CS 5264/4224; ECE 5414/4414
(Advanced) Linux Kernel Programming
Lecture 18

Virtual File System

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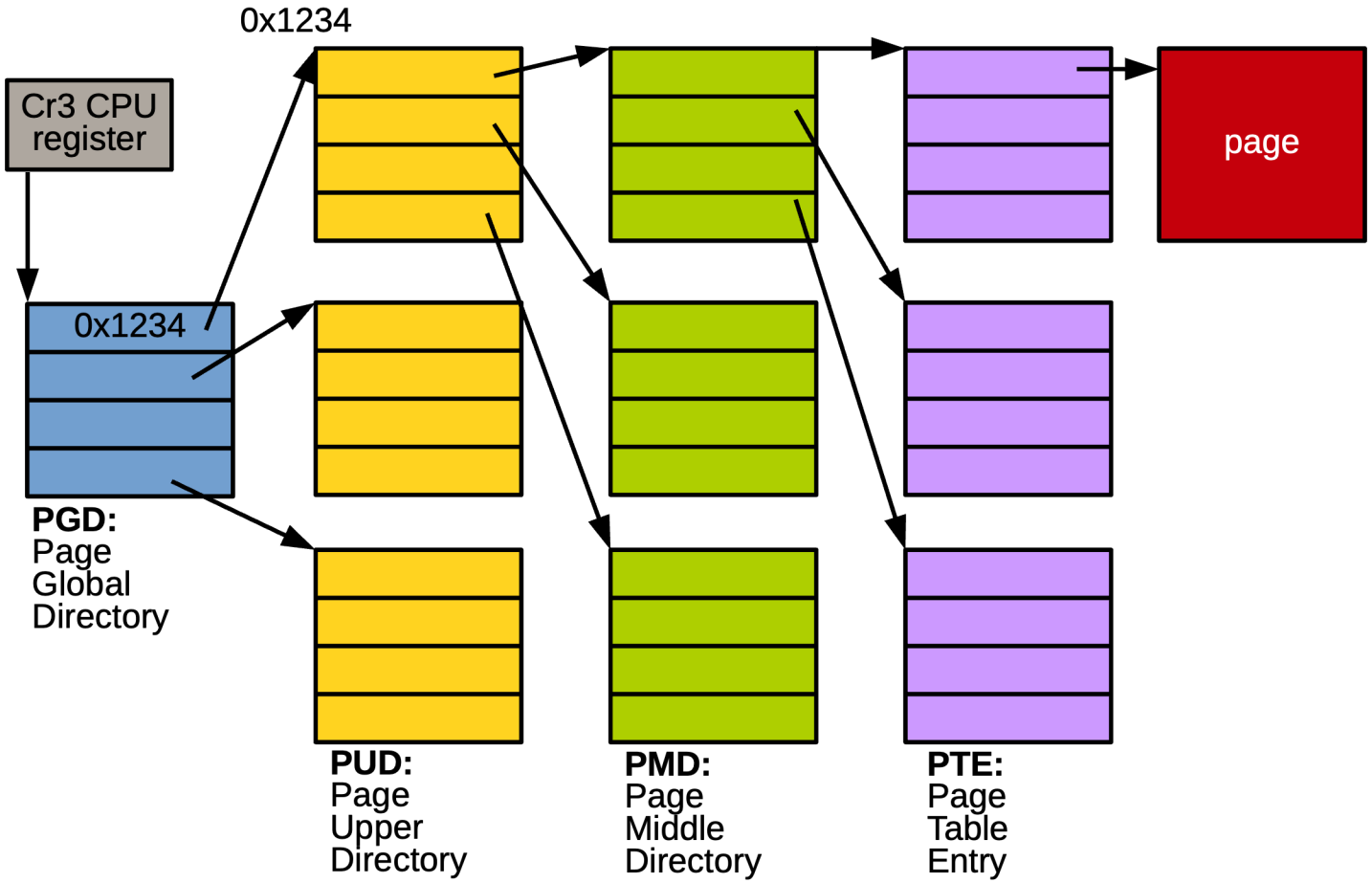
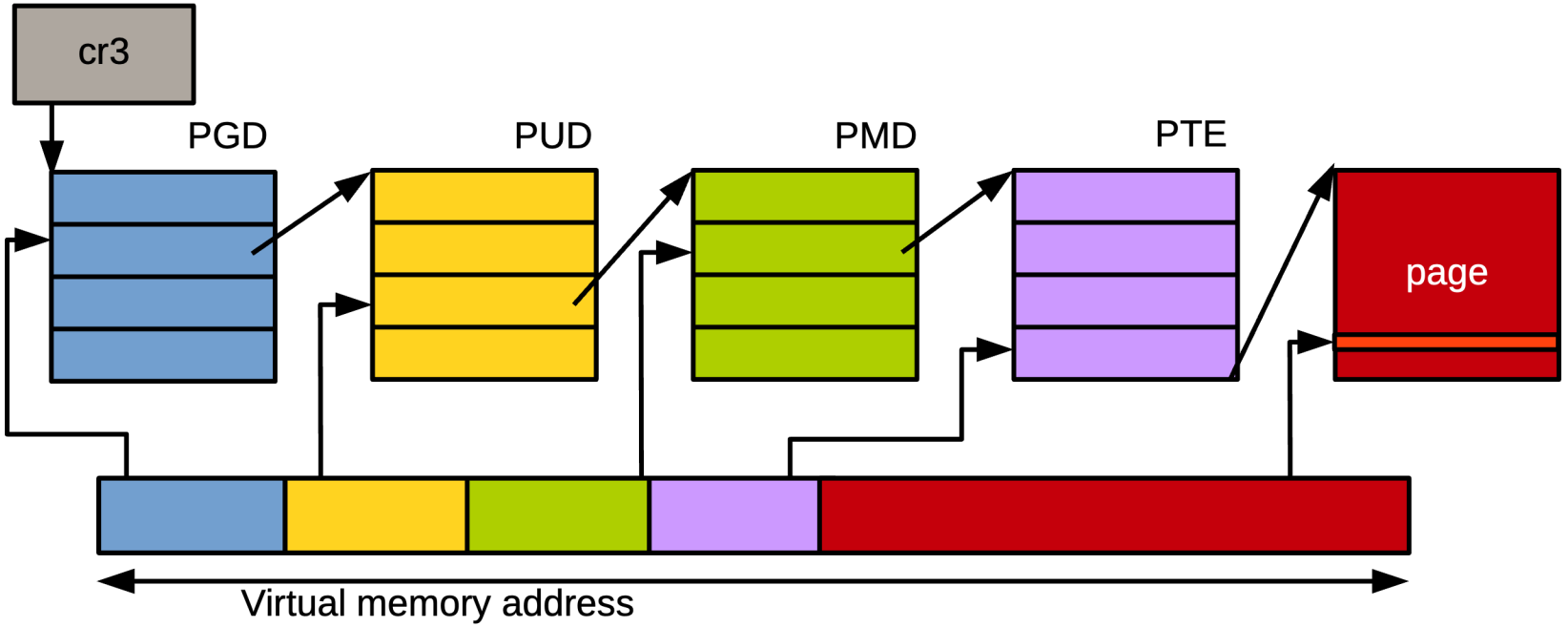
Recap: Page Tables

```
/* linux/include/linux/mm_types.h */
struct mm_struct {
    struct vm_area_struct *mmap;          /* list of VMAs */
    struct rb_root        mm_rb;          /* rbtree of VMAs */
    pgd_t                 *pgd;           /* page global directory */
    /* ... */
};
```



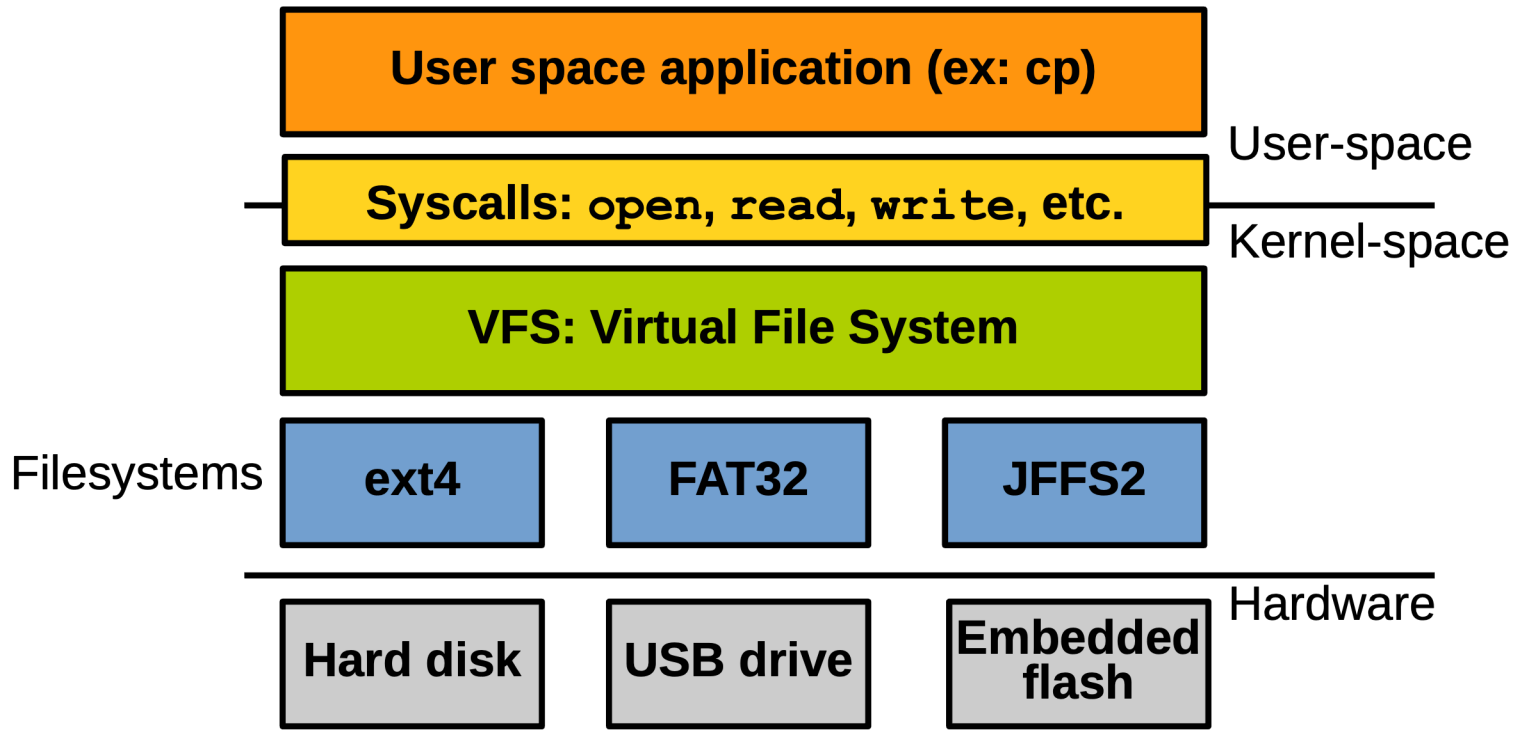
Recap: Page Tables

- Address translation is performed by the hardware (MMU)



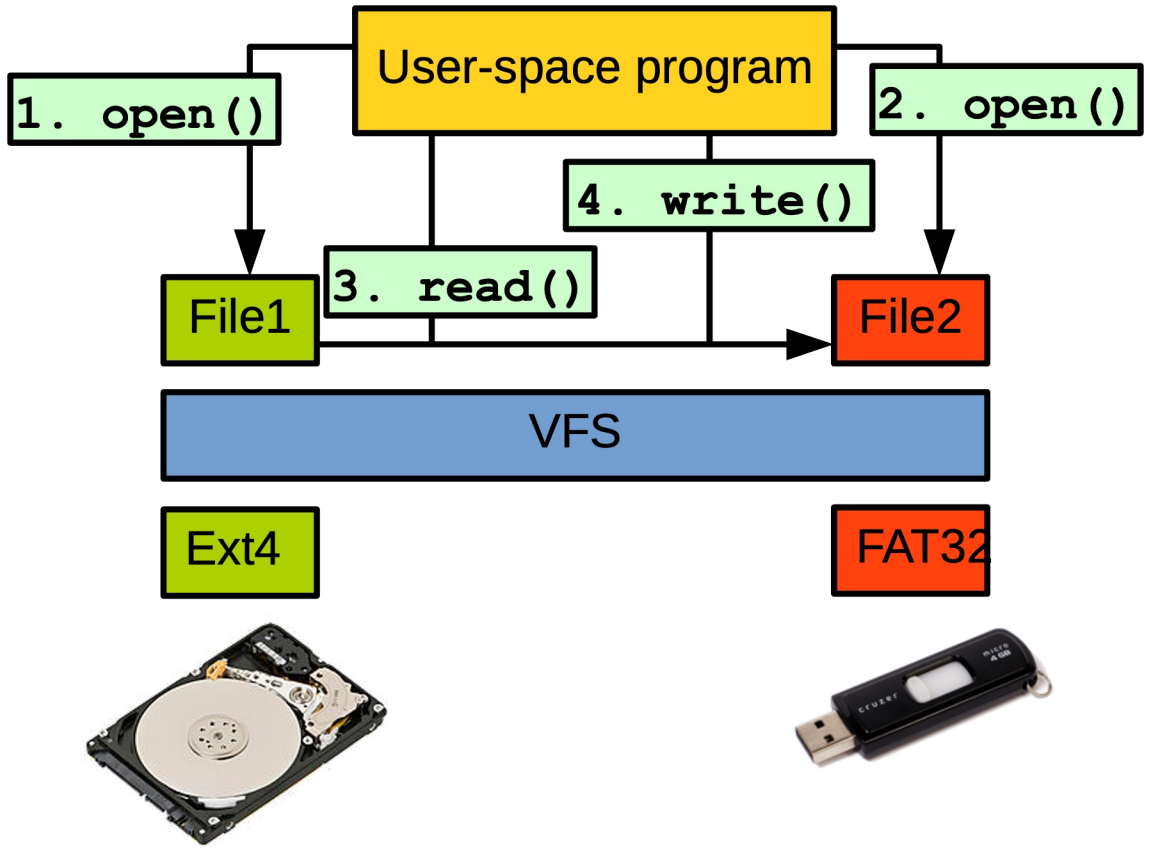
Virtual File System (VFS)

- Abstract all the filesystem models supported by Linux
  - Similar to an abstract base class in C++
- Allow FSes to coexist
  - Example: a user can have a USB drive formatted with FAT32 mounted at the same time as an HDD rootfs with ext4
- Allow them to cooperate
  - Example: a user can seamlessly copy a file between the FAT32 and ext4 partitions


User space application (ex: cp)
User-space
Syscalls: open, read, write, etc.
Kernel-space
VFS: Virtual File System
Filesystems
ext4
FAT32
JFFS2
Hardware
Hard disk
USB drive
Embedded flash

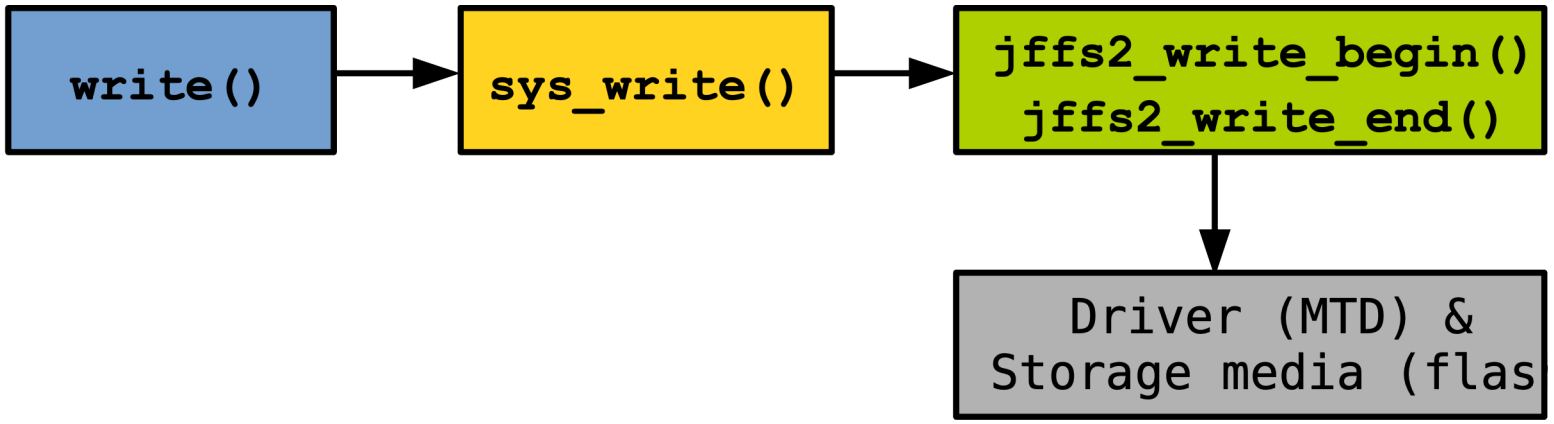
Common Filesystem Interface

- VFS allows user-space to access files independently of the concrete filesystem they are stored on with a common interface
  - Standard system calls: open(), read(), write(), lseek(), etc
  - "top" VFS interface (with user-space)
- Interface can work transparently between filesystems


User-space program
1. open()
2. open()
4. write()
3. read()
File1
File2
VFS
Ext4
FAT32

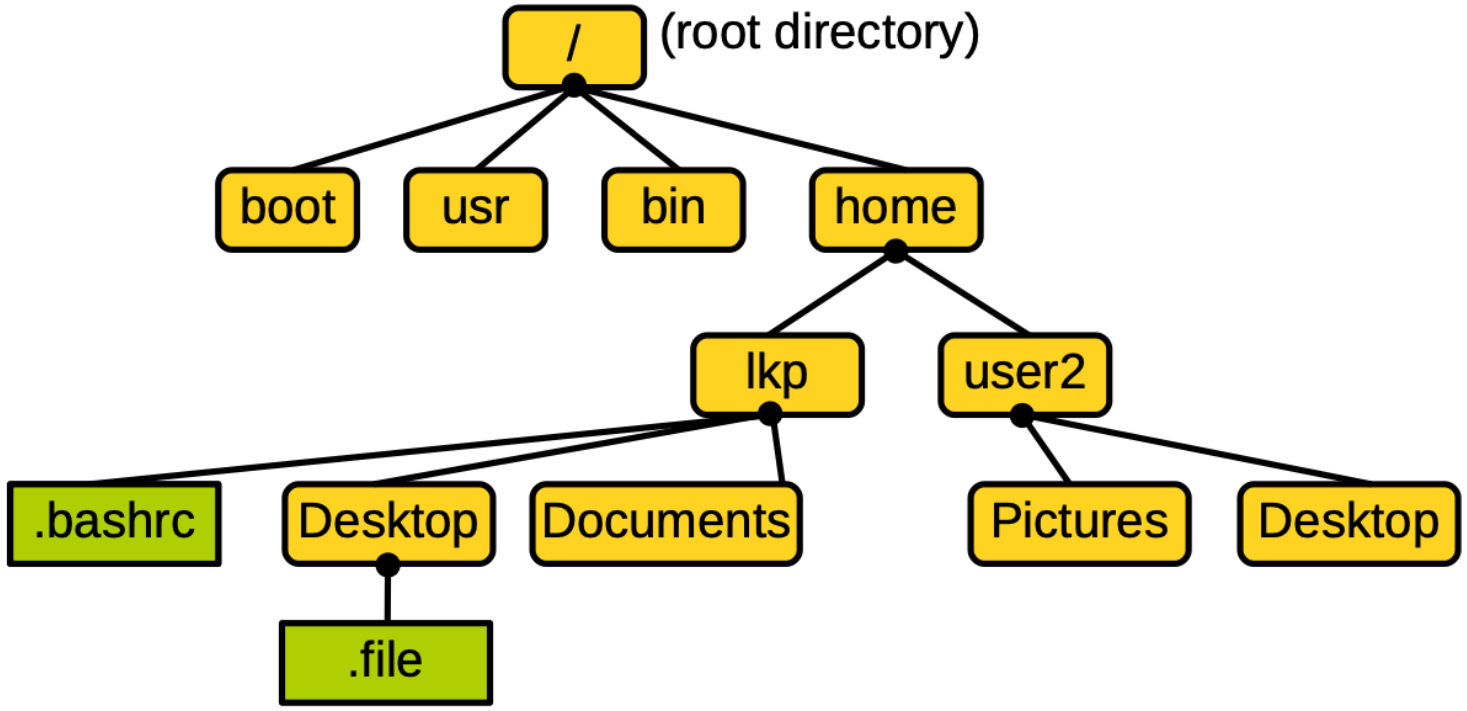
Filesystem Abstraction Layer

- VFS redirects user-space requests to the corresponding concrete filesystem
  - "bottom" VFS interface (with the filesystem)
  - Developing a new filesystem for Linux means conforming with the bottom interface



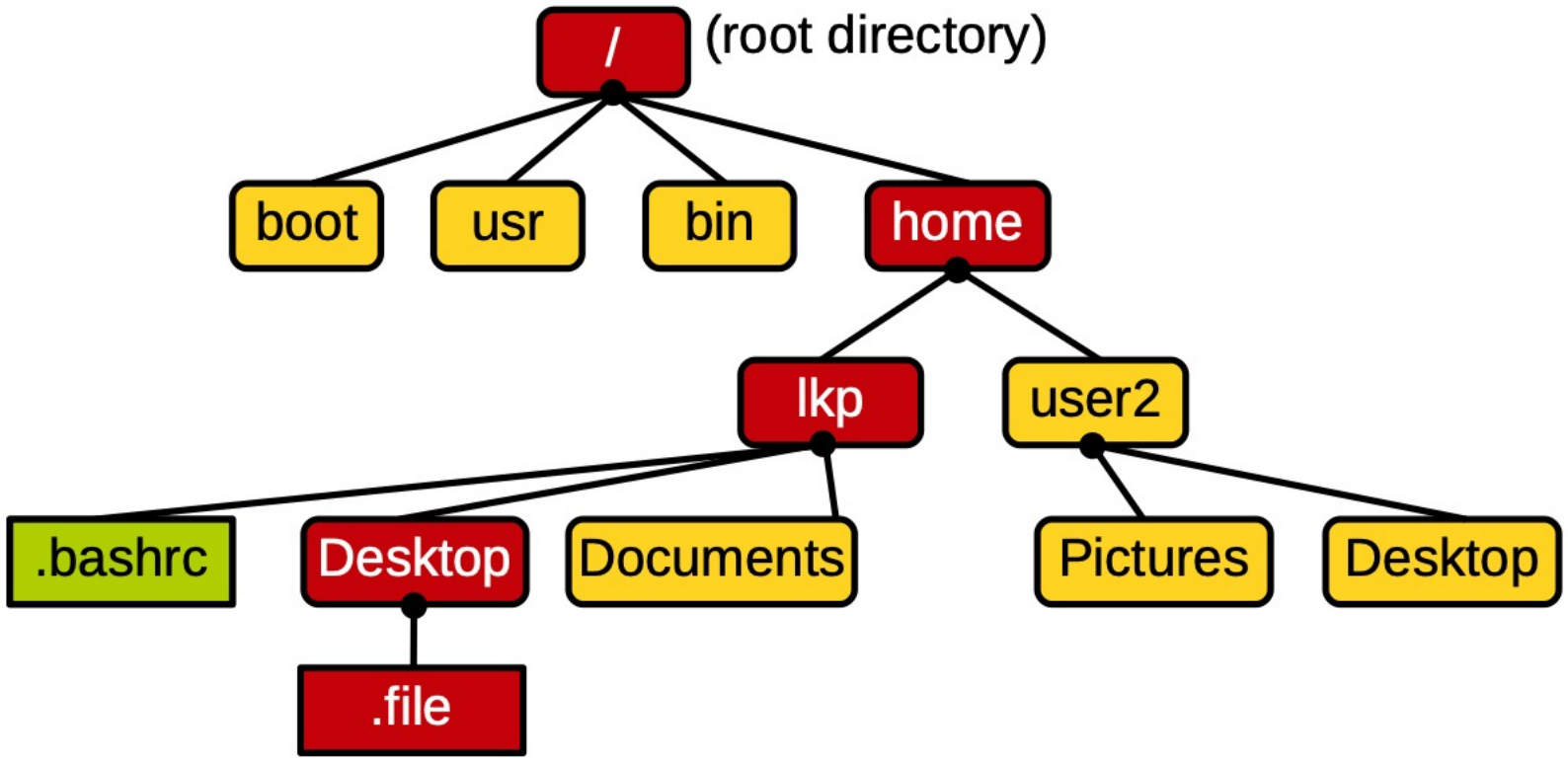
Unix Filesystem

- The term filesystem can refer to a filesystem type or a partition
- Hierarchical tree of files organized into directories



- File: ordered string of bytes from file address 0 to address (file size – 1)
  - Metadata: name, access permission, modification date, etc.
  - Separated from the file data into specific objects inodes, dentries
- directory: folder containing files or other directories (sub-directories)
  - Sub-directories can be nested to create path: /home/lkp/Desktop/file

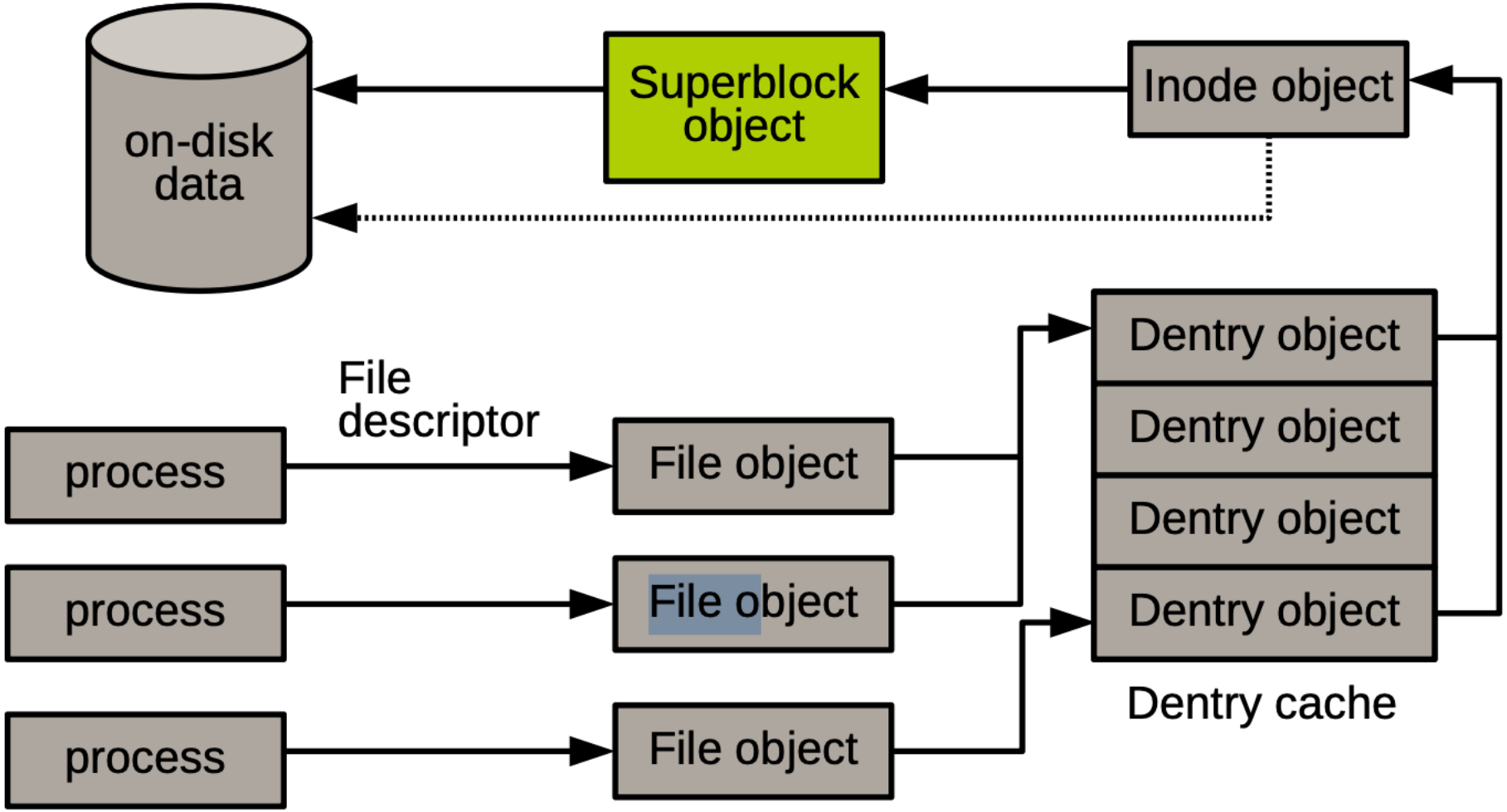
- Path example: `/home/lkp/Desktop/.file`



VFS Data Structures

- dentry: contains file/directory name and hierarchical links defining the filesystem directory tree
- inode: contains file/directory metadata
- file: contains information about a file opened by a process
- superblock: contains general information about the partition
- file_system_type: contains information about a file system type (ext4)
- Associated operations ("bottom" VFS interface):
  - super_operations
  - inode_operations
  - dentry_operations
  - file_operations

Superblock


on-disk data
Superblock object
Inode object
File descriptor
process
process
process
File object
File object
File object
Dentry object
Dentry object
Dentry object
Dentry object
Dentry cache

Superblock

- Contains global information about the filesystem (partition)
- Created by the filesystme and given to VFS at mount time:
  - Disk-based filesystem store it in a special location
  - Other filesystems have a way to generate it at mount time
- "struct super_block", include/linux/fs.h

```
/* linux/include/linux/fs.h */
struct super_block {
    struct list_head  s_list;           /** list of all superblocks **/
    dev_t             s_dev;            /* identifier */
    unsigned long     s_blocksize;      /* block size (bytes) */
    unsigned long     s_blocksize_bits; /* block size (bits) */
    loff_t            s_maxbytes;       /* max file size */
    /* ... */
```

Superblock

```
/* ... */
struct file_system_type     *s_type;        /** filesystem type **/
struct super_operations     *s_op;          /** superblock operations **/
struct dquot_operations     *dq_op;         /* quota methods */
struct quotactl_ops         *s_qcop;        /* quota control methods */
unsigned long               s_flags;        /** mount flags **/
unsigned long               s_magic;        /* filesystem magic number */
struct dentry               s_root;         /** directory mount point **/
struct rw_semaphore         s_umount;       /* umount semaphore */
int                         s_count;        /* superblock reference count */
atomic_t                    s_active;       /* active reference count */
struct xattr_handler        **s_xattr;      /* extended attributes handler
    */
struct list_head            s_inodes;       /** inodes list **/
struct hlist_bl_head        s_anon;         /* anonymous entries */
struct list_lru             s_dentry_lru;   /* list of unused dentries */
struct block_device         *s_bdev;        /** associated block device **/
struct hlist_node           s_instances;    /* instances of this filesystem
    */
struct quota_info           s_dquot;        /* quota-specific options */
char                        s_id[32];       /* text name */
void                        *s_fs_info;     /* filesystem-specific info */
```

Superblock Operations

- struct super_operations
  - Each field is a function pointer operating on a "struct super_block"
  - Usage: sb->s_op->alloc_inode(sb)

```
/* linux/include/linux/fs.h */
struct super_operations {
    struct inode *(*alloc_inode)(struct super_block *sb);
    void (*destroy_inode)(struct inode *);
    void (*dirty_inode) (struct inode *, int flags);
    int (*write_inode) (struct inode *, struct writeback_control *wbc);
    int (*drop_inode) (struct inode *);
    void (*evict_inode) (struct inode *);
    void (*put_super) (struct super_block *);
    int (*sync_fs)(struct super_block *sb, int wait);
```

Superblock operations: inode

- struct inode *alloc_inode(struct super_block *sb)
  - Create and initialize a new inode
- void destroy_inode(struct inode *inode)
  - Deallocate an inode
- void dirty_inode(struct inode *inode)
  - Marks an inode as dirty (ext filesys)

Superblock Operations: inode

- void write_inode(struct inode *inode, int wait)
  - Writes the inode to disk, wait specifies if the write should be synchronous
- void clear_inode(struct inode *inode)
  - Releases the inode and clear any page containing related data
- void drop_inode(struct inode *inode)
  - Called by VFS when the last reference to the inode is dropped

Superblock Operations: superblock

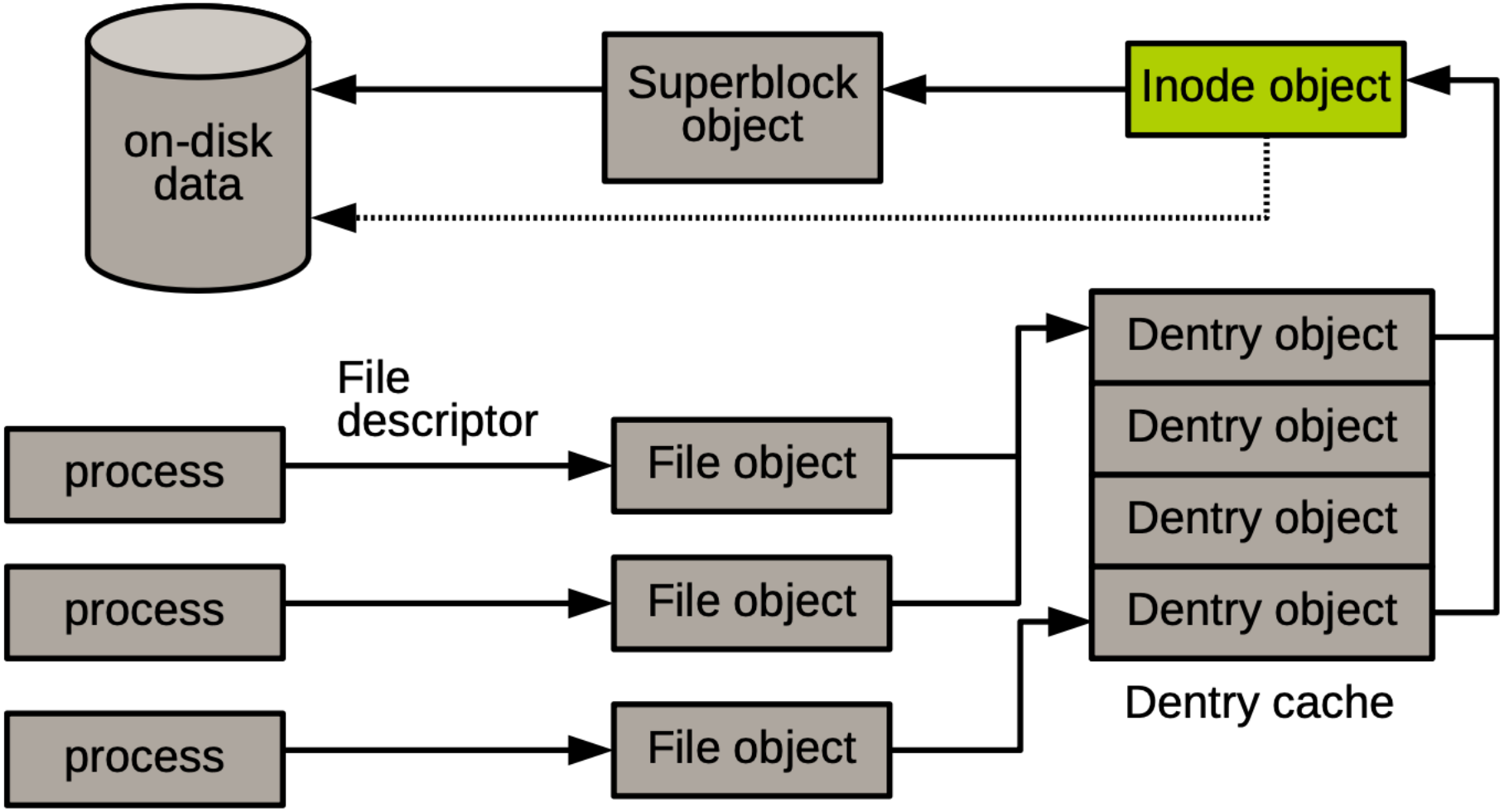
- void put_super(struct super_block *sb)
  - Called by VFS on unmount (holding s_lock)
- void write_super(struct super_block *sb)
  - Update the on-disk superblock, caller must hold s_lock

Superblock Operations: Filesystem

- int sync_fs(struct super_block *sb, int wait)
  - Synchronize filesystem metadata with on-disk filesystem, "wait" specifies if the operation should be synchronous
- void write_super_lockfs(struct super_block *sb)
  - Prevent changes to the filesystem and update the on-disk superblock (used by the Logical volume Manager)
- void unlockfs(struct super_block *sb)
  - Unlock the filesystem locked by write_super_lockfs()
- int statfs(struct super_block *sb, struct statfs *statfs)
  - Obtain filesystem statistics
- int remount_fs(struct super_block *sb, int *flags, char *data)
  - Remount the filesystem with new options, caller must hold s_lock
- void umount_begin(struct super_block *sb)
  - Called by VFS to interrupt a mount operation (NFS)

- All these functions are called by VFS and may block (except dirty_inode())
- Function to mount a file system?
  - mount_bdev() in fs/super.c

inode


on-disk data
Superblock object
Inode object
File descriptor
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Dentry object
Dentry cache

- Related to a file or directory, contains metadata plus information about how to manipulate the file/directory
- Metadata: file size, owner id/group, etc
- Must be produced by the filesystem on-demand when a file/directory is accessed
  - Read from disk in Unix-like filesystem
  - Reconstructed from on-disk information for other filesystems
- Cached in a hashtable
  - inode_hashtable in fs/inode.c

inode

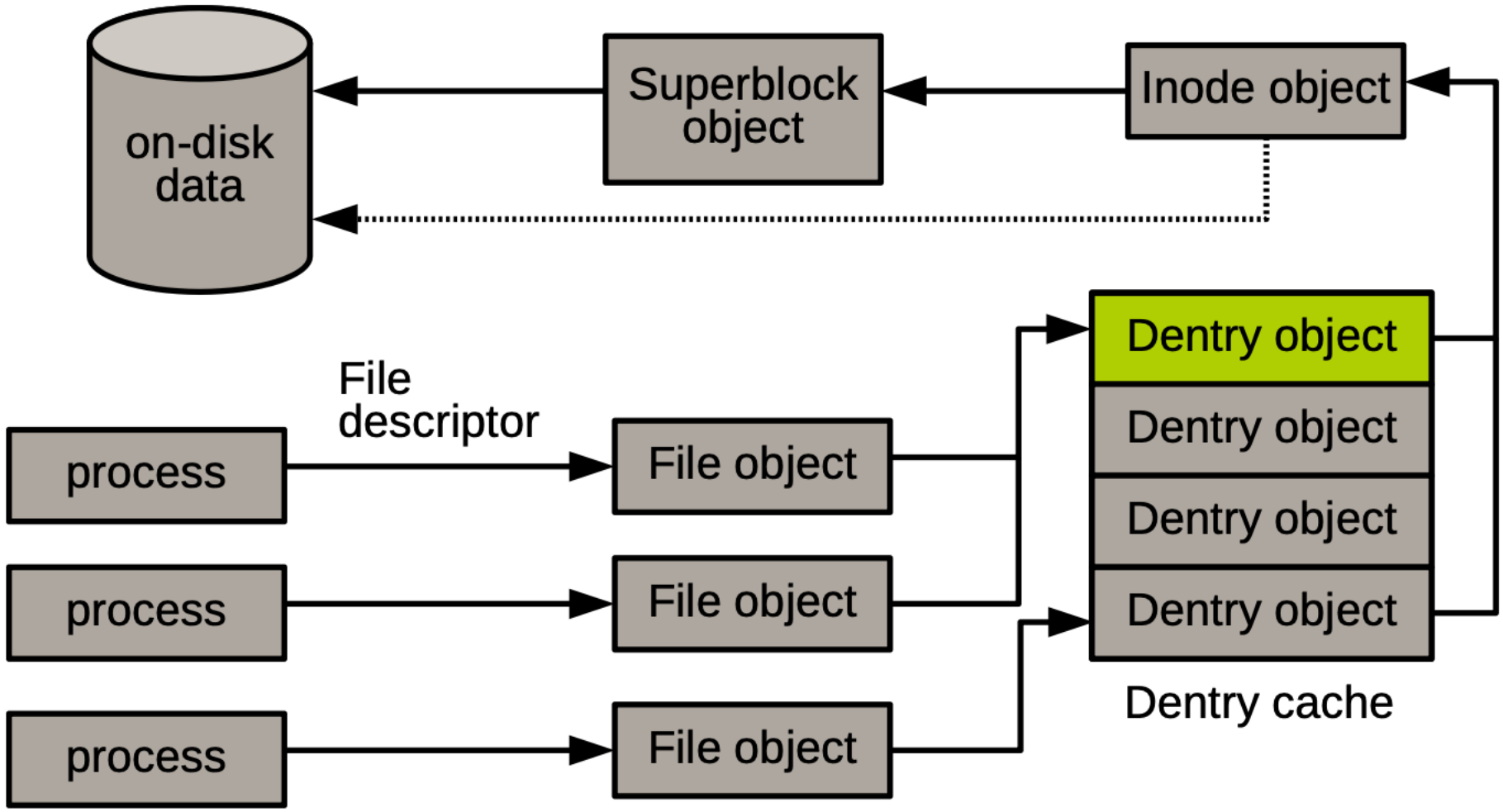
```
/* linux/include/linux/fs.h */
struct inode {
    struct hlist_node        i_hash;         /** hash list **/
    struct list_head         i_lru;          /* inode LRU list*/
    struct list_head         i_sb_list;      /** inode list in superblock **/
    struct list_head         i_dentry;       /** list of dentries **/
    unsigned long            i_ino;          /** inode number **/
    atomic_t                 i_count;        /** reference counter **/
    unsigned int             i_nlink;        /* number of hard links */
    uid_t                    i_uid;          /** user id of owner **/
    gid_t                    i_gid;          /** group id of owner **/
    kdev_t                   i_rdev;         /* real device node */
    u64                      i_version;      /* versioning number */
    loff_t                   i_size;         /* file size in bytes */
    seqcount_t               i_size_seqcount /* seqlock for i_size */
    struct timespec          i_atime;        /** last access time **/
    struct timespec          i_mtime; /** last modify time (file content) **/
    struct timespec          i_ctime; /** last change time (contents or
        attributes) **/
    unsigned int             i_blkbits;      /* block size in bits */
    const struct inode_operations *i_op;   /** inode operations **/
    struct super_block    *i_sb;           /** associated superblock **/
    struct address_space  *i_mapping;      /** associated page cache **/
    unsigned long         i_dnotify_mask;  /* directory notify mask */
    struct dnotify_struct *i_dnotify;      /* dnotify */
    struct list_head      inotify_watches; /* inotify watches */
    struct mutex          inotify_mutex;   /* protects inotify_watches */
    unsigned long         i_state;         /* state flags */
    unsigned long         dirtied_when;    /* first dirtying time */
    unsigned int          i_flags;         /* filesystem flags */
    atomic_t              i_writecount;    /* count of writers */
    void *                i_private;       /* filesystem private data */
    /* ... */
};
```

inode Operations

- int create(struct inode *dir, struct dentry *dentry, int mode)
  - Create a new inode with access mode "mode"
  - Called from "creat()" and "open() syscalls
  - Q: how does it return a new inode?
- struct dentry *lookup(struct inode *dir, struct dentry *dentry)
  - Search a directory (inode) for a file/directory (dentry)
- int link(struct dentry *old_dentry, struct inode *dir, struct dentry *dentry)
  - Creates a hard link with name dentry in the directory "dir", pointing to "old_dentry"
- int unlink(struct inode *dir, struct dentry *dentry)
  - Remove an inode "dentry" from the directory "dir"
- int symlink(struct inode *dir, struct dentry *dentry, const char *symname)
  - Creates a symbolic link named "symname, to the file dentry in directory dir

- int mkdir(struct inode *dir, struct dentry *dentry, int mode)
  - Create a directory inside "dir" with name
- int rmdir(struct inode *dir, struct dentry *dentry)
  - Remove a directory dentry from dir
- int mknod(struct inode *dir, struct dentry *dentry, int mode, dev_t rev)
  - Create a special file (device file, pipe, socket)
- int rename(struct struct inode *old_dir, struct dentry *old_dentry, struct inode *new_dir, struct dentry *new_dentry)
  - Move a file

dentry (or Directory Entry)



dentry

```
struct dentry {
    atomic_t            d_count;    /* usage count */
    unsigned int        d_flags;    /* dentry flags */
    spinlock_t          d_lock;     /* per-dentry lock */
    int                 d_mounted; /* indicate if it is a mount point */
    struct inode        *d_inode;   /** associated inode **/
    struct hlist_node d_hash;       /** list of hash table entries **/
    struct dentry       *d_parent; /** parent dentry **/
    struct qstr         d_name;     /* dentry name */
    struct list_head    d_lru;      /* unused list */
    struct list_head            d_subdirs;      /** sub-directories **/
    struct list_head            d_alias;        /** list of dentries
                                                  ** pointing to the same inode **/
    unsigned long               d_time;         /* last time validity was checked */
    struct dentry_operations *d_op;             /** operations **/
    struct super_block          *d_sb;          /** superblock **/
    void                        *d_fsdata;      /* filesystem private data */
    unsigned char               d_iname[DNAME_INLINE_LEN_MIN]; /* short name */
    /* ... */
};
```

dentry

- Associated with a file or a directory to:
  - Store the file/directory "name"
  - Store its location in the directory
  - Perform direcotry specific operations, for example pathname lookup
- /home/lkp/test.txt
  - One dentry associated with each of: "/", ""home", "lkp", and "test.txt"
- Constructed on the fly as files and directories are accessed
  - Cache of disk representation

dentry

- A dentry can be ”used”, “unused”, or ”negative”
- Used: correspond to a valid inode (pointed by d_inode) with one or more users (d_count)
  - Cannot be discarded to free memory
- Unused: valid inode, but no current users
  - Kept in RAM for caching
  - Can be discarded
- Negative: does not point to a valid inode
  - e.g., open() on a file that does not exist
  - Kept around for caching
  - Can be discarded
- Dentries are constructed on demand and kept in DRAM for quick pathname lookups
  - dentry cache or dcache
- Q: Why does Linux cache negative dentries?

dentry Cache

- Linked list of used dentries linked by the i_dentry field of their inode
  - One inode can have multiple links, thus multiple dentries
- Linked list of LRU sorted unused and negative dentries
  - LRU: quick reclamation from the tail of the list
- Hash table + hash function to quickly resolve a path into the corresponding dentry present in the dcache
- Hash table: dentry_hashtable array
  - Each element is a pointer to a list of dentries hashing to the same value
- Hashing function: d_hash()
  - Filesystem can provide its own hashing function
- Dentry lookup in the dcache: d_lookup()
  - Returs dentry on success, NULL on failure
- Inodes are similarly cached in DRAM, in the inode cache
  - Dentries in the dcache are pinning inodes in the inode cache

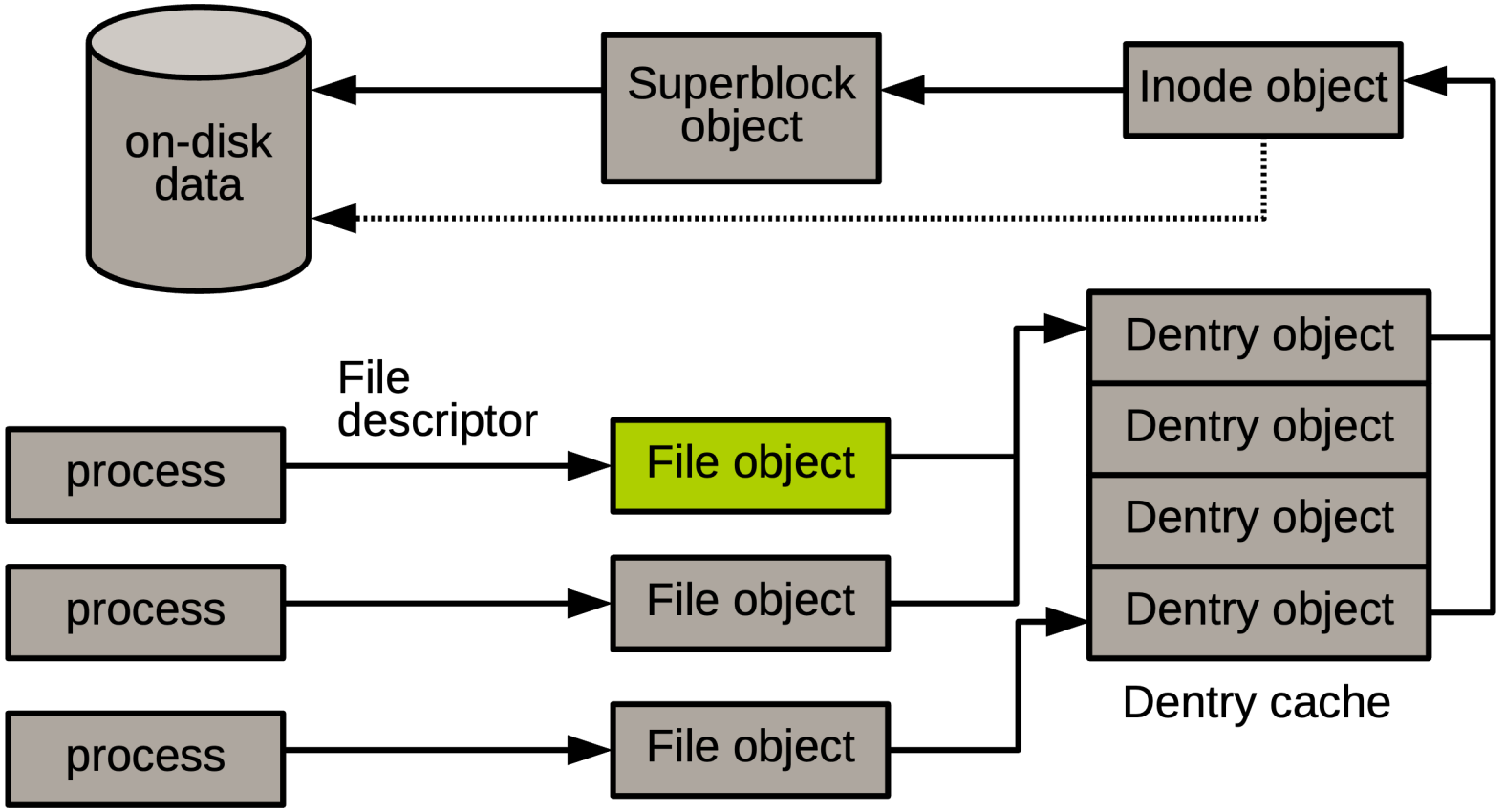
dentry Operations

```
/* linux/include/linux/dcache.h */
struct dentry_operations {
    int (*d_revalidate)(struct dentry *, unsigned int);
    int (*d_weak_revalidate)(struct dentry *, unsigned int);
    int (*d_hash)(const struct dentry *, struct qstr *);
    int (*d_compare)(const struct dentry *,
            unsigned int, const char *, const struct qstr *);
    int (*d_delete)(const struct dentry *);
    int (*d_init)(struct dentry *);
    void (*d_release)(struct dentry *);
    void (*d_prune)(struct dentry *);
    void (*d_iput)(struct dentry *, struct inode *);
    char *(*d_dname)(struct dentry *, char *, int);
    struct vfsmount *(*d_automount)(struct path *);
    int (*d_manage)(const struct path *, bool);
    struct dentry *(*d_real)(struct dentry *, const struct inode *,
                unsigned int);
} ____cacheline_aligned;
```

dentry Operations

- int d_revalidate(struct dentry *dentry, struct nameidata *)
  - Determine if an entry to use from the dcache is valid
  - Generally set to NULL
- int d_hash(struct dentry *dentry, struct qstr *name)
  - Create a hash value for a dentry to insert in the dcache
- Int d_compare(struct dentry *dentry, struct qstr *name1, struct qstr *name2)
  - compare two filenames, requires dcache_lock
- int d_delte(struct dentry *dentry)
  - Called by VFS when d_count reaches zero, requires dcache_lock and d_lock
- void d_release(struct dentry *dentry)
  - Called when the dentry is going to be freed
- void d_iput(struct dentry *dentry, struct inode *inode)
  - Called when the dentry looses its inode
  - Calls "iput()"

File Object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Dentry cache

File Object

- The "file" object
  - Represents a file opened by a process
  - Created on "open()" and destroyed on "close()"
- 2 processes opening the same file:
  - Two file objects, pointing to the same unique dentry, that points itself on a unique inode
- No corresponding on-disk data structure

File Object

```
/* linux/include/linux/fs.h */
struct file {
    struct path             f_path;         /* contains the dentry */
    struct file_operations *f_op;           /** operations **/
    spinlock_t              f_lock;         /* lock */
    atomic_t                f_count;        /* usage count */
    unsigned int            f_flags;        /* open flags */
    mode_t                  f_mode;         /* file access mode */
    loff_t                  f_pos;          /** file offset **/
    struct fown_struct      f_owner;        /* owner data for signals */
    const struct cred      *f_cred;         /* file credentials */
    struct file_ra_state    f_ra;           /* read-ahead state */
    u64                     f_version;      /* version number */
    void                   *private_data;   /* private data */
    struct list_head        f_ep_link;      /* list of epoll links */
    spinlock_t              f_ep_lock;      /* epoll lock */
    struct address_space   *f_mapping;      /** page cache
                                             ** == inode->i_mapping **/

    /* ... */
};
```

File Operations

```
/* linux/include/linux/fs.h */
struct file_operations {
    loff_t (*llseek) (struct file *, loff_t, int);
    ssize_t (*read) (struct file *, char __user *, size_t, loff_t *);
    ssize_t (*write) (struct file *, const char __user *, size_t, loff_t *);
    ssize_t (*read_iter) (struct kiocb *, struct iov_iter *);
    ssize_t (*write_iter) (struct kiocb *, struct iov_iter *);
    int (*iterate) (struct file *, struct dir_context *);
    int (*iterate_shared) (struct file *, struct dir_context *);
    unsigned int (*poll) (struct file *, struct poll_table_struct *);
    /* ... */
};
```

File Operations

- loff_t llseek(struct file *file, loff_t offset, int origin)
  - Update file offset
- ssize_t read(struct file *file, char *buf, size_t count, loff_t *offset)
  - read operation
- ssize_t aio_read(struct kiocb *iocb, char *buf, size_t count, loff_t offset)
  - asynchronous read
- ssize_t write(struct file *file, const char *buf, size_t count, loff_t *offset)
  - Write operation
- ssize_t aio_write(struct kiocb *iocb, const char *buf, size_t count, loff_t offset)
  - Async write
- int readdir(struct file *file, void *dirent, filldir_t filldir)
  - Read the next directory in a directory listing

- unsigned int poll(struct file *file, struct poll_table_struct *poll_table)
  - Sleeps waiting for activity on a given file
- int ioctl(struct inode *inode, struct file *file, unsigned int cmd, unsigned long arg)
  - Sends a command and arguments to a device
  - Unlcoked/compat versions
- int mmap(struct file *file, struct vm_area_struct *vma)
  - Maps a file into an addr space

- int open(struct inode *inode, struct file *file)
  - Opens a file
- int flush(struct file *file)
  - Called by VFS when the reference count of an open file decreases
- int release(struct inode *inode, struct file *file)
  - Called by VFS when the last reference to a file is destroyed close()/exit
- int fsync(struct file *file, struct dentry *dentry, int datasync)
  - flush cached data on disk
- int aio_fsync(struct kiocb *iocb, int datasync)
  - flush aio cached data on disk

- ssize_t sendfile(struct file *file, loff_t *offset, size_t size, read_actor_t actor, void *target)
  - Copy data from one file to another entirely in the kernel
- ssize_t snedpage(struct file *file, struct page *page, int offset, size_t size, loff_t *pos, int more)
  - Send data from one file to another
- get_unmapped_areas(), flock() ...

Filesystem Data Structures

- struct file_system_type: information about a specific concrete filesystem type
- One per filesystem supported (chosen at compile time) independently of the mounted filesystem
- include/linux/fs.h

```
struct file_system_type {
    const char *name;       /** name: e.g., ext4 **/
    int fs_flags;           /* flags */

    /** mount a partition **/
    struct dentry *(*mount) (struct file_system_type *, int,
              const char *, void *);

    /** terminate access to the superblock **/
    void (*kill_sb) (struct super_block *);
    struct module *owner;                       /* module owning the fs */
    struct file_system_type * next;             /* linked list of fs types */
    struct hlist_head fs_supers;                /* linked list of superblocks */

    /* runtime lock validation */
    struct lock_class_key s_lock_key;
    struct lock_class_key s_umount_key;
    struct lock_class_key s_vfs_rename_key;
    struct lock_class_key s_writers_key[SB_FREEZE_LEVELS];

    struct lock_class_key i_lock_key;
    struct lock_class_key i_mutex_key;
```

- When a filesystem is mounted, a vfsmount structure is created
  - Represent a specific instance of the filesystem: a mount point

```
/* linux/include/linux/fs.h */
struct vfsmount {
    struct dentry *mnt_root;    /* root of the mounted tree */
    struct super_block *mnt_sb; /* pointer to superblock */
    int mnt_flags;
};
```

Process Data Structure

- struct files_struct: contains per-process information about open files and file descriptors
  - include/linux/fdtable.h
- struct fs_struct: filesystem information related to a process
  - include/linux/fs_struct.h
- struct mnt_namespace: provide processes with unique views of a mounted filesystem
  - fs/mount.h

Summary

- Key data structures
  - struct file_system_type: file system (e.g, ext4)
  - struct super_block: mounted file system instance (ie, partition)
  - struct dentry: path name
  - struct inode: file metadata
  - struct file: open file descriptor
  - struct address_space: per-inode page cache
- Three key caches
  - dentry cache: dentry_hashtable, dentry->d_hash
  - inode cache: inode_hashtable, inode->i_hash
  - page cache: inode->i_mapping