Open Source Summit Europe 2026

Linux containers in (less than) 100 lines of shell

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Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
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8 Starting up the container 51
9 Namespaces inside the container 54
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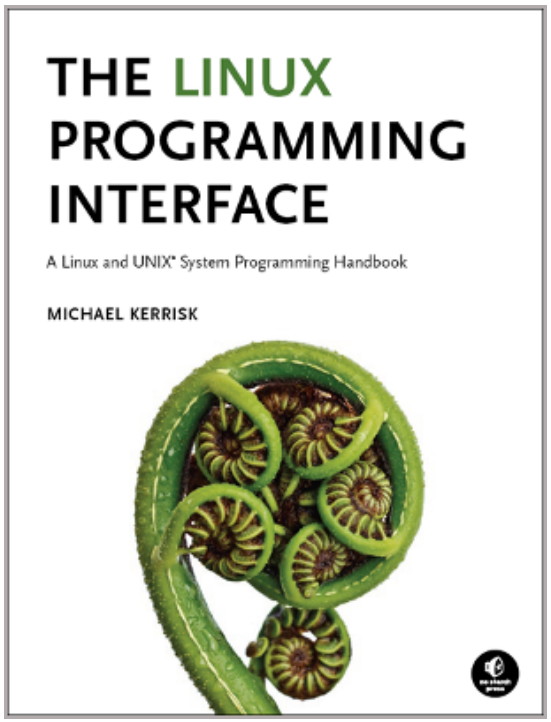
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

Who?

- Linux *man-pages* project
  - `https://www.kernel.org/doc/man-pages/`
    - Manual pages pages documenting syscalls and C library
  - Contributor since 2000
  - Maintainer 2004-2020
  - Comaintainer 2020-2021
- I wrote a book
- Trainer/writer/engineer
  `http://man7.org/training/`
- `mtk@man7.org`, `@mkerrisk`



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One day I wondered...

Can I create a (decent) container with shell commands?

Building a container with shell commands

- So, it is possible (opinions on "decent" might differ...)
  - (And can be automated in a few scripts)
- It's not a perfect container
  - Some untidy corners
  - Some set-up steps are omitted or need to be done manually
    - E.g., defining cgroup settings
  - And other limitations...
    - Only root UID/GID maps for user namespaces
    - No seccomp syscall filtering (no shell command for this)
- But, on the plus side:
  - Built using "simple" shell commands; and
  - Provides a fair approximation of the isolation of a POdman or Docker container

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Building a container with shell commands

- We'll use a few standard commands
  - *unshare(1)*, *mount(8)*, *pivot_root(8)*
    - Each of which is a layer on a system call of the same name
- And simplify things by using *busybox(1)*
  - Emulates core functionality of ≈400 shell commands
  - We can avoid copying many individual binaries into our container filesystem
  - Statically linked!
    - No need to copy shared library dependencies into filesystem

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Building a container with shell commands

- We'll automate the set-up using some scripts:
  - `create_lowerfs.sh`: **constructs** (lower layer of) **container filesystem** (FS)
    - Creates directories that should appear in a root FS, and places *busybox* in `/bin`
  - `consh_setup.sh`: **initial set-up of container**
    - Create a cgroup; launch container *init* process (a shell) in a set of new namespaces
  - `consh_post_setup.sh`: (automatically) launched in *init* shell to **complete the container setup**
    - Mount container root FS; switch to container root FS; mount a set of pseudo-filesystems; create devices; set host name
- Here goes...

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The container root filesystem

- A container needs a root filesystem (FS)
- That FS should be private to the container
  - So that FS changes don't have an effect outside container
- Each container will have **some files that are unique** to it
- But, **much of FS tree is same in all containers**
  - E.g., each container has a `/bin`, containing same binaries

How do we efficiently provide a container filesystem?

- **If each container image stored copies of all files:**
  - **Disk space would be wasted**
    - Because many files are same across all containers
  - **Container start-up would be slow**
    - Because of need to copy all of the files to create image at container start-up
- These problems can be solved with a **union mount**

Union mounts

- A union mount
  - Combines contents of multiple directories ("layers")
  - **Provides a merged view** of those layers
- Merged view is taken from:
  - One or more **read-only lower layers**
  - A **read-write upper layer** that contains the differences from combined lower layers
  - If a file with same name appears in multiple layers, merged view shows file from uppermost layer
- From a container perspective:
  - Lower layer(s) contain FS content shared by all containers
  - Upper layer contains FS content that is private to container

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OverlayFS

- In Docker and Podman, union mounts are provided using **OverlayFS**†
  - `https://docs.kernel.org/filesystems/overlayfs.html`
  - `https://wiki.archlinux.org/title/Overlay_filesystem`
  - `https://docs.docker.com/storage/storagedriver/overlayfs-driver/`

†There are other possibilities, including:

- Btrfs
- UnionFS, aufs (both older)

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OverlayFS

```
mount -t overlay overlay ./merged \
        -o lowerdir=./lower1:./lower2,upperdir=./upper,workdir=./work
```

- Creates OverlayFS mount at "merged" that combines two lower layers (lower1, lower2) and an upper layer (upper)
- workdir is a directory used internally by OverlayFS
  - Used internally to prepare files before they are atomically switched into upperdir†
  - Must be empty directory on same FS as upperdir

†E.g., consider how this must be implemented: `echo >> file-in-lower-layer`

- While doing operations in OverlayFS, try watching *workdir* (from outside container): `sudo inotifywait -m -r -format '%:e %f' work`

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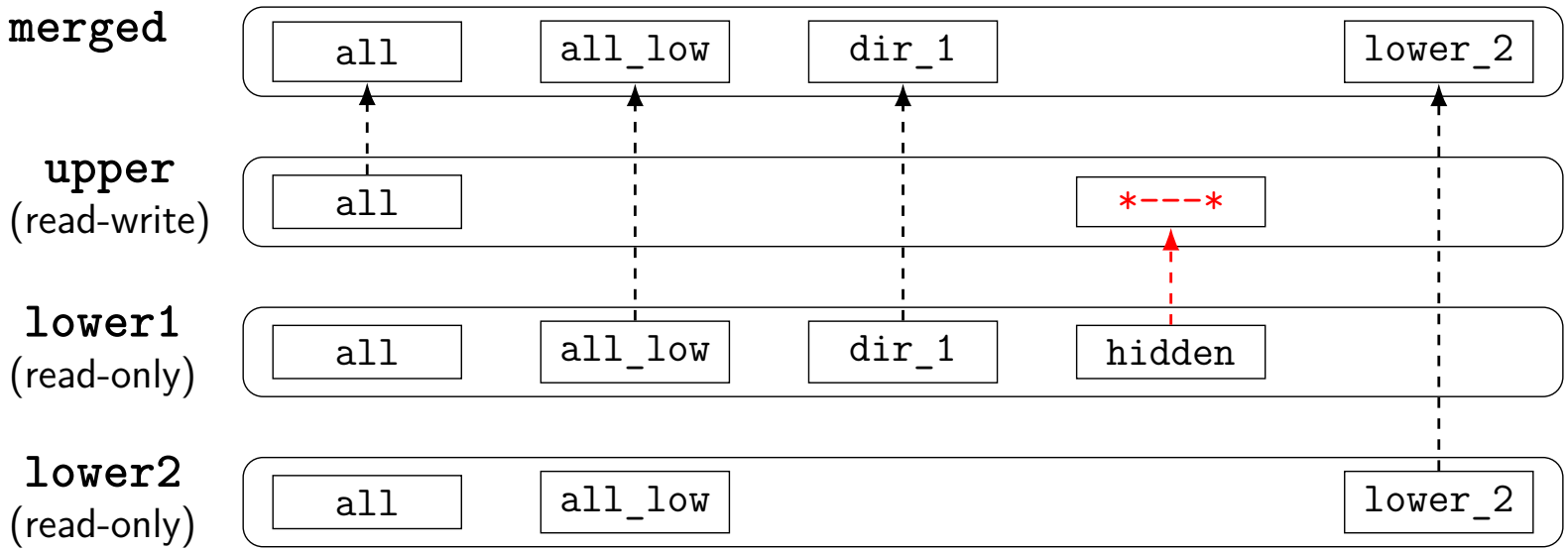
OverlayFS

```
mount -t overlay overlay ./merged \
      -o lowerdir=./lower1:./lower2,upperdir=./upper,workdir=./work
```



(See `filesys/overlayfs_example.sh`)

- Read-write upper layer is "diff" applied to lower layers
  - Diff may include "whiteouts" to represent deletion of a file from a lower layer (e.g., `hidden` above)

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Constructing the root filesystem

- To create the container FS, we'll use a **union mount** constructed with OverlayFS, **with two layers**:
  - **Lower layer** containing a base image of files that are common to all containers
  - **Upper layer** containing the files that are unique to/modified in a container instance

Constructing the root filesystem

- We'll build lower layer with a script:

```
create_lowerfs.sh <dir>
```

  - `<dir>` is directory where base image is to be created

consh/create_lowerfs.sh

```
mkdir $1
cd $1
mkdir bin dev etc home proc root sys tmp usr var

cd bin
cp $(which busybox) .
$PWD/busybox --install .
```

- Create set of directories that should appear in a root FS
  - (We won't actually populate all of those directories)
- Prepopulate `bin` with binaries to be used inside container:
  - Copy *busybox* into `bin` directory

```
$ which busybox
/usr/sbin/busybox
```

  - Use *busybox --install* to create all of the associated links
    - After this step, there will be ≈400 links in `bin`

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A container provides an illusion

- A **container provides an illusion** for the processes inside:
  - That the processes are in a "mini-system": a world of their own and no other processes exist on the system

A container provides an illusion

To support the illusion, each container should have:

- Its own set of **mounted filesystems**
- Its own **hostname**
- Its own **network infrastructure**
  - E.g., own virtual NW devices, own socket port numbers
- A **private set of PIDs**
  - PIDs of container should not be visible outside
    - Allows each container to have its own *init* (PID 1)
  - Outside PIDs shouldn't be visible inside container
- The concept of "**superuser** inside the container"
  - I.e., processes that have privilege inside the container, but not outside
- And so on...

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Implementing the illusion: namespaces

- The illusion of "a world of their own" is primarily created using namespaces (NSs)
- A NS provides a virtual instance of some global resource that is private to a group of processes

Implementing the illusion: namespaces

- There are various types of NS, including:
  - **PID** NSs: make PIDs private to container; hide outside PIDs
    - Each container can have its own PID 1!
  - **Mount** NSs: provide a **private set of mounts**
    - Each container can have its own set of mounted filesystems
  - **UTS** NSs: allow each container to have its own **hostname**
  - **Network** NSs: provide a **private instance of NW infrastructure** (devices, routing rules, socket port #s, etc.)
    - Each container can have its own (virtual) NW device that provides connectivity to outside world
- For our container, we'll create one instance of each NS type

Implementing the illusion: superuser

- Concept of superuser-in-a-container is provided via **user NSs** + capabilities
- Capabilities break power of superuser into (mostly) small pieces
  - Currently (Linux 7.3), 41 different capabilities exist
    - E.g., `CAP_KILL`, send signals to arbitrary processes; `CAP_SETUID`, make arbitrary changes to process's UIDs
  - Traditional superuser == process with all capabilities
- We'll create a new user NS for our container
  - Kernel automatically grants **all capabilities to first process** in new user NS
    - I.e., superuser powers inside container

Creating namespaces

- At the shell level, a NS is created using *unshare(1)*
  - At syscall level, NSs are created using *unshare(2)* or *clone(2)*
- Example:

```
$ id -u
1000
$ unshare --user --map-root-user --pid --fork \
        sh -c 'echo "PID $$"; UID $(id -u); Caps $(getpcaps $$)"'
PID 1; UID 0; Caps 1: =ep
```

  - As unprivileged user, create new user and PID NSs, and run a new shell that displays its PID and UID
    - First process in a new PID NS gets PID 1
    - Process has UID of 0, because "root mapping" says 1000 in outside world maps to 0 in new user NS
    - Process has all permitted and effective capabilities

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Limiting container resource usage

- Isolation also means **limiting container's use of resources**
- For example, we want to:
  - **Prevent a container from overwhelming system** with excessive resource demands
  - Be assured that **other containers can't overwhelm system**
    - So that our container obtains reasonable share of resources
  - **Limit access to resources** such as devices
  - **Measure resource consumption** of container

Control groups (cgroups)

- On Linux, resource isolation is done via **control cgroups** (cgroups)
  - Key point: resource allocation is specified at level of **group**[†] of processes
- Interface is a pseudo-filesystem (FS)
  - Mounted at `/sys/fs/cgroup`
- Cgroup manipulation is done using FS commands
  - Creating a cgroup == creating directory on FS
  - Limits are set by writing values to files inside cgroup directory

[†] Older *ulimit* mechanism sets **per-process** limits

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Cgroups example

- In one terminal, start a program that consumes CPU and measures % of CPU it receives each second:

```
$ ./cpu_burner
[47677]  %CPU = 99.86 (0)
[47677]  %CPU = 99.81 (1)
...
```

- In a second terminal, start root shell; from that shell create a cgroup, move *cpu_burner* into cgroup, and set a CPU limit:

```
$ sudo bash
# cd /sys/fs/cgroup
# mkdir mycgroup
# echo 47677 > mycgroup/cgroup.procs
# echo '50000 100000' > mycgroup/cpu.max
```

- In first terminal, we see:

```
[47677]  %CPU = 99.89 (111)
[47677]  %CPU = 52.76 (112)
[47677]  %CPU = 50.05 (113)
```

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consh/consh_setup.sh

```
consh_setup.sh [options] <lower-dir> <overlay-dir>

    # Options: -c <cgroup-path> -p <cgroup-parent> -h <hostname>
```

- We'll use a script to do the container set up
- *<lower-dir>*: directory to be used as lower layer in union mount used for container root FS
  - See earlier script, `create_lowerfs.sh`
- *<overlay-dir>*: location (pathname) in which to create other pieces needed for union mount
  - I.e., `upper`, `work`, and the mount point, `merged`
- Script places these **values into shell variables**: *lower* and *ovly_dir*

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consh/consh_setup.sh

```
consh_setup.sh [options] <lower-dir> <overlay-dir>

    # Options: -c <cgroup-path> -p <cgroup-parent> -h <hostname>
```

- *<cgroup>*: [optional] name of cgroup into which container should be placed
- *<cgroup-parent>*: [optional] pathname of cgroup under which *<cgroup>* should be attached
- *<hostname>*: hostname to use in container (default: `consh-host`)
- Script places these **values into shell variables**: *cgroup* (possibly empty), *cgroup_parent*, and *host*

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consh/consh_setup.sh

```
if [ "X$cgroup" != "X" ] ; then
  if [ "X$cgroup_parent" = "X" ] ; then
    cg_mnt="/sys/fs/cgroup"
    uslice="$cg_mnt/user.slice/user-$(id -u).slice/user@$(id -u).service"

    if [ -O $uslice ] ; then  # Check that dir. exists + that we own it
        cgroup_parent=$uslice
    else
        cgroup_parent=$cg_mnt
    fi
  fi
  ...
```

- If a cgroup name was specified:
  - If no parent cgroup was explicitly specified, try to **find suitable parent cgroup owned by user**:
    - First look in `user.slice` subhierarchy created by *systemd*
      `/sys/fs/cgroup/user.slice/user-1000.slice/user@1000.service`
      (a cgroup precreated by *systemd* and delegated to user)
    - Otherwise use `/sys/fs/cgroup` (but will need to run as *root*)

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consh/consh_setup.sh

```
if [ "X$cgroup" != "X" ] ; then
  ...
  cgpath="$cgroup_parent/$cgroup"

  mkdir -p $cgpath

  sh -c "echo $$ > $cgpath/cgroup.procs"
fi
```

- If a cgroup name was specified:
  - ...
  - **Create cgroup**
  - **Move this shell into cgroup**
    - Children of this shell will also be in this cgroup

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consh/consh_setup.sh

```
exec env -i HOME="/root" PATH="/usr/sbin:/usr/bin:/sbin:/bin" \
            HOSTNAME="$host" LOWER="$lower" OVLY_DIR="$ovly_dir" \
            ENV="$(dirname $0)/consh_post_setup.sh" \
         unshare --user --map-root-user --pid --fork \
                 --mount --net --ipc --uts --cgroup \
            busybox sh
```

- *exec*: replace the shell with the *env* command
  - Rather than executing in a child process
    - Reduces number of excess processes in container's cgroup
- Use *env* to clear environment (*–i*) and set a minimal set of environment variables
  - HOME, PATH, HOSTNMAME
  - LOWER and OVLY_DIR pass info from script args
  - Use of ENV is explained shortly
- *env* in turn does an *exec* to replace itself with *unshare*

consh/consh_setup.sh

```
exec env -i HOME="/root" PATH="/usr/sbin:/usr/bin:/sbin:/bin" \
            HOSTNAME="$host" LOWER="$lower" OVLY_DIR="$ovly_dir" \
            ENV="$(dirname $0)/consh_post_setup.sh" \
        unshare --user --map-root-user --pid --fork \
                --mount --net --ipc --uts --cgroup \
            busybox sh
```

- Use *unshare* to **create child process that runs in new NSs**
- *--user --map-root-user*: create user NS† with root mappings‡
  - This user NS will own all of the other NSs created here
- *--pid --fork*: create a PID NS and a child process
  - The child process will have PID 1 in new PID NS
- Remaining options specify creation of the other NS types

†If you are using Debian or Ubuntu, see slide 102

‡Recent (2022) versions of *unshare* have *--map-users* and *--map-groups*, to allow creation of more complex mappings

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consh/consh_setup.sh

```
exec env -i HOME="/root" PATH="/usr/sbin:/usr/bin:/sbin:/bin" \
            HOSTNAME="$host" LOWER="$lower" OVLY_DIR="$ovly_dir" \
            ENV="$(dirname $0)/consh_post_setup.sh" \
        unshare --user --map-root-user --pid --fork \
                --mount --net --ipc --uts --cgroup \
            busybox sh
```

- Run a shell in child process created by *unshare*
  - Run a *busybox* shell, in order to have a shell that is the same as that in `/bin` of the container FS

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7 Container set-up stage 2: mounts and *pivot_root()* 39
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9 Namespaces inside the container 54
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Performing initialization steps inside the container

- After the child process has been created, there are still some set-up steps to be done
- We perform those steps in another script
  - `consh/consh_post_setup.sh`
- Execution of that script is automated using the `ENV` environment variable
  - If `ENV` is defined, then a newly launched shell will execute the script it points to on start-up
- ⇒ Child shell launched by *unshare* automatically executes `consh/consh_post_set.sh`
  - As its first step, that script unsets `ENV`, so the script won't be executed by future shells run within container:

```
unset ENV
```

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consh/consh_post_setup.sh

```
mkdir -p $OVLY_DIR
mkdir $OVLY_DIR/upper $OVLY_DIR/work
mkdir $OVLY_DIR/merged

mount -t overlay -o lowerdir=$LOWER \
                      -o upperdir=$OVLY_DIR/upper \
                      -o  workdir=$OVLY_DIR/work \
                          overlay $OVLY_DIR/merged
cd $OVLY_DIR
unset LOWER OVLY_DIR              # No longer needed
```

- Create directories used in the OverlayFS union mount
  - `upper` will be upper layer of union mount
  - `work` is a directory used internally by OverlayFS
- Create mount point (`merged`)
- **Create union mount** at "`merged`"
  - *$LOWER* is directory we created with `create_lowerfs.sh`
- Change current directory to *$OVLY_DIR*

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consh/consh_post_setup.sh

```
manifest=merged/MANIFEST
echo "Created at:  $(date)"   > $manifest
echo "Creator UID: $(id -u)" >> $manifest
echo "Creator PID: $$"       >> $manifest
```

- As a demo, create a file that is private to this container
  - (File is created in `upper` layer of the union mount)

Setting up the container root FS: *pivot_root(8)*

- Our "container" shell inherited the list of mounts from the initial mount NS
- We want to **drop those mounts**, and use our **overlay mount as the root FS**
- Can do this using *pivot_root(8)*:†

```
pivot_root new_root put_old
```

  - Moves existing root mount of mount NS (and all descendant mounts) to *put_old*
  - Makes *new_root* the new root mount
  - Later, we will unmount old root FS

† *pivot_root(8)* is built on the *pivot_root(2)* syscall

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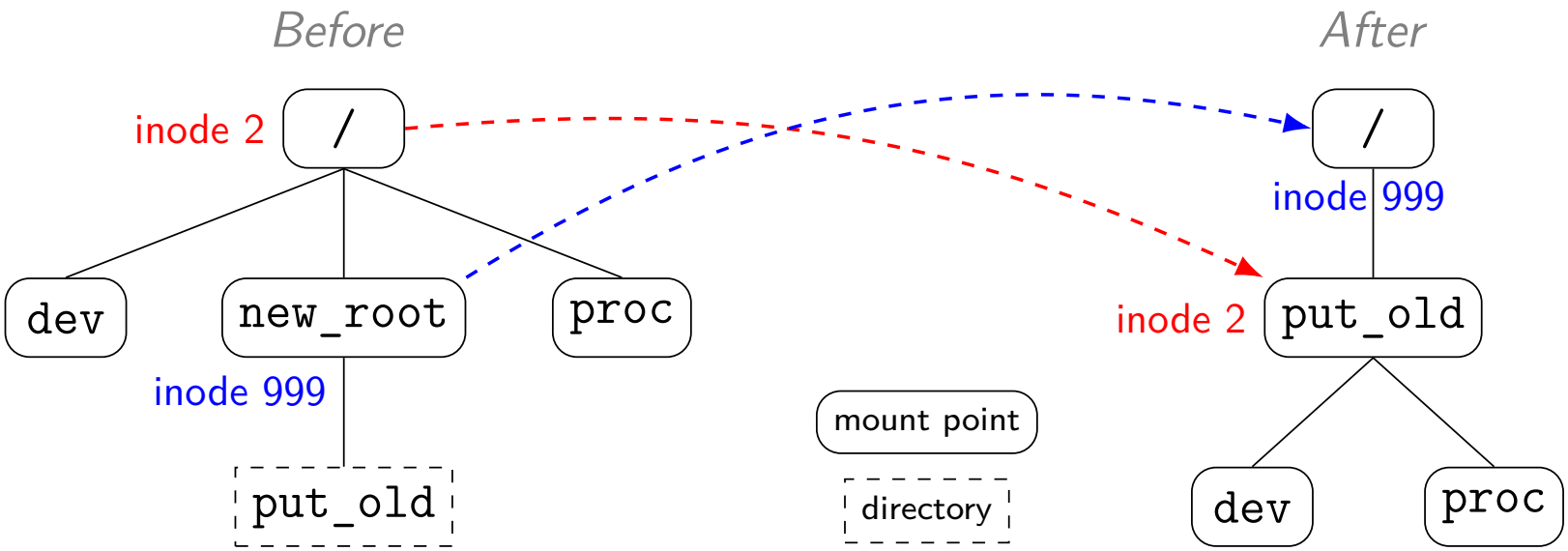
The effect of *pivot_root(8)*



- *new_root* is made the new root mount
- Old root mount (along with all descendant mounts) is shifted to *put_old*

Background notes: the root directory on a FS is always at inode 2; here, hypothetically, *new_root* has inode number 999

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pivot_root(8) rules

- There are many rules governing use of *pivot_root*...
  - (See *pivot_root(2)* manual page)
- *new_root* and *put_old* must be directories and must not be on same mount as the current root mount
- *put_old* must be at or underneath *new_root*
  - This allows us to subsequently unmount old root FS
- *new_root* must be a path for an existing mount
  - (***pivot_root()* is just shuffling entries in mount list**, so *new_root* must be a mount)
  - We can ensure *new_root* is a mount by bind mounting that path onto itself

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pivot_root(8) rules

- We need to ensure that changes made by *pivot_root(8)* do not propagate to any other mount NS:
  - (Propagation is a mechanism whereby mount events in one mount NS are duplicated to other NSs; we don't want this)
- To ensure that *pivot_root(8)* does not propagate changes to any other mount NS:
  - Propagation type of parent mount of *new_root* must not be "shared"
  - If *put_old* is an existing mount, its propagation type must not be "shared"

consh/consh_post_setup.sh

Back to our script:

```
mount --make-rprivate /

mount --bind merged merged
mkdir merged/oldrootfs

pivot_root merged merged/oldrootfs
```

- Prepare for pivot:
  - Ensure that no mounts have shared propagation
  - Ensure that new root (`merged`) is a mount point†
  - Create a directory under new root (`oldrootfs`), so that current root can be moved there
- **Pivot the root directory**

†Not strictly needed in this case, because `merged` is already a mount point, but this is how to ensure it is a mount point if needed

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consh/consh_post_setup.sh

```
cd /

mount -t proc proc /proc

mount -t sysfs sysfs /sys

mount -t cgroup2 cgroup2 /sys/fs/cgroup

mkdir -p /dev/mqueue
mount -t mqueue mqueue /dev/mqueue
```

- At this point, the current directory of our shell is outside (above) the new root directory; fix that
- **Mount** `/sys` + some NS-related **pseudofilesystems**
  - So that we have mounts that are consistent with PID, cgroup, and IPC NSs of our container
    - In particular, `/proc` **mount ensures that *ps(1)* works!**

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consh/consh_post_setup.sh

```
for name in full null random tty urandom zero; do
    touch /dev/$name
    mount --bind oldrootfs/dev/$name /dev/$name
done
```

- **Add some useful devices**, by bind mounting to devices under old root FS†

†As noted in comments in the script, using *mknod(1)* would also be possible, but would require superuser privileges in the initial user namespace.

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consh/consh_post_setup.sh

- **Unmount old root mount**:†

```
umount -l oldrootfs
rmdir oldrootfs                    # Remove now-unused mount point
```

  - This does a lazy unmount of the old root, and all of its descendant mounts
    - See description of MNT_DETACH in *umount(2)*

- **Set hostname** using value passed via environment variable:

```
hostname $HOSTNAME
```

- **And that's it!**

†For obscure reasons, this must be done after mounting /proc
(See https://lore.kernel.org/lkml/87tvsrjai0.fsf@xmission.com/T/)

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Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

Demo

- Let's use our scripts to create a container
- We do the following as an unprivileged user:

```
$ id
uid=1000(mtk) gid=1000(mtk) groups=1000(mtk),10(wheel)
```

- Create a directory for our work; inside that directory we create the base image for the union mount:

```
$ cd consh
$ mkdir demo
$ cd demo
$ ../create_lowerfs.sh lower
```

Demo

- Start the container, creating overlay mount at `ovly/merged`:

```
$ ../consh_setup.sh -c con_1 -h tekapo lower ovly
```

  - We are now running a shell in our "container"
  - The shell is in the cgroup `con_1`

- Because we'll be hopping between shells, make prompt of *this* shell more distinctive:

```
/ # PS1="bbsh# "                          # Change the shell prompt
bbsh#
```

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Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

PID namespaces

- From inside container: show PID of shell; demo use of *ps*:

```
bbsh# echo $$
1
bbsh# ps ax                              # List all processes
PID   USER     TIME  COMMAND
    1 0         0:00 busybox sh
   15 0         0:00 ps
```

  - Shell was first process in a new PID NS, and so got PID 1
  - Processes outside the container are not visible
- From outside container, show PID of shell in initial PID NS:

```
$ ps -C busybox
    PID TTY          TIME CMD
  26926 pts/3    00:00:00 busybox
```

- What's going on?

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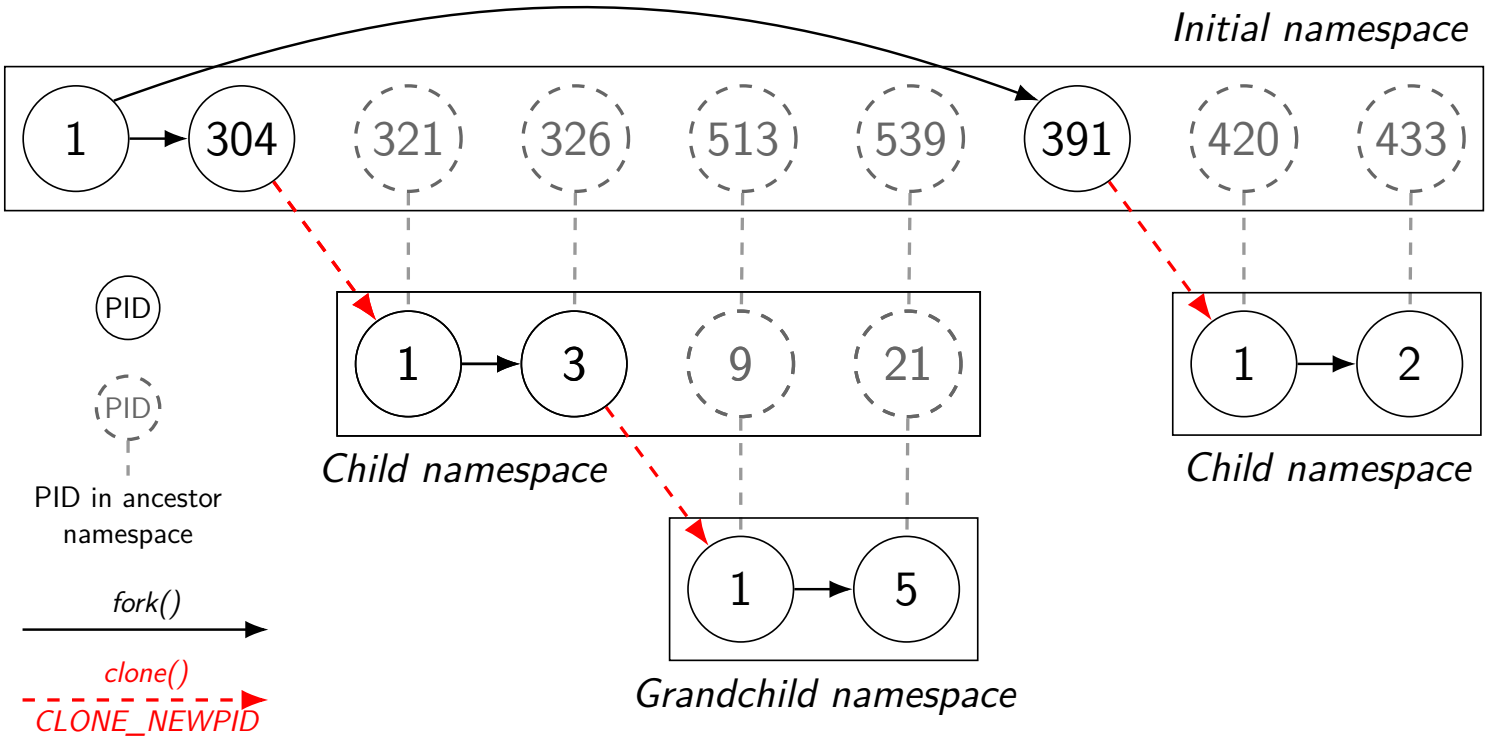
PID namespaces

- PID NSs exist in hierarchies
  - Each PID NS has a parent, which has a parent... back to initial PID NS
- A process that is member of a PID NS is also visible (i.e., has a PID in) in all ancestor NSs
  - `/proc/PID/status` shows shell's PID in each PID NS:

```
$ grep NStgid /proc/26926/status
NStgid: 26926   1
```

A PID namespace hierarchy

In a PID namespace, a process is visible in all ancestor PID NSs



Mount namespaces

- From outside the container (because *busybox* doesn't provide *findmnt*), view the mount tree of the container:

```
$ findmnt -o 'target,source,fstype' -N 26926
TARGET              SOURCE                                      FSTYPE
/                   overlay                                     overlay
├─/proc             proc                                        proc
├─/sys              sysfs                                       sysfs
│ └─/sys/fs/cgroup  cgroup2[/user.slice/user-1000.slice/.../g1] cgroup2
├─/dev/mqueue       mqueue                                      mqueue
├─/dev/full         devtmpfs[/full]                             devtmpfs
├─/dev/null         devtmpfs[/null]                             devtmpfs
├─/dev/random       devtmpfs[/random]                           devtmpfs
├─/dev/tty          devtmpfs[/tty]                              devtmpfs
├─/dev/urandom      devtmpfs[/urandom]                          devtmpfs
└─/dev/zero         devtmpfs[/zero]                             devtmpfs
```

  - This is a different (and smaller) set of mounts than is seen outside the container
  - The container has its own mount NS

findmnt –N <pid> == show mounts in NS of *<pid>* rather than `/proc/self/mountinfo`

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User namespaces

- From inside container, show credentials of shell:

```
bbsh# id
uid=0 gid=0 groups=65534,65534,65534,0
```

  - The supplementary groups are messy, but it's the best we can do from a script
    - (One of the untidy corners of our container...)

- From outside the container, show credentials of the shell:

```
$ grep '[UG]id' /proc/26926/status
Uid:    1000    1000    1000    1000
Gid:    1000    1000    1000    1000
```

- UID 1000 outside container was mapped to 0 inside via creation of a **UID map** for container's user NS:

```
$ cat /proc/26926/uid_map
         0       1000          1
```

  - Mapping was created by *unshare --map-root-user*

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UTS namespaces

- From inside container, view the hostname, and change it:

```
bbsh# hostname
tekapo
bbsh# hostname langwied
bbsh# hostname
langwied
```

  - Container is in a new UTS NS, so user can change hostname

Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

Superuser inside a container

- In previous demo, we changed the container's hostname
- How is that possible?
  - (Since privilege is required)
- And could a process inside container do superuser-y things outside the container?
  - (We certainly hope not, since *unprivileged* users can create containers)
- **How can a process be privileged inside a container while being unprivileged outside the container?**

Namespace relationships

Some things we need to know:

- Each non-user NS governs some type of global resource
  - Mount NS: mounts
  - UTS NS: hostname
  - Network NS: NW resources
  - etc.
- **Each non-user NS is owned by a user NS**
  - Ownership is established when non-user NS is created
- When our container was created, new instances of each NS type were created, including a new user NS
- Because all NSs were created at same time, **kernel made the new user NS the owner of the other new NSs**

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Capabilities and superuser powers inside a container

- Kernel (automatically) grants **all capabilities to first process in a new user NS**
  - All capabilities == superuser powers
- Show capabilities of our container shell:

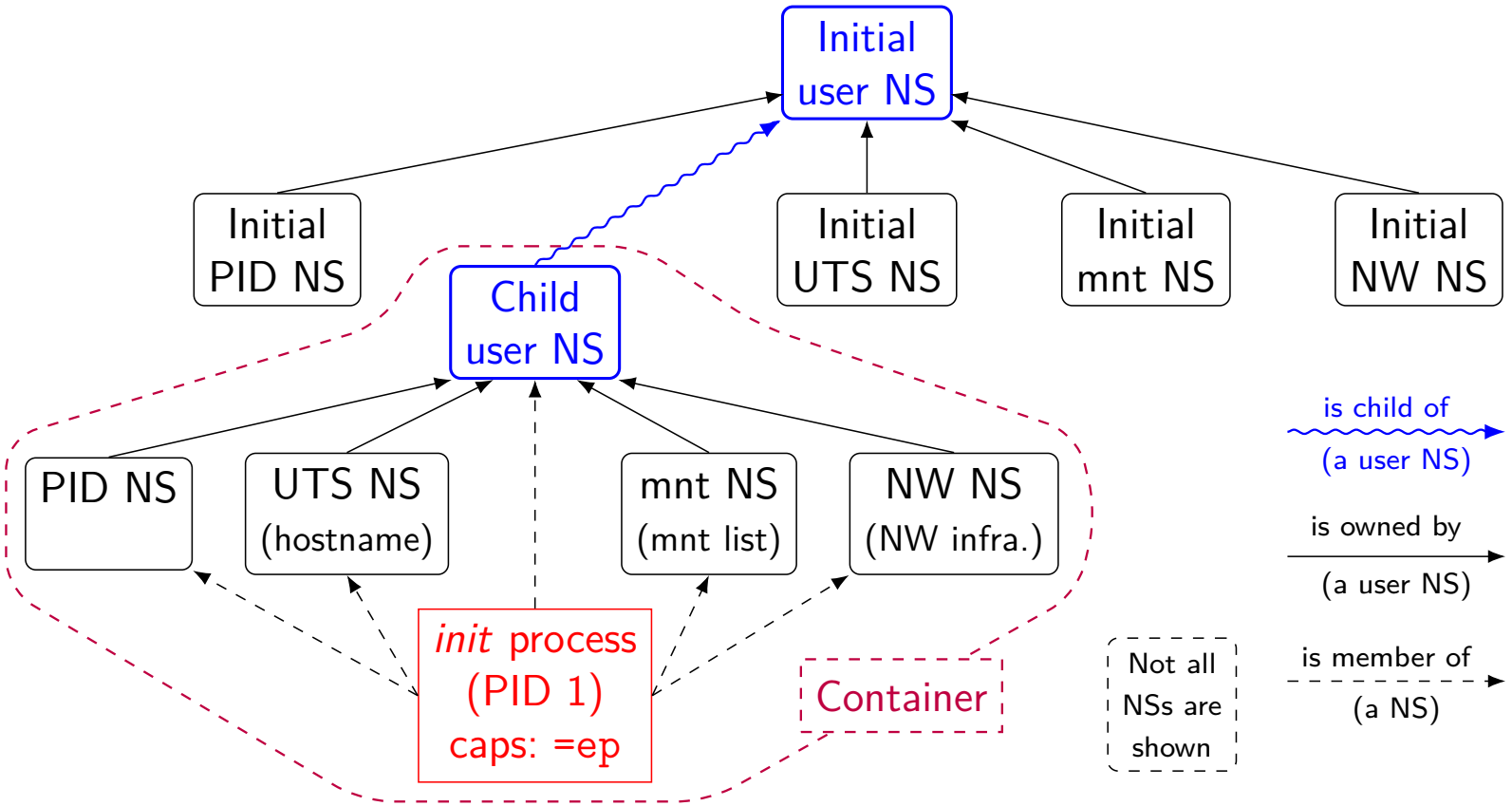
```
bbsh# grep -E 'Cap(Prm|Eff)' /proc/$$/status
CapPrm: 000001ffffffffff
CapEff: 000001ffffffffff
```

  - All permitted and effective capabilities...
    - Would be shown as "=ep" by *getpcaps(8)*

What does it mean to be superuser inside a NS?

- But those superuser powers have effect only inside container, because...
- Root power in a user NS == **privilege over resources governed by non-user NSs owned by the 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)

Namespace relationships

From a shell outside container, use my `namespaces_of.go` to compare (some) NSs of that shell with NSs of container shell:

```
$ echo $$
28736
$ sudo go run namespaces/namespaces_of.go 28736 26926
user {4 4026531837} <UID: 0>              # Initial user NS
        [ 28736 ]
    cgroup {4 4026531835}
            [ 28736 ]
    ipc {4 4026531839}
            [ 28736 ]
    mnt {4 4026531841}
            [ 28736 ]
    [...]
    user {4 4026534280} <UID: 1000>       # User NS of the container
            [ 26926 ]
        cgroup {4 4026534285}             # Indentation indicates ownership
                [ 26926 ]
        ipc {4 4026534283}
                [ 26926 ]
        mnt {4 4026534281}
                [ 26926 ]
        [...]
```

- The container has its own user NS, which owns other NSs

Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
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6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

Demo: cgroups

- From a shell outside the container, let's look at the processes in the container's cgroup:

```
$ cat /sys/fs/cgroup/[...]/user@1000.service/con_1/cgroup.procs
26911
26926
$ ps 26911 26926
    PID TTY      STAT   TIME COMMAND
  26911 pts/1    S      0:00 unshare --user --map-root --pid ...
  26926 pts/1    S+     0:00 busybox sh     # Our container shell
```

  - Another small untidiness: *unshare* process shouldn't be in the cgroup; we can manually move it out if we care

Demo: cgroups

- Inside the container, show cgroup membership of the shell:

```
bbsh# cat /proc/1/cgroup
0::/
```

  - Shell is in cgroup `[...]/user@1000.service/con_1`
  - But remount of `cgroup2` FS ensured a correctly virtualized path when looking from inside container
    - I.e., in cgroup NS of our container, `con_1` is the root cgroup

- How does cgroup membership of the container shell look from a shell in the outside world?

```
$ cat /proc/26926/cgroup
0::/user.slice/user-1000.slice/user@1000.service/con_1
```

  - This (different) path is consistent with the fact that we are looking from a different cgroup NS

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Demo: setting cgroup limits

- From a shell outside container, set a CPU limit for cgroup:

```
$ sh -c 'echo 5000 10000 > \
        /sys/fs/cgroup/user.slice/[...]/con_1/cpu.max'
```

  - 50% of one CPU

- And copy a (statically linked) program that burns CPU into the container FS:

```
$ cd consh
$ cp ../timers/cpu_burner demo/ovly/upper/
```

- From inside container, run that program:

```
bbsh# /cpu_burner
[17]  %CPU = 51.36
[17]  %CPU = 50.00
[17]  %CPU = 50.00
...
```

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Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

Demo: networking

- Let's use a virtual NW device to achieve NW connectivity into our container
- All steps are done using the standard *ip netns* command
  - See also the script, `consh/consh_nw_setup.sh`

ip netns

- One hurdle: normally, we create a NW NS using *ip netns add <name>*
  - **Creates a bind mount for NS** in `/var/run/netns`
  - That **mount is used in subsequent *ip netns* commands** in order to reach the NS
- Our container's NW NS has already been created, but we still need the bind mount for our *ip netns* commands
- ⇒ we create the bind mount manually from a shell outside the container:

```
$ sudo mkdir -p /var/run/netns           # Ensure directory exists
$ sudo touch /var/run/netns/consh        # Create the mount point
$ sudo mount --bind /proc/26926/ns/net /var/run/netns/consh
```

  - Our bind mount is named `consh`
  - `/proc/26926/ns/net` is NW NS of our container shell

Setting up network infrastructure

From a shell outside container, set up some NW infrastructure:

- Create a pair of connected virtual Ethernet (`veth`) devices:

```
sudo bash
# ip link add veth0 type veth peer name veth1
```

  - We named the two devices `veth0` and `veth1`

- Move the `veth1` device into our container:

```
# ip link set veth1 netns consh
```

- Assign IP addresses to both `veth` devices & bring them up:

```
# ip address add 10.0.0.1/24 dev veth0
# ip link set veth0 up
# ip netns exec consh ip address add 10.0.0.200/24 dev veth1
# ip netns exec consh ip link set veth1 up
```

We could assign addresses in different networks to the two `veth` endpoints, but then we would need to additionally install some routing table rules

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Setting up network infrastructure

Returning to our container shell:

- Show that the `veth1` device is present in the container:

```
bbsh# ip link show veth1
282: veth1@if283: <BROADCAST,MULTICAST,UP,LOWER_UP,M-DOWN> ...
    link/ether 2e:c2:13:c5:4e:b8 brd ff:ff:ff:ff:ff:ff
```

Demonstrating network connectivity

- How can we easily fire up a NW server inside the container?
  - *busybox* does Netcat (*¡Genial!*)
- Inside our container, start a listening server on port 50000:

```
bbsh# nc -l -p 50000 -e sh -c \
              's=; while true; do s=x$s; echo $s; sleep 1; done'
```

  - After accepting a connection, server script sends strings of ever-increasing length
- From a shell outside the container, we connect to the server and see:

```
# nc 10.0.0.200 50000
x
xx
xxx
xxxx
...
```

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Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

If this is a “decent” container,
we should be able to do
one more thing...

Can we create a container inside a container?

A container inside a container

What are the hurdles?

- The *busybox unshare* applet doesn't support *--cgroup*
  - ⇒ We'll use a statically linked version of the standard *unshare* program provided by *util-linux*
- We need a union mount for inner container, but **upper layer in OverlayFS can't itself be an OverlayFS mount**
  - IOW: we can't use FS of outer container in upper layer of inner container's FS
  - Solution: mount a new *tmpfs* + create union mount there

Creating the outer container

- First, we create the outer container:

```
$ cd consh
$ mkdir demo
$ cd demo
$ ../create_lowerfs.sh lower
$ ../consh_setup.sh -c con_1 -h tekapo lower ovly
/ # PS1="bbsh# "                          # Change the shell prompt
bbsh#
```

Preparations for the inner container

- Now we need to copy the files into outer container that will be used to set up inner container...
- From a shell outside the container, we copy our scripts into the container FS:

```
$ cd consh
$ cp  *.sh demo/lower/bin
```

- And copy in a statically linked version of the standard *unshare* command:

```
$ rm demo/lower/bin/unshare
       # Steps to build unshare.static omitted
$ cp /some/path/util-linux/unshare.static demo/lower/bin/unshare
```

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Starting the inner container

- Returning to our outer container....
- Mount a *tmpfs* FS where we will create components of union mount for the inner container:

```
bbsh# mkdir demo_inner
bbsh# mount -t tmpfs tmpfs demo_inner
```

- Create the lower layer for the union mount:

```
bbsh# cd demo_inner
bbsh# create_lowerfs.sh lower
```

- Start the inner container:

```
bbsh# consh_setup.sh -c con_2 -h pukaki lower ovly
/ #
```

  - "/ #" is prompt of *busybox* shell in inner container...

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Examining the inner container

- Start a *sleep* process in the inner container:

```
/ # /bin/sleep 1000          # Full path to avoid 'sleep' built-in
```

  - We use absolute pathname to avoid use of *sleep* built-in command (which would not create separate process)

- From a shell in the initial NS, obtain PID of *sleep*:

```
$ pidof sleep
69884
```

Examining the inner container

- Let's use my `namespaces/namespaces_of.go` to compare some NSs of a shell in initial NSs with NSs of *sleep*:

```
$ go run namespaces_of.go --namespaces=user,cgroup,pid,uts $$ 69884
user {4 4026531837} <UID: 0>                    # Initial user NS
        [ 56734 ]
    cgroup {4 4026531835}
            [ 56734 ]
    pid {4 4026531836}
            [ 56734 ]
    uts {4 4026531838}
            [ 56734 ]
    user {4 4026534072} <UID: 1000>             # User NS of outer container
        user {4 4026532574} <UID: 1000>         # User NS of inner container
                [ 69884 ]
            cgroup {4 4026534004}
                    [ 69884 ]
            pid {4 4026534003}
                    [ 69884 ]
            uts {4 4026534001}
                    [ 69884 ]
```

  - *sleep* is in grandchild user NS that owns various other NSs
    - *sleep* is also a member of those other NSs

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Examining the inner container

- Display PID of *sleep* in all PID NSs where it is present:

```
$ grep NStgid /proc/69884/status
NStgid: 69884   54      17
```

  - Three PIDs ⇒ *sleep* is in a grandchild PID NS
  - Verify by using my program to examine PID NS hierarchy:

```
$ sudo go run namespaces_of.go --pidns 69884
pid {4 4026531836}                  # Initial PID NS
    pid {4 4026535236}              # PID NS of outer container
        pid {4 4026534583}          # PID NS of inner container
                [ 69884 ]
```

- Display cgroup membership of *sleep*:

```
$ cat /proc/69884/cgroup
0::/user.slice/user-1000.slice/user@1000.service/con_1/con_2
```

  - It is in a child cgroup of the outer container's cgroup

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Sure does look like a container inside a container!

Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

One more challenge to solve

- There is a problem we did not solve in the previous slides
- Recall that a union mount consists of at least two layers:
  - Lower layer: read-only, shared by all containers
  - Upper layer: read-write, private to container
- In each different container, a different UID may map to 0 inside container; for example:
  - In container started by UID 1000, UID 1000 maps 0
  - In container started by UID 2000, UID 2000 maps 0

One more challenge to solve

- Within a container, files belonging to that container's root ID (say 1000) will (as expected) appear to have UID 0
  - (Because of the UID map)
- However, files in read-only lower layer should also have UID 0 inside container
  - E.g., on traditional system, files in `/bin`, `/etc`, and `/var` belong to `root:root`
- How can we ensure lower layer files also have UID 0 (and GID 0) inside each container?
  - Keeping in mind that each container's root ID may map to different absolute ID...

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A suboptimal solution

- Possible solution:
  - On container start-up, **make copy of lower layer** image, and change ownership of files to container's root UID+GID
- But:
  - **Expensive**: *O(number of files)*
    - Slows container start-up
  - **Wastes disk space**

ID-mapped mounts

- Nowadays, a better solution exists: **ID-mapped mounts**
  - Since Linux 5.12 (2021)
- Provides a way of creating a mount where UIDs+GIDs of resident files map to different IDs within the mount
  - Thus, e.g., "true" UID 0 would map to UID 0 in container owned by UID 1000 and also in container owned by UID 2000
- For example:
  - Suppose files in lower layer are owned by "true" UID/GID 0
  - Each container would have an ID-mapped mount that maps "true" UID/GID 0 to container's root UID/GID

ID-mapped mounts

General steps (for each container):

1. Create a user NS whose sole purpose is to define a UID map and a GID map
   - These maps will provide mapping translation for ID-mapped mount of lower layer
   - User NS is otherwise unused (no member processes)
2. Open corresponding `/proc/PID/ns/user` symlink to obtain FD that refers to that user NS
3. Create a "bind" mount of lower layer with an *idmap* attribute that specifies NS FD from previous step
   - After this, process inside user NS can terminate and NS FD can be closed

ID-mapped mounts

- At command-line, the bind mount is made via *mount --bind*
  - But, not a "traditional" bind mount (*mount(2)* `MS_BIND`)
- System call steps are:†
  - *open_tree(..., source, OPEN_TREE_CLONE)* to create unattached mount cloned from *source*
  - *mount_setattr(..., {MOUNT_ATTR_IDMAP, fd}, ...)* to attach ID map (user NS referred to by *fd*) to mount
  - *move_mount(..., target, ...)* to attach mount at *target*

†*open_tree(OPEN_TREE_CLONE)* + *move_mount()* is how a bind mount is created using the modern (Linux 5.2, 2019) mount APIs; *mount_setattr()* was added in Linux 5.12 (2021)

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ID-mapped mounts: demo

- Create directory that will be used as mount source, and populate with files with different UIDs and GIDs:

```
$ id
uid=1000(mtk) gid=1000(mtk) groups=1000(mtk),10(wheel)
$ mkdir /tmp/src
$ touch /tmp/src/{a,b,z}
$ sudo chown 0:0 /tmp/src/a
$ sudo chown 1:1 /tmp/src/b
```

- Verify file credentials:

```
$ stat -c "%u %g %n" /tmp/src/* | column -t
0     0     /tmp/src/a
1     1     /tmp/src/b
1000  1000  /tmp/src/z
```

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ID-mapped mounts: demo

- Create an ID-mapped mount based on `/tmp/src`:

```
$ mkdir /tmp/mm_1
$ sudo mount --bind --map-users  0:1000:2000 \
                    --map-groups 0:1000:2000 /tmp/src /tmp/mm_1
```

  - Maps here say that UID/GID 0 in mount source is mapped to 1000 in target mount; length of maps is 2000
    - I.e., 0..1999 maps to 1000..2999
  - Behind the scenes, *mount(8)*:
    - Creates user NS with *unshare(2)* & populates UID+GID maps
    - Creates bind mount (*open_tree()*, *mount_setattr()*, *move_mount()*)

- Could equivalently have written:

```
$ sudo mount -o bind,X-mount.idmap=b:0:1000:2000 /tmp/src /tmp/mm_1
```

  - "b" says use same map for both UIDs and GIDs

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ID-mapped mounts: demo

- View file credentials in ID-mapped mount:

```
$ stat -c "%u %g %n" /tmp/mm_1/* | column -t
1000  1000  /tmp/mm_1/a
1001  1001  /tmp/mm_1/b
2000  2000  /tmp/mm_1/z
```

- Meanwhile, in source mount, file credentials are as before:

```
$ stat -c "%u %g %n" /tmp/src/* | column -t
0     0     /tmp/src/a
1     1     /tmp/src/b
1000  1000  /tmp/src/z
```

ID-mapped mounts: demo

- Create another ID-mapped mount based on same source:

```
$ mkdir /tmp/mm_2
$ sudo mount --bind --map-users  0:2000:2000 \
                    --map-groups 0:2000:2000 /tmp/src /tmp/mm_2
```

  - Maps IDs 0..1999 to 2000..3999

- View file credentials in new ID-mapped mount:

```
$ stat -c "%u %g %n" /tmp/mm_2/* | column -t
2000  2000  /tmp/mm_2/a
2001  2001  /tmp/mm_2/b
3000  3000  /tmp/mm_2/z
```

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ID-mapped mounts: further info

- *Idmapped Mounts*, Christian Brauner, Kernel Recipes 2022, `https://www.youtube.com/watch?v=DZ-ut7RtR2I`
  - Slides at: `https://archives.kernel-recipes.org/wp-content/uploads/2025/01/brauner_christian_idmapped_mounts.pdf`
- `https://www.kernel.org/doc/html/latest/filesystems/idmappings.html`
- *ID mapping for mounted filesystems*, J. Corbet, 2020, `https://lwn.net/Articles/837566/`
- *ID-mapped mounts*, J. Edge, 2022, `https://lwn.net/Articles/896255/`
- *Idmapped mounts*, `https://github.com/brauner/mount-idmapped`, Christian Brauner
  - Provides a demo program, *mount-idmapped*, to create ID-mapped mounts (functionality is nowadays incorporated into *mount(8)*)

Outline

1 Building a container from the shell 4
2 The container root filesystem (OverlayFS) 9
3 Constructing the root filesystem 16
4 Isolating the container: namespaces 20
5 Isolating the container: cgroups 27
6 Container set-up stage 1: cgroups + namespaces 31
7 Container set-up stage 2: mounts and *pivot_root()* 39
8 Starting up the container 51
9 Namespaces inside the container 54
10 Superuser inside a container 61
11 Cgroups inside the container 68
12 Networking inside the container 72
13 One more thing... 78
14 PS: ID-mapped mounts 89
15 PS: Debian, Ubuntu, and unprivileged user namespaces 101

Debian, Ubuntu, and unprivileged user namespaces

- Some Debian and Ubuntu versions disable creation of user NSs by unprivileged users
- If you are using Debian or Ubuntu, first check if the following succeeds:

```
$ unshare -Ur sh -c 'getpcaps $$'
1856364: =ep
```

If the command does not succeed, then see the following steps

- Does the following show the value 1:

```
$ sysctl kernel.unprivileged_userns_clone
1
```

If not, set the value to 1:

```
$ sudo sysctl -w kernel.unprivileged_userns_clone=1
```

- Does the following command succeed, and show the value 0:

```
$ sysctl kernel.apparmor_restrict_unprivileged_userns
0
```

(The command may fail, if AppArmor is not in use on your system)
If the command succeeded, but showed a nonzero value, set the value to 0:

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

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Thanks!

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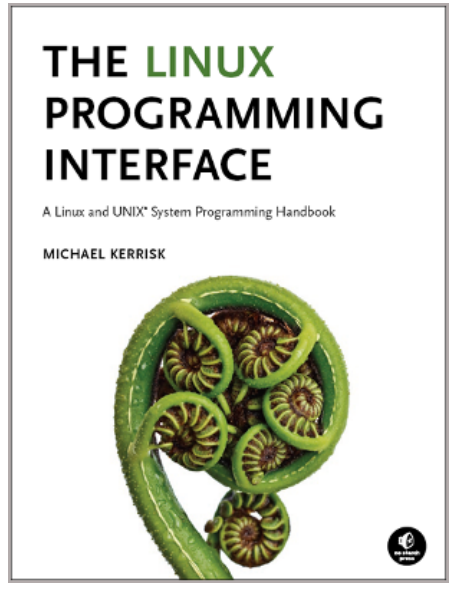
https://man7.org/training/



Slides at https://man7.org/conf/

Source code at https://man7.org/tlpi/code/