System Programming for Linux Containers

User Namespaces and Capabilities

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Outline

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Outline

What are the rules that determine the capabilities that a process has in a given user namespace?

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User namespace hierarchies

- User NSs exist in a hierarchy
  - Each user NS has a parent, going back to initial user NS
- Parental relationship is established when user NS is created:
  - *clone()*: parent of new user NS is NS of caller of *clone()*
  - *unshare()*: parent of new user NS is caller's previous NS
- Parental relationship is significant because it plays a part in determining capabilities a process has in user NS

User namespaces and capabilities

- Whether a process has an effective capability inside a "target" user NS depends on several factors:
  - Whether the capability is present in process's effective set
  - Which user NS the process is a member of
  - The process's effective UID
  - The effective UID of process that created target user NS
  - The parental relationship between process's user NS and target user NS
- See also `namespaces/ns_capable.c`
  - (A program that encapsulates the rules described next)

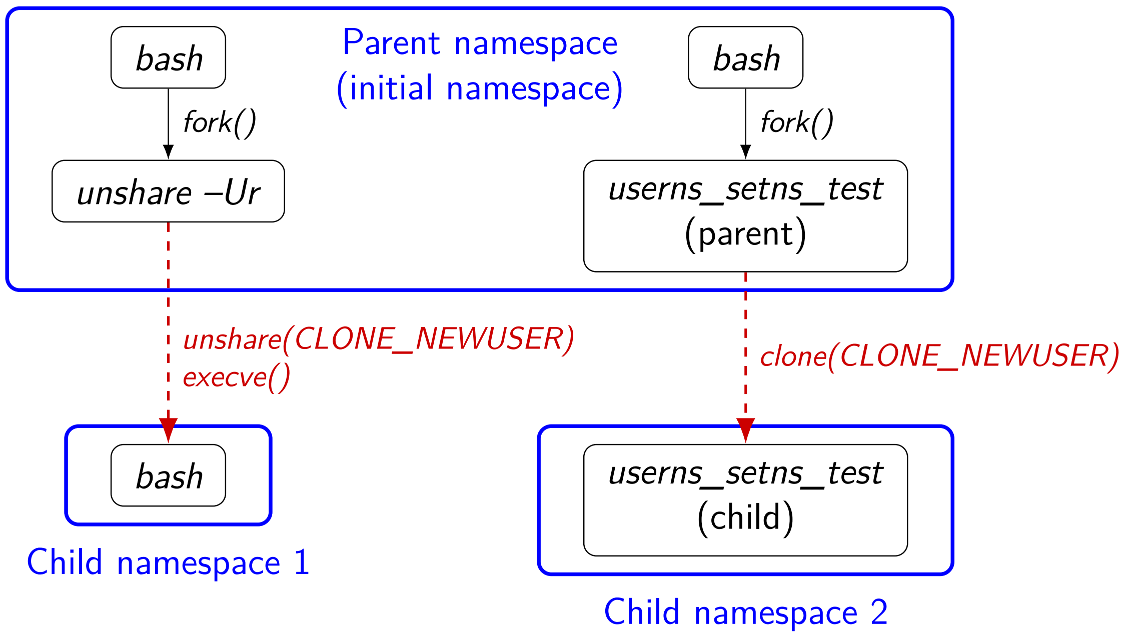
Capability rules for user namespaces

1. A process has a capability in a user NS if:
   - it is a **member of the user NS**, and
   - **capability is present in its effective set**
   - Note: this rule doesn't grant that capability in parent NS
2. A process that has a capability in a user NS **has the capability in all descendant user NSs** as well
   - I.e., members of user NS are not isolated from effects of privileged process in parent/ancestor user NS
3. A **process in a parent user NS that has same eUID as eUID of creator of child user NS** has all capabilities in that child NS
   - At creation time, **kernel records eUID of creator** as "owner" of user NS
   - By virtue of previous rule, process also has capabilities in all descendant user NSs

Outline

Demonstration of capability rules

Set up following scenario; then both `userns_setns_test` processes will try to join *Child namespace 1* using *setns()*



namespaces/userns_setns_test.c

```
./userns_setns_test /proc/PID/ns/user
```

- Creates a child process in a new user NS
- Parent and child then both call *setns()* to attempt to join user NS identified by argument
  - *setns()* requires `CAP_SYS_ADMIN` capability in target NS

namespaces/userns_setns_test.c

```
int main(int argc, char *argv[]) {
    ...
    long fd = open(argv[1], O_RDONLY);

    pid_t child_pid = clone(childFunc, stack + STACK_SIZE,
                            CLONE_NEWUSER | SIGCHLD, (void *) fd);
    test_setns("parent: ", fd);
    printf("\n");

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

- Open /proc/PID/ns/user file specified on command line
- Create child in new user NS
  - *childFunc()* receives file descriptor as argument
- Try to join user NS referred to by *fd* (*test_setns()*)
- Wait for child to terminate

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namespaces/userns_setns_test.c

```
static int childFunc(void *arg) {
    long fd = (long) arg;

    usleep(100000);
    test_setns("child: ", fd);
    return 0;
}
```

- Child sleeps briefly, to allow parent's output to appear first
- Child attempts to join user NS referred to by *fd*

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namespaces/userns_setns_test.c

```
static void display_symlink(char *pname, char *link) {
    char target[PATH_MAX];
    ssize_t s = readlink(link, target, PATH_MAX);
    printf("%s%s ==> %.*s\n", pname, link, (int) s, target);
}

static void test_setns(char *pname, int fd) {
    display_symlink(pname, "/proc/self/ns/user");
    display_creds_and_caps(pname);
    if (setns(fd, CLONE_NEWUSER) == -1) {
        printf("%s setns() failed: %s\n", pname, strerror(errno));
    } else {
        printf("%s setns() succeeded\n", pname);
        display_symlink(pname, "/proc/self/ns/user");
        display_creds_and_caps(pname);
    }
}
```

- Display caller's user NS symlink, credentials, and capabilities
- Try to *setns()* into user NS referred to by *fd*
- On success, again display user NS symlink, credentials, and capabilities

namespaces/userns_functions.c

```
static void display_creds_and_caps(char *msg) {
    printf("%seUID = %ld;  eGID = %ld;  ", msg,
            (long) geteuid(), (long) getegid());

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

    cap_free(caps);
    cap_free(s);
}
```

- Display caller's credentials and capabilities
  - (Different source file)

namespaces/userns_setns_test.c

In a terminal in initial user NS, we run the following commands:

```
$ id -u
1000
$ readlink /proc/$$/ns/user
user:[4026531837]
$ PS1='sh2# ' unshare -Ur bash
sh2# echo $$
30623
sh2# id -u
0
sh2# readlink /proc/$$/ns/user
user:[4026532638]
```

- Show UID and user NS for initial shell
- Start a new shell in a new user NS
  - Show PID of new shell
  - Show UID and user NS of new shell

namespaces/userns_setns_test.c

```
$ ./userns_setns_test /proc/30623/ns/user
parent: readlink("/proc/self/ns/user") ==> user:[4026531837]
parent: eUID = 1000; eGID = 1000;  capabilities: =
parent: setns() succeeded
parent: eUID = 0;  eGID = 0;  capabilities: =ep

child:  readlink("/proc/self/ns/user") ==> user:[4026532639]
child:  eUID = 65534; eGID = 65534;  capabilities: =ep
child:  setns() failed: Operation not permitted
```

In a second terminal window, we run our *setns()* test program:

- Results of *readlink()* calls show:
  - Parent `userns_setns_test` process is in initial user NS
  - Child `userns_setns_test` is in another user NS
- *setns()* in parent succeeded, and parent gained full capabilities as it moved into the user NS
- *setns()* in child fails; child has no capabilities in target NS

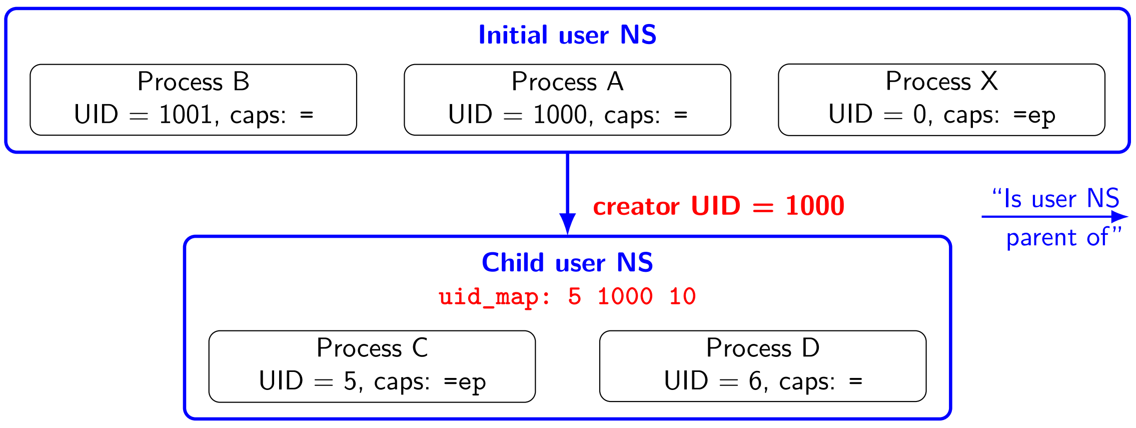
namespaces/userns_setns_test.c

```
$ ./userns_setns_test /proc/30623/ns/user
parent: readlink("/proc/self/ns/user") ==>
        user:[4026531837]
parent: setns() succeeded
parent: eUID = 0;  eGID = 0;  capabilities: =ep

child:  readlink("/proc/self/ns/user") ==>
        user:[4026532639]
child:  setns() failed: Operation not permitted
```

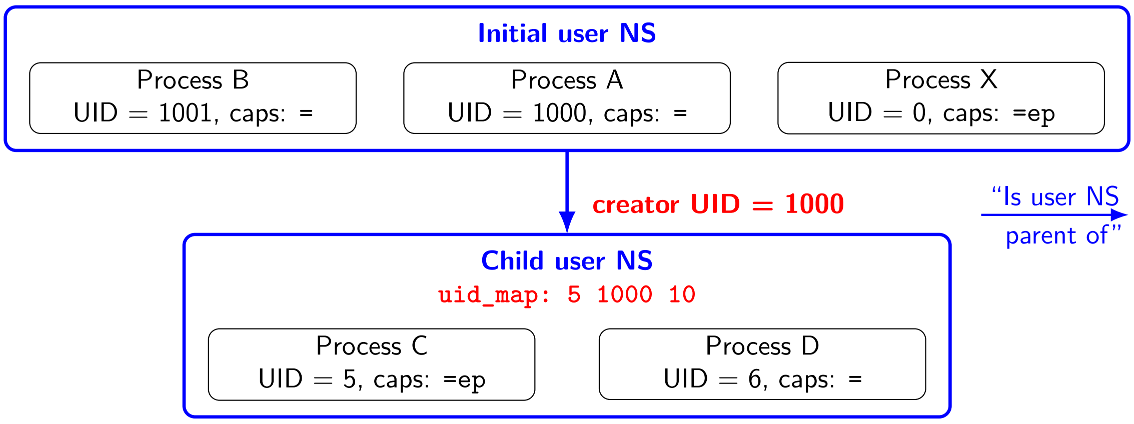
- *setns()* in child failed:
  - Rule 3: "processes in **parent** user NS that have **same eUID** as creator of user NS have all capabilities in the NS"
  - Parent `userns_setns_test` process was in **parent user NS** of target user NS and so had `CAP_SYS_ADMIN`
  - Child `userns_setns_test` process was in **sibling user NS** and so had no capabilities in target user NS

Quiz (who can signal a process in a child user NS?)



- Child user NS was created by a process with UID 1000
  - That process (which presumably was not A) had capabilities that allowed it to create a user NS with UID map with *length* > 1
- Process X has all capabilities in initial user NS
- Assume process A and process B have no capabilities in initial user NS
- Assume C was first process in child NS and has all capabilities in NS
- Process D has no capabilities

Quiz (who can signal a process in a child user NS?)



- Sending a signal requires UID match or `CAP_KILL` capability
- To which of B, C, D can process A send a signal?
- Can B send a signal to D? Can D send a signal to B?
- Can process X send a signal to processes C and D?
- Can process C send a signal to A? To B?
- Can C send a signal to D?

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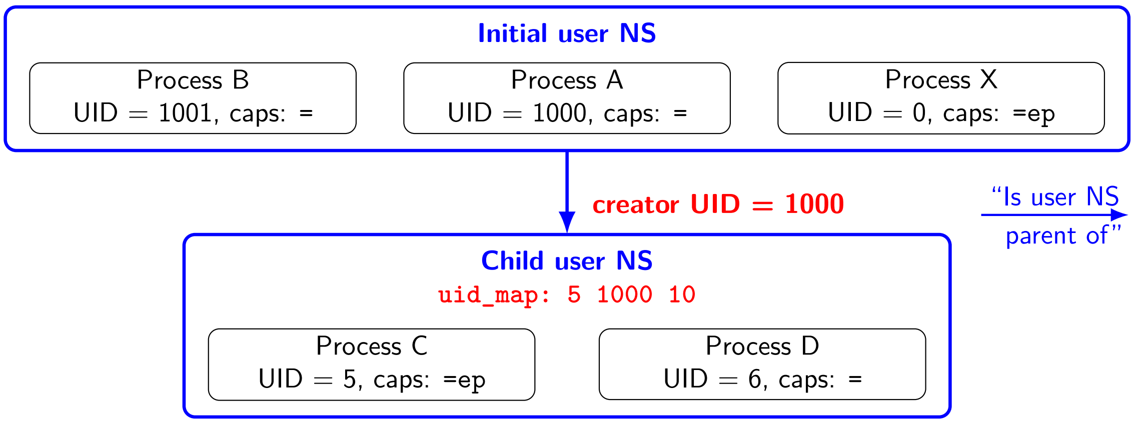
Quiz (who can signal a process in a child user NS?)



- A can't signal B, but can signal C (matching credentials) and D (because A has capabilities in D's NS)
- B can signal D (matching credentials); likewise, D can signal B
- X can signal C and D (because it has capabilities in parent user NS)
- C can signal A (credential match), but not B
- C can signal D, because it has capabilities in its NS

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Outline

Exercises

1. Perform the following steps:
   a. [Ubuntu only] If you are using Ubuntu 24.04 or later, you may need to disable an AppArmor setting that disables the creation of user namespaces by unprivileged users. First, check whether the setting is already turned off (0), using the following command:

   ```
   $ sudo sysctl kernel.apparmor_restrict_unprivileged_userns
   ```

   If the setting is not off (0), you can turn it off using the following command:

   ```
   $ sudo sysctl -w kernel.apparmor_restrict_unprivileged_userns=0
   ```

   b. As an unprivileged user, start two *sleep* processes, one as the unprivileged user and the other as UID 0:

   ```
   $ id -u
   1000
   $ sleep 1000 &
   $ sudo sleep 2000
   ```

   c. **As superuser**, in another terminal window use *unshare* to create a user namespace with root mappings and run a shell in that namespace:

   ```
   $ SUDO_PS1="ns2# " sudo unshare -U -r bash --norc
   ```

Exercises

- (Root mappings == process's UID and GID in parent NS map to 0 in child NS)
- Setting the `SUDO_PS1` environment variable causes *sudo(8)* to set the `PS1` environment variable for the command that it executes. (`PS1` defines the prompt displayed by the shell.) The *bash --norc* option prevents the execution of shell start-up scripts that might change `PS1`.

d. Verify that the shell has a full set of capabilities and a UID map "`0 0 1`" (i.e., UID 0 in the parent namespace maps to UID 0 in the child user namespace):

```
ns2# grep -E 'Cap(Prm|Eff)' /proc/$$/status    # Or: getpcaps $$
ns2# cat /proc/$$/uid_map
```

e. From this shell, try to kill each of the *sleep* processes started above:

```
ns2# ps -o 'pid uid cmd' -C sleep   # Discover 'sleep' PIDs
...
ns2# kill -9 <PID-1>
ns2# kill -9 <PID-2>
```

Which of the *kill* commands succeeds? Why?

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Exercises

2. ⏲ ⏲ ⏲ Write a program to set up two processes in a child user namespace as in the scenario shown in slide 22-20. [template: `namespaces/ex.userns_cap_sig_expt.c`]
   - After compiling the program, assign capabilities to the executable as follows:

```
sudo setcap cap_setuid,cap_setgid=pe <program-file>
```

   - While running the program, try sending signals to processes "C" and "D" from a shell in the initial user namespace, in order to verify the answers given on slide 22-20.

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Outline

User namespaces and capabilities

- Kernel grants initial process in new user NS a full set of capabilities
- But, those capabilities are available **only for operations on objects governed by the new user NS**

User namespaces and capabilities

- **Kernel associates each non-user NS instance with a specific user NS instance**
  - Each non-user NS is "owned" by a user NS
  - When creating a new non-user NS, user NS of the creating process becomes the owner of the new NS
- Suppose a process operates on global resources governed by a (non-user) NS:
  - Privilege checks are done according to process's capabilities in user NS that owns the NS
- ⇒ User NSs can deliver full capabilities inside a user NS without allowing capabilities in outer user NS(s)
  - (Barring kernel bugs)

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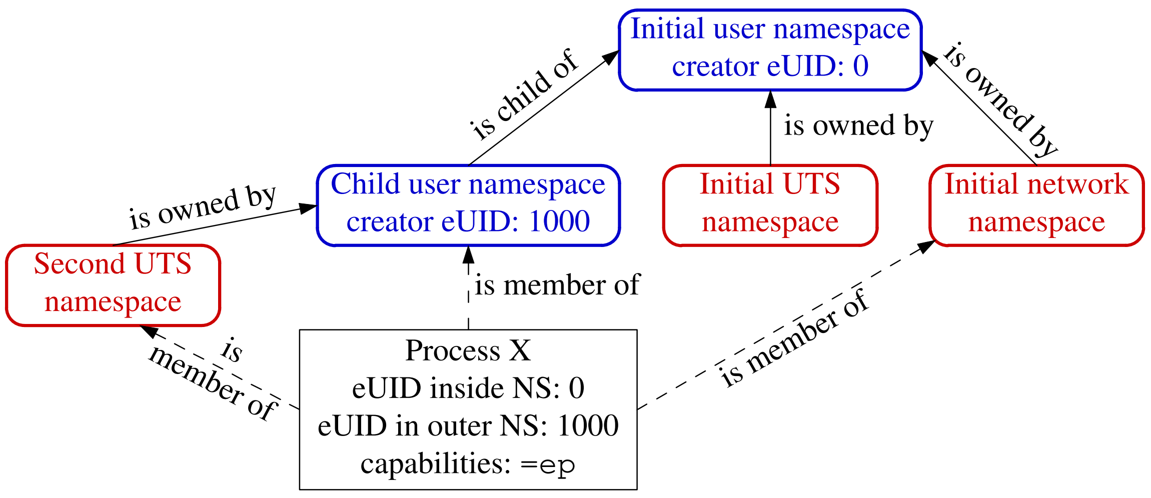
User namespaces and capabilities–an example



- Example scenario; X was created with: `unshare -Ur -u <prog>`
  - X is in a new user NS, created with root mappings
  - X is in a new UTS NS, which is owned by new user NS
  - X is in initial instance of all other NS types (e.g., network NS)

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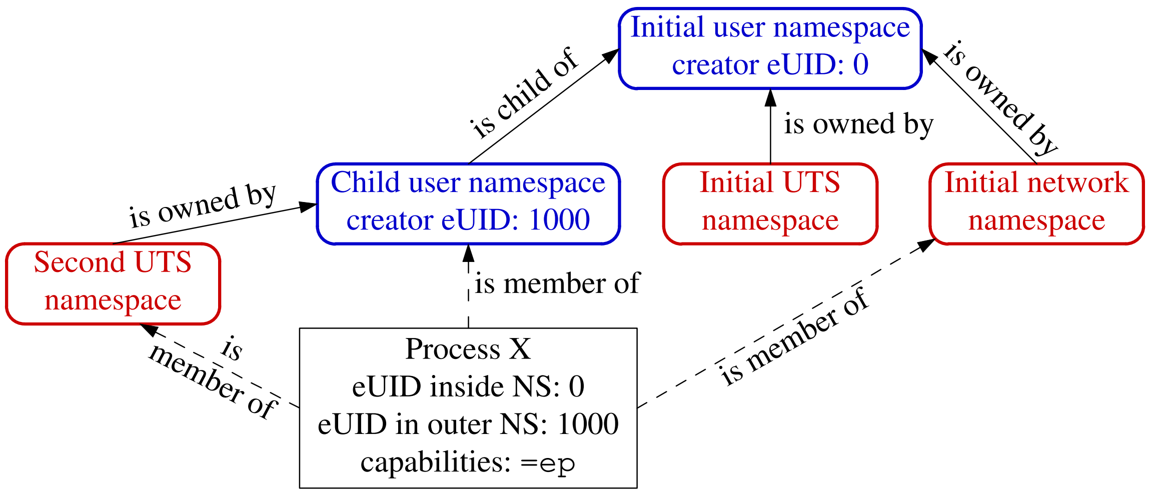
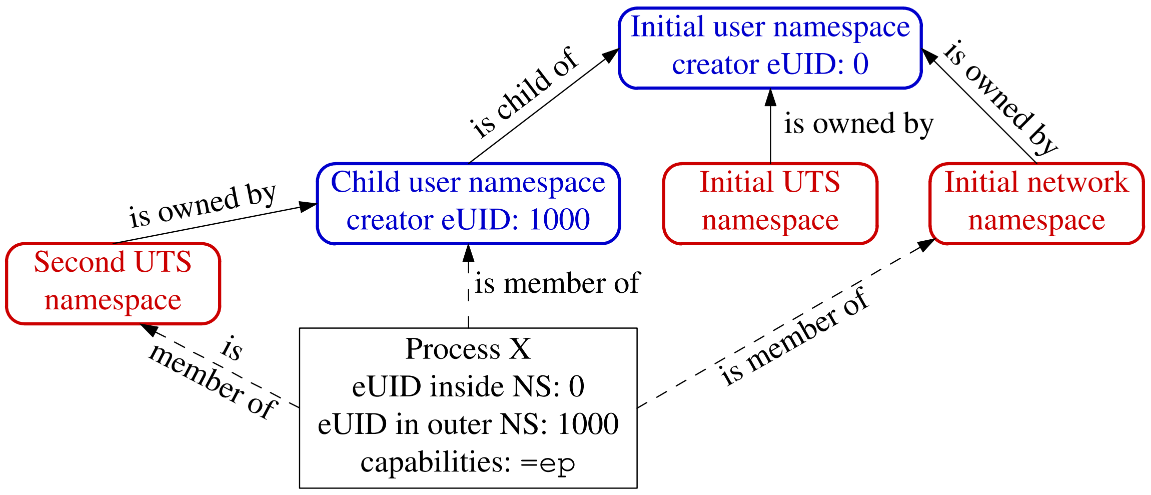
User namespaces and capabilities–an example



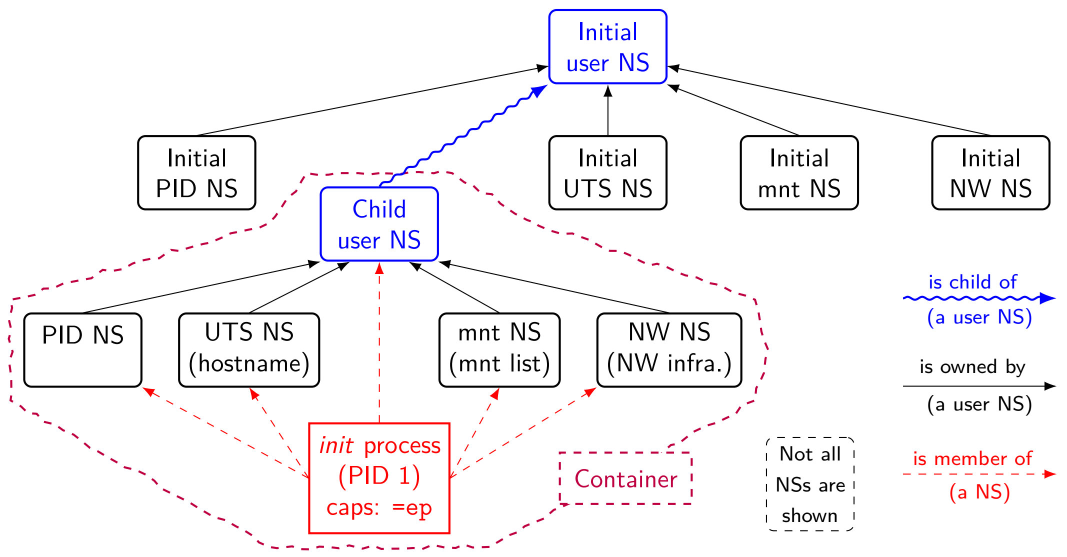
- Suppose X tries to change host name (`CAP_SYS_ADMIN`)
  - E.g., `hostname bienne`
- X is in second **UTS** NS
- Privileges checked according to X's capabilities in user NS that owns that UTS NS ⇒ succeeds (X has capabilities in user NS)

User namespaces and capabilities–an example



- Suppose X tries to bring network device up/down (`CAP_NET_ADMIN`)
  - E.g., `ip link set dev lo down`
- X is in initial **network** NS
- Privileges checked according to X's capabilities in user NS that owns network NS ⇒ attempt fails (no capabilities in initial user NS)

Containers and namespaces



- "Superuser" process in a container has **root power over resources governed by non-user NSs owned by container's user NS**
- And does **not** have privilege in outside user NS
  - (E.g., can't change mounts seen by processes outside container)

Demo: effect of capabilities in a user NS

- Create a shell in new user and UTS NSs:

```
$ unshare -Ur -u bash
# getpcaps $$
929: =ep                # Shell has all capabilities in its user NS
```

- Since this shell has all capabilities in user NS that owns its UTS NS, we can change hostname:

```
# hostname
bienne
# hostname langwied
# hostname
langwied
```

- But, this shell is in a network NS owned by **initial** user NS, and so can't turn a NW device down:

```
# ip link set dev lo down
RTNETLINK answers: Operation not permitted
```

What about resources not governed by namespaces?

- Some privileged operations relate to resources/features not (yet) governed by any namespace
  - E.g., load kernel modules, raise process nice values
- Having all capabilities in a (noninitial) user NS doesn't grant power to perform operations on features not currently governed by any NS
  - E.g., load/unload kernel modules, raise process nice values
  - IOW: to perform these operations, process must have the relevant capability in the **initial** user NS

Outline

Discovering namespace relationships

- To know whether a process has a capability in a NS, we need to know how NSs are related to each other
  - Which user NS owns a nonuser NS?
  - What is hierarchical relationship of user NSs?
  - Which NS is each process a member of?
- We can discover this info using *ioctl()* operations and `/proc/PID/ns/*` symlinks
- Info can be used to build visualization tools for NSs
  - An example: `namespaces/namespaces_of.go`
  - A better example: `https://github.com/TheDiveO/lxkns`

ioctl() operations for namespaces

```
#include <sys/ioctl.h>
int ioctl(int fd, unsigned long request, ...);
```

- There are *many* *ioctl()* operations...
- Certain *ioctl()* operations can be applied to a file descriptor (FD) that refers to a NS
  - E.g., FD obtained by opening `/proc/PID/ns/*` file
  - Details in *ioctl_ns(2)*
- Some of those operations return a (new) FD that refers to another NS
  - To determine which NS, we use *stat()*/*fstat()*

stat() and *fstat()*

```
#include <sys/stat.h>
int stat(const char *pathname, struct stat *statbuf);
int fstat(int fd, struct stat *statbuf);
```

- The “stat” system calls return metadata from a file inode
- Metadata is returned via *struct stat*, which includes fields:
  - *st_dev*: device ID
  - *st_ino*: inode number
  - Device ID + inode # form **unique identifier for NS**

Comparing namespace identifiers

- To discover NS that a file descriptor refers to, we compare with `/proc/PID/ns/*` symlinks:

```
int fd = ioctl(...);

struct stat sb1, sb2;
fstat(fd, &sb1);
stat(path, &sb2);   // 'path' is a /proc/PID/ns/* symlink

if (sb1.st_dev == sb2.st_dev && sb1.st_ino == sb2.st_ino) {
    // 'fd' and 'path' refer to same NS
}
```

ioctl() operations for namespaces

- NS_GET_USERNS: return FD referring to **owning user NS** for NS referred to by *fd*
  - Returned FD can be compared (*fstat()*, *stat()*) with /proc/PID/ns/user files to discover owning user NS
- NS_GET_PARENT: return FD referring to the **parent namespace** of NS referred to by *fd*
  - Valid only for hierarchical namespaces (PID, user)
  - Returned FD can be compared (*fstat()*, *stat()*) with /proc/PID/ns/{pid,user} files to discover parent NS
  - Synonymous with NS_GET_USERNS for user namespaces

ioctl() operations for namespaces

- NS_GET_OWNER_UID: return **UID of creator of user NS** referred to by *fd*
- NS_GET_NSTYPE: return the **type of NS** referred to by *fd*
  - Returns one of CLONE_NEW* constants
- Example code:
  - namespaces/ns_capable.c
  - namespaces/namespaces_of.go
  - namespaces/pid_namespaces.go
  - *ioctl_ns(2)*
  - http://blog.man7.org/2016/12/introspecting-namespace-relationships.html

namespaces/namespaces_of.go example

- namespaces/namespaces_of.go shows NS memberships of specified processes, in context of user NS hierarchy
- To demo, we set up scenario shown in earlier diagram:

```
$ echo $$              # PID of a shell in initial user NS
327
$ unshare -Ur -u sh    # Create new user and UTS NSs
# echo $$              # PID of shell in new NSs
353
```

  - Run a shell in new user and UTS NSs
    - That shell will be a member of initial instance of other NSs

Discovering namespace relationships

- Inspect with namespaces/namespaces_of.go program:

```
$ go run namespaces_of.go --namespaces=net,uts 327 353
user {4 4026531837} <UID: 0>
        [ 327 ]
    net {4 4026532008}
            [ 327 353 ]
    uts {4 4026531838}
            [ 327 ]
    user {4 4026532760} <UID: 1000>
            [ 353 ]
        uts {4 4026532761}
                [ 353 ]
```

  - Indentation indicates user NS ownership / parental relationship between user NSs
  - Shells are in same network NS, but different UTS NSs
  - Second UTS NS is owned by second user NS
  - NS IDs ({...}) include device ID (4) from (hidden) NS filesystem

lsns(8)

- Recent versions of *lsns(8)* can also be used to show NS relationships (*util-linux* v2.38, 2021)

```
$ lsns -o 'ns,type,pid' -t user -t net -t uts --tree=owner -p 353
NS              TYPE    PID
4026531837      user    327
├─4026532008    net     327
└─4026532760    user    353
  └─4026532761 uts      353
```

- But, more limited than `namespaces_of.go` and *lxkns*
  - Can show info only about all NSs, or NSs of a single process
  - "`PID`" is lowest PID number in NS (which might not be first process in a new NS)
  - Can't list *all* PIDs that are members of NS
- Can list NSs that have no member processes but are pinned by bind mounts using: `lsns --persistent`

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