The basics of file systems

Mount points

To make a FS visible, one ”mounts” it below a directory visible to a user.

For the OS kernel, a mount point is a mark that says, “when descending into this directory, jump to the root directory of a file system mounted here”.

```
$ ls -lh ~/testing/mount/
total 0
```

```
$ mount -t ext4 ./img ~/testing/mount/

$ ls -lh ~/testing/mount/
total 8.0K
drwxrwxr-x 1 1002 1002 4.0K Sep 25 16:59 pstorage-fes
drwxr-xr-x 1 1002 1002   83 Sep  6 21:11 rpmbuild
```

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The list of mount points can be viewed this way:

- `$ cat /proc/self/mounts`

File systems can be mounted on first access: https://linux.die.net/man/5/auto.master

File system objects and their names are separate things

We've seen that files and their names are independent from each other: `link()` and `unlink()` can create files with multiple names and files without names.

A working directory is also not tied to a path. Instead, it is a pointer "directory X in file system Y":

```
$ pwd
/home/artem/testing/students


$ ls -lh .
total 40K
-rw-r--r-- 1 artem artem  234 Sep 28 11:48 example
-rw-r--r-- 1 artem artem  11K Sep 27 21:49 proc
-rw-r--r-- 1 artem artem 1.1K Sep 27 21:49 proc.c
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The POSIX file system semantics

Virtual file systems in Linux

For a user of the POSIX API a file system does not need to represent data located on a physical device. Any implementation will do as long as it is possible to

- find a file or a directory by name,
- list the content of directories,
- read and write the content of files.

Virtual file systems in Linux: procfs

Linux has a file system where top-level directories represent processes, and files in a directory describe properties of the process.

```
$ ls -lh /proc/self/
total 0

-r--r--r-- 1 artem artem 0 Oct  2 10:08 cmdline
lrwxrwxrwx 1 artem artem 0 Oct  2 10:08 cwd -> /home/artem
lrwxrwxrwx 1 artem artem 0 Oct  2 10:08 exe -> /bin/ls
dr-x------ 2 artem artem 0 Oct  2 10:08 fd
-r--r--r-- 1 artem artem 0 Oct  2 10:08 maps
-r--r--r-- 1 artem artem 0 Oct  2 10:08 stat
......
```

To do at home:

- read `man 5 proc`,
- what does `/proc/PID/auxv` contain, and how does `execve()` fill the stack of a new process?
- write a program that hides its first command line argument from `/proc/PID/cmdline` (a hint: `man prctl` and look for `PR_SET_MM`),
- implement
  - `ps`
  - `lsof`

Virtual file systems in Linux: FUSE

Normally, file systems are implemented in the kernel.

FUSE (Filesystem in USer spacE) is a mechanism to run file system drivers as userspace processes.

FUSE file system drivers open a pipe to the kernel-space FUSE layer. Over that pipe, they receive commands like “lookup a file in a directory”, “open a file”, “read/write data to a file”, etc.

Example: sshfs, Lustre, CEPH.

Advantages of FUSE:

- Userspace processes may use any libraries that may not be fit to the kernel,
- File system drivers can be run by non-privileged users,
- FUSE enables easy experimentation with FS implementations.

Disadvantages of FUSE:

- (Much) lower performance due to numerous switches between the kernel and the userspace.

To do at home:

- Read the documentation about the FUSE high level API,
- Implement a FUSE file system that has only the root directory and one file named “hello”. Reading this file must return the string “hello, world!”. Verify that `` `ls -l` `` and `` `cat hello` `` work with your file system.

POSIX file system API

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The classical access model:

- the system tracks the set of users and the set of user groups,
- files have one owner user and one owner group,
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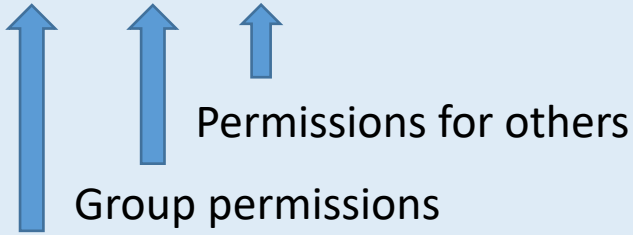
```
$ ls -lh /usr/bin
...
 rwx   r-x   --x 1 root   root     31K Feb 22  2016 afm2pl
 rwx   r-x   --x 1 root   root     38K Feb 22  2016 afm2tfm
 rwx   r-x   --x 1 root   root    485K Feb 22  2016 aleph
```



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This access model is woefully inadequate for complicated setups. It has no way to grant access to a file both to Gregory and George unless they belong to the owner group of the file.

There is a much more flexible mechanism for assigning access rights to a file, POSIX Access Control Lists. See

- `man 5 acl`,
- `man 1 getfacl`,
- `man 1 setfacl`.

POSIX file system API

There are special “access rights” that modify the way the programs are exec()ed:

```
$ ls -lh /usr/bin
...
 rws   r-x   r-x 1 root   root    134K Jan  6  2016 sudo
 rwx   rwx   rwx 1 root   root       4 Jan  6  2016 sudoedit -> sudo
 rwx   r-x   r-x 1 root   root     47K Jan  6  2016 sudoreplay
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When a set-uid binary is `exec()`ed, it runs with the credentials of the owner user. The similar thing happens with set-gid binaries.

POSIX file system API

Files and file descriptors are two separate entities. In particular, they may have unrelated access rights:

```
int fd = open(“/path/to/a/file”, O_RDWR | O_CREAT, S_IRUSR);
write(fd, buffer, size);
close(fd);
```

POSIX file system API

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```

Use cases:

- Split programs into a small trusted and audited core, and into worker processes that handle complex data.
  What is an example of a very frequently used software that follows this model?
- Binfmt handlers for files that allow only --x--x--x:
  https://lwn.net/Articles/679310/
- See also: seccomp and seccomp filters:
  https://www.kernel.org/doc/Documentation/prctl/seccomp_filter.txt

A file system is a shared resource: concurrent access and races

When multiple threads access the same memory region, they need to synchronise their access to avoid races.

What happens when multiple process access the same directory?

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What happens when multiple process access the same directory?

1. Creating a temporary file:

```
int fd = open("/tmp/tmp.1b42ac00de", O_RDWR|O_CREAT, 0);
unlink("/tmp/tmp.1b42ac00de");
... use fd to keep temp data ...
```

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2. Reading a symbolic link:

```
struct stat st;
lstat(“/path/to/symlink”, &st);
char *buf = malloc(st.st_size + 1);
readlink(“/path/to/symlink”, buf, st.st_size);
buf[st.st_size] = ‘\0’;
```

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3. Creating two files in a directory:

```
int fd0 = open("/dir/a", O_RDWR|O_CREAT, S_IRUSR);
int fd1 = open("/dir/b", O_RDWR|O_CREAT, S_IRUSR);
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1. There is a time frame when another process can open `/tmp/tmp.1b42ac00de` by name. Such process will be able steal the data from the temp file.

2. Another process can change the symlink value between the calls to `lstat()` and `readlink()`. See TOCTTOU (time of check to time of use).

3. In the time frame between two `open()`s another process can rename `/dir` and then create a different directory with the same name.

A file system is a shared resource: concurrent access and races

One of the solutions: run applications in containers:

- If processes A and B each have their ”private” `/tmp` directory, then they cannot access files of each other by construction.

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- If processes A and B each have their ”private” `/tmp` directory, then they cannot access files of each other by construction.
- Linux has “**filesystem namespaces**” which are collections of mount points. Mount points of a FS namespace are visible only to processes that run in that specific FS namespace.
- In two different FS namespaces the path `/tmp` may refer to two different tmpfs instances.

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See also:

- Pid namespaces,
- Network namespaces,
- User namespaces.

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How to populate a FS namespace?

- One can start with an empty directory that will become the root of the FS namespace,
- Add read-only images of directories with standard binaries and libraries like `/usr` and `/lib`,
- Add instances of `/tmp` and `/proc` private to the container,
- Add directories with the data of an application that runs in the container.

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  - see also: bind mounts
- Add instances of `/tmp` and `/proc` private to the container,
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  - see also: Kubernetes persistent volumes

Bind mounts

Bind mounts are a Linux-specific extension to mount points. When a path traversal descends into a mount point M, it jumps to the root of a file system mounted at M. When descending into a bind mount point M', a path traversal jumps into an arbitrary directory that is the destination of a bind mount.

```
$ ls -lh src/
total 0
-rw-r--r-- 1 artem artem 0 Oct  2 00:29 0
-rw-r--r-- 1 artem artem 0 Oct  2 00:29 1
-rw-r--r-- 1 artem artem 0 Oct  2 00:29 2

$ ls -lh dst/
total 0

$ mount --bind src/ dst/

$ ls -lh dst/
total 0
-rw-r--r-- 1 artem artem 0 Oct  2 00:29 0
-rw-r--r-- 1 artem artem 0 Oct  2 00:29 1
-rw-r--r-- 1 artem artem 0 Oct  2 00:29 2
```

Bind mounts add a huge number of edge cases:

- one can bind-mount files,
- http://lwn.net/Articles/689856/