Understanding user namespaces

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Outline

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Who am I?

- Maintainer of Linux *man-pages* project since 2004
  - \( \approx 1050 \) pages, mainly for system calls & C library functions
    - (I wrote a lot of those pages...)

- Author of a book on the Linux programming interface
  - http://man7.org/tlpi/

- **Trainer**/writer/engineer
  - http://man7.org/training/

- Email: mtk@man7.org
  - Twitter: @mkerrisk
Time is short

- Normally, I would spend several hours on this topic
- Many details left out, but I hope to give an idea of big picture
- We’ll go fast
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Traditional UNIX privilege model divides users into two groups:

- **Normal users**, subject to privilege checking based on UIDs and GIDs
- **Superuser** (UID 0) bypasses many of those checks

Traditional mechanism for giving privilege to unprivileged users is **set-UID-root program**

```
# chown root prog
# chmod u+s prog
```

- When executed, **process assumes UID of file owner**
  - ⇒ process gains privileges of superuser
- Powerful, but dangerous
The traditional privilege model is a problem

- Coarse granularity of traditional privilege model is a problem:
  - E.g., say we want to give a program the power to change system time
    - Must also give it power to do everything else root can do
  - \( \Rightarrow \textbf{No limit on possible damage} \) if program is compromised

- **Capabilities** are an attempt to solve this problem
Background: capabilities

- Capabilities: divide power of superuser into small pieces
  - 38 capabilities as at Linux 5.4 (see `capabilities(7)`)
- Examples:
  - `CAP_DAC_OVERRIDE`: bypass all file permission checks
  - `CAP_SYS_ADMIN`: do (too) many different sysadmin operations
  - `CAP_SYS_TIME`: change system time
- Instead of set-UID-`root` programs, have programs with one/a few attached capabilities
  - Attached using `setcap(8)` (needs `CAP_SETFCAP` capability!)
  - When program is executed ⇒ process gets those capabilities
  - Program is `weaker` than set-UID-`root` program
    - ⇒ less dangerous if compromised
Background: capabilities

Summary:
- Processes can have capabilities (subset of power of root)
- Files can have attached capabilities, which are given to process that executes program
- Privileged binaries/processes using capabilities are less dangerous if compromised
Namespaces

- A namespace (NS) “wraps” some global system resource to provide resource isolation
- Linux supports multiple NS types
  - Seven currently, and counting...
Each NS isolates some kind of resource(s)

- **Mount** NS: isolate mount point list
  - (CLONE_NEWNS; 2.4.19, 2002)

- **UTS** NS: isolate system identifiers (e.g., hostname)
  - (CLONE_NEWUTS; 2.6.19, 2006)

- **IPC** NS: isolate System V IPC and POSIX MQ objects
  - (CLONE_NEWIPC; 2.6.19, 2006)

- **PID** NS: isolate PID number space
  - (CLONE_NEWPID; 2.6.24, 2008)

- **Network** NS: isolate NW resources (firewall & routing rules, socket port numbers, /proc/net, /sys/class/net, ...)
  - (CLONE_NEWNET; ≈2.6.29, 2009)
Each NS isolates some kind of resource(s)

- **User NS**: isolate user ID and group ID number spaces
  - (CLONE_NEWUSER; 3.8, 2013)

- **Cgroup NS**: virtualize (isolate) certain cgroup pathnames
  - (CLONE_NEWCGROUP; 4.6, 2016)
Namespaces

For each NS type:

- Multiple **instances** of NS may exist on a system
- At system boot, there is one instance of each NS type—the **initial namespace**
- A process resides in one NS instance (of each of NS types)
- To processes inside NS instance, it appears that only they can see/modify corresponding global resource
  - (They are unaware of other instances of resource)
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UTS namespaces (CLONE_NEWUTS)

- UTS NSs are simplest NS, and so provide an easy example
- Isolate two system identifiers returned by `uname(2)`
  - `nodename`: system hostname (set by `sethostname(2)`)
  - `domainname`: NIS domain name (set by `setdomainname(2)`)
- Container configuration scripts might tailor their actions based on these IDs
  - E.g., `nodename` could be used with DHCP, to obtain IP address for container
- “UTS” comes from `struct utsname` argument of `uname(2)`
  - Structure name derives from “UNIX Timesharing System”
Running system may have multiple UTS NS instances

Processes within single instance access (get/set) same *nodename* and *domainname*

Each NS instance has its own *nodename* and *domainname*

Changes to *nodename* and *domainname* in one NS instance are invisible to other instances
Each UTS NS contains a set of processes (the circles) which see/modify same hostname (and domain name, not shown)
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Some “magic” symlinks

- Each process has some symlink files in `/proc/PID/ns`

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<th>Description</th>
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<td><code>/proc/PID/ns/cgroup</code></td>
<td># Cgroup NS instance</td>
</tr>
<tr>
<td><code>/proc/PID/ns/ipc</code></td>
<td># IPC NS instance</td>
</tr>
<tr>
<td><code>/proc/PID/ns/mnt</code></td>
<td># Mount NS instance</td>
</tr>
<tr>
<td><code>/proc/PID/ns/net</code></td>
<td># Network NS instance</td>
</tr>
<tr>
<td><code>/proc/PID/ns/pid</code></td>
<td># PID NS instance</td>
</tr>
<tr>
<td><code>/proc/PID/ns/user</code></td>
<td># User NS instance</td>
</tr>
<tr>
<td><code>/proc/PID/ns/uts</code></td>
<td># UTS NS instance</td>
</tr>
</tbody>
</table>

- One symlink for each of the NS types
Some “magic” symlinks

- Target of symlink tells us which NS instance process is in:

  ```
  $ readlink /proc/$$/ns/uts
  uts:[4026531838]
  ```

- Content has form: `ns-type: [magic-inode-#]`

- Various uses for the `/proc/PID/ns` symlinks, including:
  - If processes show same symlink target, they are in same NS
APIs and commands

- Programs can use various system calls to work with NSs:
  - `clone(2)`: create new (child) process in new NS(s)
  - `unshare(2)`: create new NS(s) and move caller into it/them
  - `setns(2)`: move calling process to another (existing) NS instance

- There are analogous **shell commands**:
  - `unshare(1)`: create new NS(s) and execute a command in the NS(s)
  - `nsenter(1)`: enter existing NS(s) and execute a command
The `unshare(1)` and `nsenter(1)` commands

`unshare(1)` and `nsenter(1)` have flags for specifying each NS type:

```
unshare [options] [command [arguments]]
- C   Create new cgroup NS
- i   Create new IPC NS
- m   Create new mount NS
- n   Create new network NS
- p   Create new PID NS
- u   Create new UTS NS
- U   Create new user NS
```

```
nsenter [options] [command [arguments]]
- t PID PID of process whose NSs should be entered
- C   Enter cgroup NS of target process
- i   Enter IPC NS of target process
- m   Enter mount NS of target process
- n   Enter network NS of target process
- p   Enter PID NS of target process
- u   Enter UTS NS of target process
- U   Enter user NS of target process
- a   Enter all NSs of target process
```
Privilege requirements for creating namespaces

- Creating **user** NS instances requires no privileges
- Creating instances of **other** (nonuser) NS types requires privilege
  - **CAP_SYS_ADMIN**
Demo

- Two terminal windows (sh1, sh2) in initial UTS NS

```
sh1$ hostname # Show hostname in initial UTS NS
antero
```

- In sh2, create new UTS NS, and change hostname

```
sh2$ hostname # Show hostname in initial UTS NS
antero
$ PS1='sh2# ' sudo unshare -u bash
sh2# hostname bizarro # Change hostname
sh2# hostname # Verify change
bizarro
```

- Used `sudo` because we need privilege (CAP_SYS_ADMIN) to create a UTS NS
Demo

- In `sh1`, verify that hostname is unchanged:

  ```
  sh1$ hostname
  antero
  ```

- Compare `/proc/PID/ns/uts` symlinks in two shells

  ```
  sh1$ readlink /proc/$$/ns/uts
  uts: [402653 1838]
  
  sh2# readlink /proc/$$/ns/uts
  uts: [402653 2855]
  ```

- The two shells are in different UTS NSs
From *sh1*, use *nsenter*(1) to create a new shell that is in same NS as *sh2*:

```
sh2# echo $$    # Discover PID of sh2
5912
```

```
sh1$ PS1='sh3#' sudo nsenter -t 5912 -u
sh3# hostname
bizarro
sh3# readlink /proc/$$/ns/uts
uts:[4026532855]
```

- Comparing the symlink values, we can see that this shell (*sh3#*) is in the second (*sh2#*) UTS NS
What do user namespaces do?

- Allow per-namespce **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**
  - Understanding what that means is our goal...
User NSs have a **hierarchical relationship**:

- **Parent of a user NS** == user NS of process that created this user NS
  - Using `clone(2)`, `unshare(2)`, or `unshare(1)`

- Parental relationship determines some rules about how capabilities work
  - (End slides)
A user namespace hierarchy

Initial user NS
creator eUID: 0
uid_map: 0 0 4294967295
gid_map: 0 0 4294967295

User NS "X"
creator eUID: 1000
uid_map: 0 1000 1
gid_map: 0 1000 1

User NS "Y"
creator eUID: 1001
uid_map: 0 1001 1
gid_map: 0 1001 1

User NS "X2"
creator eUID: 1000
uid_map: 0 0 1
gid_map: 0 0 1

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Understanding user namespaces
The first process in a new user NS has root privileges

- When a new user NS is created (\textit{unshare(1), clone(2), unshare(2)}), first process in NS has all capabilities
- That process has power of superuser!
- ... but only inside the user NS
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One of first steps after creating a user NS is to define **UID and GID mappings** for NS

Defined by writing to 2 files: `/proc/PID/uid_map` and `/proc/PID/gid_map`

For security reasons, there are many rules + restrictions on:
- How/when files may be updated
- Who can update the files
- Way too many details to cover here...
  - See `user_namespaces(7)`
UID and GID mappings

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

<table>
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<th>ID-inside-ns</th>
<th>ID-outside-ns</th>
<th>length</th>
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- `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

- Commonly these files are initialized with a single line containing “root mapping”:

  | 0 | 1000 | 1 |

- One ID, 0, inside NS maps to ID 1000 in outer NS
Example: creating a user NS with “root” mappings

- `unshare -U -r` creates user NS with root mappings

Create a user NS with root mappings running new shell, and examine map files:

```bash
$ id  # Show credentials in current shell
uid=1000(mtk) gid=1000(mtk) ...

$ PS1='uns2$ ' unshare -U -r bash
uns2$ cat /proc/$$/uid_map
 0       1000     1
uns2$ cat /proc/$$/gid_map
 0       1000     1
```
Example: creating a user NS with “root” mappings

- Examine credentials and capabilities of new shell:

  ```bash
  uns2$ id
  uid=0(root) gid=0(root) groups=0(root) ...
  uns2$ egrep '[UG]id|CapEff' /proc/$$/status
  Uid: 0 0 0 0
  Gid: 0 0 0 0
  CapEff: 0000003fffffffff # Hex bit mask
  ```

- **0x3fffffffff** is bit mask with all 38 capability bits set
  - `getpcaps` from `libcap` project gives same info more readably
Example: creating a user NS with “root” mappings

- Discover PID of shell in new user NS:

  ```bash
  uns2$ echo $$
  21135
  ```

- From a shell in initial user NS, examine credentials of that PID:

  ```bash
  $ grep '[UG]id' /proc/21135/status
  Uid: 1000 1000 1000 1000 1000
  Gid: 1000 1000 1000 1000 1000
  ```
I’m superuser! (But, you’re a big fish in a little pond)

- From the shell in new user NS, let’s try to change the hostname
  - Requires `CAP_SYS_ADMIN`

```
uns2$ hostname bizarro
hostname: you must be root to change the host name
```

- Shell is UID 0 (superuser) and has `CAP_SYS_ADMIN`
- What went wrong?
- The new shell is in new user NS, but **still resides in initial UTS NS**
  - (Remember: hostname is isolated/governed by UTS NS)
  - Let’s look at this more closely...
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Kernel grants **all** capabilities to initial process in new user NS of capabilities.

But, those capabilities are available **only for operations on objects governed by the new user NS**.

But what does that 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 mount points
  - Network: IP routing tables, port numbers, /proc/net, ...

Adding to this: each nonuser NS instance is owned by some user NS instance

- When creating new nonuser NS, kernel marks that NS as owned by user NS of process creating the new NS
- If a process operates on resources governed by nonuser NS:
  - Permission checks are done according to that process’s capabilities in user NS that owns the nonuser NS
To illustrate, let’s look at set-up resulting from command:

```
unshare -Ur -u <prog>
```

(Create process running `prog` in new user NS with root mappings + new UTS NS)
Example scenario; **X was created with:** `unshare -Ur -u <prog>`

- X is in new user NS, with root mappings, and has all capabilities
- 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)
Suppose X tries to change hostname (CAP_SYS_ADMIN)

X is in second **UTS** NS

Permissions checked according to X’s capabilities in user NS that owns that UTS NS ⇒ succeeds (X has capabilities in that user NS)
Suppose X tries to bind to reserved socket port (CAP_NET_BIND_SERVICE).

X is in initial network NS.

Permissions checked according to X's capabilities in user NS that owns network NS ⇒ attempt fails (no capabilities in initial user NS).
Discovering namespace relationships

- There are APIs to discover parental relationships between user NSs and ownership relationships between user NSs and nonuser NSs
  - See `ioctl_ns(2)`, http://blog.man7.org/2016/12/introspecting-namespace-relationships.html
  - Code example: `namespaces/namespaces_of.go`
    - Shows namespace memberships of specified processes, in context of user NS hierarchy
Discovering namespace relationships

- Commands to replicate scenario shown in previous slides:

  ```
  $ 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
  ```

- Inspect with `namespaces/namespaces_of.go` program:

  ```
  $ go run namespaces_of.go --namespaces=net,uts 327 353
  user {3 4026531837}  <UID: 0>
    [ 327 ]
  net {3 4026532008}
    [ 327 353 ]
  uts {3 4026531838}
    [ 327 ]
  user {3 4026532760}  <UID: 1000>
    [ 353 ]
  uts {3 4026532761}
    [ 353 ]
  ```

- Shells are in same network NS, but different UTS+user NSs
- Second UTS NS is owned by second user NS
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User namespaces permit novel applications

- User NSs permit novel applications; for example:
  - Running Linux containers **without** *root* privileges
    - Docker, LXC
  - Chrome-style sandboxes without set-UID-*root* helpers
    - Set-UID-*root* helpers are (were) used to set up sandbox
      - https://chromium.googlesource.com/chromium/src/+/?/master/docs/design/sandbox.md
  - User namespace with single UID identity mapping \(\Rightarrow\) no superuser possible!
    - E.g., `uid_map: 1000 1000 1`
User namespaces permit novel applications; more examples:

- `chroot()`-based applications for process isolation
  - User NSs allow unprivileged process to create new mount NSs and use `chroot()`

- `fakeroot`-type applications without `LD_PRELOAD/dynamic linking tricks`
User namespaces permit novel applications; more examples:

- **Firejail**: namespaces + seccomp + capabilities for generalized, **simplified** sandboxing of any application
  - https://firejail.wordpress.com/, https://lwn.net/Articles/671534/

- **Flatpak**: namespaces + seccomp + capabilities + cgroups for application packaging / sandboxing
  - Allows upstream project to provide packaged app with all necessary runtime dependencies
    - No need to rely on packaging in downstream distributions
    - Package once; run on any distribution
  - Desktop applications run seamlessly in GUI
  - http://flatpak.org/, https://lwn.net/Articles/694291/
Namespaces: sources of further information

- My LWN.net article series *Namespaces in operation*
  - https://lwn.net/Articles/531114/
  - Many example programs and shell sessions...

- Man pages:
  - *namespaces*(7), *user_namespaces*(7), *mount_namespaces*(7), *pid_namespaces*(7), etc.
  - *unshare*(1), *nsenter*(1)
  - *capabilities*(7)
  - *clone*(2), *unshare*(2), *setns*(2), *ioctl_ns*(2)

- “Linux containers in 500 lines of code”
Thanks!

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Slides at http://man7.org/conf/
Source code at http://man7.org/tlpi/code/

THE LINUX PROGRAMMING INTERFACE
A Linux and UNIX System Programming Handbook
MICHAEL KERRISK
Combining user namespaces and other namespace types

- Earlier, we noted that `CAP_SYS_ADMIN` is needed to create nonuser NSs.
- So, why can unprivileged user do this:
  
  ```
  $ unshare -U -r bash
  ```

- Can do this, because kernel first creates user NS, giving child all privileges, so that UTS NS can also be created.
- Equivalent to following, but without intervening child process:
  
  ```
  $ unshare -U -r bash  # Child in new user NS
  $ unshare -u bash    # Grandchild in new UTS NS
  ```
Some privileged operations relate to resources/features not (yet) governed by any namespace
  E.g., system time, kernel modules

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., can’t change system time or load/unload kernel modules
But what about accessing files (and other resources)?

- Suppose UID 1000 is mapped to UID 0 inside a user NS.
- What happens when process with UID 0 inside user NS tries to access file owned by ("true") UID 0?
- When accessing files, IDs are mapped back to values in initial user NS.
  - There is a chain of user NSs starting at NS of process and going back to initial NS.
  - Examining the mappings in this chain allows kernel to know "true" UID and GID of processes in user NSs.
  - Same principle for checks on other resources that have UID+GID owner.
    - E.g., Various IPC objects.
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What are the rules that determine the capabilities that a process has in a given user namespace?
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:
  - Parent of a new user NS is user NS of process that created new user NS
- Parental relationship is significant because it plays a part in determining capabilities a process has in user NS
Whether a process has a capability inside a user NS depends on several factors:

- Whether the capability is present in the process’s (effective) capability set
- Which user NS the process is a member of
- The (effective) process’s UID
- The (effective) UID of the process that created the user NS
  - At creation time, *kernel records eUID of creator* as “owner UID” of user NS
- The parental relationship between user NSs
- (*namespaces/ns_capable.c* program encapsulates the rules shown on next slide—it answers the question, does process P have capabilities in namespace X?)
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. (All) processes in **parent** user NS that have **same eUID** as eUID of creator of user NS have all capabilities in the NS
   - At creation time, **kernel records eUID of creator** as “owner UID” of user NS
   - By virtue of previous rule, capabilities also propagate into all descendant user NSs
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User namespaces are hard (even for kernel developers)

- Developer(s) of user NSs put much effort into ensuring capabilities couldn’t leak from inner user NS to outside NS
  - Potential risk: some piece of kernel code might not be refactored to account for distinct user NSs
  - $\Rightarrow$ unprivileged user who gains all capabilities in child NS might be able to do some privileged operation in outer NS
- User NS implementation touched a lot of kernel code
  - Perhaps there were/are some unexpected corner case that wasn’t correctly handled?
  - A number of such cases have occurred (and been fixed)
  - Common cause: many kernel code paths that could formerly be exercised only by root can now be exercised by any user