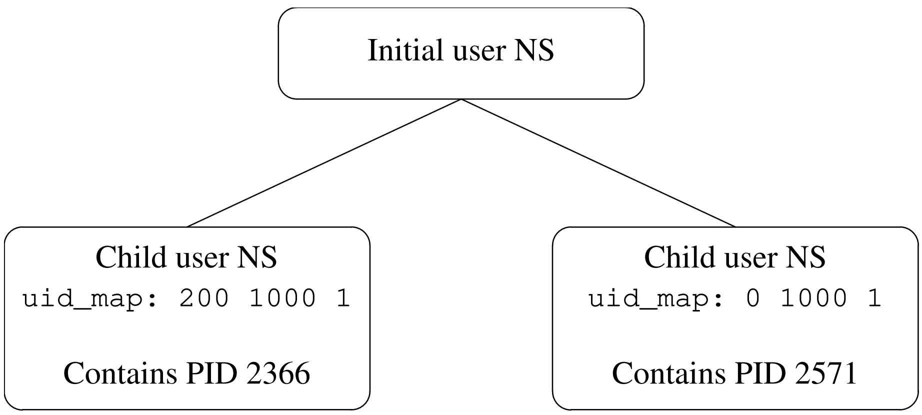


- "What does ID X in namespace Y map to in namespace Z?" means "what is the equivalent ID (if any) in namespace Z?"
- What does ID 5 in NS 1 map to in the initial NS (NS 0)?
- What does ID 5 in NS 1 map to in NS 2 and NS 3?
- What does ID 15 in NS 3 map to in NS 2 and NS 1?
- What does the UID 0 in NS 4 map to in NS 1?

Interpretation of *ID-outside-ns*

- ⚠ Interpretation of *ID-outside-ns* depends on whether process opening `uid_map`/`gid_map` is in same NS as *PID*
    - NB: contents of `uid_map`/`gid_map` are generated on the fly by the kernel, and can be different in different processes
- If "opener" and *PID* are in **same user NS**:
    - *ID-outside-ns* interpreted as **ID in parent user NS** of *PID*
    - Common case: process is writing its own mapping file
- If "opener" and *PID* are in **different user NSs**:
    - *ID-outside-ns* interpreted as **ID in opener's user NS**
    - Equivalent to previous case, if "opener" is (parent) process that created user NS using *clone()*

Quiz: reading `/proc/PID/uid_map`



- If PID 2366 reads `/proc/2571/uid_map`, what should it see?
    - `0 200 1`
- If PID 2571 reads `/proc/2366/uid_map`, what should it see?
    - `200 0 1`

Example: updating a mapping file

- Let's run demo_userns with an argument, so it loops:

```
$ id -u      # Display user ID of shell
1000
$ id -G      # Display group IDs of shell
1000 10
$ ./demo_userns x
PID of child: 2810
eUID = 65534; eGID = 65534; capabilities: =ep
```

- Then we switch to another terminal window (i.e., a shell process in parent user NS), and write a UID mapping:

```
echo '0 1000 1' > /proc/2810/uid_map
```

- Returning to window where we ran demo_userns, we see:

```
eUID = 0; eGID = 65534; capabilities: =ep
```


Example: updating a mapping file

- But, if we go back to second terminal window, to create a GID mapping, we encounter a problem:

```
$ echo '0 1000 1' > /proc/2810/gid_map
bash: echo: write error: Operation not permitted
```

- There are **(many) rules** governing updates to mapping files
  - Inside the new user NS, user is getting full capabilities
  - **It is critical that capabilities can't leak**
    - I.e., user must not get more privileges than they would otherwise have **outside the NS**

Validity requirements for updating mapping files

If any of these rules are violated, *write()* fails with `EINVAL`:

- There is a limit on the number of lines that may be written
  - Linux 4.14 and earlier: between 1 and 5 lines
    - An arbitrarily chosen limit that was expected to suffice
    - 5 * 12-byte records: small enough to fit in a 64B cache line
  - Since Linux 4.15 (2017): between 1 and 340 lines
    - The limit of 5 had become an issue for some use cases
    - 340 * 12-byte records: can fit in 4KiB
- Each line contains 3 valid numbers, with *length* $>$ 0, and a newline terminator
- The ID ranges specified by the lines may not overlap

Permission rules for updating mapping files

If any of these "permission" rules are violated when updating `uid_map` and `gid_map` files, *write()* fails with `EPERM`:

- Each map may be **updated only once**
- Writer must be in target user NS or in parent user NS
- The mapped IDs must have a mapping in parent user NS
- Writer must have following **capability in target user NS**
  - `CAP_SETUID` for `uid_map`
  - `CAP_SETGID` for `gid_map`

Permission rules for updating mapping files

As well as preceding rules, one of the following also applies:

- **Either**: writer has CAP_SETUID (for uid_map) or CAP_SETGID (for gid_map) capability in **parent** user NS:
  - ⇒ no further restrictions apply (more than one line may be written, and arbitrary UIDs/GIDs may be mapped)
- **Or**: otherwise, all of the following restrictions apply:
  - Only a single line may be written to uid_map (gid_map)
  - That line maps only the writer's eUID (eGID)
    - Usual case: we are writing a mapping for eUID/eGID of process that created the NS
  - eUID of writer must match eUID of creator of NS
    - (e**U**ID restriction also applies for gid_map)
  - For gid_map only: corresponding /proc/PID/setgroups file must have been previously updated with string "deny"
    - We revisit reasons later

Example: updating a mapping file

- Going back to our earlier example:

```
$ echo '0 1000 1' > /proc/2810/gid_map
bash: echo: write error: Operation not permitted
$ echo 'deny' > /proc/2810/setgroups
$ echo '0 1000 1' > /proc/2810/gid_map
$ cat /proc/2810/gid_map
         0       1000          1
```

  - After writing "deny" to /proc/PID/setgroups file, we can update gid_map
- Upon returning to window running demo_userns, we see:

```
eUID = 0; eGID = 0; capabilities: =ep
```

Exercises

1. Try replicating the steps shown earlier on your system:
   - Use the *id(1)* command to discover your UID and GID; you will need this information for a later step.
   - Run the `namespaces/demo_userns.c` program with an argument (any string), so it loops. Verify that the child process has all capabilities.
   - Inspect (*readlink(1)*) the `/proc/PID/ns/user` file for the process running `demo_userns` and compare it with the `/proc/PID/ns/user` for a shell running in the initial user namespace. You should find that the two processes are in different user namespaces.
   - From a shell in the initial user NS, define UID and GID maps for the process running `demo_userns` (i.e., for the UID and GID that you discovered in the first step). Map the *ID-outside-ns* value for both IDs to IDs of your choice in the inner NS.
     - This step will involve writing to the `uid_map`, `setgroups`, and `gid_map` files in the `/proc/PID` directory.
   - Verify that the UID and GID displayed by the looping `demo_userns` program have changed.

   [Further exercises follow on the next slide]

Exercises

2. What are the contents of the UID and GID maps of a process in the initial user namespace?

```
$ cat /proc/1/uid_map
```

3. The script `namespaces/show_non_init_uid_maps.sh` shows the processes on the system that have a UID map that is different from the *init* process (PID 1). Included in the output of this script are the capabilities of each processes. Run this script to see examples of such processes. As well as noting the UID maps that these processes have, observe the capabilities of these processes.