ECE391
Computer System Engineering

Lecture 16

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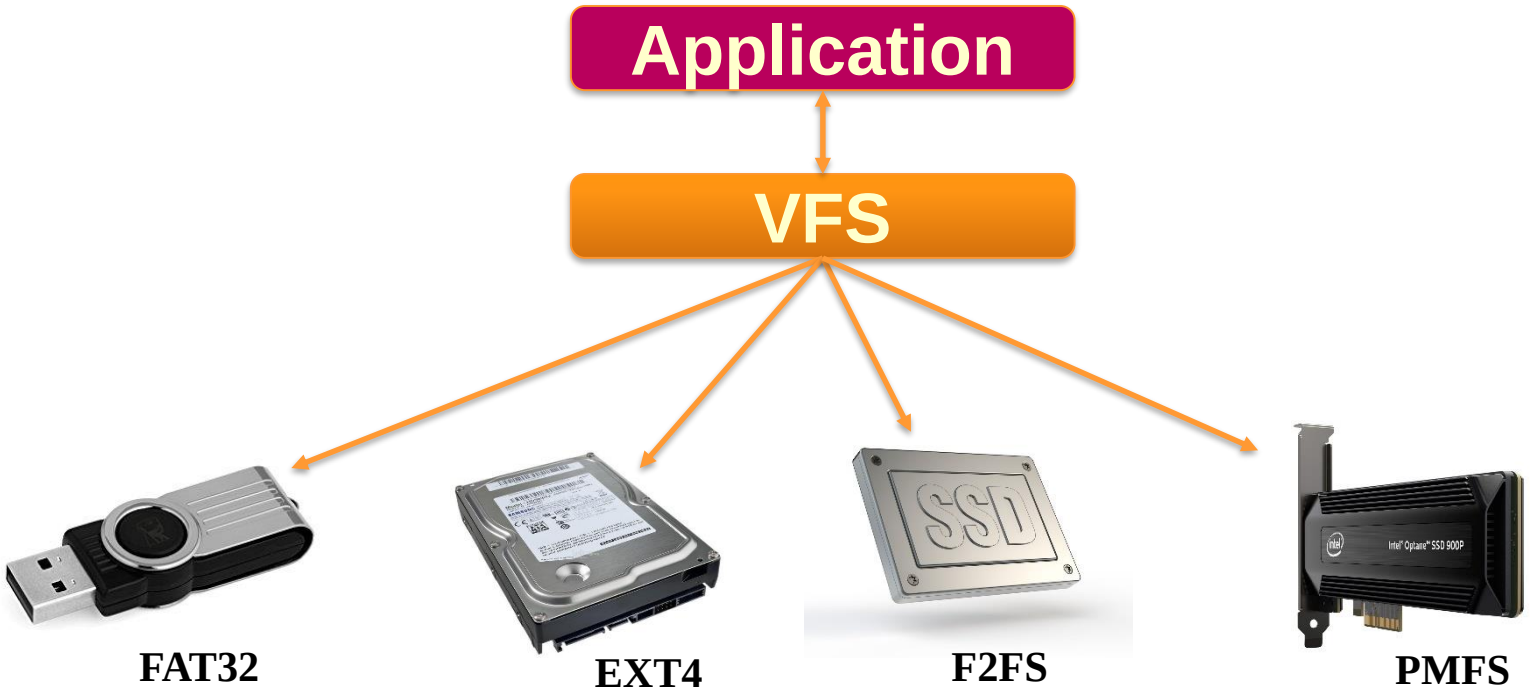
Lecture Topics

- File system
  - Linux file structure
  - file operations
  - ext2 filesystem (on disk)
- MP3 file system

Aministrivia

- **MP3.2 Posted**
  - **Checkpoint 2 due Monday, Oct. 29**

Virtual File System

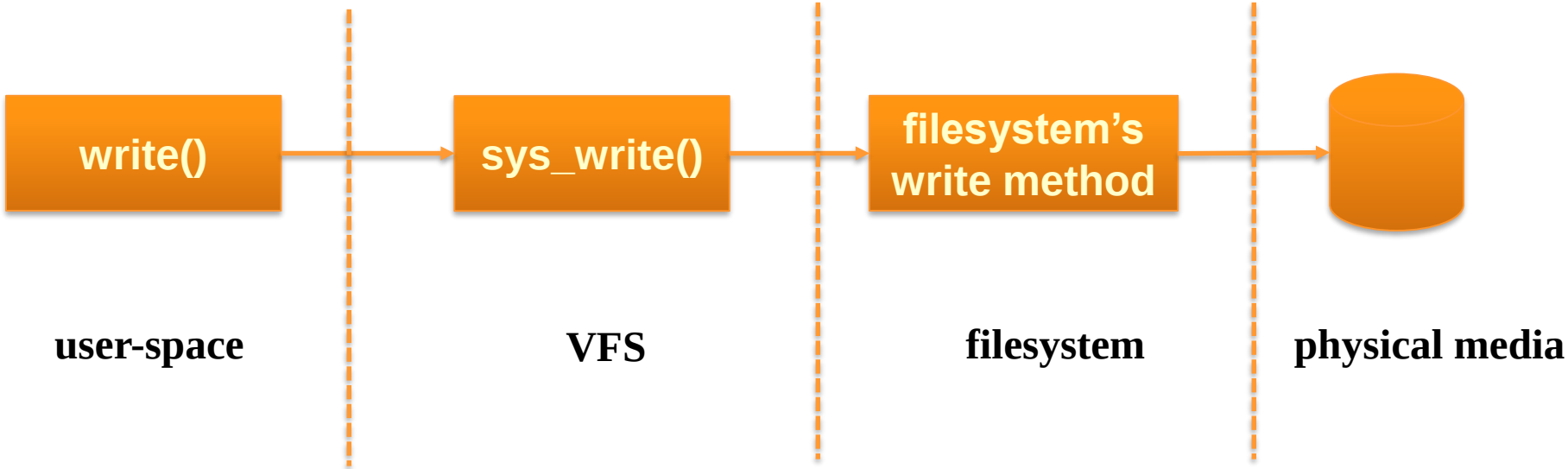


File System Abstraction Layer

- VFS provides common file system interfaces
  - create, open, read, write, etc
- Each file system implements the real functionalities on top of the device drivers

An Example

- write (fd, &buf, len)

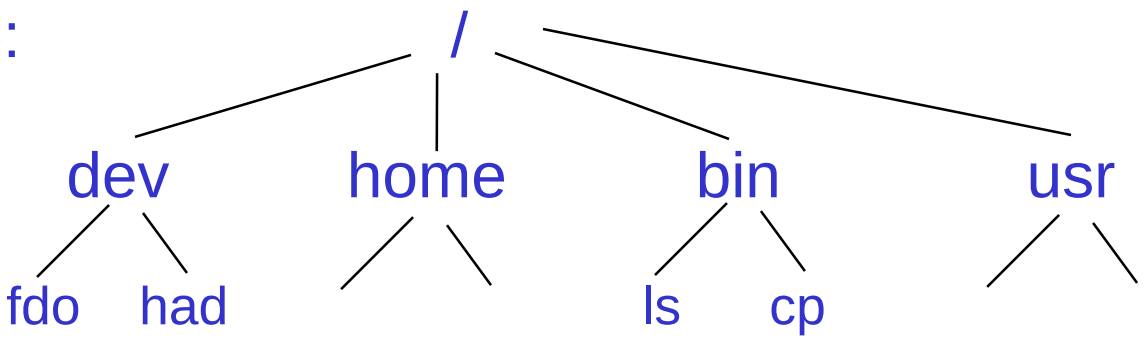


UNIX File Systems

- Four basic fs-related abstractions
  - Files: an ordered string of bytes
  - Directory entries: components of a path
  - Inodes: file metadata
  - Mount points: where file systems are mounted in the global directory hierarchy

File System

- A Unix-like file system is an information container structured as a sequence of bytes
- Files are organize in a tree structured namespace
- Example:



- All nodes (except leaves) denote directories
- The directory corresponding to the root is called the root directory [slash (/)]

File Types

- Regular files
- Directory
- Symbolic Link
- Block-oriented device file
- Character-oriented device file
- Pipe and named pipes
- Socket

File Descriptor and Inode

- There is clear distinction between the contents of a file and the information about a file
  - With the exception of device files and files of special file systems, each file contains a sequence of bytes

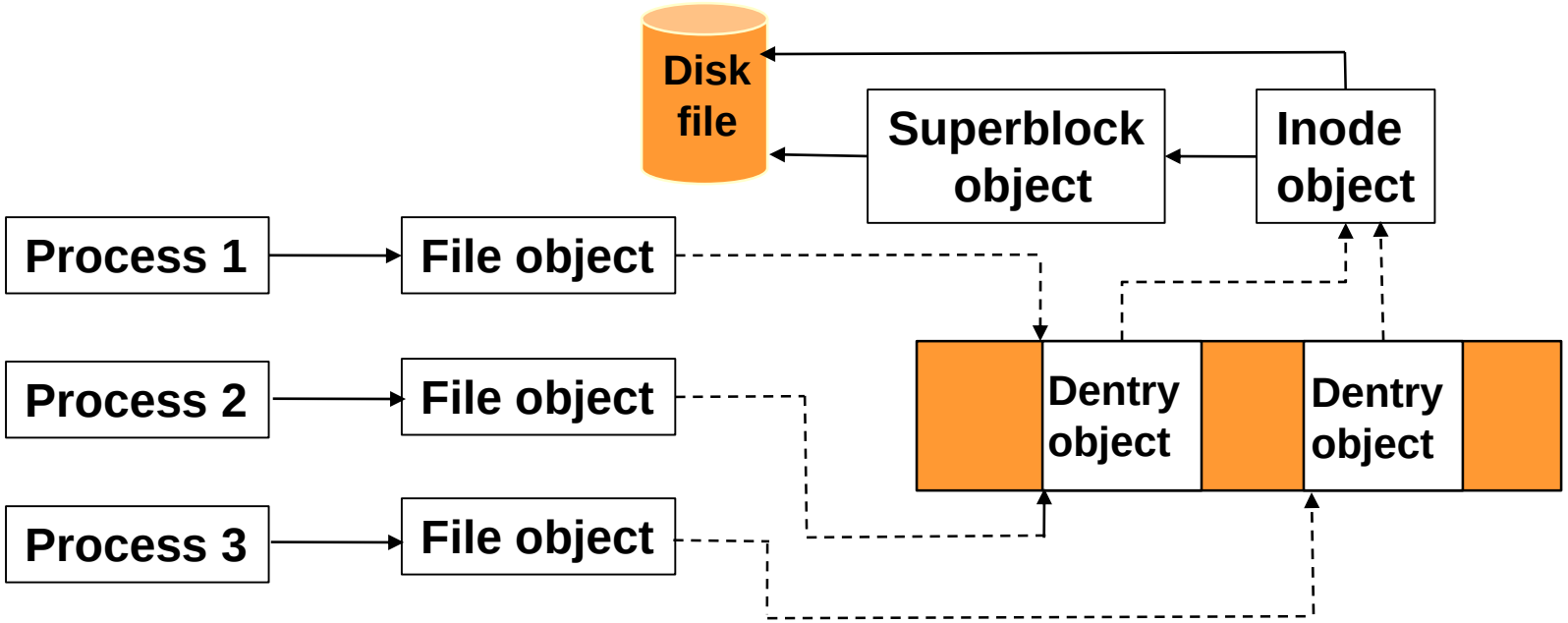
- *Inode* contains Information needed by the file system to handle a file (access permissions, size, owner..)
  - each file has its own *inode*
- File descriptor is an index to a data structure (at the kernel level) containing the details of all open files
  - created by a process when a file is opened

File Descriptor and Inode

- superblock object – represents a specific mounted file system
- inode object – represents a specific file
- dentry object – represents a directory entry, a single component of a path
- file object – represents an open file as associated with a process (exits only in the kernel memory)

- All objects are stored in a suitable data structure
  - includes object attributes and a pointer to a table of object methods

Interaction – Processes and Filesystem Objects



- Processes open the same file
- Two of them use the same link (i.e., same dentry)
- Each uses its own file object

Linux File Structure *(file object)*

```
struct file {
        /*
         * fu_list becomes invalid after file_free is called and queued via
         * fu_rcuhead for RCU freeing
         */
        union {
                struct list_head        fu_list;
                struct rcu_head         fu_rcuhead;
        } f_u;

        struct path             f_path;
#define f_dentry        f_path.dentry
#define f_vfsmnt        f_path.mnt

        const struct file_operations    *f_op;
        atomic_t                f_count;
        unsigned int            f_flags;
        mode_t                  f_mode;
        loff_t                  f_pos;
        struct fown_struct      f_owner;
        unsigned int            f_uid, f_gid;
        struct file_ra_state    f_ra;

        unsigned long           f_version;

        void                    *f_security;

        /* needed for tty driver, and maybe others */
        void                    *private_data;

        /* Used by fs/eventpoll.c to link all the hooks to this file */
        struct list_head        f_ep_links;
        spinlock_t              f_ep_lock;

        struct address_space    *f_mapping;
};
```

- list of files / read-copy-update cleanup list
- directory entry
- virtual file system (VFS) mount point
- file operations structure
- # of openers and uses (system calls) in progress
- asynchronous I/O and other flags
- file position
- for FASYNC signaling
- user and group ID of file's opener
- file read ahead control fields
- used for some types of files (FIFO, pipes)
- generic data block for more advanced security model
- data allocated and released by associated driver
- support for Linux-specific variant of poll
- address space into which file is memory-mapped

- The file structure (file object) is created when the file is opened
- No corresponding image on the disk

Comments on Linux's internal file structure

f_u	list of files / read-copy-update cleanup list

(these two are macros; part of struct path f_path)

f_dentry	directory entry
f_vfsmnt	virtual filesystem (VFS) mount point

f_op	file operations structure (ops explained later)
f_count	# of openers and uses (system calls) in progress
f_flags	asynchronous I/O and other flags
f_mode	read/write modes (user, group, other)

Comments on Linux's internal file structure

`f_pos` file position

`f_owner` for FASYNC signaling (async. I/O signals to user processes)

`f_uid, f_gid` user and group ID of file's opener

`f_ra` file read ahead control fields

`f_version` used for some types of files (FIFO, pipes, etc.)

`f_security` generic data block for more advanced security model support (e.g., capabilities); see **`fs/security.h`**

Comments on Linux's internal file structure

`f_private_data` data allocated and released by associated driver

`f_ep_links` support for Linux-specific variant of poll: see **`epoll(7)`**

`f_ep_lock`

`f_mapping` address space into which file is memory-mapped

File Operations

- File operations structure
  - jump table of file operations / character driver operations
  - generic instance for files on disk
  - distinct instances for sockets, etc.
  - one instance per device type

File Operations Structure

include/linux/fs.h

```
struct file_operations {
        struct module *owner;
        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 (*aio_read) (struct kiocb *, const struct iovec *, unsigned long, loff_t);
        ssize_t (*aio_write) (struct kiocb *, const struct iovec *, unsigned long, 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);
        long (*unlocked_ioctl) (struct file *, unsigned int, unsigned long);
        long (*compat_ioctl) (struct file *, unsigned int, unsigned long);
        int (*mmap) (struct file *, struct vm_area_struct *);
        int (*open) (struct inode *, struct file *);
        int (*flush) (struct file *, fl_owner_t id);
        int (*release) (struct inode *, struct file *);
        int (*fsync) (struct file *, struct dentry *, int datasync);
        int (*aio_fsync) (struct kiocb *, int datasync);
        int (*fasync) (int, struct file *, int);
        int (*lock) (struct file *, int, struct file_lock *);

        /* ... plus a couple more rarely used functions */
};
```

Comments on File Operations

- Several direct mappings from system calls
  - llseek, read, write, etc.
  - arguments are identical
  - fsync: flashes the file by writing all cached data to disk

- offset pointer (**`loff_t*`**) argument
  - usually points to file's **`f_pos`**
  - but some system calls allow override, thus passed as pointer

Comments on File Operations

- flush is called each time a file is closed (may be open more than once)
- release is called after the last close (after the flush call)

- lock call used for file locking operations

- readv and writev
  - read and write vector operations (gather/scatter)
  - Emulated if function pointer is NULL

VFS Objects

- Four primary objects:
  - superblock
  - inode
  - dentry
  - file
- Other objects:
  - file_system_type
  - vfsmount
  - namespace

SuperBlock

- http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs.h#L738
- http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs.h#L956

inode

- http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs.h#L420
- http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs.h#L919

dentry

- http://elixir.bootlin.com/linux/v4.12-rc7/source/include/linux/dcache.h#L84

- http://elixir.bootlin.com/linux/v4.12-rc7/source/include/linux/dcache.h#L130

file

- http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs.h#L566
- http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs.h#L891

Other objects

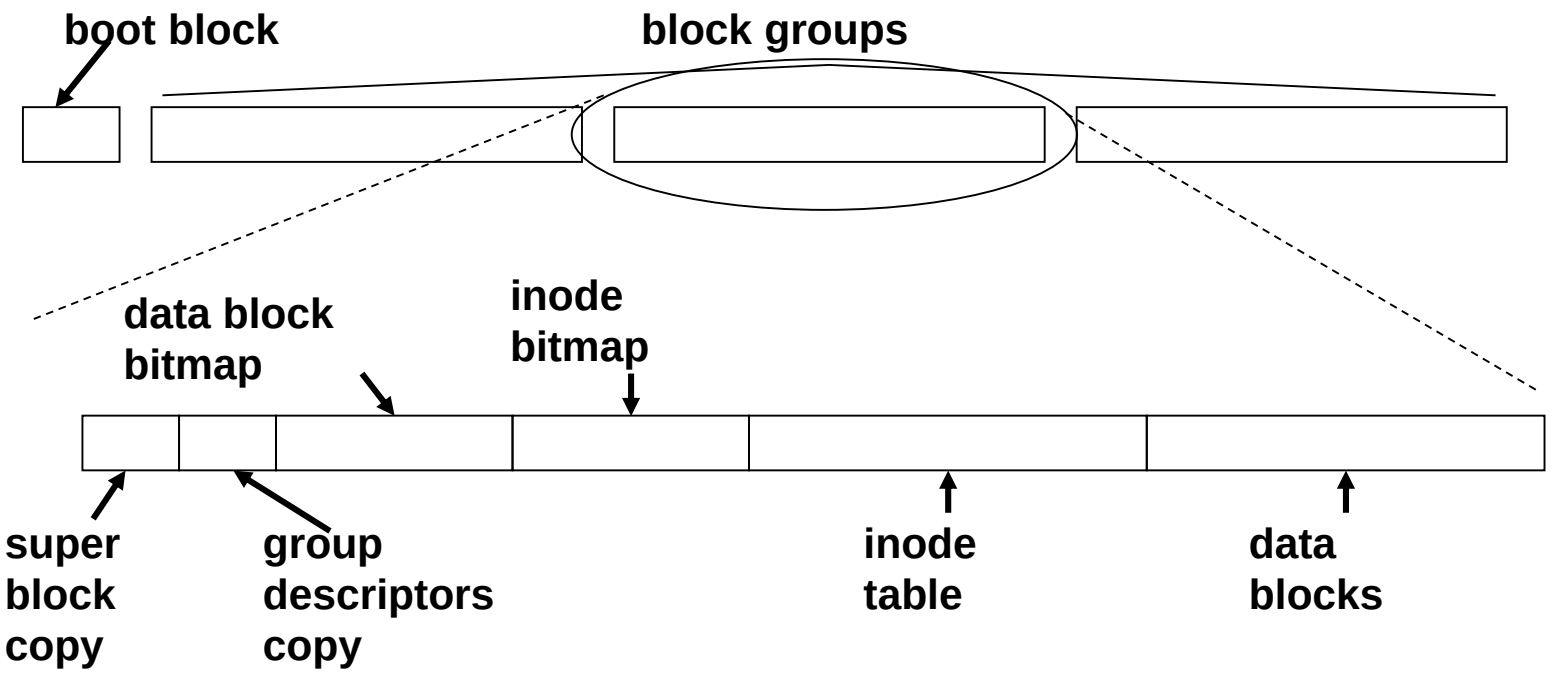
- file_system_type: http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs.h#L1119
- vfsmount: http://lxr.linux.no/linux-bk+v2.6.9/include/linux/mount.h#L21
- fs_struct: http://lxr.linux.no/linux-bk+v2.6.9/include/linux/fs_struct.h#L7
- namespace: https://elixir.bootlin.com/linux/v2.6.18-rc6/source/include/linux/namespace.h#L8

File System on Disk

- Disks are slow
  - fast ones rotate at ~10,000 rpm
  - average of (60 sec/10000)/2 = 3 ms to wait for disk to turn
  - another few milliseconds to move read head side to side
  - 5-10 millisecond access time

- Disks use blocks (and prefetching) to alleviate problems
  - filesystems can use several adjacent disk blocks to further improve
  - ext2 allows 1- 4kB blocks (chosen when filesystem is created)

ext2 (Second Extended Filesystem) on Disk



ext2 on Disk

- ext2 blocks are fixed size (1kB to 4kB) chosen at creation time
- Groups are fixed size, also chosen at creation time
- Two blocks replicated in each block group for reliability
  - super block describes filesystem (e.g., choice of block size)
  - group descriptors describes block groups
- bitmaps used to represent free blocks for index nodes (metadata) and data

Superblock Image on Disk

- Sized at 1kB, so fits within any selected block size
- Sizes selected for filesystem
- Filesystem check information
  - # mounts between checks, time between checks, errors found
  - also state of filesystem
    - 0 when mounted/uncleanly dismounted
    - 1 when cleanly dismounted
    - 2 if errors have been found
- Reserved blocks & authentication data
- Volume name
- Performance specs (e.g., preallocation)

Group Descriptor Image on Disk

- Sized at 32B, so 32 of them fit within any selected block size
- Shortcuts to block/inode bitmaps and inode table/data blocks
- Free block counts

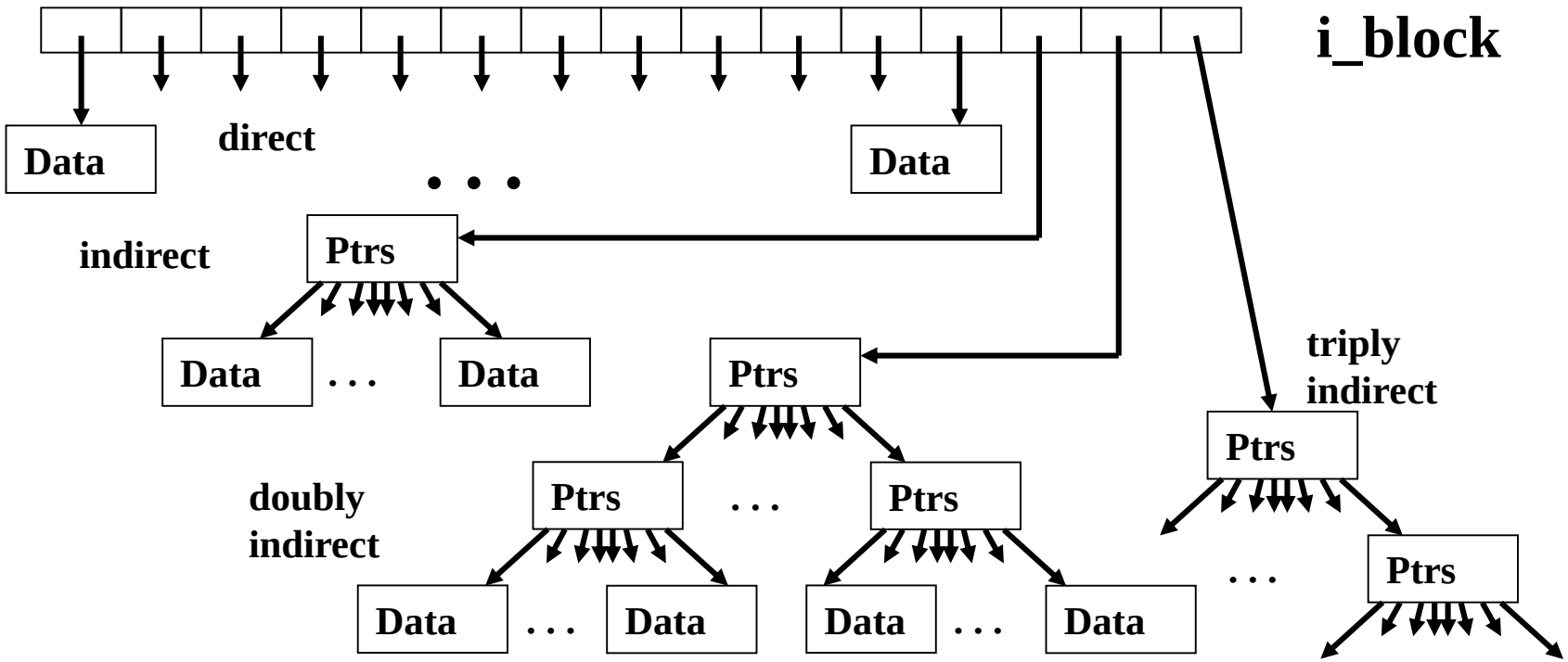
Index Node on Disk (128B total)

`i_mode`	file type & access rights (e.g., readable by group)
`i_uid`	owner
`i_size`	length in bytes
`i_atime`	time of last access
`i_ctime`	time of last creation
`i_mtime`	time of last modification
`i_dtime`	time of last deletion
`i_gid`	group id
`i_links_count`	# of hard links
`i_blocks`	blocks in file (disk blocks, in 512B units)
`i_flags`	e.g., immutable, append-only
`i_block[15]`	data block #'s
`i_generation`	generation (incremented on each modification)

File Data Blocks Stored Hierarchically

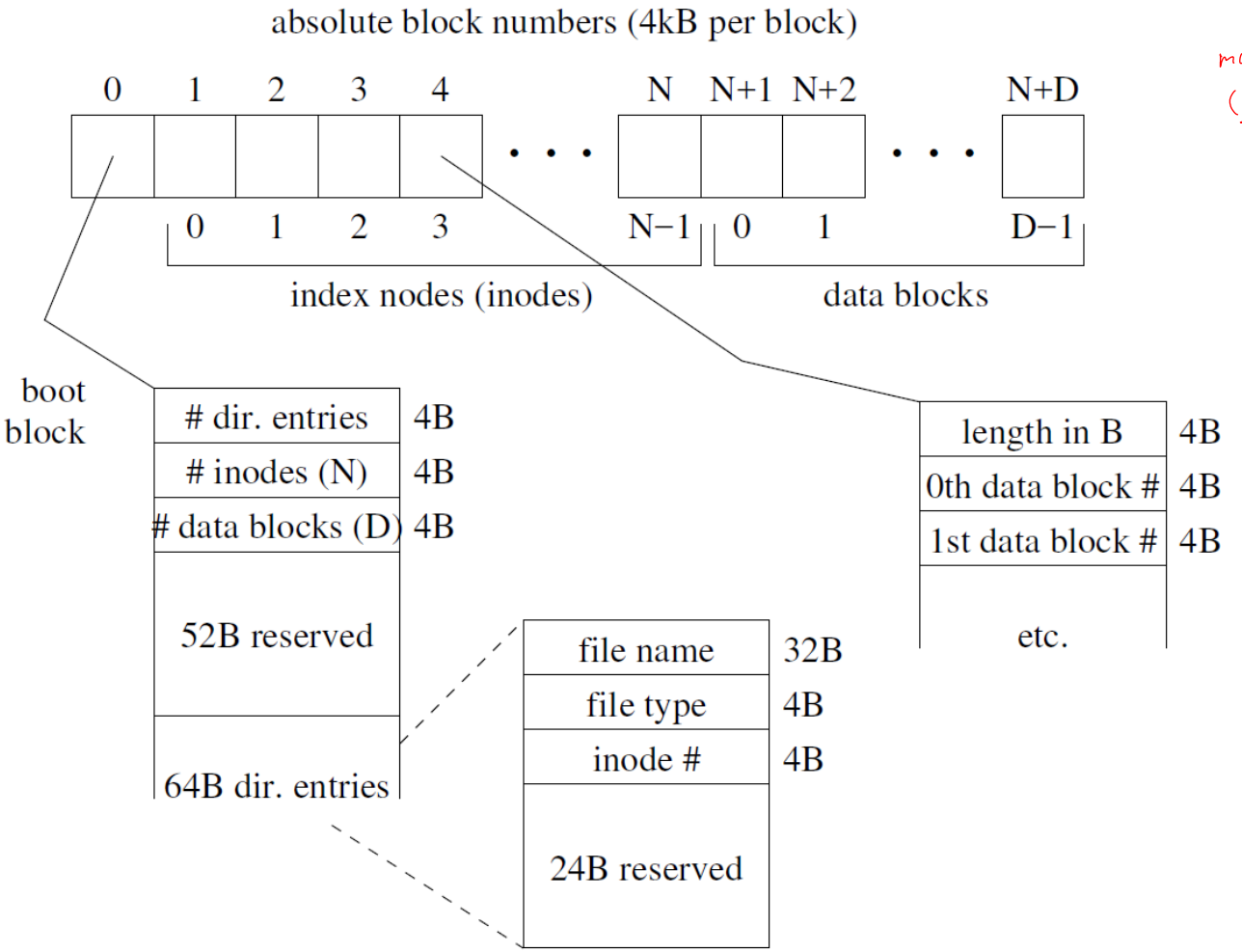
- let ***b*** denote block size
- first 12 block pointers are direct: block #'s
  (first 12***b*** bytes of file)
- 13th block pointer is indirect: block # of a block of block #'s
  (***b***/4 pointers, so the next $b^2/4$ data bytes in file)
- 14th block pointer is doubly indirect (next $b^3/16$ data bytes in file)
- 15th block pointer is triply indirect (last $b^4/64$ data bytes in file)
- small files only need direct blocks

File Data Blocks



block size b	4 kB	2 kB	1 kB
direct	48 kB	24 kB	12 kB
indirect	4 MB	1 MB	256 kB
doubly ind.	4 GB	512 MB	64 MB
triply ind.	4 TB	256 GB	16 GB

MP3 File System



max file size in MP3:
(1024−1) · 4096 Bytes
numbers for block indices in one inode

MP3 File System: example declaration of data structures

- Memory file system -> all data kept in memory

- boot block:
  - int32_t dir_count;
  - int32_t inode_count;
  - int32_t data_count;
  - int8_t reserved[52];
  - <dentry> direntries[63];

- dentry:
  - int8_t filename[FILENAME_LEN];
  - int32_t filetype;
  - int32_t inode_num;
  - int8_t reserved[24];

- inode:
  - int32_t length;
  - int32_t data_block_num [1023];

MP3 File System Utilities (used by the kernel)

```
int32_t read_dentry_by_name (const uint8_t* fname, dentry_t* dentry);
int32_t read_dentry_by_index (uint32_t index, dentry_t* dentry);
int32_t read_data (uint32_t inode, uint32_t offset, uint8_t* buf, uint32_t length);
```

read_dentry_by_name () {

< Scans through the directory entries in the “boot block” to find the file name >

Call *read_dentry_by_index() {*

< Populates the dentry parameter -> file name, file type, inode number >

}

}

You call *read_dentry_by_name ()* in *sys_open()* *system call*

< open a file; set up the file object -> inode, fops, flags, position >

MP3 File System Abstractions

- **Each task can have up to 8 open files**
- **Open files are represented with a file array (in a Process Control Block; PCB)**
- **File array is indexed by a *file descriptor***