Filesystems & Virtual Filesystems

Have a look

- Before getting into **Filesystems** & **Virtual Filesystems**, please take a look at
  - *Prof. Ahmed Elarabawy Course.*

    Course 102: Lecture 5: File Handling Internals
    Course 102: Lecture 26: FileSystems in Linux (Part 1)
    Course 102: Lecture 27: FileSystems in Linux (Part 2)
    Course 102: Lecture 28: Virtual FileSystems

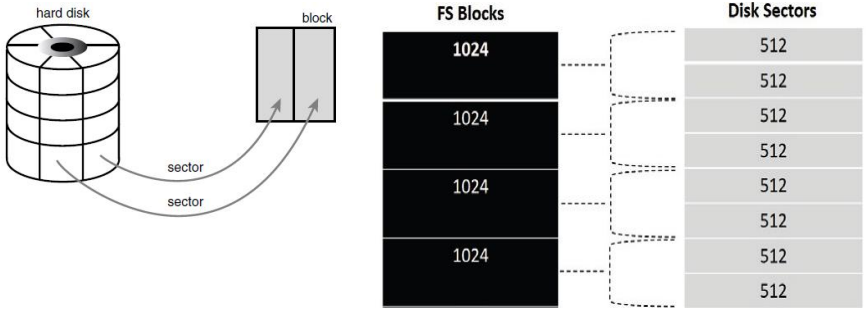
Filesystems

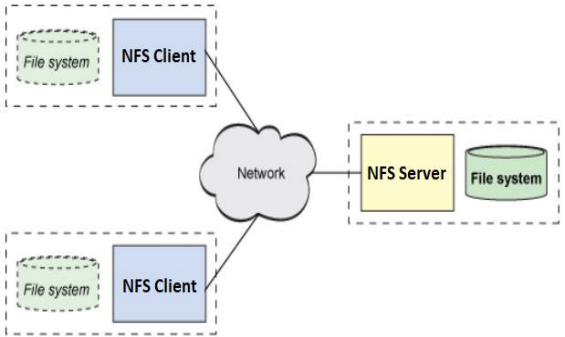
- Filesystem Types
  - **Disk-based** filesystems : i.e. Ext2/3, Reiserfs, FAT.
    From the filesystem point of view, the underlying devices are nothing more than a list of storage **blocks** for which an appropriate organization scheme must be adopted.**block** may be one sector or multiples of **sector** size.

  - **Virtual filesystems** : Generated in the kernel itself, i.e. *proc* FS, it requires no storage space on any HW device. Instead, the kernel creates a **hierarchical** file structure whose entries contain information on a particular part of the system.

  - **Network** filesystems : It's between disk-based and virtual filesystems, all operations on **files** in this filesystem are carried out over a **network** connection.
    Nevertheless, the kernel needs information on the size of files, their position within the **directory hierarchy.**

    So as a result of the VFS layer, userspace processes see no difference between a local filesystem and a filesystem available only via a network.





Filesystems

- Metadata
  - Inode
    contain metadata info to a file such as filename, type of file, last access timestamp, owner, access privileges, last modification timestamp, creation time, size of file data, and references to disk blocks containing file data.

    Filesystems reserve a few disk **blocks** for storing inode instances and the rest for storing corresponding file data.

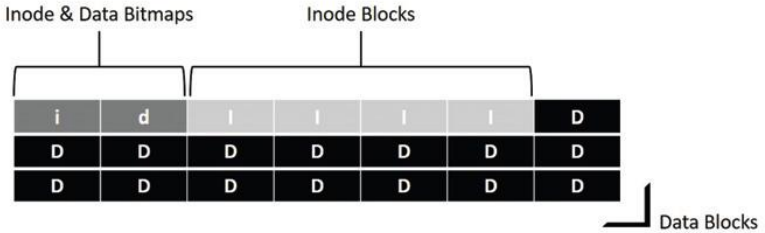
    The on-disk list of all **inodes** held in these **blocks** called the **inode table**.

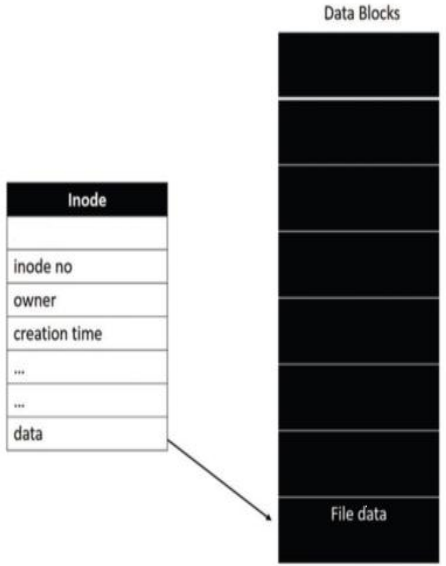
    Filesystems tracks the status of the inode and data blocks through ***bitmaps*** (free inodes and data blocks).

  - Data block map
    inode should record the locations of data blocks in which corresponding file data is stored.

    it uses differnet ways in order to point to the data blocks of the file.

Disk Storage Layout





Filesystems

- Metadata, *Con'td*
  - Data block map, *Cont'd*

    - **Direct Pointers** : The number of such direct pointers would depend on filesystem design.

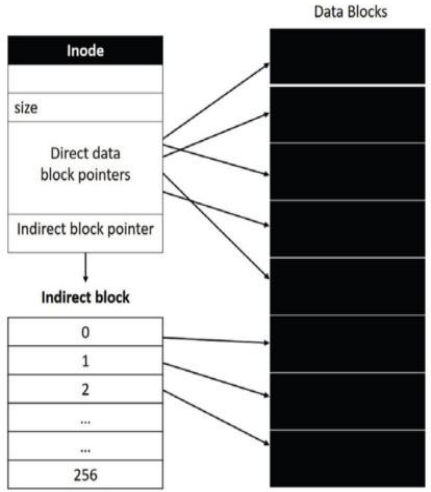
      This method is productive for small files which span a few data blocks.

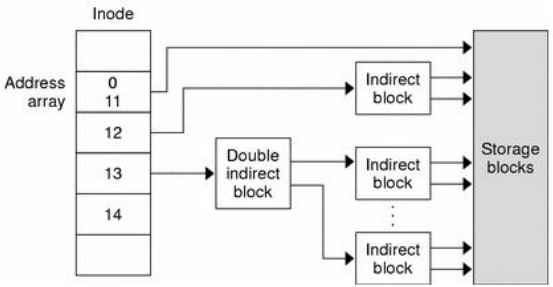
      - **Indirect Pointers** : refers to a block containing direct pointers to data blocks of the file.

      To support more larger files, **double-indirect** pointer, which refers to a block containing indirect pointers with each entry referring to a block containing direct pointers.

      This technique can be extended with a **triple-indirection** pointer, resulting in even more metadata to be managed by filesystems.

      - **Extent Lists** : You can check this article https://www.linux.org/threads/intro-to-extents.8625/





Filesystems

- Metadata, *Con'td*
  - Directories : Filesystems consider it as a special file. ***type*** field, which is marked as directory.

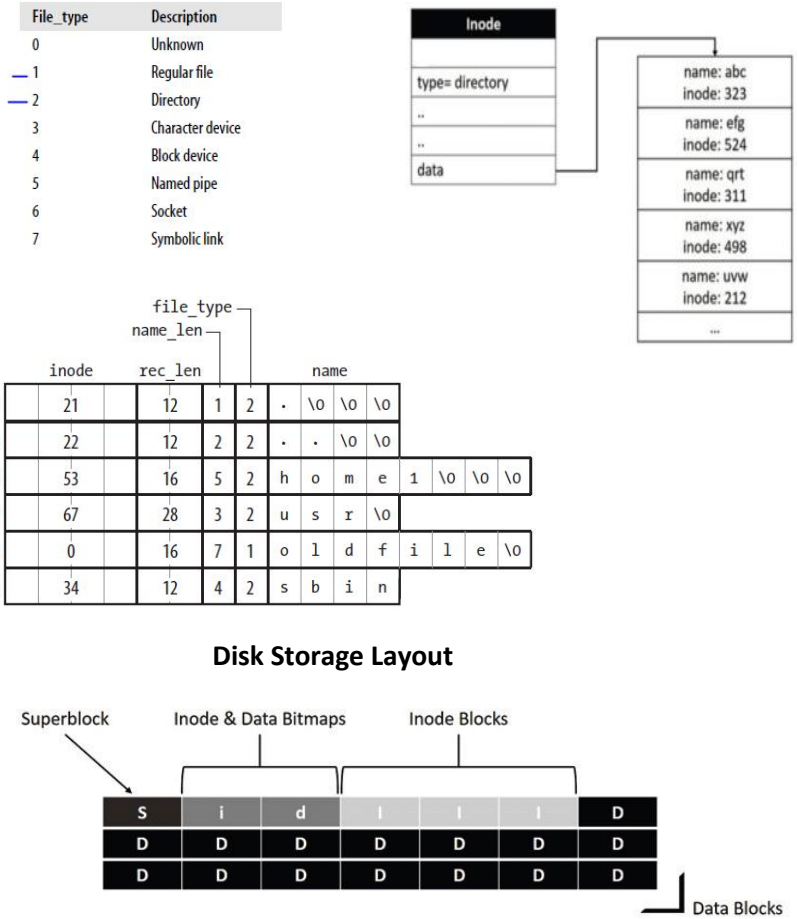
    Each directory is assigned data blocks where it holds information about files and subdirectories it contains represented as (name : inode).

    File name length is defined by the filesystem's naming policy.

    Example of **Ext2** filesystem directory structure stored in disk blocks.

  - Superblock : filesystems also need to maintain metadata with respect to disk volume as a whole, such as size of the volume, total block count, current state of filesystem, count of inode blocks, count of inodes, count of data blocks,...

    During initialization of filesystem on disk volume, the superblock is organized at start of disk storage.



Filesystems

- Each Filesystem (Ext2,...) should implement some basic functionalties of VFS abstraction layer related to (***inode, super block, dir, file***), will discuss them later in VFS layer.

- The VFS layer builds called **rootfs**, under which all filesystems can enumerate their directories and files.

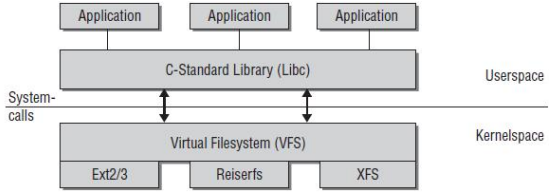
- General Filesystems Operations
  - Mount : operation of enumerating an on-disk superblock and metadata into **memory** for the filesystem's use.

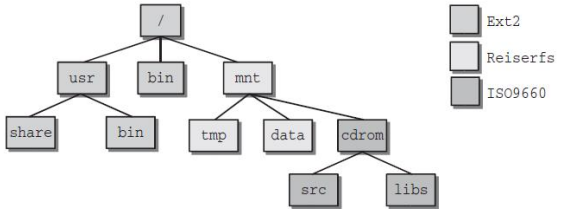
    It creates **in-memory** data structures that describe file metadata and present the host operating system with a view of the directory and file layout in the volume.

  - Unmount : operation of flushing the **in-memory** state of filesystem data structures back **to disk**.

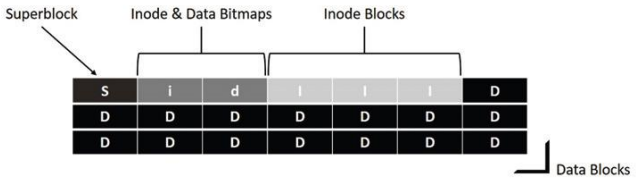
    The ***superblock*** contains the state of the filesystem; it indicates whether the volume is **consistent** or **dirty**.

```
struct inode_operations {
    ...
}

struct super_operations {
    ...
}

struct dentry_operations {
    ...
}

struct file_operations {
    ...
}
```





Disk Storage Layout



Filesystems

- General Filesystems Operations, *Cont'd*
  - File creation and deletion

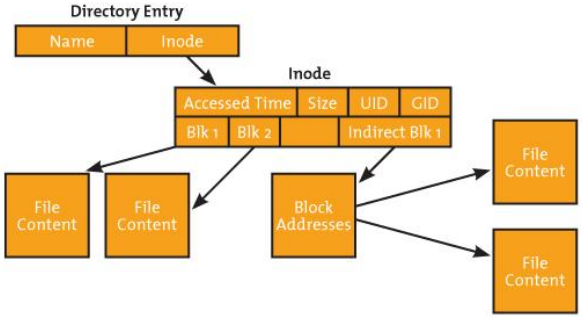
    Creation : Instantiation of a new inode with appropriate attributes (***filename***, ***directory*** under which file is to be created, ***access permissions*** for users,...).

    Deletion : release its data blocks to the list of free data blocks, and inode to list of free inodes.
    But before doing this, checks the file's reference count to determine the number of **processes** currently using the file.

  - File open and close

    Open : Once a process triggers ***open*** operation it invokes the ***open()*** of the filesystem, that traverse until gets ***inode*** number of the specified file, then instantiates a ***file*** structure related to the requestd **process.**

    Close : the ***file*** structure is destroyed and the file's reference count is decremented.
    The caller **process** will no longer be able to initiate any other file operation until it can open the file all over again.




```c
struct file {
    ...
    file_operations *f_op;
    ...
}
```

```c
const struct file_operations ext4_file_operations = {
    ...
    .open       = ext4_file_open,
    ...
}
```

/fs/ext4/file.c

Filesystems

- General Filesystems Operations, *Cont'd*
  - File read and write

    Read : Once a process triggers ***read*** operation, filesystem's ***read()*** routine is invoked.

    Operations begin with a lookup into the file's **data block** map to locate the appropriate data disk **sector** to be read, then allocates a ***page*** from the **page cache** and schedules disk I/O (**Block Layer**).

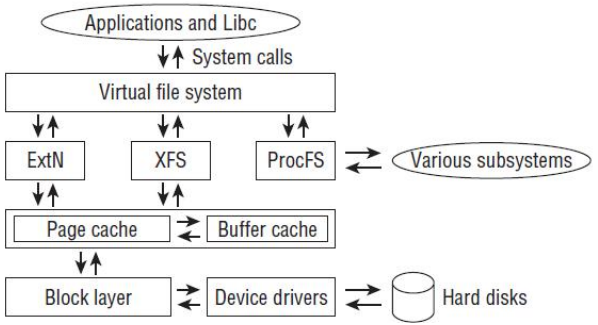
    On completion of I/O transfer, the filesystem moves requested data into the application's buffer and updates the file offset position in the process's ***file*** structure.

    Write : retrieves data passed from user buffer and writes it into the appropriate offset of file buffer in the page cache, and marks the page with the ***PG_dirty*** flag.

/include/linux/fs.h

```
struct file_operations {
    ...
    ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
    ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
    ...
}
```

```
const struct file_operations fat_dir_operations = {
    ...
    .read       = generic_read_dir,
    ...
}
```




```
struct file {
    ...
    loff_t          f_pos;
    ...
}
```

Filesystems

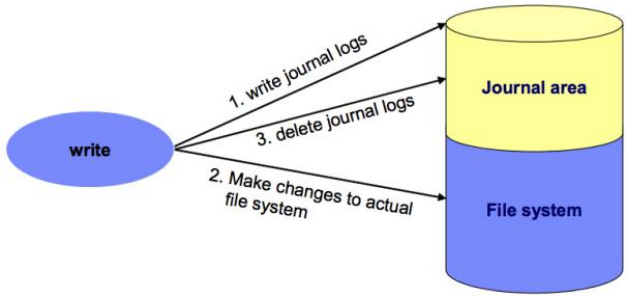
- General Filesystems Operations, *Cont'd*
  - Filesystem consistency and crash recovery
    Possibility to occur (power down, OS crash,...), causing interruption of a partially committed critical update.

    This results in corruption of on-disk structures and leaves the filesystem in an inconsistent state.

    Journaling : is a technique implemented by most modern filesystem for quick and reliable crash recovery.

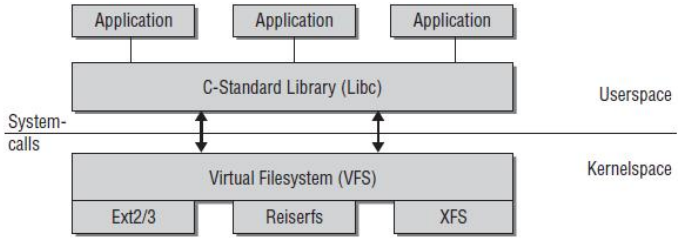
    Journaling idea is to prepare a log (note) listing out changes to be committed to the on-disk image of the filesystem, and writing the log to a special disk block called a journal block, before beginning the actual update operation.

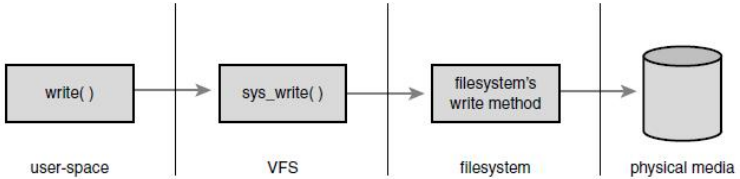
    So, the filesystem can easily detect inconsistencies and fix them by looking through information recorded in the log.



Virtual Filesystem (VFS)

- VFS is the subsystem of the kernel that implements the file and filesystem-related interfaces (Common Filesystem Interface) provided to user-space programs.
- VFS enables system calls such as ***open()***, ***read()***, and ***write()*** to work regardless of the filesystem or underlying physical medium (Filesystem abstraction).
- Flow of data from user-space, issuing a ***write()*** call, through the VFS's generic system call, into the filesystem's specific write method, and finally arriving at the physical media.





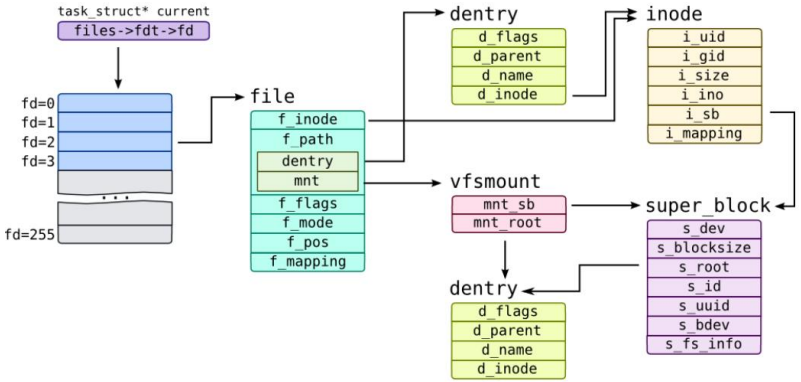
Virtual Filesystem (VFS)

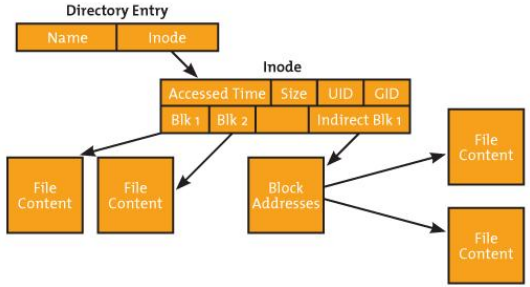
- VFS Objects & Data structures
  - Primary objects
    inode : represents a specific file in the system.
    dentry : represents a directory entry, which is a single component of a path.

    i.e. Pathname Lookup
    when looking up the */tmp/test* pathname, the kernel creates a dentry object for the */* root directory, a second dentry object for the ***tmp*** entry of the root directory, a third will be for ***test***

    Lookup examines the entry matching the first name to derive the corresponding **inode**.
    Then the directory file that has that inode is read from disk and the entry matching the second name is examined to derive the corresponding **inode**. This procedure is repeated for each name included in the path.

    The **dentry cache** considerably speeds up the procedure, because it keeps the most recently used dentry **objects** in memory.





Virtual Filesystem (VFS)

- VFS Objects & Data structures, *Cont'd*
  - Primary objects, *Cont'd*

    super_block : info describe the disk volume as a whole which is related to a specific mounted filesystem.

    file *:* represents open file associated with a process.

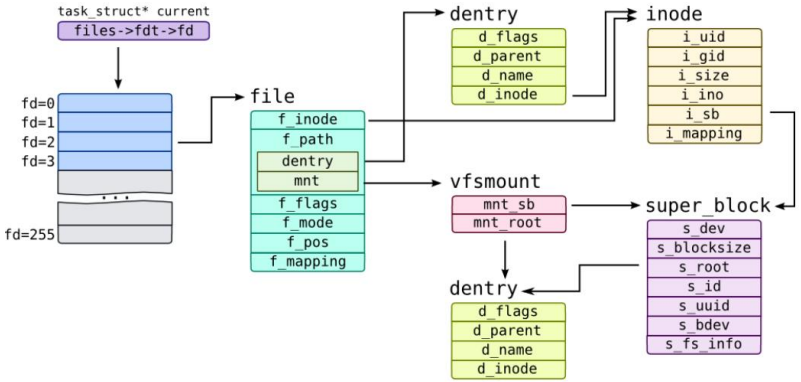
  - Operations objects : pointers injected in primary objects.

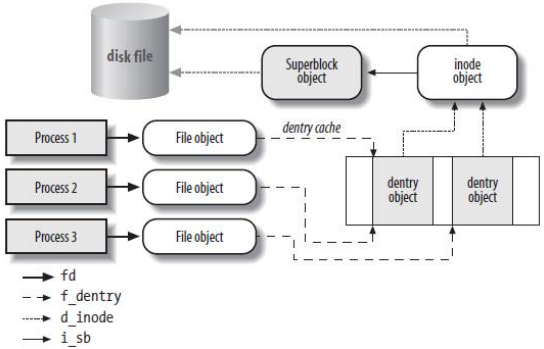
    inode_operations **:** methods, the kernel invokes on a specific filesystem ***create()*** and ***link().***

    dentry_operations : invoked on a specific directory entry, such as ***d_compare()*** and ***d_delete().***

    super_operations : invoked on a specific filesystem, such as ***write_inode()*** and ***sync_fs().***

    file_operations : methods that a process can invoke on an open file, such as ***read()*** and ***write().***





Virtual Filesystem (VFS)

- VFS Structures Details
  - ***super_block*** : Each FS needs to create an object of ***super_block*** to fill in its superblock details during **mount**.

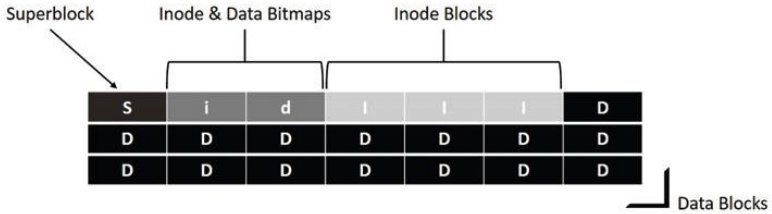
    s_list : list of mounted superblocks.

    s_dev : device ID.

    s_maxbytes : max file size.

    s_type : points to ***file_system_type*** type.

    s_root : points to the dentry object of the filesystem's root directory.



/include/linux/fs.h

```
struct super_block {
    struct list_head    s_list;
    dev_t               s_dev;
    loff_t              s_maxbytes;
    struct file_system_type *s_type;
    ...
    struct dentry       *s_root;
    ...
} __randomize_layout;
```

Virtual Filesystem (VFS)

- VFS Structures Details, *Cont'd*
  - *super_operations*
    alloc_inode() : create and allocate space for the new *inode* object and initialize it under the superblock.

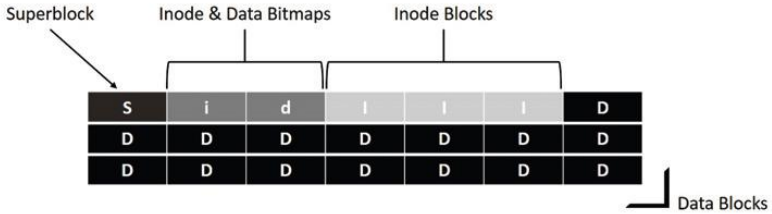
    write_inode() : write an inode on to the disk.

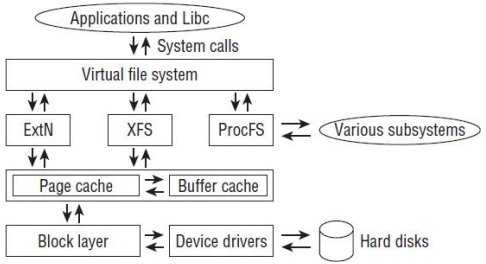
    put_super() : when VFS needs to free the superblock.

    sync_fs() : invoked to synchronize filesystem data with that of the underlying block device.

    remount_fs() : when the filesystem needs to be remounted,
    This is commonly used to change the mount flags for a filesystem, especially to make a readonly filesystem writeable.

    unmount_begin() : when the VFS is unmounting a filesystem.






```
struct super_operations {
    struct inode *(*alloc_inode)(struct super_block *sb);
    int (*write_inode) (struct inode *, struct
    void (*put_super) (struct super_block *);
    ...
    int (*sync_fs)(struct super_block *sb, int wait);
    int (*remount_fs) (struct super_block *, int *, char *);
    void (*umount_begin) (struct super_block *);
    ...
};
```

/include/linux/fs.h

Virtual Filesystem (VFS)

- VFS Structures Details, *Cont'd*
  - ***inode*** : contains all info to manipulate a file/directory (normal file, special files such as device files or pipes).

  - ***inode_operations***
    struct dentry * lookup(struct inode *dir, struct dentry *dentry, int flags) : searches a directory for a filename specified in the given dentry.

    Assume, dir ***(/tmp)*** , and lookup for a filename(***f1***) while the kernel created on-the-fly ***denty*** and fill it with filename(***f1***) to ease the search, So the kernel checks whether the ***dentry*** that coupled with the filename is one of the directory components.

    int link(struct dentry *old_dentry, struct inode *dir, struct dentry *dentry) : create a hard link of the file ***old_dentry*** in the directory ***dir*** with the new filename ***dentry***.

```
struct inode {
    ...
    const struct inode_operations   *i_op;
    ...
    struct pipe_inode_info  *i_pipe;
    struct cdev     *i_cdev;
    ...
}
```

/include/linux/fs.h

```
struct inode_operations {
    struct dentry * (*lookup) (struct inode *,struct dentry *, unsigned int)
    const char * (*get_link) (struct dentry *, struct inode *, struct
delayed_call *);
    int (*permission) (struct user_namespace *, struct inode *, int);
    struct posix_acl * (*get_acl)(struct inode *, int, bool);

    int (*readlink) (struct dentry *, char __user *,int);

    int (*create) (struct user_namespace *, struct inode *,struct dentry *,
            umode_t, bool);
    int (*link) (struct dentry *,struct inode *,struct dentry *);
    int (*unlink) (struct inode *,struct dentry *);
    int (*symlink) (struct user_namespace *, struct inode *,struct dentry *,
        const char *);
    int (*mkdir) (struct user_namespace *, struct inode *,struct dentry *,
            umode_t);
    int (*rmdir) (struct inode *,struct dentry *);
    int (*mknod) (struct user_namespace *, struct inode *,struct dentry *,
            umode_t,dev_t);
    int (*rename) (struct user_namespace *, struct inode *, struct dentry *,
            struct inode *, struct dentry *, unsigned int);
    int (*setattr) (struct user_namespace *, struct dentry *,
            struct iattr *);
    int (*getattr) (struct user_namespace *, const struct path *,
            struct kstat *, u32, unsigned int);
    ssize_t (*listxattr) (struct dentry *, char *, size_t);
    int (*fiemap)(struct inode *, struct fiemap_extent_info *, u64 start,
            u64 len);
    int (*update_time)(struct inode *, struct timespec64 *, int);
    int (*atomic_open)(struct inode *, struct dentry *,
            struct file *, unsigned open_flag,
            umode_t create_mode);
    int (*tmpfile) (struct user_namespace *, struct inode *,
            struct dentry *, umode_t);
    int (*set_acl)(struct user_namespace *, struct inode *,
            struct posix_acl *, int);
    int (*fileattr_set)(struct user_namespace *mnt_userns,
            sruct dentry *dentry, struct fileattr *fa);
    int (*fileattr_get)(struct dentry *dentry, struct fileattr *fa);
} ____cacheline_aligned;
```

Virtual Filesystem (VFS)

- VFS Structures Details, *Cont'd*
  - ***inode_operations, Con'td***
    int symlink(struct user_namespace *mnt_userns, struct inode *dir, struct dentry *dentry, const char *symname) :
    create a symbolic link named ***symname*** to the file represented by ***dentry*** in the directory ***dir***.

    int mkdir(struct user_namespace *mnt_userns, struct inode *dir, struct dentry *dentry, umode_t mode) :
    create a new directory.

    int mknod(struct user_namespace *mnt_userns, struct inode *dir, struct dentry *dentry, umode_t mode, dev_t rdev) :

    create a special file (device file, pipe, or socket).
    The file is referenced by the device ***rdev*** and the name ***dentry*** in the directory ***dir***.

```
struct inode {
    ...
    const struct inode_operations   *i_op;
    ...
    struct pipe_inode_info  *i_pipe;
    struct cdev     *i_cdev;
    ...
}
```

/include/linux/fs.h

```
struct inode_operations {
    struct dentry * (*lookup) (struct inode *,struct dentry *, unsigned int)
    const char * (*get_link) (struct dentry *, struct inode *, struct
delayed_call *);
    int (*permission) (struct user_namespace *, struct inode *, int);
    struct posix_acl * (*get_acl)(struct inode *, int, bool);

    int (*readlink) (struct dentry *, char __user *,int);

    int (*create) (struct user_namespace *, struct inode *,struct dentry *,
            umode_t, bool);
    int (*link) (struct dentry *,struct inode *,struct dentry *);
    int (*unlink) (struct inode *,struct dentry *);
    int (*symlink) (struct user_namespace *, struct inode *,struct dentry *,
        const char *);
    int (*mkdir) (struct user_namespace *, struct inode *,struct dentry *,
            umode_t);
    int (*rmdir) (struct inode *,struct dentry *);
    int (*mknod) (struct user_namespace *, struct inode *,struct dentry *,
            umode_t,dev_t);
    int (*rename) (struct user_namespace *, struct inode *, struct dentry *,
        struct inode *, struct dentry *, unsigned int);
    int (*setattr) (struct user_namespace *, struct dentry *,
        struct iattr *);
    int (*getattr) (struct user_namespace *, const struct path *,
        struct kstat *, u32, unsigned int);
    ssize_t (*listxattr) (struct dentry *, char *, size_t);
    int (*fiemap)(struct inode *, struct fiemap_extent_info *, u64 start,
            u64 len);
    int (*update_time)(struct inode *, struct timespec64 *, int);
    int (*atomic_open)(struct inode *, struct dentry *,
            struct file *, unsigned open_flag,
            umode_t create_mode);
    int (*tmpfile) (struct user_namespace *, struct inode *,
        struct dentry *, umode_t);
    int (*set_acl)(struct user_namespace *, struct inode *,
            struct posix_acl *, int);
    int (*fileattr_set)(struct user_namespace *mnt_userns,
            sruct dentry *dentry, struct fileattr *fa);
    int (*fileattr_get)(struct dentry *dentry, struct fileattr *fa);
} ____cacheline_aligned;
```

Virtual Filesystem (VFS)

- VFS Structures Details, *Cont'd*
  - *dentry*

    Dentry State : there are 3 states for dentry object,
    1) **Used** : used, and points to a valid inode.
    2) **Unused** : not used , and points to a valid inode.
    3) **Negative** : dentry is not associated with a valid inode.

    Dentry Cache : As we know, when requesting operation related to path, VFS resolving each element into a dentry object.All these dentry objects, the kernel caches them in a cache called ***dcache*** to make use of them in the upcomming operations related to paths.

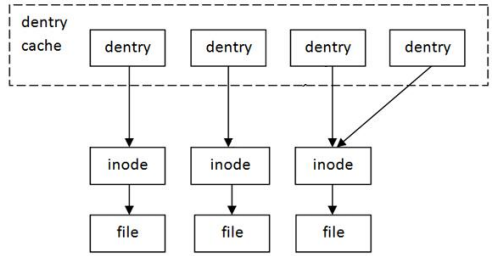
    dentry cache consists of 3 parts :
    1) Lists of "**used**" dentries linked off their associated inode via the ***i_dentry*** field of the inode object.

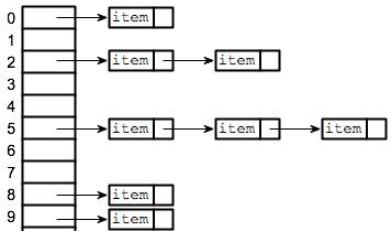
    2) A doubly linked "**least recently used**" list of unused and negative dentry objects.

    3) A **hash table and hashing function** used to quickly resolve a given path into the associated dentry object by ***d_lookup()***.

```
struct dentry {
    ...
    struct hlist_bl_node d_hash; /* lookup hash list */
    struct dentry *d_parent; /* parent directory */
    struct qstr d_name;
    struct inode *d_inode; /* Where the name belongs to - NULL is negative */
    unsigned char d_iname[DNAME_INLINE_LEN];    /* small names */
    ...
} __randomize_layout;
```

/include/linux/dcache.h






```
struct dentry *d_lookup(const struct dentry
*parent, const struct qstr *name)
{
    struct dentry *dentry;
    unsigned seq;

    do {
        seq = read_seqbegin(&rename_lock);
        dentry = __d_lookup(parent, name);
        if (dentry)
            break;
    } while (read_seqretry(&rename_lock,
seq));
    return dentry;
}
EXPORT_SYMBOL(d_lookup);
```

Virtual Filesystem (VFS)

- VFS Structures Details, *Cont'd*
  - ***dentry, Cont'd***
    The most important elements ***d_parent, d_name, d_inode, d_op***.

  - ***dentry_operations***
    d_revalidate() : Invoked when VFS needs to revalidate a dentry.Whenever a name lookup returns a dentry in the dcache, this is called.

    d_compare() : Invoked to compare the filenames of two dentry instances. It compares a dentry name with a given name.

    d_hash() : Invoked when VFS adds a dentry to the hash table.

```
struct dentry {
    ...
    struct hlist_bl_node d_hash; /* lookup hash list */
    struct dentry *d_parent; /* parent directory */
    struct qstr d_name;
    struct inode *d_inode; /* Where the name belongs to - NULL is negative */
    unsigned char d_iname[DNAME_INLINE_LEN];    /* small names */
    ...
} __randomize_layout;
```

/include/linux/dcache.h

```
struct dentry_operations {
    int (*d_revalidate)(struct dentry *, unsigned int);
    ...
    int (*d_hash)(const struct dentry *, struct qstr *);
    int (*d_compare)(const struct dentry *,
    ...
} ____cacheline_aligned;
```

Virtual Filesystem (VFS)

- VFS Structures Details, *Cont'd*
  - ***file, file_operations :***
    fsync() : Called by the fsync() system call to write all cached data for the file to disk.

    compat_ioctl() : a portable variant of old ***ioctl()*** for use on 64-bit systems by 32-bit applications.

    what was ***ioctl()?***
    It sends a command and argument pair to a device. It is used when the file is an open device node.

    mmap() : Memory maps the given file onto the given address space and is called by the mmap() system call.

```
struct file {
    struct inode        *f_inode;
    const struct file_operations    *f_op;
    ...
    spinlock_t      f_lock;
    unsigned int        f_flags;
    fmode_t         f_mode;
    struct mutex        f_pos_lock;
    loff_t          f_pos;
    struct fown_struct  f_owner;
    ...
    struct address_space    *f_mapping;
} __randomize_layout
  __attribute__((aligned(4)));
```

```
struct file_operations {
    ...
    long (*compat_ioctl) (struct file *, unsigned int, unsigned long);
    int (*mmap) (struct file *, struct vm_area_struct *);
    int (*fsync) (struct file *, loff_t, loff_t, int datasync);
    ...
} __randomize_layout;
```

Virtual Filesystem (VFS)

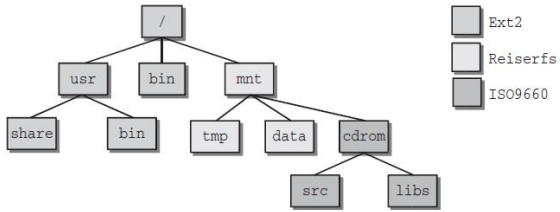
- Data Structures Associated with Filesystems
  - ***file_system_type*** : describe a specific variant of a filesystem, such as ext3, ext4.
  - ***vfsmount*** : it's the mounted filesystem descriptor.
    mnt_root : Points to the dentry of the root directory of this filesystem.

    mnt_sb : Points to the superblock object of this filesystem.

```
struct vfsmount {
    struct dentry *mnt_root;    /* root of the mounted tree */
    struct super_block *mnt_sb; /* pointer to superblock */
    int mnt_flags;
    struct user_namespace *mnt_userns;
} __randomize_layout;
```

```
struct super_block {
    struct list_head    s_list;
    dev_t           s_dev;
    loff_t          s_maxbytes;
    struct file_system_type *s_type;
    ...
    struct dentry       *s_root;
    ...
} __randomize_layout;
```

```
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;
    ...
};
```



Special Filesystems

Special Filesystems

- Kernel implements special filesystems do not deal with persistent data, they do not consume disk blocks.
- These filesystems enables simplified application development, debugging, and easier error detection.
- Special FS
  - **Procfs** : Procfs is mounted to the */proc* directory (mount point) of rootfs.
    Each file is an interface through which users can trigger associated operations.

    i.e. Read operation on a ***proc*** file invokes the associated read callback function bound to the file entry.

```
karim-eshapa@karimeshapa-Inspiron-5537:/$ cat /proc/cpuinfo
processor       : 0
vendor_id       : GenuineIntel
cpu family      : 6
model           : 69
model name      : Intel(R) Core(TM) i5-4200U CPU @ 1.60GHz
stepping        : 1
microcode       : 0x26
cpu MHz         : 1290.332
cache size      : 3072 KB
physical id     : 0
siblings        : 4
```

File name	Description
/proc/cpuinfo	Provides low-level cpu details such as vendor, model, clock speed, cache size, number of siblings, cores, CPU flags, and bogomips.
/proc/meminfo	Provides a summarized view of physical memory state.
/proc/ioports	Provides details on current usage of port I/O address space supported by the x86 class of machines. This file is not present on other architectures.
/proc/iomem	Shows a detailed layout describing current usage of memory address space.
/proc/interrupts	Shows a view of the IRQ descriptor table that contains details of IRQ lines and interrupt handlers bound to each.
/proc/slabinfo	Shows a detailed listing of slab caches and their current state.
/proc/buddyinfo	Shows the current state of buddy lists managed by the buddy system.
/proc/vmstat	Shows virtual memory management statistics.
/proc/zoneinfo	Shows per-node memory zone statistics.
/proc/cmdline	Shows boot arguments passed to the kernel.
/proc/timer_list	Shows a list of active pending timers, with details of clock source.
/proc/timer_stats	Provides detailed statistics on active timers, used for tracking timer usage and debugging.
/proc/filesystems	Presents a list of filesystem services currently active.
/proc/mounts	Shows currently mounted devices with their mountpoints.
/proc/partitions	Presents details of current storage partitions detected with associated /dev file enumerations.
/proc/swaps	Lists out active swap partitions with status details.
/proc/modules	Lists out names and status of kernel modules currently deployed.
/proc/uptime	Shows length of time kernel has been running since boot and spent in idle mode.
/proc/kmsg	Shows contents of kernel's message log buffer.
/proc/kallsyms	Presents kernel symbol table.

Special Filesystems

- Special FS, *Cont'd*
  - Sysfs : mounted to the */sys* directory of the rootfs.
    - ***devices*** : present a unified list of devices currently enumerated and managed by respective driver.

    - ***bus*** : a listing of subdirs, each representing the physical bus type that has support registered in the kernel. Each bus type dir contains 2 subdirs :

      1) devices : listing of devices currently discovered or bound to that bus type.
      Each file in the listing is a symbolic link to the device file in ***device's*** dir in the global device tree.

      2) drivers : contains dirs describing each device driver registered with the bus manager.

      Each driver directories lists attributes that show the current configuration of driver parameters, which can be modified, and symbolic links that point to the physical device directory that the driver is bound to.

```
karim-eshapa@karimeshapa-Inspiron-5537:/$ ls /sys/
block  bus  class  dev  devices  firmware  fs  hypervisor  kernel  module  power

karim-eshapa@karimeshapa-Inspiron-5537:/$ ls /sys/devices/virtual/
bdi    dmi  graphics  input  misc  powercap  sound    tty  vtconsole
block  drm  hwmon     mem    net   ppp       thermal  vc   workqueue

karim-eshapa@karimeshapa-Inspiron-5537:/sys/bus/usb$ ls
devices  drivers  drivers_autoprobe  drivers_probe  uevent

karim-eshapa@karimeshapa-Inspiron-5537:/sys/bus/usb/devices$ ls
1-0:1.0  1-1:1.0  1-1.5:1.0  1-1.7      1-1.8      1-1.8:1.1  3-0:1.0  usb2
1-1      1-1.5    1-1.5:1.1  1-1.7:1.0  1-1.8:1.0  2-0:1.0    usb1     usb3
karim-eshapa@karimeshapa-Inspiron-5537:/sys/bus/usb/devices$ ls -al 1-0\:1.0
lrwxrwxrwx 1 root root 0 Aug 27 16:42 1-0:1.0 -> ../../../devices/pci0000:00/000
0:00:1d.0/usb1/1-0:1.0

karim-eshapa@karimeshapa-Inspiron-5537:/sys/bus/usb/drivers/hub$ ls
1-0:1.0  2-0:1.0  bind    new_id    uevent
1-1:1.0  3-0:1.0  module  remove_id  unbind
karim-eshapa@karimeshapa-Inspiron-5537:/sys/bus/usb/drivers/hub$ ls -al 1-0\:1.0
lrwxrwxrwx 1 root root 0 Aug 27 18:34 1-0:1.0 -> ../../../../devices/pci0000:00/
0000:00:1d.0/usb1/1-0:1.0
```

Special Filesystems

- Special FS, *Cont'd*
  - Sysfs, *Cont'd*

    - ***class*** : contains representations of device classes that are currently registered with the kernel.
    Each device class dir contains subdirs representing devices currently allocated and registered under this class.

    For most of the class device objects, their dirs contain symbolic links to the device dirs in the global ***devices*** hierarchy.

    - ***Firmware*** : contains interfaces for viewing and manipulating platform-specific firmware that is run during power on/reset, such as BIOS or UEFI on x86 and OpenFirmware for PPC platforms.

```
karim-eshapa@karimeshapa-Inspiron-5537:/$ cd /sys/class/
karim-eshapa@karimeshapa-Inspiron-5537:/sys/class$ ls
ata_device      drm             leds            power_supply  sound
ata_link        drm_dp_aux_dev  mdio_bus        ppdev         spi_master
ata_port        extcon          mei             ppp           spi_slave
backlight       firmware        mem             printer       thermal
bdi             gpio            memstick_host   pwm           tpm
block           graphics        misc            rapidio_port  tpmrm
bluetooth       hmm_device      mmc_host        regulator     tty
bsg             hwmon           nd              rfkill        vc
devcoredump     i2c-adapter     net             rtc           video4linux
devfreq         i2c-dev         pci_bus         scsi_device   virtio-ports
devfreq-event   ieee80211       pci_epc         scsi_disk     vtconsole
dma             input           phy             scsi_generic  watchdog
dmi             iommu           powercap        scsi_host     wmi_bus
karim-eshapa@karimeshapa-Inspiron-5537:/sys/class$ ls -al i2c-dev/i2c-0
lrwxrwxrwx 1 root root 0 Aug 27 16:42 i2c-dev/i2c-0 -> ../../devices/pci0000:00/
0000:00:02.0/i2c-0/i2c-dev/i2c-0
```

```
karim-eshapa@karimeshapa-Inspiron-5537:/sys/firmware$ ls
acpi  dmi  memmap
karim-eshapa@karimeshapa-Inspiron-5537:/sys/firmware$ ls acpi/tables/
 APIC    ASPT   data   DSDT      FACP   FPDT   LPIT   SSDT1   SSDT3   SSDT5
'ASF!'   BOOT   DBGP   dynamic   FACS   HPET   MCFG   SSDT2   SSDT4   UEFI

What:           /sys/firmware/acpi/fpdt/
Date:           Jan 2021
Contact:        Zhang Rui <rui.zhang@intel.com>
Description:

                ACPI Firmware Performance Data Table (FPDT) provides
                information for firmware performance data for system boot,
                S3 suspend and S3 resume. This sysfs entry contains the
                performance data retrieved from the FPDT.
```

Special Filesystems

- Special FS, *Cont'd*
  - **Sysfs**, *Cont'd*
    - ***module*** : contains subdirs that represent each kernel module currently deployed. Each dir is enumerated with the name of the module it is representing. Each module dir contains information about a module such as ***refcount***, ***modparams***, and its core size.

  - **Debugfs** : Unlike procfs and sysfs, which are implemented to present specific information through the virtual file interface, debugfs is a generic memory filesystem that allows kernel developers to export any arbitrary information that is useful for debugging.

    Generally mounted to the ***/sys/kernel/debug*** dir.

  - Many other special filesystems such as **pipefs**, **mqueue**, and **sockfs.**

```
karim-eshapa@karimeshapa-Inspiron-5537:/sys/module$ ls
8250                  glue_helper       scsi_mod
acpi                  gpiolib_acpi      serio_raw
acpi_cpufreq          i2c_algo_bit      sg
acpiphp               i8042             shpchp
aesni_intel           i915              snd
aes_x86_64            ima               snd_hda_codec
ahci                  input_leds        snd_hda_codec_generic
amdgpu                intel_cstate      snd_hda_codec_hdmi
apparmor              intel_idle        snd_hda_codec_realtek
arc4                  intel_powerclamp  snd_hda_core
ata_generic           intel_rapl        snd_hda_intel
ata_piix              intel_rapl_perf   snd_hwdep
ath                   ip_tables         snd_pcm
ath3k                 ipv6              snd_rawmidi
ath9k                 irqbypass         snd_seq
ath9k_common          joydev            snd_seq_device
ath9k_hw              kdb               snd_seq_midi
autofs4               kernel            snd_seq_midi_event
battery               keyboard          snd_timer
block                 kgdb_nmi          soundcore
bluetooth             kgdboc            sparse_keymap
bnep                  kvm               spurious
```

```
karim-eshapa@karimeshapa-Inspiron-5537:/sys/module$ ls acpi/parameters/
acpica_version     ec_delay           ec_polling_guard     trace_method_name
aml_debug_output   ec_event_clearing  ec_storm_threshold   trace_state
debug_layer        ec_freeze_events   immediate_undock
debug_level        ec_max_queries     trace_debug_layer
ec_busy_polling    ec_no_wakeup       trace_debug_level
```

```
karim-eshapa@karimeshapa-Inspiron-5537:/sys$ sudo ls kernel/debug/
acpi               fault_around_bytes  pinctrl           suspend_stats
bdi                frontswap           pkg_temp_thermal  sync
block              gpio                pm_genpd          tracing
bluetooth          ieee80211           pm_qos            usb
cleancache         intel_powerclamp    pwm               vgaswitcheroo
clear_warn_once    iosf_sb             ras               virtio-ports
clk                kprobes             regmap            wakeup_sources
dell_laptop        kvm                 regulator         x86
dma_buf            mce                 sched_debug       zswap
dri                mei0                sched_features
dynamic_debug      mmc0                sleep_time
extfrag            opp                 split_huge_pages
karim-eshapa@karimeshapa-Inspiron-5537:/sys$ sudo ls kernel/debug/acpi
acpidbg
```