Advanced Operating Systems (and System Security)
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Virtual file system

1. VFS basic concepts
2. VFS design approach and architecture
3. Device drivers
4. The Linux case study

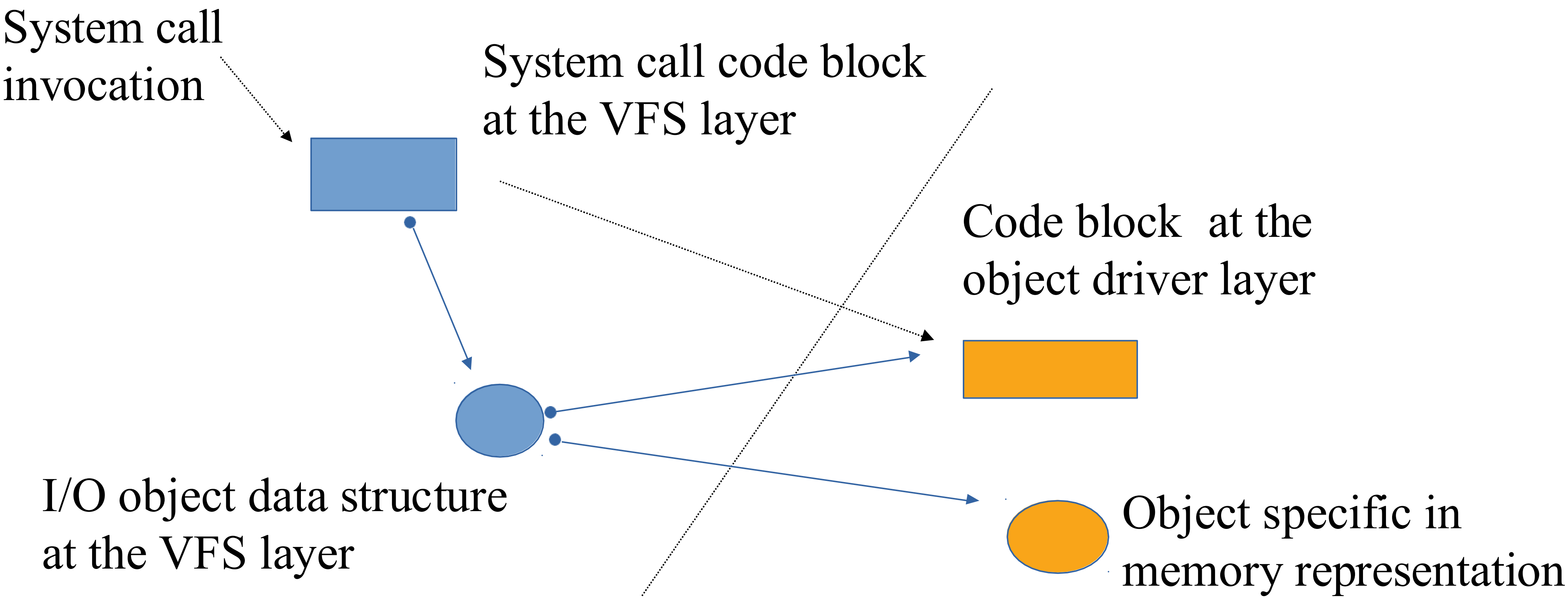
File system representations

- In RAM
  - Partial/full representation of the current structure and content of the File System (namely of its I/O objects)
- On device
  - (non-updated) representation of the structure and of the content of the File System
- Data access and manipulation
  - <u>FS independent part (VFS)</u>: interfacing-layer towards other subsystems within the kernel
  - <u>FS dependent part</u>: data access/manipulation modules targeted at a specific file system type

Connections

- Any FS object (dir/file) is represented in RAM via specific data structures
- These data structures are generic (VFS style)
- The object <u>keeps a reference to the module instances</u> for its own operations
- The reference is accessed in a File System independent manner by any overlying kernel layer → the virtual file system (VFS)
- This is achieved thanks to multiple different instances of a same function-pointers' (drivers') table

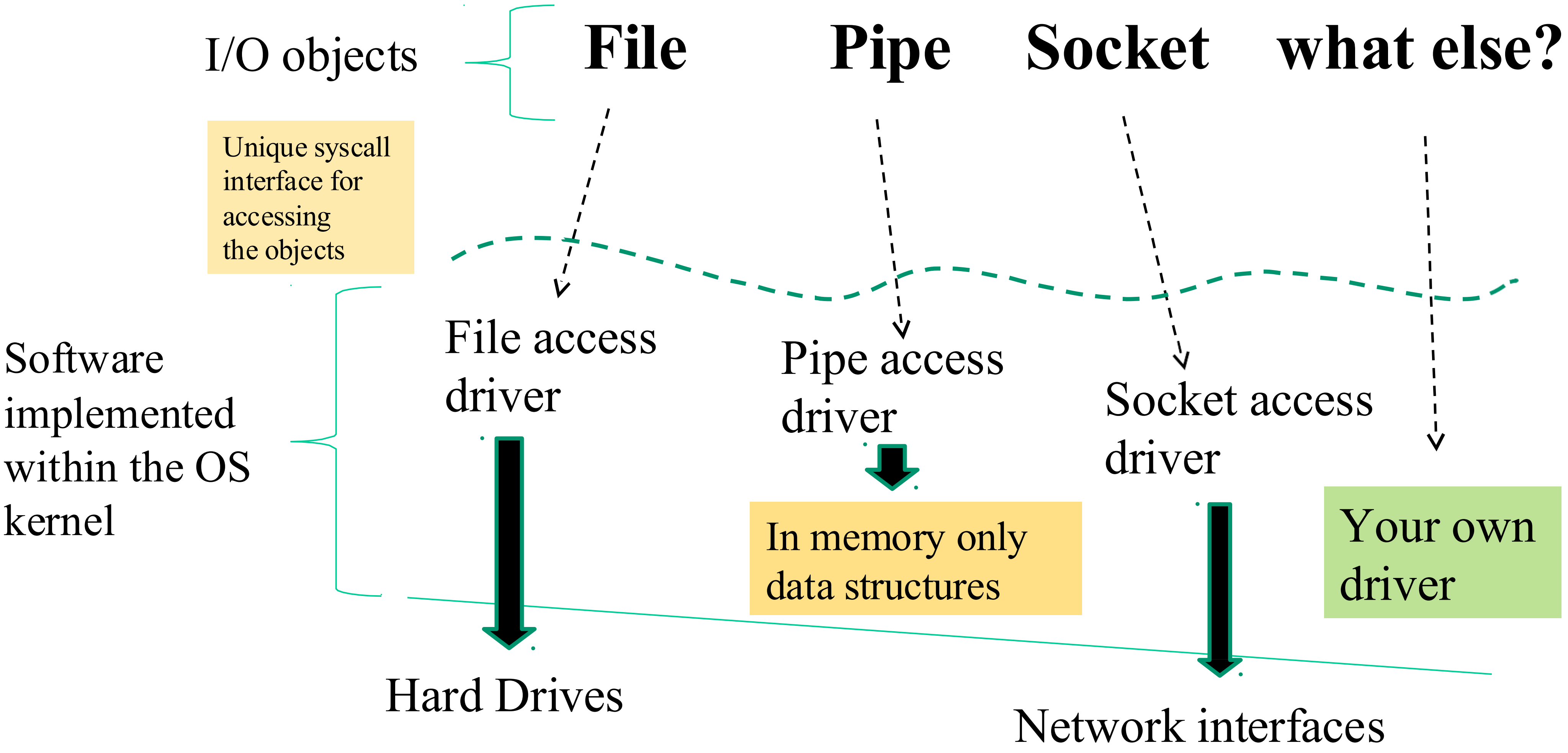
Architectural hints



VFS hints

- **Devices can be seen as files**
- What we drive, in terms of state update, is the structure used to represent the device in memory
- Then we can also reflect such state somewhere out of memory (on a hardware component)
- Classical devices we already know of
  - ✓ Pipes and FIFO
  - ✓ sockets

An overall scheme



Lets’ focus on the true files example

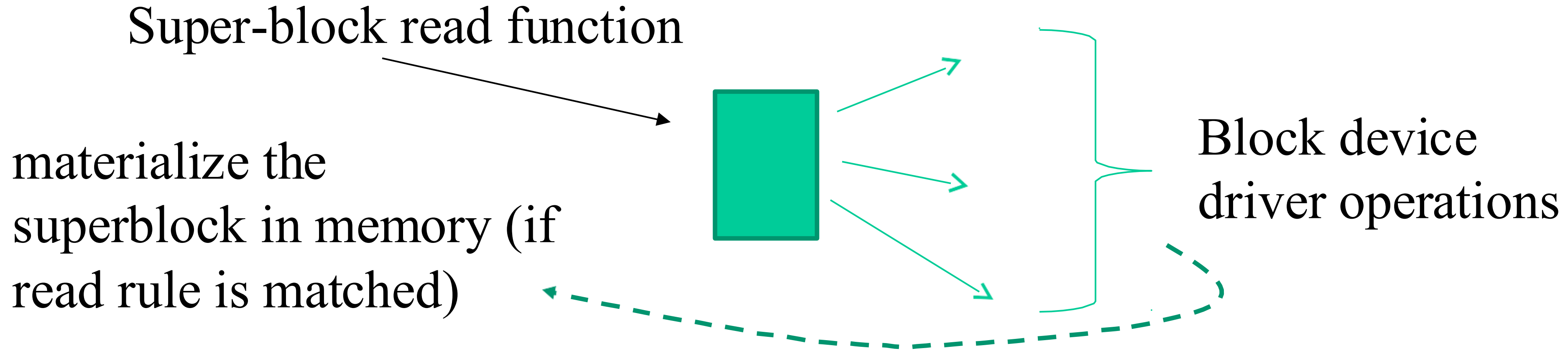
- Files are backed by data on a hard drive
- What **software modules do we need** for managing files on that hard drive in a well shaped OS-kernel??
  1. A function to read the device superblock for determining what files exist and where their data are
  2. A function to read device blocks for bringing them into a buffer cache
  3. A function to flush updated blocks back to the device
  4. A set of functions to actually work on the in-memory cached data and to trigger the activation of the above functions

Block vs char device drivers

- The first three points in the previous slide are linked to the notion of block device and **block-device driver**
- The last point (number 4) is linked to the notion of char device and **char-device driver**
- These drivers are essentially tables of function pointers, pointing to the actual implementation of the operations that can be executed on the target object
- **The core point is therefore how to allow a VFS supported system call to determine what is the actual driver to run when a given system call is called**

File system types in Linux

- To be able to manage a file system type we need a **superblock read function**
- This function relies on the block-device driver of a device to instantiate the corresponding file system superblock in memory
- Each file system type has a superblock that needs to match its read function

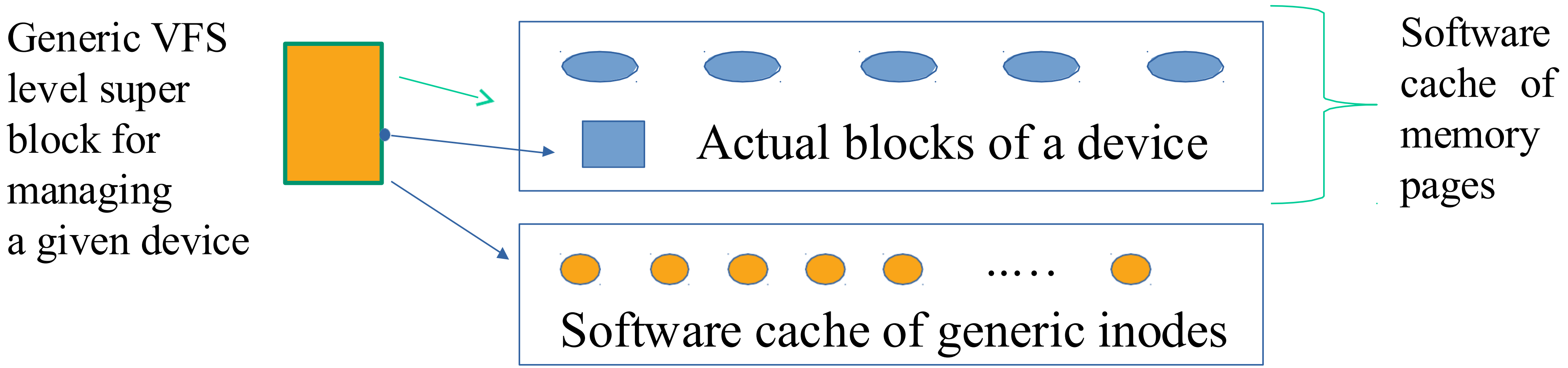


Intermediary software – the buffer/page cache

- It allows the superblock read function (and other driver functions) to read the block-device <u>passing through a generic superblock data structure</u>

- In the essence, the superblock data structure is the access data structure for a cache of blocks of a given device

- The cached blocks are indexed (we can operate at a given index)



Actual architecture (i)

- The super-block read function can exploit kernel level API in order to setup the VFS portion of the superblock, like:
  - mount_bdev(), which mounts a file system stored on a block device
  - mount_single(), which mounts a file system that shares an instance between all mount operations
  - mount_nodev(), which mounts a file system that is not on a physical device

Actual architecture (ii)

- All the previously listed functions will take a call-back function as a parameter, which will be called in order to finalize the super-block materialization
- This will be done in file-system specific manner
- This function typically just **<u>fills</u>** the super-block content

Super-block read function

Fill callback-function

mount_bdev()

This intermediate functions sets up the page cache

The mount_bdev(...) signature

```
struct dentry *mount_bdev(struct file_system_type *fs_type,
                          int flags,
                          const char *dev_name,
                          void *data,
                          int (*fill_super)(struct super_block *, void *, int))
```

Name of the device for which the page cache needs to be setup

Name of the fill callback-function

Before the callback takes place the VFS generic superblock is allocated

The “magic number”

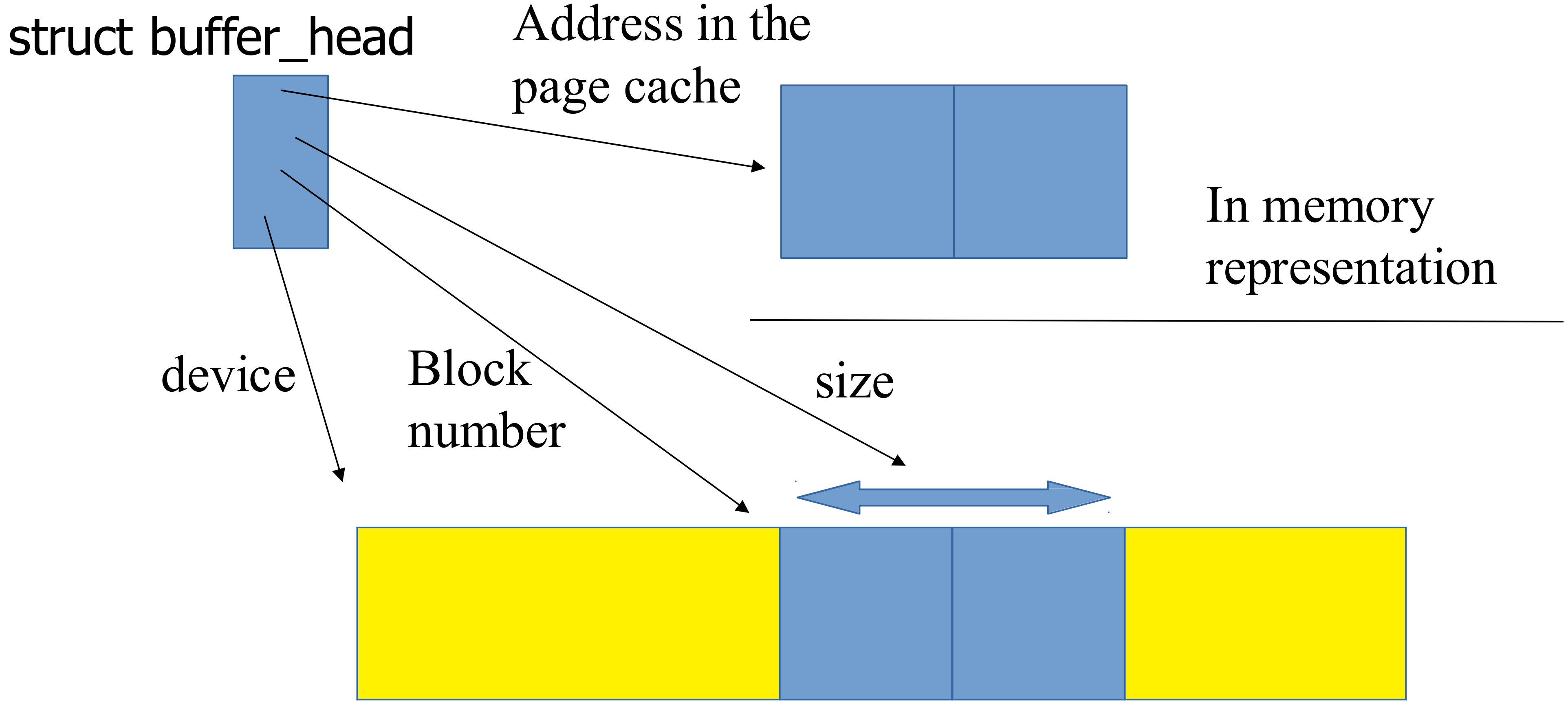
- In the end a block device is anyhow a sequence of bytes
- We can read this sequence and check whether it contains (e.g. in the super block) some identifying code we are expecting
- If this is not true, then we can abort the instantiation of the superblock in memory
- For Posix the command “`file [-s] /dev/{device-name}`” allows to extract the magic number (the code) and reports the information on the actual file system type kept by a device

Buffer/page cache details

- It is simply a memory area where we keep blocks of devices for managing operations (read/write)

- Linux offers the struct buffer_head data structure to manage these blocks, which is made by the following main data
  - *b_data, pointer to a memory area where the data was read from or where the data must be written to
  - b_size, buffer size
  - *b_bdev, the block device
  - b_blocknr, the number of the block on the device that has been loaded or needs to be saved on the device (essentially this is an index)

A scheme


struct buffer_head
Address in the page cache
In memory representation
device
Block number
size

Getting/putting device blocks

__bread() → reads a block with the given number and given size in a buffer_head structure; returns a pointer to the buffer_head structure (NULL on error)

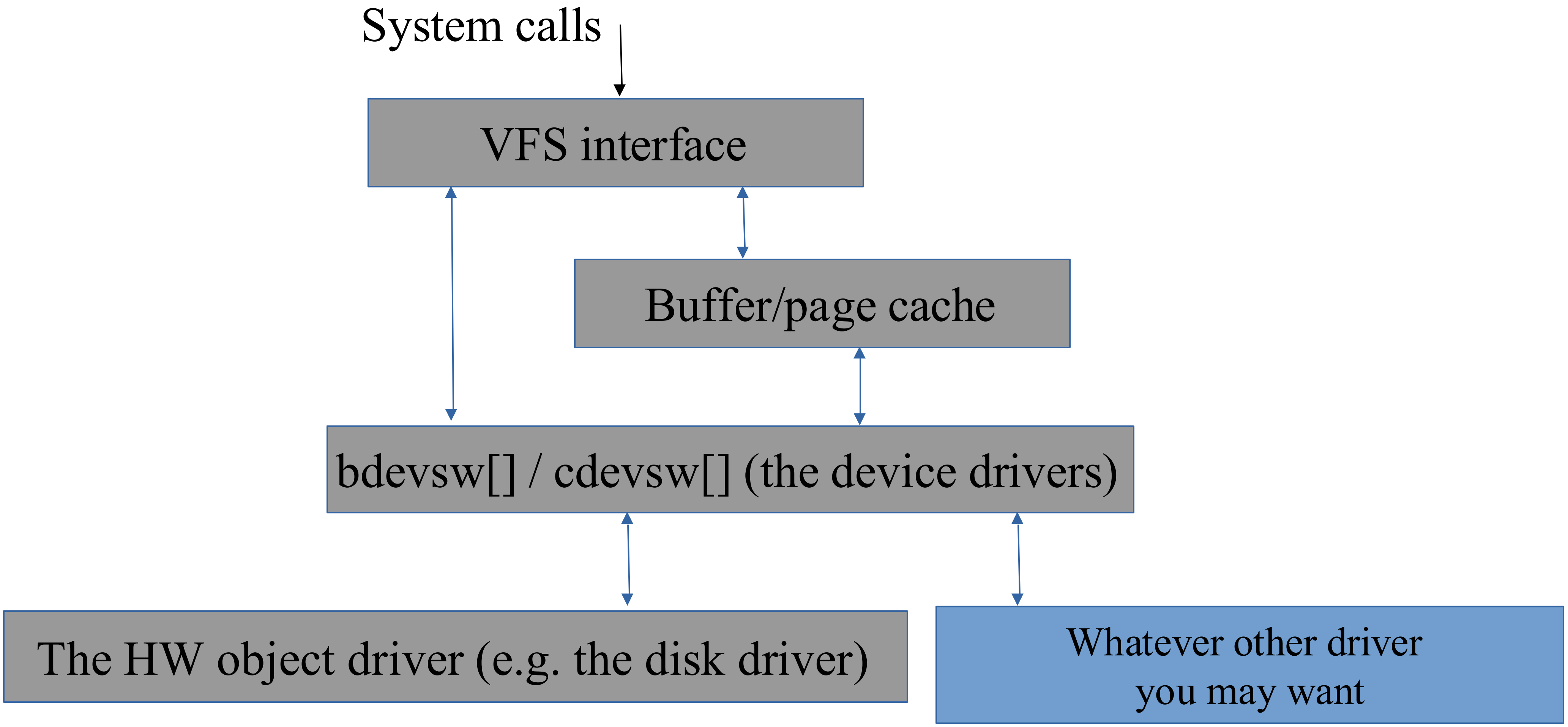
sb_bread() → the size of the block to read is taken from the superblock;

mark_buffer_dirty() →marks the buffer as dirty (sets the BH_Dirty bit); the buffer will be written to the hard drive at a later time (from time to time the bdflush kernel thread, or more recently **kworkers**, wake up and write the buffers to disk);

brelse() → frees up the memory used by the buffer, after it has previously written the buffer on disk if needed;

map_bh() → associates the buffer-head with the corresponding sector (block)

The overall layering



Regular files vs devices

- Any regular file can be seen as a block device hosting a file system

- To correctly associate this role to the file we will need to mount the corresponding file system using a specific block-device driver

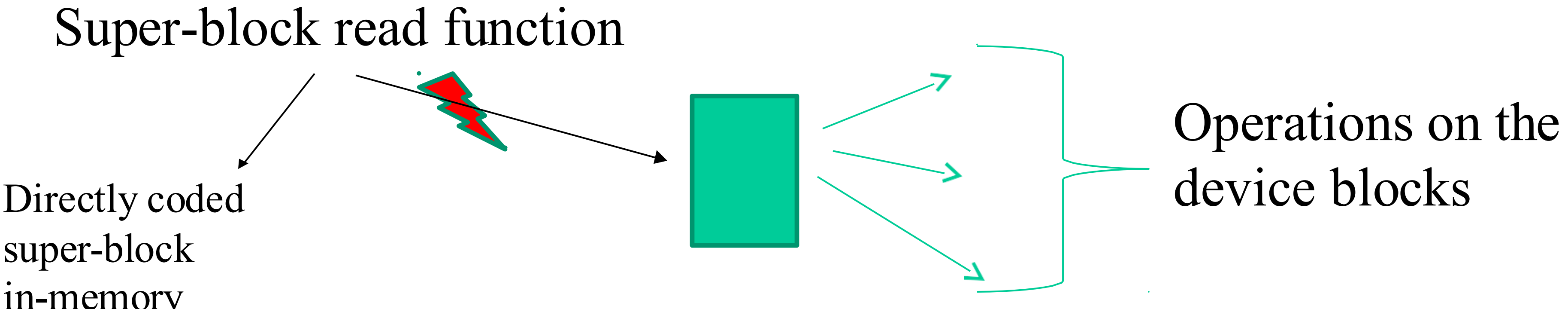
- This is the -o loop driver

- This enables passing through the VFS architecture multiple times (in terms of actual actions executed when system calls are called)

- <u>We can therefore create a stack of file system devices</u>

What about RAM file systems?

- These are file systems whose data disappear at system shutdown
- On the basis of what described before, these file systems **<u>do not have an on-device</u>** representation
- Their superblock read function does not really need to read blocks from a device
- It typically relies on in-memory instantiation of a fresh superblock representing the new incarnation of the file system



RAM file system fill example – from kernel 5

```
static int ramfs_fill_super(struct super_block *sb, struct fs_context *fc){

        struct ramfs_fs_info *fsi = sb->s_fs_info;
        struct inode *inode;

        sb->s_maxbytes             = MAX_LFS_FILESIZE;
        sb->s_blocksize            = PAGE_SIZE;
        sb->s_blocksize_bits       = PAGE_SHIFT;
        sb->s_magic                = RAMFS_MAGIC;
        sb->s_op                   = &ramfs_ops;
        sb->s_time_gran            = 1;

        inode = ramfs_get_inode(sb, NULL, S_IFDIR | fsi->mount_opts.mode, 0);

        sb->s_root = d_make_root(inode);
        if (!sb->s_root)
                return -ENOMEM;

        return 0;
}
```

Here we are simply allocating other two data structures in memory, namely the <u>inode</u> and the <u>dentry</u>

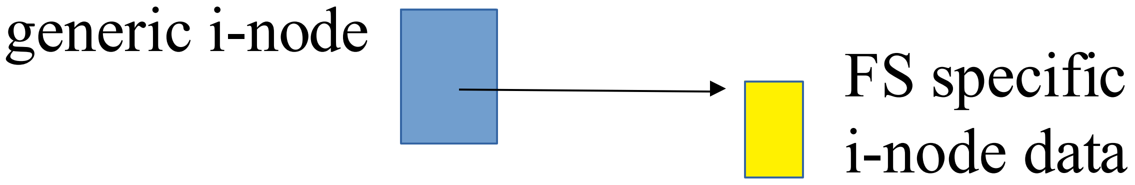
Baseline API for i-nodes and dentry

struct inode *new_inode(struct super_block *sb) → we simply allocate a generic i-node data structure making it refer to a generic super-block data structure

struct dentry *d_make_root(struct inode *root_inode) → we simply create a generic dentry data structure that will figure out as the root one, and we link it to the root-inode

The root-inode can be populated in a FS specific manner (e.g. upon file system mount) reading an actual i-node from a device

It is typical that these data structures will keep generic fields used by the VFS plus some field (e.g. a pointer) usable for linking FS specific data



Baseline structure of a superblock-fill function

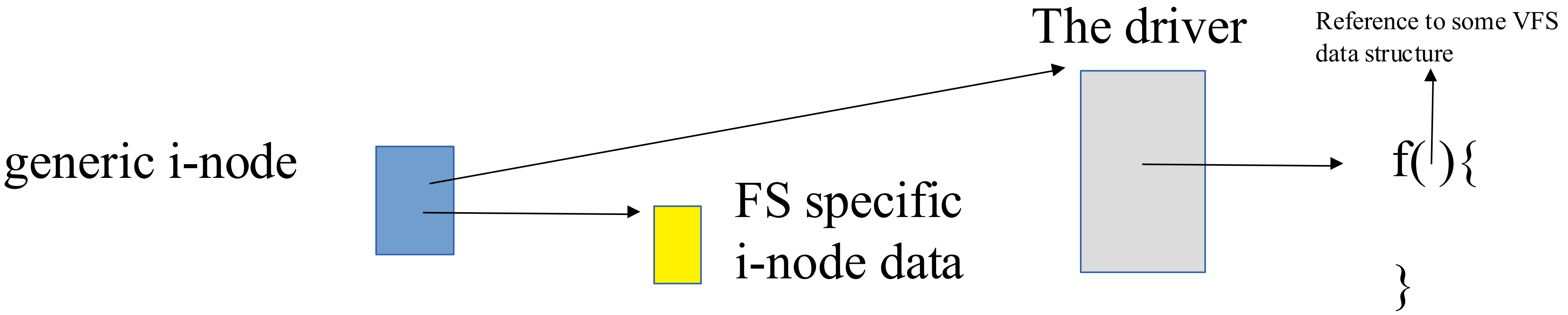
```
int <FS_name>_fill_super(struct super_block *sb, ...){
        ……
        bh = sb_bread(….); //read the FS specific superblock from device
        … // populate the FS-specific structure in memory
        brelse(bh); //release the page-cache kept data (not mandatory)
        root_inode = <FS_name>_iget(sb,0) //get the root inode (generic + FS specific data)
        …
        d_make_root(root_inode);
        …
}
```

index 0 is typical of the root-inode of any file system

```
inode* <FS_name>_iget(struct super_block *sb, int inode_index){
        ……
        inode_buffer = … // allocate a generic inode
        …
        bh = sb_bread(….); //read the FS-specific inode with given index from device
        inode_buffer → <field> = bh → <something>;

        brelse(bh); //release the page-cache kept data (not mandatory)
        …
}
```

Data structures vs drivers

- A driver for operations on a data structure in the VFS is a table of function pointers
- When one of the operations is invoked we can pass as parameter the address of the generic data structure
- From this address the driver can access (more or less directly) the FS specific data
- As mentioned before a data structure in the VFS keeps a reference to the actual driver for its operations



The VFS startup in Linux

- This is the minimal startup path
  - ➢`vfs_caches_init()`
    - ➢`mnt_init()`
      - ✓`init_rootfs()`
      - ✓`init_mount_tree()`

This tells we are instantiating at least one FS type – the **Rootfs**

- Typically, at least two different FS types are supported
  - ➢Rootfs (file system in RAM)
  - ➢Ext (in the various flavors)
- However, in principles, the Linux kernel could be configured such in a way to support no FS
- In this case, any task to be executed needs to be coded within the kernel (hence being loaded at boot time)

"File system types" data structures

- The description of a specific FS type is done via the structure `file_system_type` defined in `include/linux/fs.h`
- This structure keeps information related to
  - ➢ The actual file system type
  - ➢ A pointer to a function to be executed upon mounting the file system (superblock-read)

Here it is

```
struct file_system_type {
    const char *name;
    int fs_flags;
    …
    …
    struct dentry *(*mount) (struct file_system_type *,
                                    int, const char *, void *);
    void (*kill_sb) (struct super_block *);
    struct module *owner;
    struct file_system_type * next;
    …
    …
}
```

Beware this!!

Rootfs and basic fs-type API (i)

- Upon booting, a compile time defined instance of the structure `file_system_type` keeps meta-data for the **Rootfs**
- <u>This file system only lives in main memory</u> (hence it is re-initialized each time the kernel boots)
- The associated data act as initial “inspection” point for reaching additional file systems (starting from the root one)
- We can exploit kernel macros/functions in order to allocate/initialize a `file_system_type` variable for a specific file system, and link it to a proper list
- The linkage one is

```
int register_filesystem(struct file_system_type *)
```

Rootfs and basic fs-type API (ii)

- Allocation of the structure keeping track of **Rootfs** is done statically (compile time)
- The linkage to the list is done by the function `init_rootfs()`
- The name of the structured variable is `rootfs_fs_type`

```
int __init init_rootfs(void){
 …
 register_filesystem(&rootfs_fs_type);
 …
}
```

let's check with the details →

Kernel 4.xx instance

```
static struct file_system_type rootfs_fs_type = {
        .name           = "rootfs",
        .mount          = rootfs_mount,
        .kill_sb        = kill_litter_super,
};

int __init init_rootfs(void)
{
        int err = register_filesystem(&rootfs_fs_type);

        if (err)
                return err;

        if (IS_ENABLED(CONFIG_TMPFS) && !saved_root_name[0] &&
                (!root_fs_names || strstr(root_fs_names, "tmpfs"))) {
                err = shmem_init();
                is_tmpfs = true;
        } else {
                err = init_ramfs_fs();
        }

        if (err)
                unregister_filesystem(&rootfs_fs_type);

        return err;
}
```

A few modifications in the structure of init_rootfs() are in kernel 5

User level checks on the managed file systems

- The file system currently manageable by the kernel can be listed by accessing the `/proc/filesystems` file

- The `nodev` field in the output tells that a specific file system is handled as a in-memory one, e.g.:

```
nodev   sysfs
nodev   rootfs
nodev   ramfs
……
nodev   proc
……
ext3
ext4
```

- Among the `nodev` file systems we typically find `sys` and `proc`

Creating and mounting the Rootfs instance

- Creation and mounting of the **Rootfs** instance takes place via the function `init_mount_tree()`
- The whole task relies on manipulating 4 data structures
  - `struct vfsmount`
  - `struct super_block`
  - `struct inode`
  - `struct dentry`
- The instances of `struct vfsmount` and `struct super_block` keep file system proper information (e.g. in terms of relation with other file systems)
- The instances of `struct inode` and `struct dentry` are such that one copy exits for any file/directory of the specific file system

More details on the data structures

`struct vfsmount` → Tells, e.g., what is the parent FS

`struct super_block` → Keeps basic FS metadata

`struct inode` → Keeps per I/O object metadata

`struct dentry` → Tells what is a name for an I/O object along the FS hierarchy

The structure vfsmount

```
struct vfsmount {
    struct mount *mnt;     /* points to the mount tree node */
    struct dentry *mnt_root;
};
```

vfsmount->mnt->mnt_parent

Randstruct (see CONFIG_GCC_PLUGIN_RANDSTRUCT)

- Access to any field of a structure is based on compiler rules when relying on classical ‘.’ or ‘–>’ operators

- Machine code is generated in such a way to correctly displace into the proper field

- `__randomize_layout` introduces a reshuffle of the fields, with the inclusion of padding

- This is done based on pseudo random values selected at compile time

- Hence an attacker who discovers the address of a structure but does not know what’s the randomization, will not be able to easily trap into the target field

- Linux usage (stable since kernel 4.8):
  - on demand (via `__randomize_layout`)
  - by default on any **struct** only made by function pointers (a driver!!!)
  - the latter can be disabled with `__no_randomize_layout`

The structure super_block – Kernel 5 example

```
struct super_block {
     struct list_head    s_list;        /* Keep this first */
     dev_t               s_dev;         /* search index; _not_ kdev_t */
     …
     unsigned long       s_blocksize;
     loff_t              s_maxbytes;    /* Max file size */
     struct file_system_type  *s_type;
     const struct super_operations *s_op;
     …
     unsigned long       s_magic;
     struct dentry       *s_root;
     …
     struct list_head    s_mounts; /* list of mounts */
     struct block_device *s_bdev;
     …
     void            *s_fs_info;    /* Filesystem private info */
     …
     const struct dentry_operations *s_d_op; /* default d_op for dentries */
     …
     struct user_namespace *s_user_ns;
     …
} __randomize_layout;
```

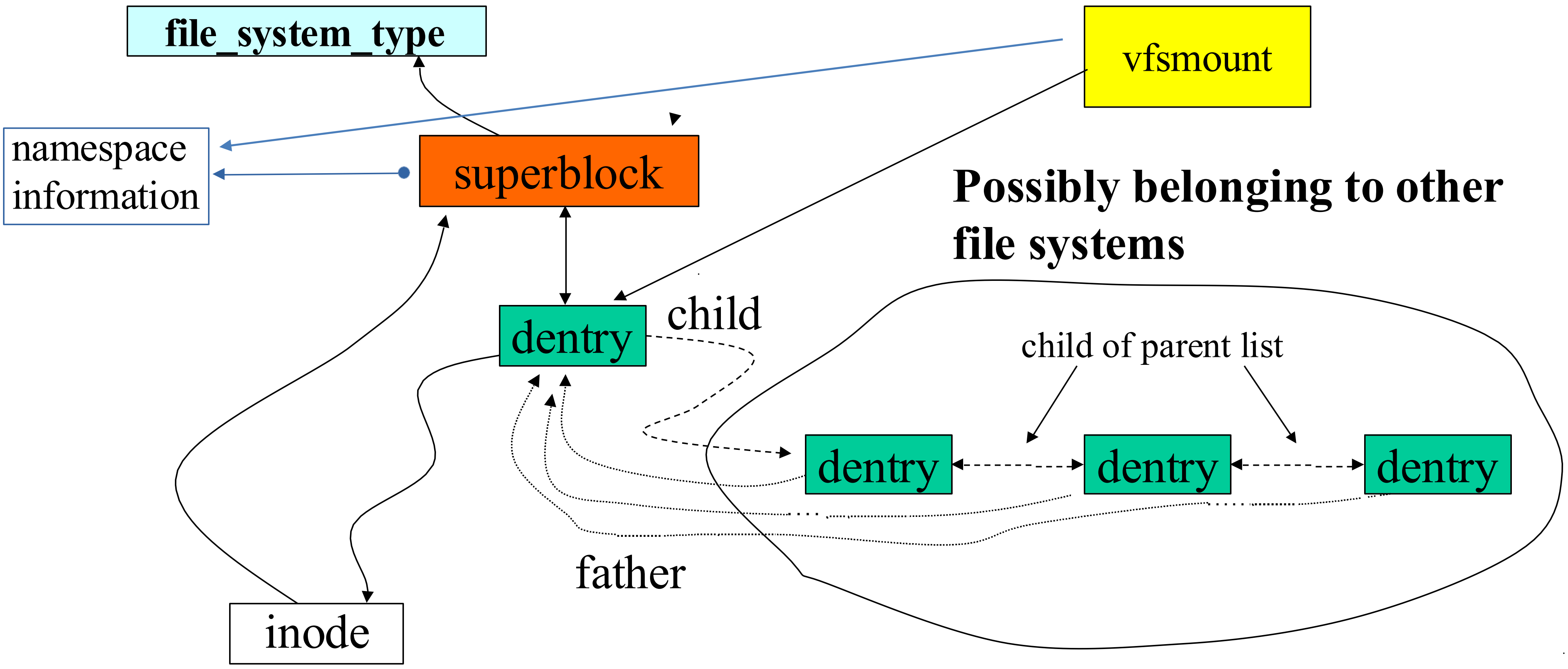
The structure dentry – Kernel 5 example

```
struct dentry {
    …
    struct dentry *d_parent;   /* parent directory */
    struct qstr d_name;
    struct inode *d_inode;  /* Where the name belongs to */
    unsigned char d_iname[DNAME_INLINE_LEN];    /* small names */
    …
    const struct dentry_operations *d_op;
    struct super_block *d_sb;  /* The root of the dentry tree */
    …
    void *d_fsdata;          /* fs-specific data */
    …
    struct list_head d_child;  /* child of parent list */
    struct list_head d_subdirs;   /* our children */
    …
} __randomize_layout;
```

The structure inode – Kernel 6 example (with removed fields)

```
struct inode {
    umode_t                         i_mode;
    unsigned int                    i_flags;
    kuid_t                          i_uid;
    kgid_t                          i_gid;
    unsigned int                    i_nlink;
    loff_t                          i_size;
    struct super_block             *i_sb;

    /*
     * inode_operations:
     *   - For regular files: metadata ops (getattr, setattr)
     *   - For directories: directory operations (lookup, mkdir, rmdir, etc.)
     */
    const struct inode_operations *i_op;

    /*
     * file_operations:
     *   - For regular files: read/write/mmap
     *   - For directories: readdir()/iterate()
     */
    const struct file_operations  *i_fop;

    struct address_space           *i_mapping;

    atomic_t                        i_count;
    atomic_t                        i_writecount;

    void                           *i_private;

   __randomize_layout
};
```

Overall scheme



Initializing the Rootfs instance

- The main tasks, carried out by `init_mount_tree()`, are

    1. Allocation of the 4 data structures for **Rootfs**
    2. Linkage of the data structures
    3. Setup of the name "/" for the root of the file system
    4. <u>Linkage between the IDLE PROCESS and Rootfs</u>

- The first three tasks are carried out via the function `do_kern_mount()` or `vfs_kern_mount()`, which are in charge of invoking the execution of the super-block read-function for **Rootfs**

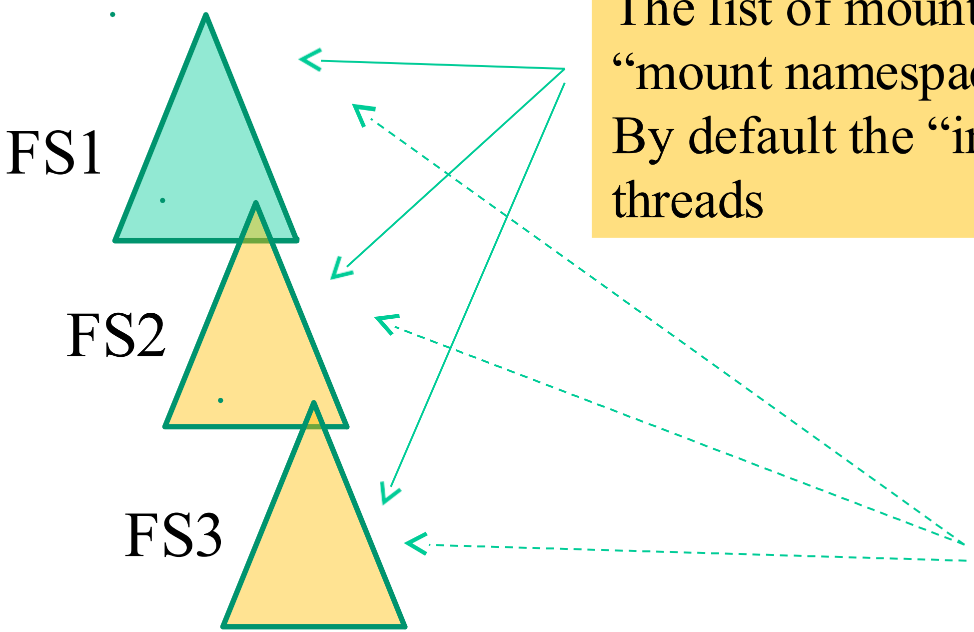
- Linkage with the IDLE PROCESS occurs via the functions `set_fs_pwd()` and `set_fs_root()`

Mount tree setup – kernel 3 example

```
static void __init init_mount_tree(void){
    struct vfsmount *mnt;
    struct namespace *namespace;
    struct task_struct *p;

    mnt = do_kern_mount("rootfs", 0, "rootfs", NULL);
    if (IS_ERR(mnt))
        panic("Can't create rootfs");
    ………

    set_fs_pwd(current->fs, namespace->root,
               namespace->root->mnt_root);
    set_fs_root(current->fs, namespace->root,
               namespace->root->mnt_root);
}
```

…. very minor changes of this function are in kernel 4.xx/5.xx

FS mounting and namespaces



The list of mount points along the three is a so called "mount namespace"
By default the "initial namespace" is seen by active threads

We can make a thread start working with a new mount namespace which is initially a copy of another one

Moving to another mount namespace makes `mount/unmount` operations only acting on the current namespace (except if the mount operation is tagged with SHARED)

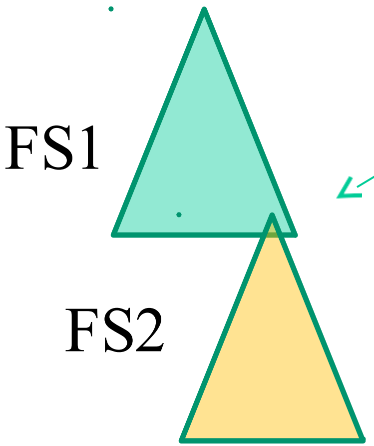
Actual system calls for mount namespaces

```
clone(... int flags ...)
```

CLONE_NEWNS

```
unshare(int flags)
```

An example of what we can do



We can mount FS2 after unsharing the mount namespace

All the threads that will leave in the newly generated mount namespace will be able to access data on FS2

this file system can become the root one for a container

Be careful to the command
switch_root newroot init

An overall view

Super operations

- Update superblock (and flush on device)
- Get superblock info (e.g. `statfs/fstatfs`)
- Manage i-nodes (read/write them from/ to superlock)

Dentry operations

- Allocate/deallocate dentries
- Link them to other data structures

i-node operations

- `creat/link/unlink/lookup`

The char-device driver

file operations

- Actual operations on data

struct file_operations (a bit more fields in very recent kernel versions)

```
sruct file_operations {
     struct module *owner;
     loff_t (*llseek) (struct file *, loff_t, int);
     ssize_t (*read) (struct file *, char *, size_t, loff_t *);
     ssize_t (*write) (struct file *, const char *, size_t, loff_t *);
     int (*readdir) (struct file *, void *, filldir_t);
     unsigned int (*poll) (struct file *, struct poll_table_struct *);
     int (*ioctl) (struct inode*, struct file *, unsigned int, unsigned long);
     int (*mmap) (struct file *, struct vm_area_struct *);
     int (*open) (struct inode *, struct file *);
     int (*flush) (struct file *);
     int (*release) (struct inode *, struct file *);
     int (*fsync) (struct file *, struct dentry *, int datasync);
     int (*fasync) (int, struct file *, int);
     int (*lock) (struct file *, int, struct file_lock *);
     ssize_t (*readv) (struct file *, const struct iovec *,
              `    unsigned long, loff_t *);
     ssize_t (*writev) (struct file *, const struct iovec *,
                   unsigned long, loff_t *);
     ssize_t (*sendpage) (struct file *, struct page *, int, size_t,
                        loff_t *, int);
     unsigned long (*get_unmapped_area)(struct file *, unsigned long,
                   unsigned long, unsigned long, unsigned long);
};
```

TCB vs VFS

- The TCB keeps the field `struct fs_struct *fs` pointing to information related to the current directory and the root directory for the associated process

- `fs_struct` was defined as follows in kernel 2.4

```
struct fs_struct {
 atomic_t count;
 rwlock_t lock;
 int umask;
 struct dentry * root, * pwd, * altroot;
 struct vfsmount * rootmnt, * pwdmnt,
              * altrootmnt;
};
```

3.xx/4.7 kernel style

See include/linux/fs_struct.h

```
struct fs_struct {
        int users;
        spinlock_t lock;
        seqcount_t seq;
        int umask;
        int in_exec;
        struct path root, pwd;
};
```

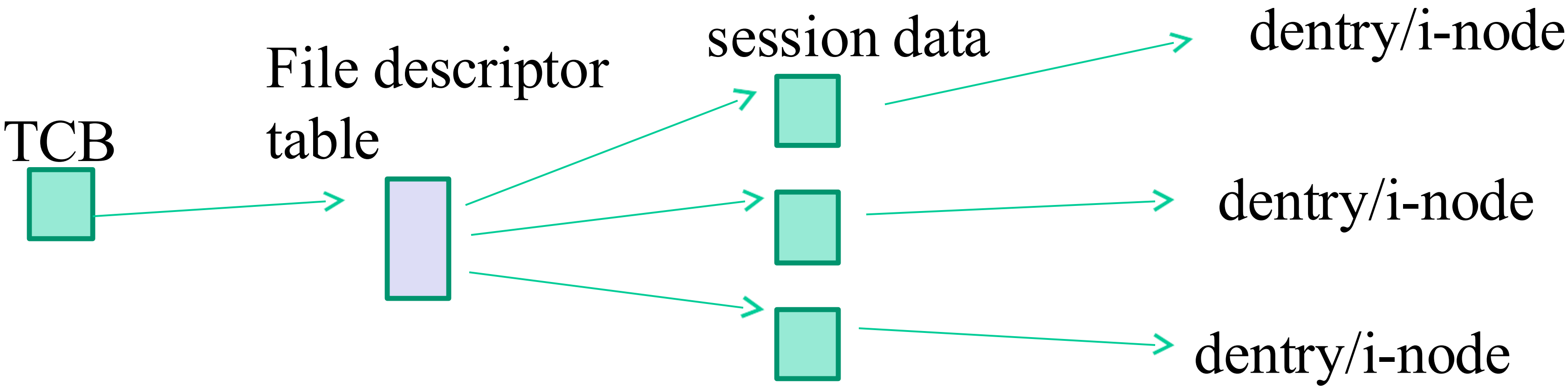
… and then 4.8 or later style

```
struct fs_struct {
    int users;
    spinlock_t lock;
    seqcount_t seq;
    int umask;
    int in_exec;
    struct path root, pwd;
} __randomize_layout;
```

Towards more security

File descriptor table

- It builds a **<u>relation between an I/O channel</u>** (a numerical ID code) and **<u>an I/O object</u>** we are currently working with along an I/O session
- It enables fast search of the data structures used to represent I/O objects and sessions
- The search is based on the channel ID as the key
- The actual implementation of the layout for the file descriptor table is system specific
- In Linux we have the below scheme



Classical file descriptor table (a few variations in very recent kernel versions)

- TCB keeps the field `struct files_struct *files` which points to the descriptor table

- This table is defined in as

```
struct files_struct {
  atomic_t count;
  rwlock_t file_lock;   /* Protects all the below                     members.
                        Nests inside tsk->alloc_lock */
  int max_fds; int
  max_fdset; int next_fd;
  struct file ** fd;
                        /* current fd array */
  fd_set *close_on_exec;
  fd_set *open_fds;
  fd_set close_on_exec_init;
  fd_set open_fds_init;
  struct file * fd_array[NR_OPEN_DEFAULT];
};
```

bitmap for close on exec

bitmap identifying open fds

The session data - struct file (the very classical shape)

```
struct file {
    struct list_head f_list;
    struct dentry    *f_dentry;
    struct vfsmount   *f_vfsmnt;
    struct file_operations    *f_op;
    atomic_t      f_count;
    unsigned int      f_flags;
    mode_t        f_mode;
    loff_t        f_pos;
    unsigned long    f_reada, f_ramax, f_raend, f_ralen, f_rawin;
    struct fown_struct    f_owner;
    unsigned int f_uid, f_gid;
    int           f_error;
    unsigned long    f_version;
    /* needed for tty driver, and maybe others */
    void          *private_data;
    /* preallocated helper kiobuf to speedup O_DIRECT */
    struct kiobuf    *f_iobuf;
    long          f_iobuf_lock;
};
```

3.xx/4.xx/5.xx style (quite similar to 2.4)

```
struct file {
        union {
                struct llist_node       fu_llist;
                struct rcu_head         fu_rcuhead;
        } f_u;
        struct path             f_path;
#define f_dentry        f_path.dentry
        struct inode            *f_inode;       /* cached value */
        const struct file_operations    *f_op;

        /*
         * Protects f_ep_links, f_flags.
         * Must not be taken from IRQ context.
         */
        spinlock_t              f_lock;
        atomic_long_t           f_count;
        unsigned int            f_flags;
        fmode_t                 f_mode;
        struct mutex            f_pos_lock;
        loff_t                  f_pos;
        struct fown_struct      f_owner;
        const struct cred       *f_cred;
        struct file_ra_state    f_ra;

…….
……. __randomize_layout;;
```

Now we have randomized layout and a few fields are moved to other pointed tables

Randomized from kernel 4.8

Linux VFS API layering

- System call layer
  - ✓ Session setup
  - ✓ Channel ID based data access/manipulation
- Path-based VFS layer
  - ✓ Do something on file system based on a path passed as parameter
- Data structure based VFS layer
  - ✓ Do something on file system based on pointers to data structures

Relations

System call layer

open
read/write
…

Path-based VFS API

filp_open
path_lookup
lookup_create
…

Data-structure-based VFS API

vfs_create
vfs_mkdir
vfs_read
vfs_write
dget
dput
alloc_inode
…

Path-based API examples

`struct file *filp_open(const char * filename, int flags, int mode)`

returns the address of the `struct file` associated with the opened file

`open()` system-call

kernel-level

`filp_open()`

i-node operation `lookup()`

In the end we pass trough dentry/i-node/char-dev/superblock drivers

Data-structure based API examples

`int vfs_mkdir(struct inode *dir, struct dentry *dentry, int mode)`

Creates an i-node and associates it with `dentry`. The parameter `dir` is used to point to a parent i-node from which basic information for the setup of the child is retrieved. `mode` specifies the access rights for the created object

`int vfs_create(struct inode *dir, struct dentry *dentry, int mode)`

Creates an i-node linked to the structure pointed by `dentry`, which is child of the i-node pointed by `dir`. The parameter `mode` corresponds to the value of the permission mask passed in input to the open system call. Returns 0 in case of success (it relies on the i-node-operation `create`)

`static __inline__ struct dentry * dget(struct dentry *dentry)`

Acquires a dentry (by incrementing the reference counter)

`void dput(struct dentry *dentry)`

Releases a dentry (this module relies on the dentry operation `d_delete`)

… still on data-structure based API examples

```
ssize_t vfs_read(struct file *file, char __user *buf,
size_t count, loff_t *pos)
ssize_t vfs_write(struct file *file, char __user *buf,
size_t count, loff_t *pos)
```

file operation `read(......)`
file operation `write(......)`

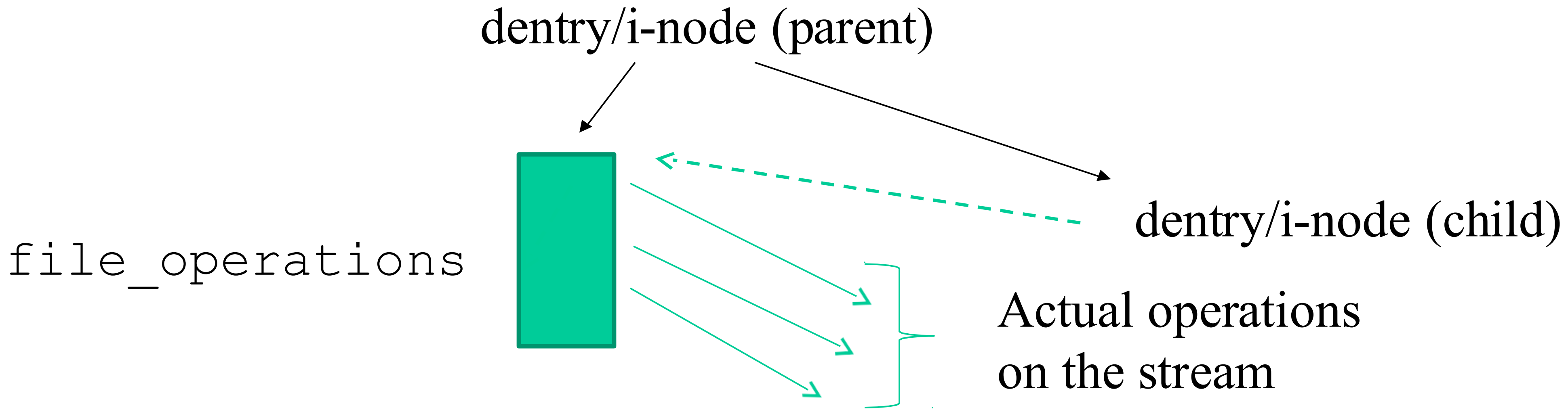
In the end we traverse dentry/i-node structures to retrieve the file operations table associated with that dentry

Relating I/O objects and drivers - the MAJOR number

- A driver (for either a block or a char device) is registered into a so called device-drivers table
- The table is an array and the displacement into the array where the driver is registered is called MAJOR number
- Suppose we have to instantiate in memory the dentry/i-node of a file, then we need to:
  - ✓ Identify the char-dev driver for operating on the file (this will depend on where we registered the driver for that device into the table)
  - ✓ Link the dentry/i-node to that driver (recall a char-device driver is a table of file-operations)

Lets' simplify the job

- Suppose we instantiate in memory a dentry/i-node that depends on another one on the same file system
- They are "homogeneous"
- In this case we simply inherit the same char-device driver of the parent (or a file system specific one)



What about data isolation?

- Generally the i-node identifies what data are touched by a call to a function in `file_operations`
- This might not be the case with generic I/O objects that are not regular files
- As an example, what about things that are not files??
- We may have an I/O object that
  - ✓ Can be managed by a given char-device driver
  - ✓ Can be an instance in a group of many that need to be driven by the same char-device driver (they are homogeneous but are not regular files)

VFS "nodes" and device numbers

- The field `umode_t i_mode` within `struct inode` keps an information indicating the type of the i-node, e.g.:
  - ➢ directory
  - ➢ file
  - ➢ char device
  - ➢ block device
  - ➢ (named) pipe

- `sys_mknod()` allows creating an i-node associated with a generic type

- In case the i-inode represents a device, the operations for managing the device are retrieved via the device driver tables

- Particularly, the i-node keeps the field `kdev_t i_rdev` which logs information related to both **MAJOR and MINOR** numbers for the device

The mknod() system call

```
int mknod(const char *pathname, mode_t mode, dev_t dev)
```

- `mode` specifies the permissions to be used and the type of the node to be created
- permissions are filtered via the `umask` of the calling process `(mode & umask)`
- several different macros can be used for defining the node type → `S_IFREG, S_IFCHR, S_IFBLK, S_IFIFO`
- when using `S_IFCHR` or `S_IFBLK`, the parameter `dev` specifies **MAJOR and MINOR numbers for the device file that gets created**, otherwise this parameter is a don’t care

Device numbers

- for x86 machines, device numbers are represented as bit masks
- MAJOR corresponds to the least significant byte within the mask
- MINOR corresponds to the second least significant byte within the mask
- The macro `MKDEV(ma,mi)`, which is defined in `include/linux/kdev_t.h`, can be used to setup a correct bit mask by starting from the two numbers

Usage of MINOR numbers in drivers

- The functions belonging to the driver take a pointer to `struct file` in input
- Therefore we know the session – the dentry – and the i-node ...
- …. hence we know the MINOR!
- …. and we can do stuff based on the MINOR!
- … as an example we might have that the driver manages an array of tables, each associated with the state of an I/O object with a given MINOR (an index)

Char devices table

```
struct device_struct {
    const char * name;
    struct file_operations * fops;
};

static struct device_struct chrdevs[MAX_CHRDEV];
```

Device name

Device operations

- in `fs/devices.c` we can find the following functions for registering/deregistering a driver

  `int register_chrdev(unsigned int major, const char * name, struct file_operations *fops)`

  Registration takes place onto the entry at displacement MAJOR (0 means the choice is up to the kernel). The actual MAJOR number is returned

  `int unregister_chrdev(unsigned int major, const char * name)`

  Releases the entry at displacement MAJOR

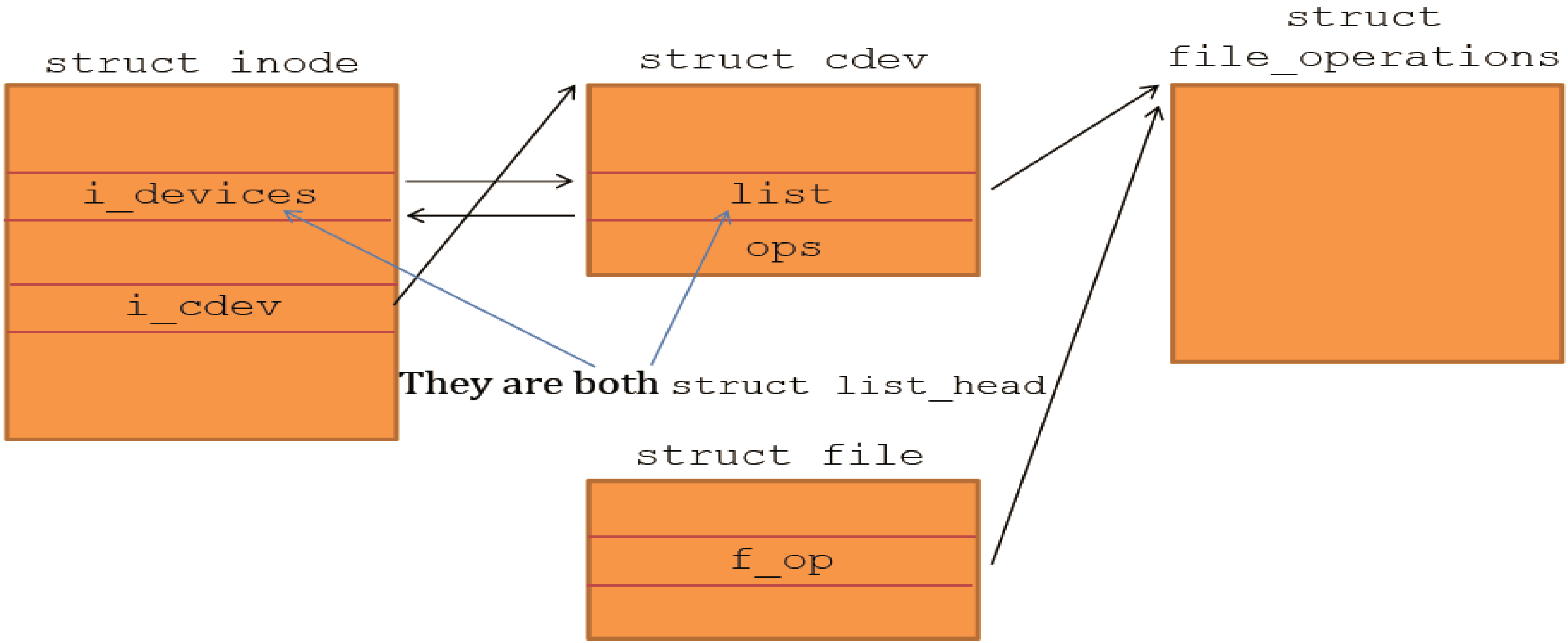
Kernel 3 or later - augmenting flexibility and structuring

```
#define CHRDEV_MAJOR_HASH_SIZE 255
static struct char_device_struct {
        struct char_device_struct *next;
        unsigned int major;
        unsigned int baseminor;
        int minorct;
        char name[64];
        struct cdev *cdev;
} *chrdevs[CHRDEV_MAJOR_HASH_SIZE];
```

Minor number ranges already indicated and flushed to the `cdev` table

Pointer to file-operations is here

A scheme on i-node to file operations mapping for kernel 3 or later



Operations remapping

```
int register_chrdev(unsigned int major, const char
*name, struct file_operations *fops)
```

New features

```
int __register_chrdev(unsigned int major, unsigned
int baseminor, unsigned int count, const char
*name, const struct file_operations *fops)
```

```
int unregister_chrdev(unsigned int major, const char *name)
```

```
void __unregister_chrdev(unsigned int major, unsigned
int baseminor, unsigned int count, const char *name)
```

Final part of the boot - activating the INIT thread - 2.4 style

- The last function invoked while running `start_kernel()` is `rest_init()` and is defined in `init/main.c`
- This function spawns INIT, which is initially created as a kernel level thread, and eventually activates the l’IDLE PROCESS function

```
static void rest_init(void)
{
 kernel_thread(init, NULL, CLONE_FS | CLONE_FILES | CLONE_SIGNAL);
 unlock_kernel();
 current->need_resched = 1;
 cpu_idle();

}
```

… and 3.xx or later style

see **linux/init/main.c**

```
static noinline void __init_refok rest_init(void)
{
         int pid;

         rcu_scheduler_starting();
         /*
          * We need to spawn init first so that it obtains pid 1, however
          * the init task will end up wanting to create kthreads, which, if
          * we schedule it before we create kthreadd, will OOPS.
*/
          kernel_thread(kernel_init, NULL, CLONE_FS);
          ……..
           numa_default_policy();

……..
…..
```

Switch off round-robin to first-touch

The function init()

- The `init()` function for INIT is defined in `init/main.c`
- This function is in charge of the following main operations
  - ➢ Mount of ext2 (or the reference root file system)
  - ➢ Activation of the actual INIT process (or a shell in case of problems)

```
static int init(void * unused){
   struct files_struct *files;
   lock_kernel();
   do_basic_setup();
   prepare_namespace();
   .........
   if (execute_command)  run_init_process(execute_command);
   run_init_process("/sbin/init");
   run_init_process("/etc/init");
   run_init_process("/bin/init");
   run_init_process("/bin/sh");
   panic("No init found.  Try passing init= option to kernel.");
}
```

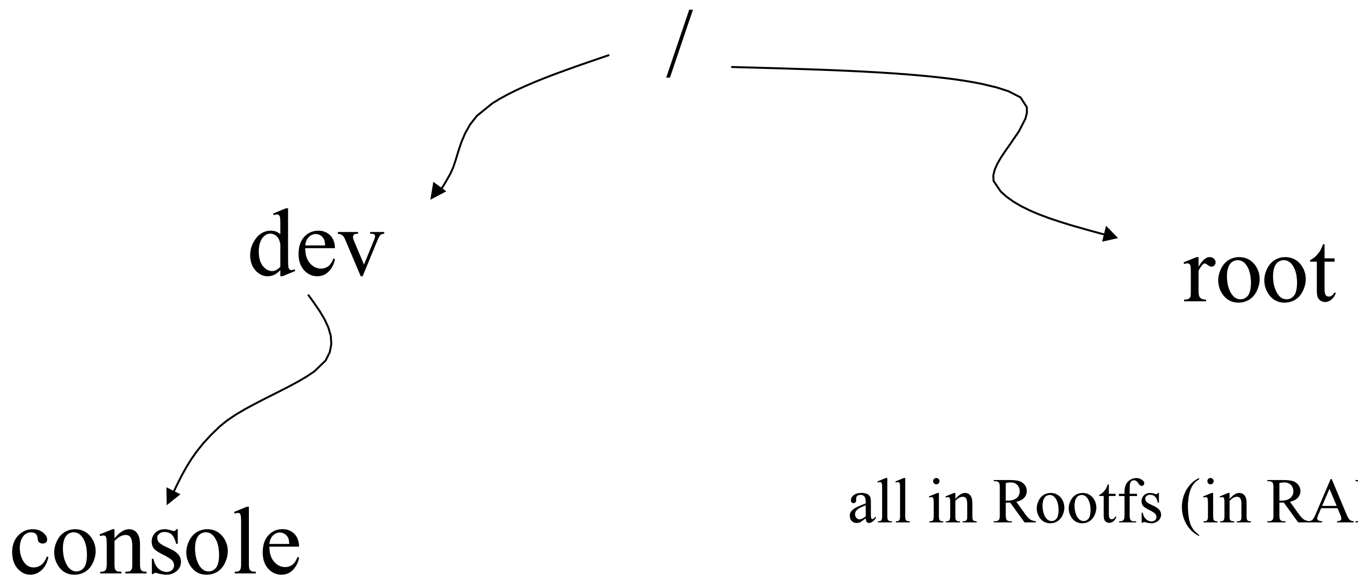
registering drivers

The prepare_namespace() function (2.4 style - minor variations are in kernels 3/4/5)

```
void prepare_namespace(void){
    ……
    sys_mkdir("/dev", 0700);
    sys_mkdir("/root", 0700);
    sys_mknod("/dev/console", S_IFCHR|0600,
                        MKDEV(TTYAUX_MAJOR, 1));
    ……
    mount_root();
out:
    ……
    sys_mount(".", "/", NULL, MS_MOVE, NULL);
    sys_chroot(".");
    ……
}
```

The scheme

This is the typical state before calling `mount_root()`



all in Rootfs (in RAM)

The mount_root() function

```
static void __init mount_root(void) {
    ……
    create_dev("/dev/root", ROOT_DEV,
                    root_device_name);
    ……
    mount_block_root("/dev/root", root_mountflags);
}

static int __init create_dev(char *name, kdev_t dev,
    char *devfs_name) {

    void *handle;
    char path[64];
    int n;

    sys_unlink(name);
    if (!do_devfs)
        return sys_mknod(name, S_IFBLK|0600,
                        kdev_t_to_nr(dev));
    ……
}
```

The function mount_block_root()

```
static void __init mount_block_root(char *name, int flags) {
     char *fs_names = __getname(); char *p;
     get_fs_names(fs_names);
retry:  for (p = fs_names; *p; p += strlen(p)+1) {
        int err = sys_mount(name, "/root", p, flags, root_mount_data);
         switch (err) {
               case 0: goto out;
               case -EACCES:  flags |= MS_RDONLY;  goto retry;
               case -EINVAL:
               case -EBUSY:  continue;
         }
     printk ("VFS: Cannot open root device \"%s\" or %s\n",
               root_device_name, kdevname (ROOT_DEV));
     printk ("Please append a correct \"root=\" boot option\n");
     panic("VFS: Unable to mount root fs on %s", kdevname(ROOT_DEV));
     }
     panic("VFS: Unable to mount root fs on %s", kdevname(ROOT_DEV));
out:    putname(fs_names);
     sys_chdir("/root");
     ROOT_DEV = current->fs->pwdmnt->mnt_sb->s_dev;
     printk("VFS: Mounted root (%s filesystem)%s.\n",
          current->fs->pwdmnt->mnt_sb->s_type->name,
          (current->fs->pwdmnt->mnt_sb->s_flags & MS_RDONLY) ?
          " readonly" : "");
}
```

The mount() system call

```
int  mount(const  char  *source, const char *target, const char *filesystemtype,
               unsigned long mountflags, const void *data);
```

MS_NOEXEC   Do not allow programs to be executed from this file system.

MS_NOSUID   Do not honour set-UID and set-GID bits when execut ing programs from this file system.

MS_RDONLY   Mount file system read-only.

MS_REMOUNT Remount an existing mount. This is allows you to change the mountflags and data of an existing mount without having to unmount and remount the file system. source and target should be the same value specified in the initial mount() call; filesystem type is ignored.

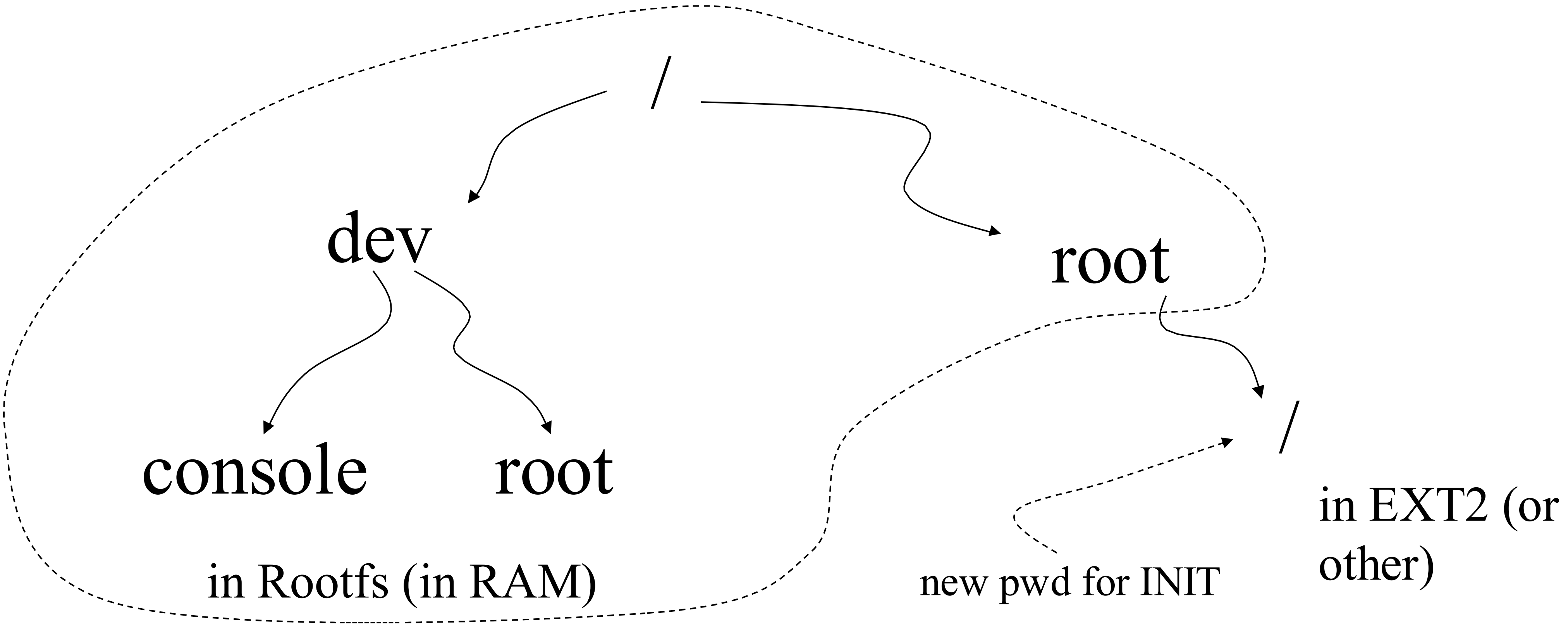
MS_SYNCHRONOUS Make writes on this file system synchronous (as though the O_SYNC flag to open(2) was specified for all file opens to this file system).

Mounting scheme

- The device to be mounted is used for accessing the driver (e.g. to open the device and to load the super-block)
- The superblock read function is identified via the device (file system type) to be mounted
- The super-block read-function will check whether the superblock is compliant with what expected for that device (i.e. file system type)
- In case of success, the 4 classical file system representation structures get allocated and linked in main memory
- **Note** → `sys_mount` relies on `do_kern_mount()`

The scheme

- This is the state at the end of the execution of `mount_root()`



Mount point

- Any directory selected as the target for the mount operation becomes a so called “mount point”
- `struct dentry` keeps the field `int d_mounted` to determine whether we are in presence of a mount point
- This approach allows building views of the file system that can in general be articulated in a complex manner with respect to the mounted file system instances
- One of the advantages has been the introduction of “bind mounts” (more different paths towards the same mounted file system)

Description of open() – kernel side

The steps

1. Get a free file descriptor (via `current->files->fd`)

1. Get the dentry via `filp_open()` (internally calls `file_operation` open)

1. Link the two things together

Description of close() – kernel side

The steps

1. Release the dentry (by file descriptor) via `filp_close()` (internally calls `file_operation` close)

2. Release the file decriptor (via `current->files->fd`)

Description of a read()/write() – kernel side

The steps

1. Get reference to dentry via file descriptor
2. Get reference to `file_operations`
3. Call the associated interface in `file_operations`

proc file system

- It is an in-memory file system which provides information on
  - ➢ Active programs (processes)
  - ➢ The whole memory content
  - ➢ Kernel level settings (e.g. the currently mounted modules)
- Common files on `/proc` are
  - ➢ `cpuinfo` contains the information established by the kernel about the processor at boot time, e.g., the type of processor, including variant and features
  - ➢ `kcore` contains the entire RAM contents as seen by the kernel
  - ➢ `meminfo` contains information about the memory usage, how much of the available RAM and swap space are in use and how the kernel is using them
  - ➢ `version` contains the kernel version information that lists the version number, when it was compiled and who compiled it

- `net/` is a directory containing network information
- `net/dev` contains a list of the network devices that are compiled into the kernel. For each device there are statistics on the number of packets that have been transmitted and received
- `net/route` contains the routing table that is used for routing packets on the network
- `net/snmp` contains statistics on the higher levels of the network protocol
- `self/` contains information about the current process. The contents are the same as those in the per-process information described below

- `pid/` contains information about process number *pid*. The kernel maintains a directory containing process information for each process
- `pid/cmdline` contains the command that was used to start the process (using null characters to separate arguments)
- `pid/cwd` contains a link to the current working directory of the process
- `pid/environ` contains a list of the environment variables that the process has available
- `pid/exe` contains a link to the program that is running in the process
- `pid/fd/` is a directory containing a link to each of the files that the process has open
- `pid/mem` contains the memory contents of the process
- `pid/stat` contains process status information
- `pid/statm` contains process memory usage information

Registering/creating the proc file system type

- The `/proc` file system is configured via the function `proc_root_init()` defined in `fs/proc/root.c`

- This is called by the `start_kernel()` function
- `proc_root_init()` is in charge of
  - ➢ registering `/proc`
  - ➢ creating the actual instance

- Additional tasks by this function include creating some subdirs of proc such as
  - ➢ `net`
  - ➢ `sys`
  - ➢ `sys/fs`

Core data structures for proc (classical)

```
struct proc_dir_entry {
        unsigned short low_ino;
        unsigned short namelen;
        const char *name;
        mode_t mode;
        nlink_t nlink;    uid_t uid;    gid_t gid;
        unsigned long size;
        struct inode_operations * proc_iops;
        struct file_operations * proc_fops;
        get_info_t *get_info;
        struct module *owner;
        struct proc_dir_entry *next, *parent, *subdir;
        void *data;
        read_proc_t *read_proc;
        write_proc_t *write_proc;
        atomic_t count;        /* use count */
        int deleted;       /* delete flag */
        kdev_t  rdev;
    };
```

Core data structures for proc (very latest kernels)

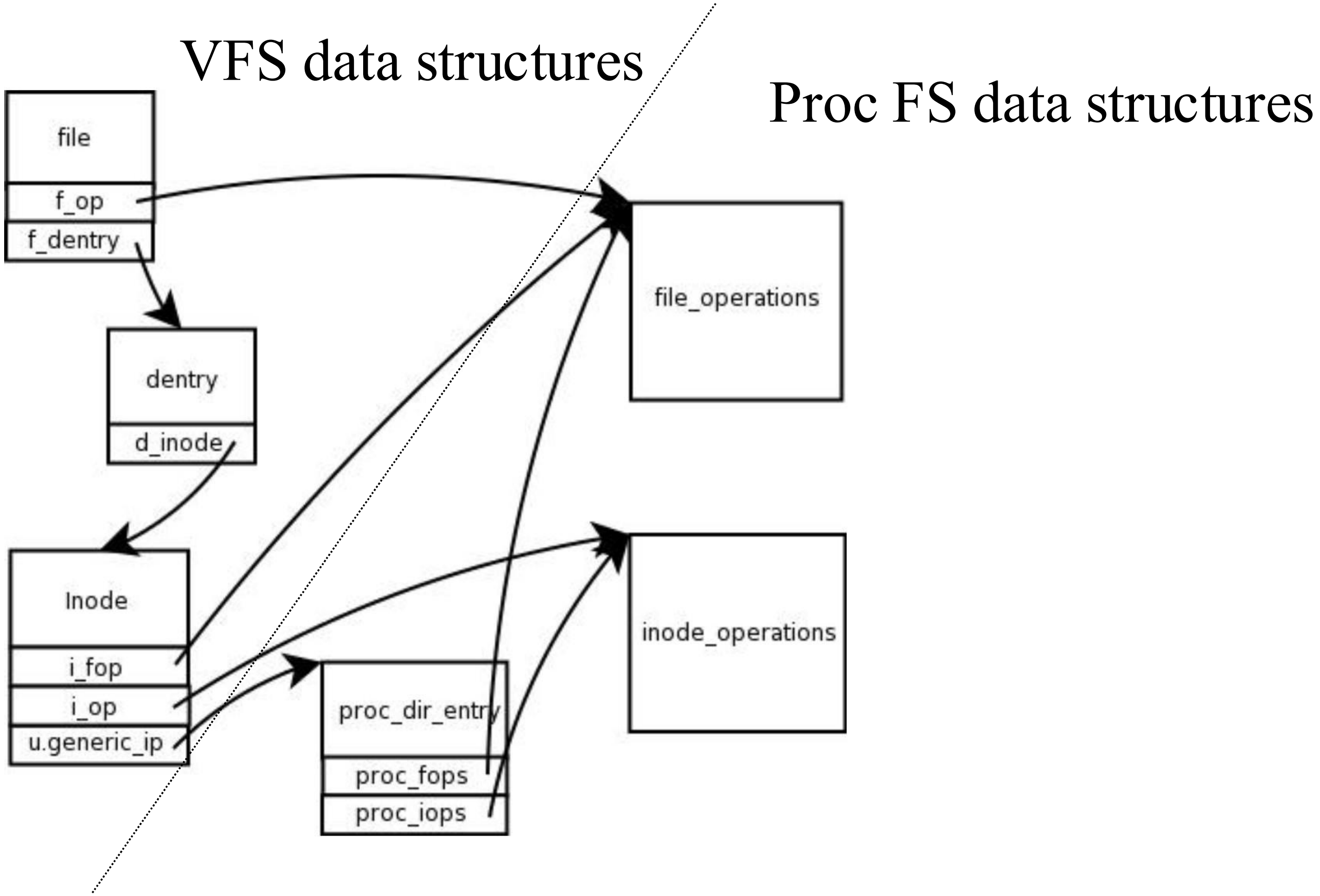
```
struct proc_dir_entry {
………
const struct inode_operations *proc_iops;
union {
    const struct proc_ops *proc_ops;
    const struct file_operations *proc_dir_ops;
};
const struct dentry_operations *proc_dops;
….
proc_write_t write;
void *data;
………
} __randomize_layout;
```

for a file

for a directory

improvement of security

Data structure layout



Properties of struct proc_dir_entry

- It fully describes any element of the proc file system in terms of
  - name
  - i-node operations
  - file operations
  - <u>specific read/write functions for the element</u>
- We have specific functions to create proc entries, and to link the `proc_dir_entry` to the file system tree

Mounting proc

- The proc file system is not necessarily mounted upon booting the kernel, it only gets instantiated if configured
- The proc file system gets mounted by INIT (if not before)
- This is done in relation to information provided by `/etc/fstab` or as a configured/default runtime task (e.g. by systemd)
- Typically, the root of the application level root-file-system keeps the directory `/proc` that is exploited as the mount point for the proc-file-system
- **NOTE**
  - ➢ No device needs to be specified for mounting proc, thus only the type of file system is required as parameter
  - ➢ Hence the `/etc/fstab` line for mounting proc does not specify any device

API for handling proc directories

```
struct proc_dir_entry *proc_mkdir(const char *name,
         struct proc_dir_entry *parent);
```

Creates a directory called `name` within the directory pointed by `parent`

Returns the pointer to the new `struct proc_dir_entry`

API for handling proc entries (i)

```
static inline struct proc_dir_entry
*proc_create(const char *name, umode_t mode, struct
              proc_dir_entry *parent, const struct
              file_operations *proc_fops)
```

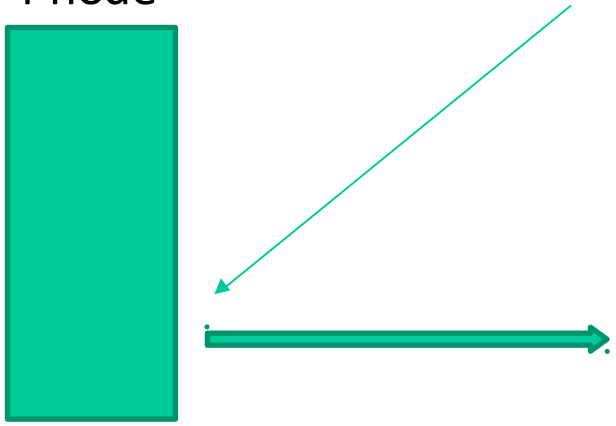
Moved to `struct proc_ops`

`name`: The name of the proc entry
`mode`: The access mode for proc entry
`parent`: The name of the parent directory under /proc
`proc_fops`: The structure in which the file operations for the proc entry will be created

API for handling proc entries (ii)

```
static inline struct proc_dir_entry
*proc_create_data(const char *name, umode_t mode,
                  struct proc_dir_entry *parent,
                  const struct proc_ops *proc_fops,
                  void* data)
```

i-node



Get directly to some data
via this pointer

Read/Write operations

- Read/write operations for proc have the same interface as for any file system handled by VFS, that is →

```
ssize_t (*read) (struct file *, char *,   size_t, loff_t *)

ssize_t (*write) (struct file *, const char *, size_t,
                     loff_t *);
```

- … <u>on the history</u> → in kernel 5 the direct write operation reappeared, resembling direct read/write operations time ago offered by kernel 2
- The signature is → typedef int (*proc_write_t)(struct file *, char *, size_t)
- No explicit usage of the offset is adopted

The sys file system (available since kernel 2.6)

- Similar in spirit to /proc
- It is an alternative way to make the kernel export information (or set it) via common I/O operations
- Very simple API
- Clear-cut structuring
- sysfs is compiled into the kernel by default depending on the configuration option CONFIG_SYSFS (visible only if CONFIG_EMBEDDED is set)

Internal	External
Kernel Objects	Directories
Object Attributes	Regular Files
Object Relationships	Symbolic Links

Baseline architectural concepts - kernel objects

- The `/sys` file system is based on data structures that play a more ample role within the Linux kernel
- This is the <u>kernel object</u> data structure architecture
- What is a kernel object
  - Something that allows to identity individual things
  - Something that allows to identify groups of things
  - Something that allows to identify the typology of things
  - Something that allows to associate the same typology to many
  - Something that allows to identify hierarchies

The kobject structure

```
struct kobject{
   const char          *name;
   struct list_head    entry;
   struct kobject      *parent;
   struct kset         *kset;
   struct kobj_type    *ktype;
   struct kernfs_node *sd;
         /*sysfs directory entry*/
   struct kref        kref;
   ……
   ……
}
```

Reference counting

The kobj_type structure

```
struct kobj_type{
   void (*release)(struct kobject*);
   struct sysfs_ops *sysfs_ops;
   struct attribute **default_attrs;
}
```

We can have multiple attributes

Called when reference counting reaches the value zero

Actual operations to be executed on the object

The specification of the read/write operations occurs via the sysfs_ops couple of functions

```
struct sysfs_ops {
        /* method invoked on read of a sysfs file */
        ssize_t (*show) (struct kobject *kobj,
                         struct attribute *attr,
                         char *buffer);

        /* method invoked on write of a sysfs file */
        ssize_t (*store) (struct kobject *kobj,
                          struct attribute *attr,
                          const char *buffer,
                          size_t size);
}
```

What can we do with kernel objects

- We can represent data that can be used by software to keep track of the current state of both logical and physical entities

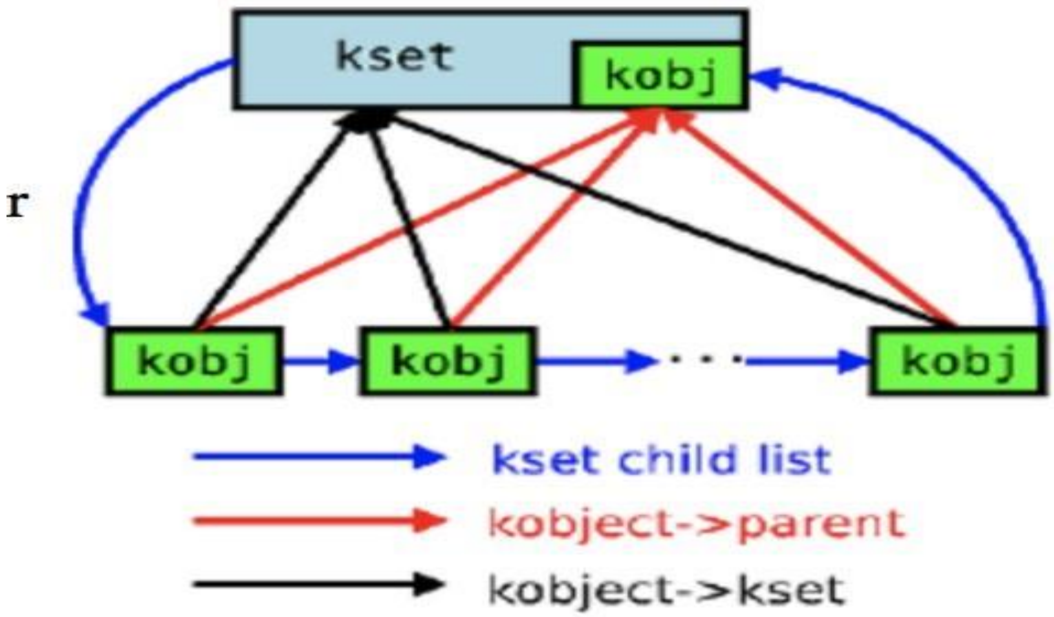
- Examples are related to the representation of
  - ✓ The USB bus subsystem
  - ✓ The char devices subsystem
  - ✓ The block devices subsystem

- A kernel object may belong to only one subsystem!

- A subsystem must contain only identical kernel object elements!

- In Linux we use `struct kset` to group together all the kernel objects we want to have within the same subsystem

A representation of the linkage



Although it is not mandatory, we should keep all these kernel objects linked to the same type specification

File system linkage

- A `kset` element is associated with an I/O element of the `/sys` file system

- On the other hand, a kernel object can be either associated or not to an element of the `/sys` file system

  ✓ it is associated if it is in `kset`

  ✓ it can be out of the `/sys` file system if it is not inside a `kset`

- This also provides the importance of the kernel object reference counter

Baseline API

```
int kobject_add(struct kobject *kobj, struct kobject
                    *parent, const char* fmt ...)

void kobject_del(struct kobject *kobj)
```

Add/remove from, e.g. a pointed to `kset`

Baseline management

There is also

kobject_register, which is a combination of ***kobject_init*** and ***kobject_add***

kobject_unregister, which is a combination of ***kobject_del*** and ***kobject_put***

kset API

```
void kset_init(struct kset *kset)

int kset_register(struct kset *kset)

void kset_unregister(struct kset *kset)

struct kset *kset_get(struct kset *kset)

void kset_put(struct kset *kset)

kobject_set_name(my_set->kobj,“thename")
```

Event to user space

- It is used to notify that something has changed in relation to things that are handled by kernel objects
- The architecture is based on a function pointer that is called **`kobject_uevent`**
- This function pointer is recorded into the `kset` data structure
- The identified function is typically used to let the kernel start some user space application when something occurs at the kernel side
- The classical example is when inserting an USB drive, in this case a user space program is started to let the user know about the insertion (and to ask what to do)

sysfs core API for kernel objects

```
int sysfs_create_dir(struct kobject * k);

void sysfs_remove_dir(struct kobject * k);

int sysfs_rename_dir(struct kobject *, const char *new_name);
```

Main fields: `parent - name`

- it is possible to call `sysfs_create_dir` without `k->parent` set
- it will create a directory at the very top level of the sysfs file system
- this can be useful for writing or porting a new top-level subsystem using the `kobject/sysfs` model

sysfs core API for object attributes

```
int sysfs_create_file(struct kobject *, const struct attribute *);

void sysfs_remove_file(struct kobject *, const struct attribute *);

int sysfs_update_file(struct kobject *, const struct attribute *);
```

```
struct attribute {
    char            *name;
    struct module   *owner;
    mode_t          mode;
};
```

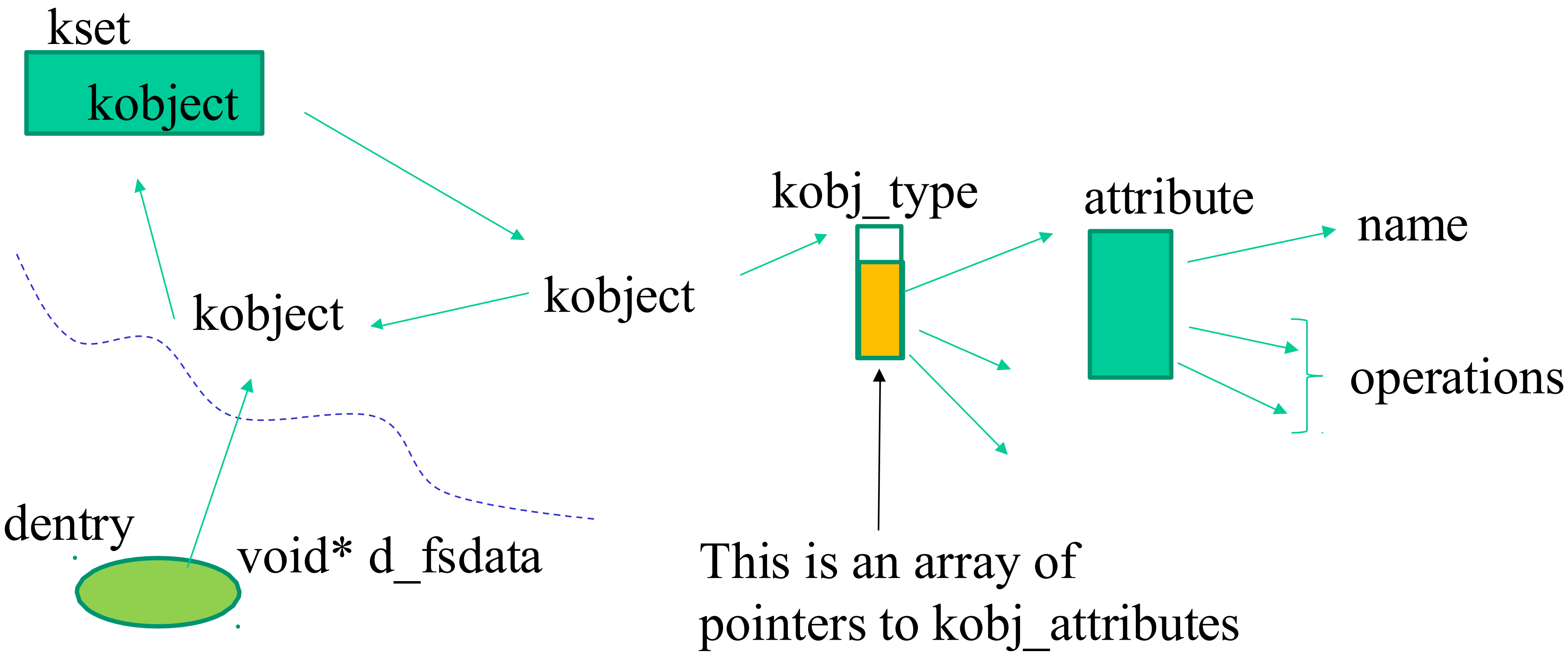
Minimal modifications along kernel releases

The owner field may be set by the caller to point to the module in which the attribute code exists

Actual object attributes

```
struct kobj_attribute {
   struct attribute attr;
   ssize_t (*show)(struct kobject *kobj,
      struct kobj_attribute *attr, char *buf);
   ssize_t (*store)(struct kobject *kobj,
         struct kobj_attribute *attr,
         const char *buf, size_t count);
}
```

Overall architecture



Kernel API for creating devices in /sys

- `/sys/class` is a device file that internally hosts the reference to other device files

- To create a device file in this “directory” one can resort to:

```
static struct class* class_create(struct moudule* owner, char*
 class_name)

static struct class* device_create(static struct class* the_class, …
 kdev_t i_rdev, … char* name)
```

- There are similar API functions for destroying the device and the class