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Sistemas de Operação/
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sofs20 September, 2020

Previous note

The *sofs20* is a simple and limited file system, based on the ext2 file system, which was designed for purely educational purposes and is intended to be developed in the practical classes of the Operating Systems and Fundamentals of Operating System courses during academic year of 2020/2021. The physical support is a regular file from any other file system.

1 Introduction

Almost all programs, during their execution, produce, access and/or change information that is stored in external storage devices, which are generally called mass storage. Fit in this category magnetic disks, optical disks, SSD, among others.

Independently of the physical support, structurally one can verify that:

- mass storage devices are usually seen as an array of blocks, each block being 256 to 8 Kbytes long;
- blocks are sequentially numbered (LBA model), and access to a block, for reading or writting, is done given its identification number.

Direct access to the contents of the device should not be allowed to the application programmer. The complexity of the internal structure and the necessity to enforce quality criteria, related to efficiency, integrity and sharing of access, demands the existence of a uniform interaction model.

The concept of **file** appears, then, as the logic unit of mass memory storagement. This means reading and writing in a mass storage device is always done in the context of files.

From the application programmer point of view, a file is an abstract data type, composed of a set of attributes and operations. Is the operating system's responsability to provide a set of system calls that implement such abstract data type. These system calls should be a simple and safe interface with the mass storage device. The component of the operating system dedicated to this task is the **file system**. Different approaches conduct to different types of file systems, such as `NTFS`, `ext3`, `FAT*`, `UDF`, `APFS`, among others.

2 File as an abstract data type

The actual attributes of a file depend on the implementation. The following represents a set of the most common ones:

name — a user-convenient identifier to access the file upon creation;

internal identifier — a unique (numerical) internal identifier, more suitable to access the file from the file system point of view;

size — the size in bytes of the file's data;

ownership — an indication of who the file belongs to, suitable for access control;

permissions — a set of bit-attributes that in conjunction with the ownership allows to grant or deny access to the file;

monitoring times — typically, time of creation, time of last modification and time last access;

type — the type of files that can be hold by the file system; here, 3 types are considered:

- **regular file** — what a user usually defines as a file;
- **directory** — an internal file type, with a predefined format, that allows to view the file system as a hierarchical structure of folders and files;
- **shortcut (symbolic link)** — an internal file type, with a predefined format, that points to the absolute or relative path of another file;

localization of the data — internal means to identify the blocks/clusters where the file's data is stored.

The operations that can be applied to a file depend on the operating system. However, there is a set of basic ones that are always present. These operations are available through system calls, i.e., functions that are entry points into the operating system. If follows a list, not complete, of system calls provided by Unix/Linux to manipulate the 3 considered file types:

- common to the 3 file types: `open`, `close`, `chmod`, `chown`, `utime`, `stat`, `rename`;
- common to regular files and shortcuts: `link`, `unlink`;
- only for regular files: `mknod`, `read`, `write`, `truncate`, `lseek`;
- only for directories: `mkdir`, `rmdir`, `getdents`;
- only for shortcuts: `symlink`, `readlink`;

You can get a description of any one of these system calls executing, in a terminal, the command

```
man 2 <syscall>
```

where `<syscall>` is one of the aforementioned system calls.

3 FUSE

In general terms, the introduction of a new file system in an operating system requires the accomplishement of two different tasks. One, is the integration of the software that implements the new file system into the operating system's kernel; the other, is its instantiation on one or more disk devices using the new file system format.

In monolitic kernels, the integration task involves the recompilation of the kernel, including the sofware that implements the new file system. In modular kernels, the new software should be compiled and linked separalely and attached to the kernel at run time. Any way, it is a demanding task, that requires a deep knowledge of the hosting system.

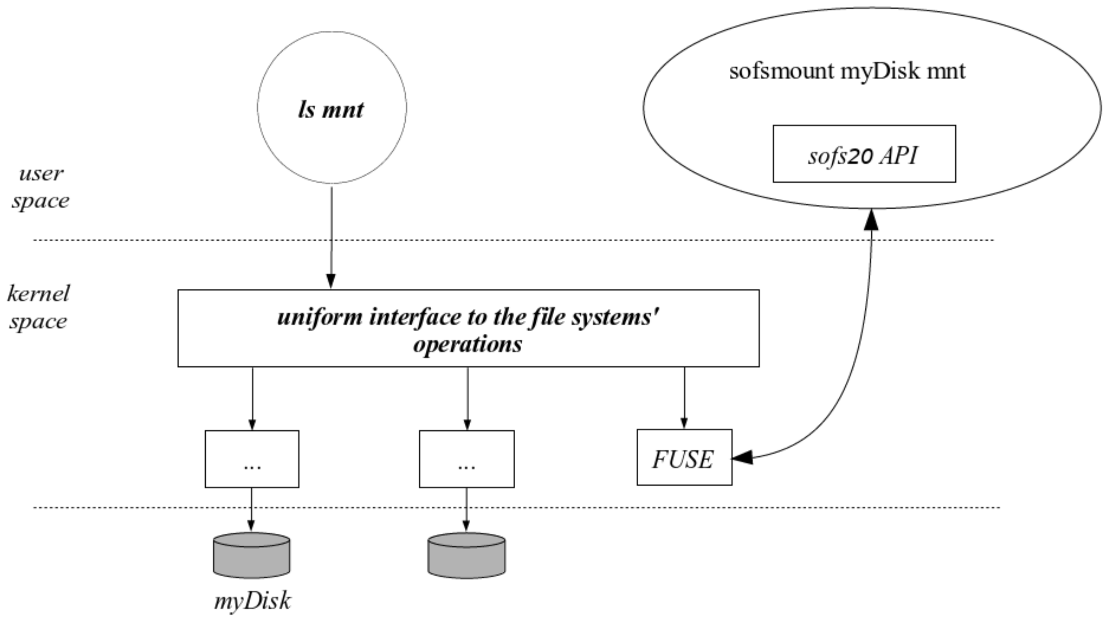
FUSE (File system in User SpacE) is a canny solution that allows for the implementation of file systems in user space (memory where normal user programs run). Thus, any effect of flaws of the suporting software are restricted to the user space, keeping the kernel imune to them.

The infrastructure provided by FUSE is composed of two parts:

- Interface with the file system — works as a mediator between the kernel system calls and the file system implementation in used space.
- Implementation library — provides the data structures and the prototypes of the functions that must be developed; also provides means to instantiate and integrate the new file system.

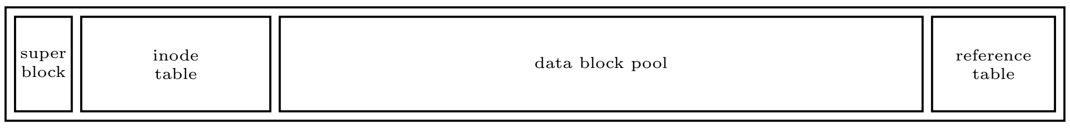
The following diagram illustrates how the *sofs20* file system is integrated into: the operating system using FUSE. Assuming a `sofs20` file system is mounted in directory `mnt`, the execution of the command `ls mnt` proceeds as follows:

1. The execution is decomposed in a sequence of calls to file system system calls in user space.
2. Each of these system calls enters the kernel space at the uniform interface.
3. Identified as `FUSE/sofs20`, it is redirect through the `FUSE` kernel module to the `sofs20` API, again in user space.
4. Since, in the case of `sofs20`, the disk is a file in another file system, new system calls are called to access that file.
5. The response is delivered to the `FUSE` kernel module, that, next, constructs the response to the original system call.



4 The *sofs20* architecture

As mentioned above a disk is seen as a set of numbered blocks. For *sofs20* it was decided that each block is 1024 bytes long. In a general view, the N blocks of a *sofs20* disk are divided into 4 areas, as shown in the following figure.



The **superblock** is a data structure stored in block number 0, containing global attributes for the disk as a whole and for the other main file system structures.

An **inode** is a data structure that contains all the attributes of a file, except the name. There is a contiguous region of the disk, called **inode table**, reserved for storing all inodes. This means that the number of inodes in a *sofs20* disk is fixed after formatting. This also means the identification of an inode can be given by a number representing its relative position in the inode table, thus an integer number in the range $[0, N[$, being N the total number of inodes.

The actual data of any file is stored in blocks taken from the **data block pool**, being a contiguous sequence of blocks after the inode table. This means that the number of blocks in a *sofs20* disk is fixed after formatting. This also means the identification of a data block can be given by a number representing its relative position in the data block zone, thus an integer number in the range $[0, M[$, being M the total number of data blocks.

Managing the file system requires to know which inodes and data blocks are free and to keep this information stored in the disk. The list of free inodes is totally stored in the superblock. The list of free data blocks is partially stored in the superblock and part in a dedicated sequence of blocks at the of the disk, the **reference table**.

4.1 List of free inodes

At any given time, there are inodes in use, while others are available to be used (free). When a new file is to be created, a free inode must be assigned to it. It is therefore necessary to:

- define a policy to decide which free inode should be used when one is required;
- define and store in the disk a data structure suitable to implement such policy.

In *sofs20*, for each inode in the inode table there is a bit that represents its in-use state, either free (value 0) or in-use (value 1). These bits are stored in the superblock, in a field called **free inodes bitmap**.

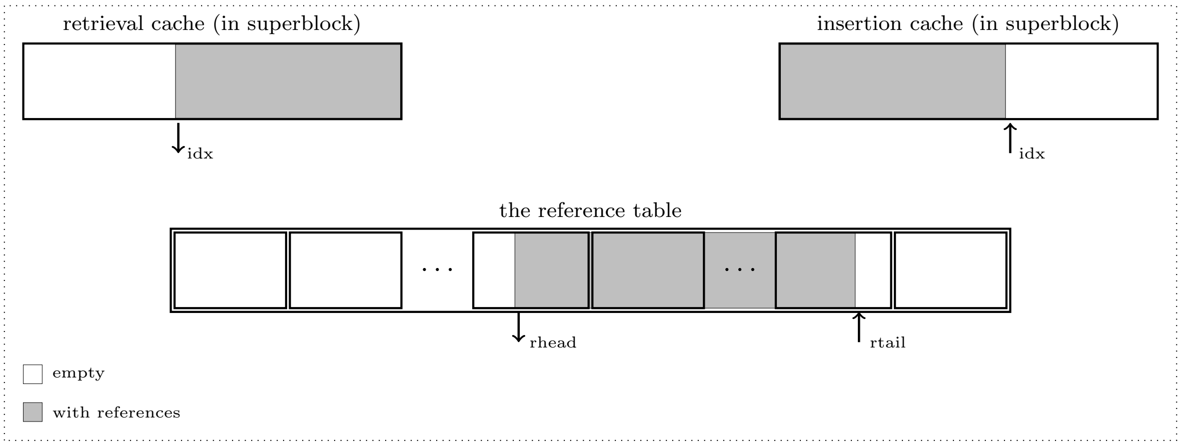
The operation of looking for a free inode (corresponding bit in the bitmap at zero) is called *inode allocation*. There is not specific order by which inodes are allocated. However, in order to introduce a kind of rotativity in the allocation process, the bits in the bitmap are considered as forming a circular bit chain and the search for a 'free' bit starts in the position circularly next to the last one allocated. A field in the superblock holds this bit position, being updated by the inode allocation operation.

4.2 List of free data blocks

Similar to what was stated for inodes, at any given moment, some data blocks will be in use (for example, by files stored in the disk), while others will be available (free). Thus, again, it is necessary:

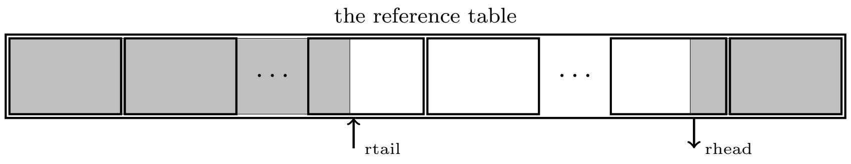
- to define a policy to decide which free data block should be used when one is required;
- to define and store in the disk a data structure suitable to implement such policy;

In *sofs20*, a FIFO policy is adopted, meaning that the first free data block to be used is the oldest one in a list. The implementation of this FIFO is based in a list of references to free data blocks, stored in the superblock and some dedicated blocks (the **reference table** at the end of the disk), as illustrated by the next figure.


retrieval cache (in superblock)
insertion cache (in superblock)
idx
idx
the reference table
rhead
rtail
empty
with references

The list of free data blocks can be seen as a sequence of sub-sequences of references. The first sub-sequence is stored in the **retrieval cache**, and represents the oldest references in the list, so the first to be used. At a given moment, this cache may be partially empty, meaning that some references (necessarily at the begining) were already retrieved. An index (`idx` in the figure) points to the first cell with a reference. The last sub-sequence is stored in the **insertion cache**, and represents the most recent references in the list, so the last to be used. At a given moment, this cache may be partially filled, meaning that some references (at the begining) were already inserted. An index (`idx` in the figure) points to the first empty cell.

The remaining of the references to free data blocks are stored in the reference table. In general, at a given moment, only part of this table will be filled, as illustrated in the figure (gray area). Two fields in the superblock (`rt_start` and `rt_size`) delimit the region of the disk with the reference table. Another field (`reftable`), composed of three subfields (`blk_idx`, `ref_idx`, and `count`), stores the state of the reference table. The reference table is managed in a circular way, meaning the position after the last one is index 0. Thus, it may happen that the occupied region resembles that of the next figure (gray area).



Every empty cell, either in the caches or in the reference table, stores a special value, referred to as the `BlockNullReference`.

4.3 List of blocks used by a file (inode)

Blocks are not shared among files, thus, an in-use block belongs to a single file. The number of blocks required by a file to store its information is given by

$$N_b = \texttt{roundup}(\frac{\texttt{size}}{\texttt{BlockSize}})$$

where `size` and `BlockSize` represent, respectively, the size in bytes of the file and the size in bytes of a block.

N_b can be very high. Assuming, for instance, that the block size in bytes is 1024, a 2 GByte file needs two million blocks to store its data. But, N_b can also be very small. In fact, for a 0 bytes file, N_b is equal to zero. Thus, it is impractical that all the blocks used by a file are contiguous in disk. The data structure used to represent the sequence of blocks used by a file must be flexible, both in size and location, growing as necessary.

The access to the file data is in general not sequencial, but instead random. Consider for instance that, in a given moment, one needs to access byte index j of a given file. What is the block that stores such byte? Dividing j by the block size in bytes, one get the index of the block, in the file point of view, that contains the byte. But, what is the number of the block in the disk point of view? The data structure should allow for an efficient way of finding that number.

In *sofs20*, the defined data structure is dynamic and allows for a quick identification of any data block. Each inode allows to access a dynamic array, denoted d, that represents the sequence of blocks used to store the data of the associated file. Being `BlockSize` the size in bytes of a block, $d[0]$ stores the number of the block that contains the first `BlockSize` bytes, $d[1]$ the next `BlockSize` bytes, and so forth.

Array d is not stored in a single place. The first 4 elements are stored directly in the inode, in a field named `d`. The next elements, when they exist, are stored in an indirect and double indirect way. Inode field `i1` represents the first 3 elements of an array i_1 ($i_1[0] \cdots i_1[7]$), each element being used to indirectly extend array d. Being `RPB` the number of references to blocks that can be stored in a block, $i_1[0]$ is the number of the data block that extends array d from $d[8]$ to $d[\texttt{RPB} + 7]$, $i_1[1]$ is the number of the data block that extends array d from $d[\texttt{RPB} + 8]$ to $d[2 * \texttt{RPB} + 7]$, and so forth.

For bigger files, the double indirect approach is used. Inode field `i2` represents an 8-elements array i_2 ($i_2[0] \cdots i_2[7]$), each element being used to indirectly extend array i_1. Thus, $i_2[0]$ is the number of the block that extends array i_1 from $i_1[8]$ to $i_1[\texttt{RPB} + 7]$, $i_2[1]$ is the number of the block that extends array i_1 from $i_1[\texttt{RPB} + 8]$ to $i_1[2 * \texttt{RPB} + 7]$, and so forth.

Pattern `BlockNullReference` is used to represent a non-existent block. For example: if `d[1]` is equal to `BlockNullReference`, the file does not contains block index 1; if `i1[0]` is equal to `BlockNullReference`, it means $d[4]$ to $d[\texttt{RPB} + 7]$ are equal to `BlockNullReference`; if `i2[0]` is equal to `BlockNullReference`, it means $i_1[2]$ to $i_1[\texttt{RPB} + 7]$ are equal to `BlockNullReference`, and thus $d[8 * \texttt{RPB} + 4]$ to $d[\texttt{RPB}^2 + 8 * \texttt{RPB} + 7]$ are equal to `BlockNullReference`.

A file can contain holes, meaning that a reference to a data block may be equal to `BlockNullReference` while another one afterwards not. A `BlockNullReference` that is covered by the size of a file represents a block of zeros.

4.4 Directories

A **directory** is a special type of file that allows to implement the typical hierarchical access to files, the so-called *paths*. A directory is composed of a set of **directory entries**, each one associating a name to an inode. It is assumed that the root directory is associated to inode number 0.

On *sofs20*, a directory entry is a data structure composed of a fixed-size array of bytes, used to store the name of a file, and an inode reference, used to indicate the inode associated to that file. Thus, a directory can be seen as an array of fixed-size cells, each one with capacity to store a directory entry. The data structure is defined such that a data block stores an integer number of directory entries.

The size of a directory must be equal to the size in bytes that its entries occupy. Since the entries have a fixed size, this means that the number of entries in a directory can be obtained by dividing its size in bytes by the size of an entry.

It also implies that when an entry is cleaned (as a result of removing a file), it may be necessaty to rewrite the directory in order to eliminate the resulting hole. The way to do this in *sofs20* is transferring the last entry to that hole. As a consequence, the last used block may become empty, in which case it must be released.

Upon creation, a directory has a data block assigned to it, being the first two entries occupied by two special entries. They are named, `"."` e `".."`', the former representing the directory itself and the latter representing the parent directory.

5 Formatting

The formatting operation must fill the blocks of a disk in order to make it an empty *sofs20* well-formatted device. It is the operation to be performed before the disk can be used.

In a newly formatted disk, there is one inode in-use, associated to the root directory, while all the others are free. The root directory is assigned inode number 0. The parent of the root directory is the root itself. The free inodes bitmap in the superblock must be filled to reflect this state.

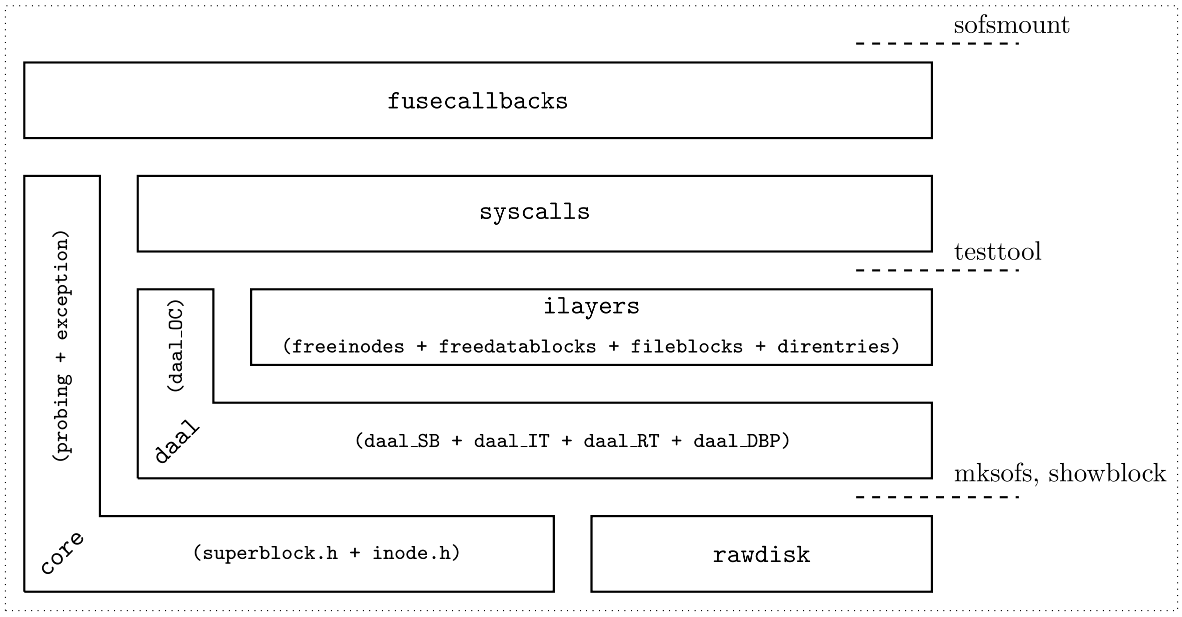
In a newly formatted disk, there is one data block in-use, while all the others are free. Data block number 0 is used by the root directory, to store the entries `"."` and `".."`. The list of free data blocks must start in data block number 1 and go sequentially to the last. The first elements of this list must be stored in the retrieval cache of the superblock; the remaining must be stored in the reference table.

Thus the formating operation must:

- Choose the appropriated values for the number of inodes, the number of data blocks, and the number of blocks for the reference table, taking into consideration the number of inodes requested by the user and the total number of blocks of the disk.
- Fill in all fields of the superblock, taking into consideration the state of a newly formatted disk. The insertion cache should be empty and the retrieval cache should be filled (totally if possible).
- Fill in the table of inodes, knowing that inode number 0 is used by the root and that all other inodes are free.
- Fill in the reference table.
- Fill in the root directory.
- Fill in with zeros all free data blocks, if such is required by the formatting command.

6 Code structure

Supporting code is structured in layers, as depicted in the following figure.



rawdisk – This layer implements the physical access to the disk.

core – This layer implements a debugging library (`probing`), the exception handling (`exception`) and defines the *sofs20* data types (`superblock`, `inode` and `direntry`).

daal – daal stands for disk access abstraction layer and implements the access to the different regions of a *sofs20* disk (superblock, inode table, data block pool and reference table); it also includes functions to open and close the disk.

ilayers – This layer implements a set of intermmediate functions that facilitataes the implementation of the system calls. It is composed of 3 modules: management of the free lists (freelists); access to the blocks of a file (fileblocks); and manipulation of directories (direntries).

syscalls – System calls are the entry points into the operating system. These are the *sofs20* version of the file system calls.

fusecallbacks – FUSE imposes a format to register file system calls to the operating system. This layer implements the interface with the syscalls layer.

mksofs – This is the (executable) formatting tool. It is the first program that have to be developed. Only upon formatting a disk it can be seen as a *sofs20* one.

showblock – This is a (executable) tool to visualize blocks. An option may be used to define how to interpret the blocks (superblock, sequence of inodes, sequence of directory entries, ...).

testtool – This is a (executable) tool to test the intermmediate layer functions during development.

sofsmount – This is the main tool to register the *sofs20* file system into the operating system (Linux).