6th Slide Set
Operating Systems

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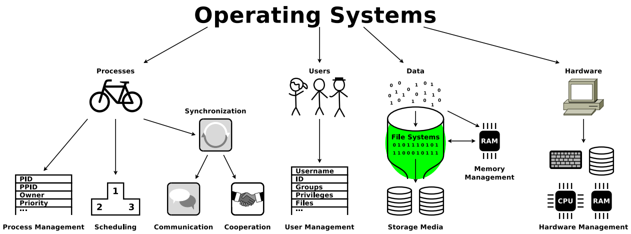
Learning Objectives of this Slide Set

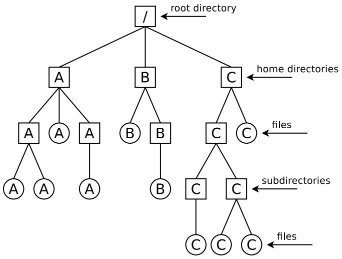
- At the end of this slide set You know/understand. . .
  - the **functions and basic terminology of file systems**
  - what **inodes** and **clusters** are
  - how **block addressing** works
  - the **structure** of selected file systems
  - an overview about **Windows file systems** and their characteristics
  - what **journaling** is and why it is used by many file systems today
  - how addressing via **extents** works
  - what **copy-on-write** is
  - how **defragmentation** works and when it makes sense to defragment

Exercise sheet 6 repeats the contents of this slide set which are relevant for these learning objectives



File Systems. . .

- organize the storage of files on data storage devices
  - Files are sequences of Bytes of any length which belongs together with regard to content
- manage file names and attributes (metadata) of files
- form a namespace
  - Hierarchy of directories and files



- **Absolute path names**: Describe the complete path **from the root to the file**
- **Relative path names**: All paths, which do **not begin with the root**

- are a layer of the operating system
  - Processes and users access files via their abstract file names and not via their memory addresses
- should cause only little overhead for metadata

Technical Principles of File Systems

- File systems address **clusters** and not blocks of the storage device
  - Each file occupies an integer number of clusters
  - In literature, the clusters are often called **zones** or **blocks**
    - This results in confusion with the sectors of the devices, which are in literature sometimes called blocks too
- The size of the clusters is essential for the efficiency of the file system
  - The smaller the clusters are...
    - Rising overhead for large files
    - Decreasing capacity loss due to internal fragmentation
  - The bigger the clusters are...
    - Decreasing overhead for large files
    - Rising capacity loss due to internal fragmentation

The bigger the clusters, the more memory is lost due to internal fragmentation

- File size: 1 kB. Cluster size: 2 kB $\Longrightarrow$ 1 kB gets lost
- File size: 1 kB. Cluster size: 64 kB $\Longrightarrow$ 63 kB get lost!

- The cluster size can be specified, while creating the file system

Basic Terminology of Linux File Systems

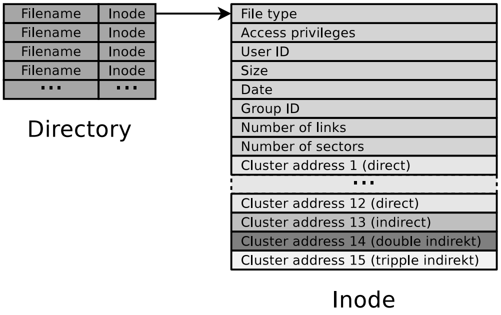
In Linux: Cluster size $\leq$ size of memory pages (page size)

- The page size depends on the architecture
- x86 = 4 kB, Alpha and UltraSPARC = 8 kB, Apple Silicon = 16 kB, IA-64 = 4/8/16/64 kB

- The creation of a **file** causes the creation of an **Inode** (*index node*)
  - It stores a file's metadata, except the file name
    - Metadata are among others the size, UID/GID, permissions and date
  - Each inode has a unique inode number inside the file system
  - The inode contains references to the file's clusters
  - All Linux file systems base on the functional principle of inodes
- A **directory** is a file too (see slide 12)
  - Content: File name and inode number for each file in the directory
- The traditional working method of Linux file systems: **Block addressing**
  - Actually, the term is misleading because file systems always address clusters and not blocks (of the volume)
    - However, the term is established in literature since decades

Block Addressing using the Example ext2/3

- Each inode directly stores the numbers of up to 12 clusters


Filename
Inode
...
Directory
File type
Access privileges
User ID
Size
Date
Group ID
Number of links
Number of sectors
Cluster address 1 (direct)
...
Cluster address 12 (direct)
Cluster address 13 (indirect)
Cluster address 14 (double indirekt)
Cluster address 15 (tripple indirekt)
Inode

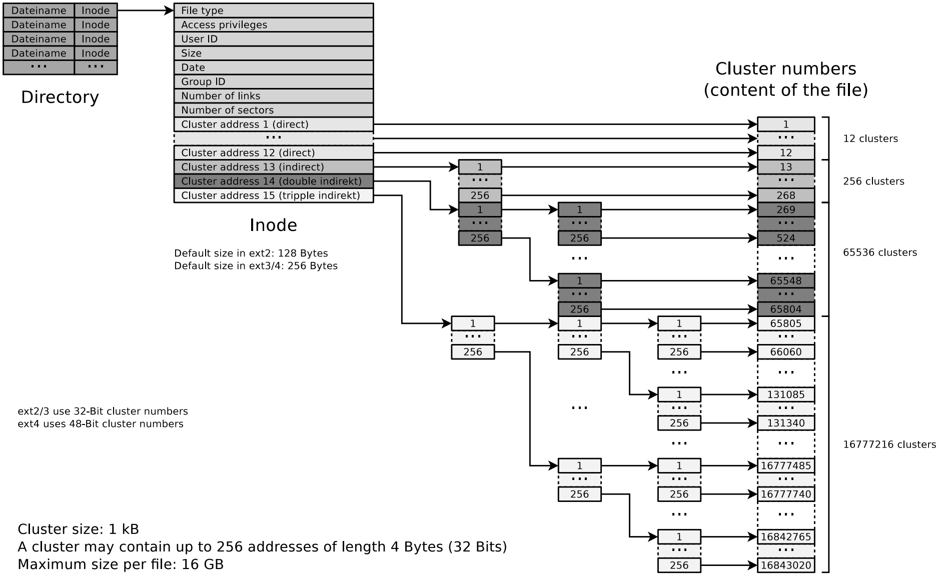
- If a file requires more clusters, these clusters are indirectly addressed
- Minix, ext2/3, ReiserFS and Reiser4 implement block addressing

Good explanation

`http://lwn.net/Articles/187321/`

- Scenario: No more files can be created in the file system, despite the fact that sufficient capacity is available
- Possible explanation: No more inodes are available
- The command `df -i` shows the number of existing inodes and how many are still available

Direct and indirect Addressing using the Example ext2/3



Default size in ext2: 128 Bytes
Default size in ext3/4: 256 Bytes

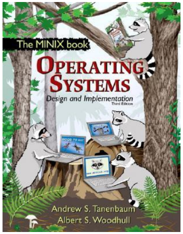
ext2/3 use 32-Bit cluster numbers
ext4 uses 48-Bit cluster numbers

Cluster size: 1 kB
A cluster may contain up to 256 addresses of length 4 Bytes (32 Bits)
Maximum size per file: 16 GB

Minix

The Minix operating system http://www.minix3.org

- Unix-like operating system
- Developed since 1987 by Andrew S. Tanenbaum for education purposes
  https://www.youtube.com/watch?v=bx3KuE7UjGA
- Latest revision is 3.3.0 is from 2014
- Intel chipsets post-2015 run MINIX 3 internally as the software component of the Intel Management Engine
  https://www.zdnet.com/article/minix-intels-hidden-in-chip-operating-system/
  https://linuxnews.de/2017/11/minix-in-der-intel-management-engine/
  https://itsfoss.com/fact-intel-minix-case/



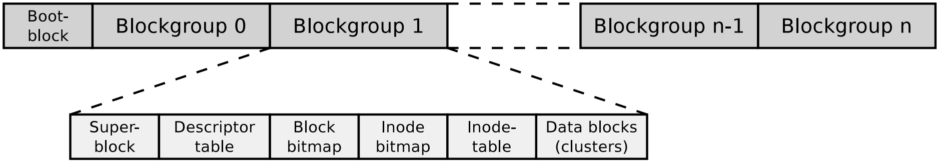
- Standard Linux file system until 1992
  - Not surprising, because Minix was the basis of the development of Linux
- The Minix file system causes low overhead
  - Useful applications „today“: Boot floppy disks and RAM disks
- Storage is represented as a linear chain of equal-sized blocks (1-8 kB)
- A Minix file system contains just 6 areas
  - The simple structure makes it ideal for education purposes

Minix File System Structure

Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Boot block (1 cluster)	Super block (1 cluster)	Inodes bitmap (1 cluster)	Cluster bitmap (1 cluster)	Inodes (15 clusters)	Data (remaining clusters)

- **Boot block**. Contains the boot loader that starts the operating system
- **Super block**. Contains information about the file system,
  - e.g. number of inodes and clusters
- **Inodes bitmap**. Contains a list of all inodes with the information, whether the inode is occupied (value: 1) or free (value: 0)
- **Clusters bitmap**. Contains a list of all clusters with the information, whether the cluster is occupied (value: 1) or free (value: 0)
- **Inodes**. Contains the inodes with the metadata
  - Every file and every directory is represented by at least a single inode, which contains the metadata
    - Metadata is among others the file type, UID/GID, access privileges, size
- **Data**. Contains the contents of the files and directories
  - This is the biggest part in the file system

ext2/3/4 File System Structure



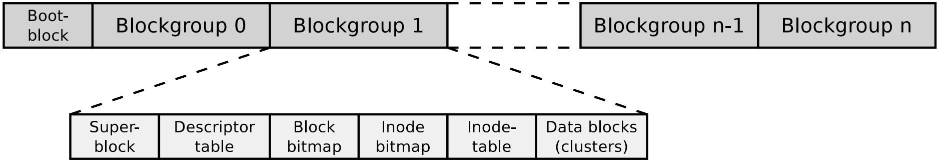
- The clusters of the file system are combined to **block groups** of the same size
  - The information about the metadata and free clusters of each block group are maintained in the respective block group

Maximum size of a block group: 8x cluster size in bytes

Example: If the cluster size is 4096 Bytes, each block group can contain up to 32768 clusters.
$\Longrightarrow$ The maximum block size is 32768 clusters $\times$ 4096 Bytes cluster size = 134,217,728 Bytes = 131,072 kB = 128 MB

- Benefit of block groups (when using HDDs!): Inodes (metadata) are physically located close to the clusters, they address
  - This reduces seek times and the degree of fragmentation
  - When using flash storage, the position of the data in the individual memory cells is irrelevant for the performance

ext2/3/4 Block Group Structure



- The first cluster of the file system contains the **boot block** (size: 1 kB)
  - It contains the boot manager, which starts the operating system
- Each block group contains a **copy of the super block**
  - This improves the data security
- The **descriptor table** contains among others:
  - The cluster numbers of the block bitmap and inode bitmap
  - The number of free clusters and inodes in the block group
- **Block bitmap** and **inode bitmap** are each a single cluster big
  - They contain the information, which clusters and inodes in the block group are occupied
- The **inode table** contains the inodes of the block group
- The remaining clusters of the block group can be used for the **data**

Analyze File Systems (1/3)

We already know...

Directories are files that store file names and inode numbers

Let's take a look inside...

With the specification of the file system and some tools, the individual fields of the directory records can be examined. For example the record of `liesmich.txt`

```
# lsblk | grep sda1
sda             8:0     1   29,3G  0 disk
  sda1          8:1     1   29,3G  0 part

# mkfs.ext4 /dev/sda1

# mkdir /mnt/test
# mount -t ext4 /dev/sda1 /mnt/test/

# df -h | grep test
/dev/sda1          29G      45M    28G     1% /mnt/test

# ls -l /mnt/test
insgesamt 16
drwx------ 2 root root 16384 Sep 14 09:38 lost+found

# mkdir /mnt/test/testfolder
# echo "Betriebssysteme" > /mnt/test/testfolder/liesmich.txt
# echo "OpSys" > /mnt/test/testfolder/file2.txt
# echo "12345" > /mnt/test/testfolder/anotherfile.dat
# touch /mnt/test/testfolder/empty_file

# ls -lai /mnt/test/testfolder/
insgesamt 20
392449 drwxr-xr-x 2 root root 4096 Sep 14 09:59 .
     2 drwxr-xr-x 4 root root 4096 Sep 14 09:46 ..
392452 -rw-r--r-- 1 root root    6 Sep 14 09:58 anotherfile.dat
392453 -rw-r--r-- 1 root root    0 Sep 14 09:59 empty_file
392451 -rw-r--r-- 1 root root    6 Sep 14 09:47 file2.txt
392450 -rw-r--r-- 1 root root   16 Sep 14 09:47 liesmich.txt
```

Analyze File Systems (2/3)

```
# debugfs /dev/sda1
debugfs 1.44.5 (15-Dec-2018)
debugfs: imap <392449>
Inode 392449 is part of block group 48
  located at block 1572896, offset 0x0000
debugfs: dump testfolder testfolder.out
debugfs: quit

# ls -l testfolder.out
-rw-r--r-- 1 root root 4096 Sep 14 10:00 testfolder.out

# hexdump -C testfolder.out
00000000 01 fd 05 00 0c 00 01 02 2e 00 00 00 02 00 00 00 |................|
00000010 0c 00 02 02 2e 2e 00 00 02 fd 05 00 14 00 0c 01 |................|
00000020 6c 69 65 73 6d 69 63 68 2e 74 78 74 03 fd 05 00 |liesmich.txt....|
00000030 14 00 09 01 66 69 6c 65 32 2e 74 78 74 00 00 00 |....file2.txt...|
00000040 04 fd 05 00 18 00 0f 01 61 6e 6f 74 68 65 72 66 |........anotherf|
00000050 69 6c 65 2e 64 61 74 00 05 fd 05 00 9c 0f 0a 01 |ile.dat.........|
00000060 65 6d 70 74 79 5f 66 69 6c 65 00 00 00 00 00 00 |empty_file......|
00000070 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 |................|
...
```

We analyze the contents of `testfolder.out` with command line tools like `hexdump` or `od` (octal dump). Alternatively, it is possible to use a graphical tool such as `wxHexEditor` (see slide 27).

A hex editor visualizes data in several ways

- 1st column: Number of previous bytes $\Longrightarrow$ offset or position indicator (address) inside the file in hexadecimal representation
- 2nd column: Bytes of the line in hexadecimal representation
- 3rd column: Bytes of the line in ASCII representation

Some fundamentals...

- Hexadecimal system $\Longrightarrow$ base 16
- 1 hexadecimal digit represents 4 bits
- 2 hexadecimal digits represent 1 byte

Analyze File Systems (3/3)

https://ext4.wiki.kernel.org/index.php/Ext4_Disk_Layout

Offset	Size	Name	Description
0x0	4 Bytes	inode	Number of the inode that this directory record points to
0x4	2 Bytes	record length	Directory record length
0x6	1 Byte	name length	Length of the file name
0x7	1 Byte	file type	0x0 = unknown, 0x1 = regular file, 0x2 = directory, 0x3 = character-device special file, 0x4 = block-device special file, 0x5 = FIFO (named pipe), 0x6 = socket, 0x7 = symbolic link
0x8		character string	File name

Information about Big-Endian vs. Little-Endian Byte Order

x86 processors use the **little-endian byte order**. If a data field is several bytes long, the least significant byte (LSB) is in the first position, i.e. on the lowest memory address. The more significant bytes are on the following memory addresses

```
00000010 -- -- -- -- -- -- -- -- 02 fd 05 00 14 00 0c 01 |................|
00000020 6c 69 65 73 6d 69 63 68 2e 74 78 74 -- -- -- -- |liesmich.txt....|
```

Inode number: 02 fd 05 00 $\Longrightarrow$ 00 05 fd 02

```
$ printf "%d\n" 0x0005fd02
392450
```

Directory record length: 14 00 $\Longrightarrow$ 00 14 $\Longrightarrow$ 20 Bytes

```
$ printf "%d\n" 0x0014
20
```

File name length: 0c $\Longrightarrow$ 12 Bytes
File type: 01 $\Longrightarrow$ regular file

File Allocation Table (FAT)

The FAT file system was released in 1980 with QDOS, which was later renamed to MS-DOS

QDOS = Quick and Dirty Operating System

- The File Allocation Table (FAT) file system is based on the data structure of the same name
- The FAT (**File Allocation Table**) is a table of fixed size
- For each cluster in the file system, an entry exists in the FAT with the following information about the cluster:
  - Cluster is free or the storage medium is damaged at this point
  - Cluster is occupied by a file
    - In this case it stores the address of the next cluster, which belongs to the file or it is the last cluster of the file
- The clusters of a file are a linked list (**cluster chain**)
  $\Longrightarrow$ see slides 18 und 20

FAT File System Structure (1/2)

Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Boot block	Reserved blocks	FAT1	FAT2	Root directory	Data region

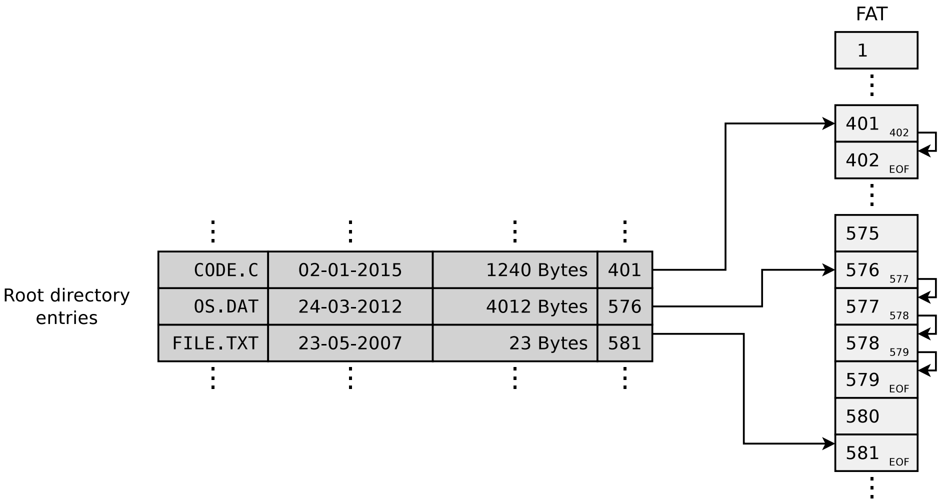
- The **boot sector** contains executable x86 machine code, which starts the operating system, and information about the file system:
  - Block size of the storage device (512, 1024, 2048 or 4096 Bytes)
  - Number of blocks per cluster
  - Number of blocks (sectors) on the storage device
  - Description (name) of the storage device
  - Description of the FAT version
- Between the boot block and the first FAT, optional **reserved blocks** may exist, e.g. for the boot manager
  - These clusters can not be used by the file system

FAT File System Structure (2/2)

Area 1	Area 2	Area 3	Area 4	Area 5	Area 6
Boot block	Reserved blocks	FAT1	FAT2	Root directory	Data region

- The **File Allocation Table** (FAT) stores a record for each cluster in the file system, which informs, whether the cluster is occupied or free
  - The FAT's consistency is essential for the functionality of the file system
    - Therefore, usually a copy of the FAT exists, in order to have a complete FAT as backup in case of a data loss
- In the **root directory**, every file and every directory is represented by an entry:
  - With FAT12 and FAT16, the root directory is located directly behind the FAT and has a fixed size
    - The maximum number of directory entries is therefore limited
  - With FAT32, the root directory can reside at any position in the data region and has a variable size
- The last region contains the actual **data**

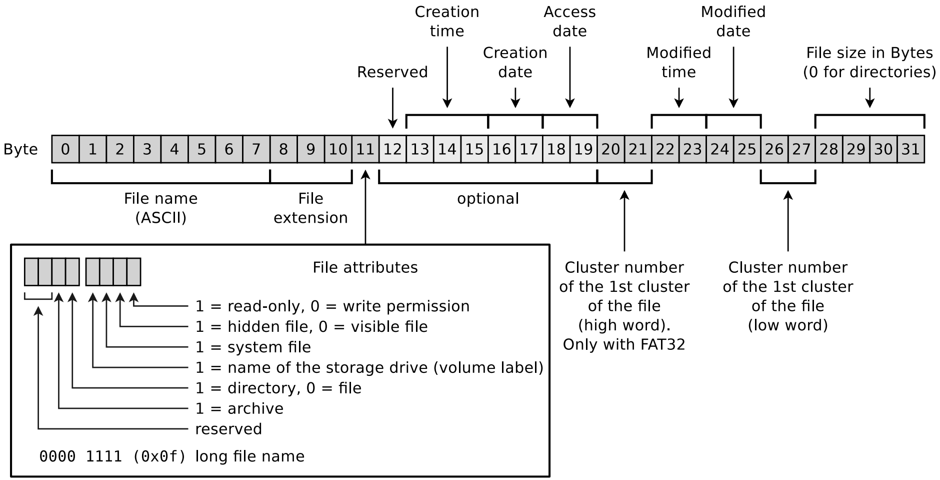
Root Directory and FAT


FAT
1
401 402
402 EOF
575
576 577
577 578
578 579
579 EOF
580
581 EOF
Root directory entries
CODE.C 02-01-2015 1240 Bytes 401
OS.DAT 24-03-2012 4012 Bytes 576
FILE.TXT 23-05-2007 23 Bytes 581

The topic FAT is well explained by. . .

- **Betriebssysteme**, *Carsten Vogt*, 1st edition, Spektrum Akademischer Verlag (2001), P. 178-179

Structure of Root Directory Entries

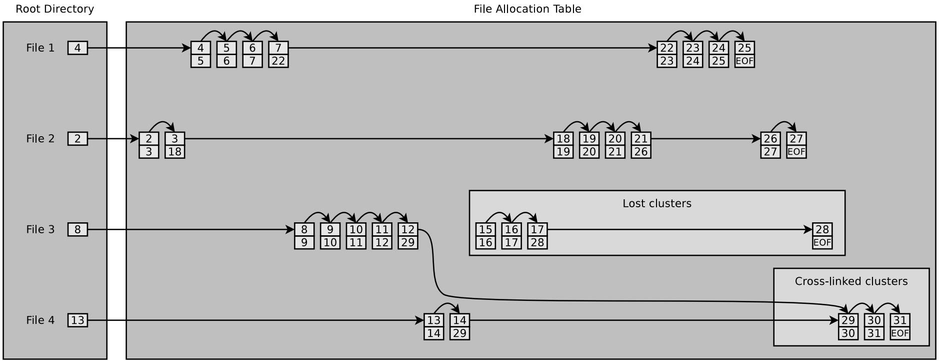

Byte
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31
Reserved
Creation time
Creation date
Access date
Modified time
Modified date
File size in Bytes (0 for directories)
File name (ASCII)
File extension
optional
Cluster number of the 1st cluster of the file (high word). Only with FAT32
Cluster number of the 1st cluster of the file (low word)
File attributes
1 = read-only, 0 = write permission
1 = hidden file, 0 = visible file
1 = system file
1 = name of the storage drive (volume label)
1 = directory, 0 = file
1 = archive
reserved
0000 1111 (0x0f) long file name

Why is 4 GB the maximum file size on FAT32?

Only 4 Bytes are available for specifying the file size.

Risk of File System Inconsistencies

- Typical problems of file systems based on a FAT:
  - lost clusters
  - cross-linked clusters



Source: `http://www.sal.ksu.edu/faculty/tim/ossg/File_sys/file_system_errors.html`

FAT12

Released in 1980 with the first QDOS release

- Length of the cluster numbers: 12 bits
  - Up to $2^{12} = 4096$ clusters can be addressed
- Cluster size: 512 Bytes to 4 kB
- Supports storage media (partitions) up to 16 MB

$$2^{12} * 4\,\text{kB cluster size} = 16384\,\text{kB} = 16\,\text{MB maximum file system size}$$

- File names are supported only in 8.3 format
  - Up to 8 characters can be used to represent the file name and 3 characters for the file name extension

Used „today“ only for DOS and Windows floppy disks

FAT16

- Released in 1983 because it was foreseeable that an address space of 16 MB is insufficient
- Up to $2^{16} = 65524$ clusters can be addressed
  - 12 clusters are reserved
- Cluster size: 512 Bytes to 256 kB
- File names are supported only in 8.3 format
- Main field of application today: Mobile storage media ≤ 2 GB

Sources:
http://support.microsoft.com/kb/140365/de
http://secrets.mysfyts.com/index.asp?Page=Fat
http://web.allensmith.net/Storage/HDDlimit/FAT16.htm

Partition size	Cluster size
up to 31 MB	512 Bytes
32 MB - 63 MB	1 kB
64 MB - 127 MB	2 kB
128 MB - 255 MB	4 kB
256 MB - 511 MB	8 kB
512 MB - 1 GB	16 kB
1 GB - 2 GB	32 kB
2 GB - 4 GB	64 kB
4 GB - 8 GB	128 kB
8 GB - 16 GB	256 kB

The table contains default cluster sizes of Windows 2000/XP/Vista/7/8/10. The cluster size can be manually specified during the file system creation

Some operating systems (e.g. MS-DOS and Windows 95/98/Me) do not support clusters > 32 kB

Some operating systems (e.g. Windows 2000/XP/7/8/10) do not support clusters > 64 kB

FAT32

- Released in 1997 because of the rising HDD capacities and because clusters > 32 kB waste a lot of storage
- Size of the cluster numbers records in the FAT: 32 Bits
  - 4 Bits are reserved
  - Therefore, only $2^{28} = 268,435,456$ clusters can be addressed
- Cluster size: 512 Bytes to 32 kB
- Maximum file size: 4 GB
  - Reason: Only 4 Bytes are available for indicating the file size
- Main field of application today: Mobile storage media > 2 GB

Partition size	Cluster size
up to 63 MB	512 Bytes
64 MB - 127 MB	1 kB
128 MB - 255 MB	2 kB
256 MB - 511 MB	4 kB
512 MB - 1 GB	4 kB
1 GB - 2 GB	4 kB
2 GB - 4 GB	4 kB
4 GB - 8 GB	4 kB
8 GB - 16 GB	8 kB
16 GB - 32 GB	16 kB
32 GB - 2 TB	32 kB

The table contains default cluster sizes of Windows 2000/XP/Vista/7/8/10. The cluster size can be manually specified during the file system creation

Sources: `http://support.microsoft.com/kb/140365/de`

Longer File Names by using VFAT

- VFAT (Virtual File Allocation Table) was released in 1997
  - Extension for FAT12/16/32 to support long filenames
- Because of VFAT, Windows supported for the first time. . .
  - file names that do not comply with the 8.3 format
  - file names up to a length of 255 characters
- Implements Unicode character encoding

Long File Names (LFN)

- VFAT = great example for implementing a new feature + keeping backward compatibility
- LFNs (255 characters max) are split into max. 20 pseudo-directory records (see slide 25)
- File systems without LFN support ignore pseudo-directory records and show only the shortened name
- The first 4 bits of the **file attributes** field of VFAT records have value 1 (see slide 18)
- Special attribute: Upper/lower case is displayed, but ignored

Compatibility with MS-DOS and Windows up to v3.11

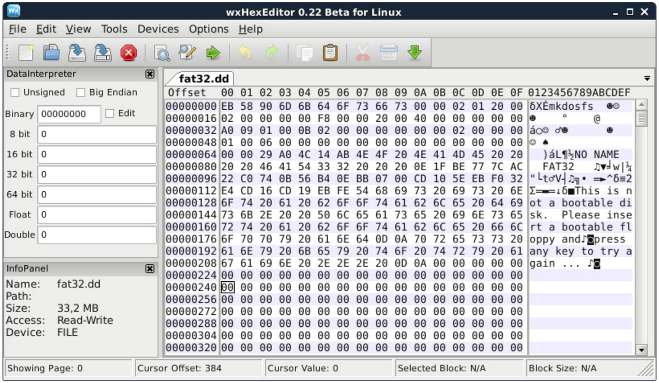
- VFAT and NTFS (see slide 38) store for every file a unique filename in 8.3 format
  - Operating systems without the VFAT extension ignore the pseudo-directory entries and only show the shortened file name
    - This way, Microsoft operating systems without NTFS and VFAT support can access files on NTFS partitions
- Challenge: **The short file names must be unique**
- Solution:
  - All special characters and dots inside the name are erased
  - All lowercase letters are converted to uppercase letters
  - Only the first 6 characters are kept
    - Next, a `~1` follows before the dot
  - The first 3 characters after the dot are kept and the rest is erased
  - If a file with the same name already exists, `~1` is replaced with `~2`, etc.
- Example:

  `A very long filename.test.pdf` $\Longrightarrow$ `AVERYL~1.pdf`

Analyze FAT File Systems (1/3)

```
# dd if=/dev/zero of=./fat32.dd bs=1024000 count=34
34+0 Datensätze ein
34+0 Datensätze aus
34816000 Bytes (35 MB) kopiert, 0,0213804 s, 1,6 GB/s
# mkfs.vfat -F 32 fat32.dd
mkfs.vfat 3.0.16 (01 Mar 2013)

# mkdir /mnt/fat32
# mount -o loop -t vfat fat32.dd /mnt/fat32/

# mount | grep fat32
/tmp/fat32.dd on /mnt/fat32 type vfat (rw,relatime,fmask=0022,dmask=0022,codepage=437,iocharset=utf8,shortname
      =mixed,errors=remount-ro)
# df -h | grep fat32
/dev/loop0      33M    512   33M    1% /mnt/fat32

# ls -l /mnt/fat32
insgesamt 0

# echo "Betriebssysteme" > /mnt/fat32/liesmich.txt
# cat /mnt/fat32/liesmich.txt
Betriebssysteme
# ls -l /mnt/fat32/liesmich.txt
-rwxr-xr-x 1 root root 16 Feb 28 10:45 /mnt/fat32/liesmich.txt

# umount /mnt/fat32/
# mount | grep fat32
# df -h | grep fat32

# wxHexEditor fat32.dd
```

Analyze FAT File Systems (2/3)



DataInterpreter

Unsigned	☐
Big Endian	☐
Binary	00000000
Edit	☐
8 bit	0
16 bit	0
32 bit	0
64 bit	0
Float	0
Double	0

InfoPanel

Name:	fat32.dd
Path:	
Size:	33,2 MB
Access:	Read-Write
Device:	FILE

```
Offset   00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 0123456789ABCDEF
00000000 EB 58 90 6D 6B 64 6F 73 66 73 00 00 02 01 20 00 δXÉmkdosfs  ☻☺
00000016 02 00 00 00 00 F8 00 00 20 00 40 00 00 00 00 00 ☻    °   @
00000032 A0 09 01 00 0B 02 00 00 00 00 00 00 02 00 00 00 á○☺ ♂☻      ☻
00000048 01 00 06 00 00 00 00 00 00 00 00 00 00 00 00 00 ☺ ♠
00000064 00 00 29 A0 4C 14 AB 4E 4F 20 4E 41 4D 45 20 20   )áL¶½NO NAME
00000080 20 20 46 41 54 33 32 20 20 20 0E 1F BE 77 7C AC   FAT32   ♫▼╛w|¼
00000096 22 C0 74 0B 56 B4 0E BB 07 00 CD 10 5E EB F0 32 "└t♂V┤♫╗• ═►^δ≡2
00000112 E4 CD 16 CD 19 EB FE 54 68 69 73 20 69 73 20 6E Σ═▬═↓δ■This is n
00000128 6F 74 20 61 20 62 6F 6F 74 61 62 6C 65 20 64 69 ot a bootable di
00000144 73 6B 2E 20 20 50 6C 65 61 73 65 20 69 6E 73 65 sk.  Please inse
00000160 72 74 20 61 20 62 6F 6F 74 61 62 6C 65 20 66 6C rt a bootable fl
00000176 6F 70 70 79 20 61 6E 64 0D 0A 70 72 65 73 73 20 oppy and♪◙press
00000192 61 6E 79 20 6B 65 79 20 74 6F 20 74 72 79 20 61 any key to try a
00000208 67 61 69 6E 20 2E 2E 2E 20 0D 0A 00 00 00 00 00 gain ... ♪◙
00000224 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000240 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000256 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000272 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000288 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000304 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000320 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

Showing Page: 0 | Cursor Offset: 384 | Cursor Value: 0 | Selected Block: N/A | Block Size: N/A

A hex editor visualizes data in several ways

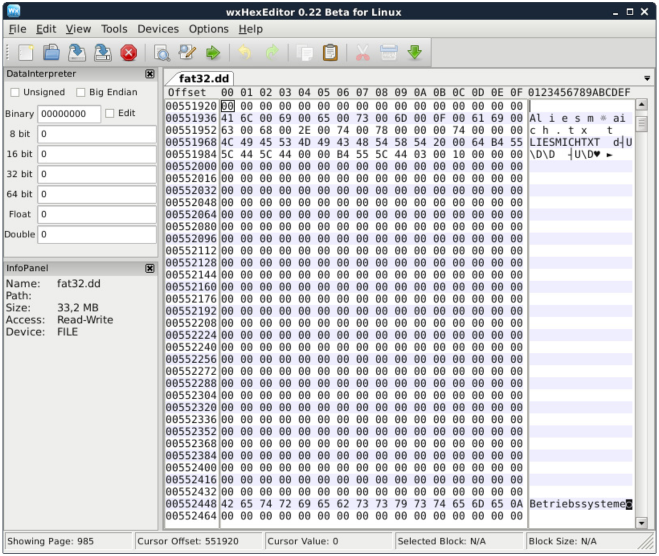
- 1st column: Number of previous bytes $\Longrightarrow$ offset
- 2nd column: Bytes of the line in hexadecimal representation
- 3rd column: Bytes of the line in ASCII representation

Some fundamentals...

- Hexadecimal system $\Longrightarrow$ base 16
- 1 hexadecimal digit represents 4 bits
- 2 hexadecimal digits represent 1 byte

`http://dorumugs.blogspot.de/2013/01/file-system-geography-fat32.html`
`http://www.win.tue.nl/~aeb/linux/fs/fat/fat-1.html`

Analyze FAT File Systems (3/3)


wxHexEditor 0.22 Beta for Linux
File Edit View Tools Devices Options Help
DataInterpreter
InfoPanel
fat32.dd

```
Unsigned   Big Endian
Binary 00000000   Edit
8 bit  0
16 bit 0
32 bit 0
64 bit 0
Float  0
Double 0
```

```
Name:    fat32.dd
Path:
Size:    33,2 MB
Access:  Read-Write
Device:  FILE
```

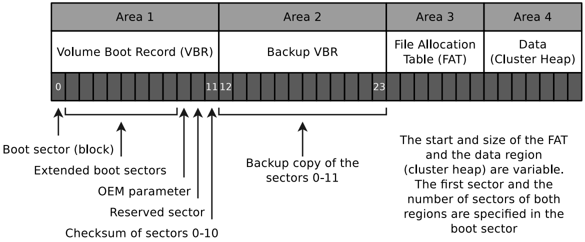
```
Offset   00 01 02 03 04 05 06 07 08 09 0A 0B 0C 0D 0E 0F 0123456789ABCDEF
00551920 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00551936 41 6C 00 69 00 65 00 73 00 6D 00 0F 00 61 69 00 Al i e s m ☼ ai
00551952 63 00 68 00 2E 00 74 00 78 00 00 00 74 00 00 00 c h . t x   t
00551968 4C 49 45 53 4D 49 43 48 54 58 54 20 00 64 B4 55 LIESMICHTXT  d┤U
00551984 5C 44 5C 44 00 00 B4 55 5C 44 03 00 10 00 00 00 \D\D  ┤U\D♥ ►
00552000 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552016 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552032 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552048 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552064 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552080 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552096 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552112 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552128 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552144 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552160 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552176 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552192 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552208 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552224 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552240 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552256 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552272 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552288 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552304 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552320 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552336 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552352 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552368 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552384 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552400 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552416 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552432 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00552448 42 65 74 72 69 65 62 73 73 79 73 74 65 6D 65 0A Betriebssysteme◙
00552464 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
```

```
Showing Page: 985   Cursor Offset: 551920   Cursor Value: 0   Selected Block: N/A   Block Size: N/A
```

exFAT

- Released in 2006 (usage is royalty-free since 2019)
- Up to $2^{32} = 4,294,967,296$ clusters can be addressed
- Cluster size: 512 Bytes to 64 MB
- Maximum file size: 16 EB (2^{64} Bytes)
- Main field of application: mobile flash memory (> 32 GB)
  - Fewer write operations than file systems with a journal (e.g. NTFS $\Longrightarrow$ slide 38)

In contrast to the other FAT file system versions, the root directory does not have a fixed position. It is located within the data area and usually does not reside there in one piece, but is fragmented.



Area 1
Area 2
Area 3
Area 4
Volume Boot Record (VBR)
Backup VBR
File Allocation Table (FAT)
Data (Cluster Heap)
0
11
12
23
Boot sector (block)
Extended boot sectors
OEM parameter
Reserved sector
Checksum of sectors 0-10
Backup copy of the sectors 0-11
The start and size of the FAT and the data region (cluster heap) are variable. The first sector and the number of sectors of both regions are specified in the boot sector

Partition size	Cluster size
up to 256 MB	4 kB
256 MB - 32 GB	32 kB
32 GB - 256 TB	128 kB

The table contains default cluster sizes of Windows 2000/XP/Vista/8/10. The cluster size can be manually specified during the file system creation https://support.microsoft.com/de-de/kb/140365

Problem: Write Operations

- If files or directories are created, relocated, renamed, erased, or modified, write operations in the file system are carried out
  - **Write operations shall convert data from one consistent state to a new consistent state**
- If a failure occurs during a write operation, the consistency of the file system must be checked
  - If the size of a file system is multiple GB, the consistency check may take several hours or days
  - Skipping the consistency check, may cause data loss
- Objective: **Narrow down the data, which need to be checked by the consistency check**
- Solution: Collect the write operations in a journal
  $\Longrightarrow$ **Journaling file systems**

Journaling File Systems

- Implement a journal, where write operations are collected before being committed to the file system
  - At fixed time intervals, the journal is closed and the write operations are carried out
- Advantage: After a crash, only the files (clusters) and metadata must be checked, for which a record exists in the journal
- Drawback: Journaling increases the number of write operations, because modifications are first written to the journal and next carried out
- 2 variants of journaling:
  - **Metadata journaling**
  - **Full journaling**

Helpful descriptions of the different journaling concepts. . .

- **Analysis and Evolution of Journaling File Systems**, *Vijayan Prabhakaran, Andrea C. Arpaci-Dusseau, Remzi H. Arpaci-Dusseau*, 2005 USENIX Annual Technical Conference, `http://www.usenix.org/legacy/events/usenix05/tech/general/full_papers/prabhakaran/prabhakaran.pdf`
- `http://www.ibm.com/developerworks/library/l-journaling-filesystems/index.html`

Metadata Journaling and Full Journaling

- **Metadata journaling** (*Write-Back*)
  - The journal contains only metadata (inode) modifications
    - Only the consistency of the metadata is ensured after a crash
  - Modifications to clusters are carried out by `sync()` ($\Longrightarrow$ write-back)
    - The `sync()` system call commits the page cache, that is also called = buffer cache (see slide 42) to the HDD/SDD
  - Advantage: Consistency checks only take a few seconds
  - Drawback: Loss of data due to a system crash is still possible
  - Optional with ext3/4 and ReiserFS
  - NTFS and XFS provides only metadata journaling
- **Full journaling**
  - Modifications to metadata and clusters of files are written to the journal
  - Advantage: Ensures the consistency of the files
  - Drawback: All write operation must be carried out twice
  - Optional with ext3/4 and ReiserFS

The alternative is therefore high data security and high write speed

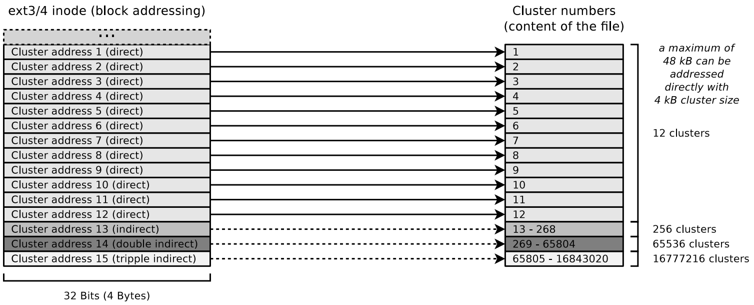
Compromise between the Variants: Ordered Journaling

- Most Linux distributions use by default a compromise between both variants
- **Ordered journaling**
  - The journal contains only metadata modifications
  - **File modifications are carried out in the file system first and next the relevant metadata modifications are written into the journal**
  - Advantage: Consistency checks only take a few seconds and high write speed equal to journaling, where only metadata is journaled
  - Drawback: Only the consistency of the metadata is ensured
    - If a crash occurs while incomplete transactions in the journal exist, new files and attachments get lost because the clusters are not yet allocated to the inodes
    - Overwritten files after a crash may have inconsistent content and maybe cannot be repaired, because no copy of the old version exists
  - Examples: Only option when using JFS, standard with ext3/4 and ReiserFS

Interesting: `https://www.heise.de/newsticker/meldung/Kernel-Entwickler-streiten-ueber-Ext3-und-Ext4-209350.html`

Problem: Metadata Overhead

- Every inode at block addressing addresses a certain number of cluster numbers directly
- If a file requires more clusters, they are indirectly addressed

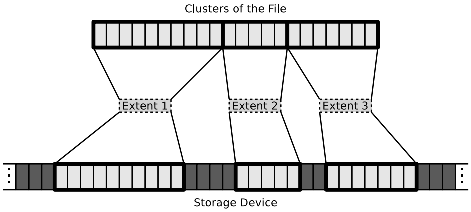


ext3/4 inode (block addressing)
...
Cluster address 1 (direct)
Cluster address 2 (direct)
Cluster address 3 (direct)
Cluster address 4 (direct)
Cluster address 5 (direct)
Cluster address 6 (direct)
Cluster address 7 (direct)
Cluster address 8 (direct)
Cluster address 9 (direct)
Cluster address 10 (direct)
Cluster address 11 (direct)
Cluster address 12 (direct)
Cluster address 13 (indirect)
Cluster address 14 (double indirect)
Cluster address 15 (tripple indirect)
32 Bits (4 Bytes)
Cluster numbers (content of the file)
1
2
3
4
5
6
7
8
9
10
11
12
13 - 268
269 - 65804
65805 - 16843020
a maximum of 48 kB can be addressed directly with 4 kB cluster size
12 clusters
256 clusters
65536 clusters
16777216 clusters

- This addressing scheme causes rising overhead with rising file size
- Solution: Extents

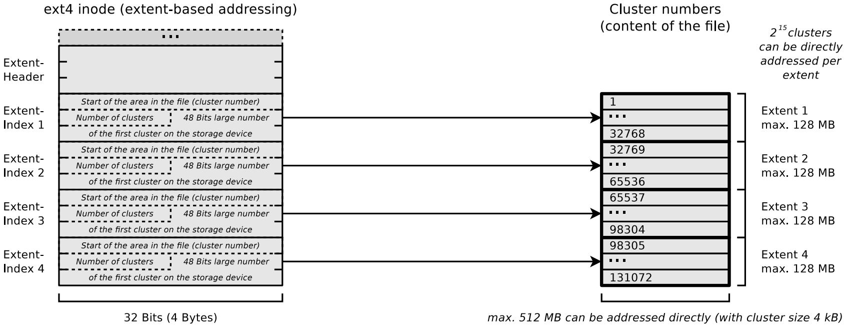
Extent-based Addressing

- Inodes do not address individual clusters, but instead create large areas of files to areas of contiguous blocks (**extents**) on the storage device
- Instead of many individual clusters numbers, only 3 values are required:
  - Start (cluster number) of the area (extent) in the file
  - Size of the area in the file (in clusters)
  - Number of the first cluster on the storage device
- Result: Lesser overhead
- Examples: JFS, XFS, btrfs, NTFS, ext4



Extents using the Example ext4

- With block addressing in ext2/3, each inode contains 15 areas with a size of 4 Bytes each ($\Longrightarrow$ 60 Bytes) for addressing clusters
- ext4 uses this 60 Bytes for an extent header (12 Bytes) and for addressing 4 extents (12 Bytes each)

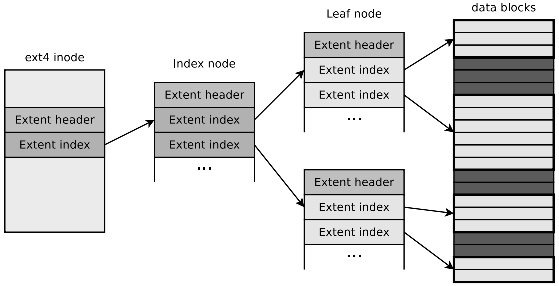

ext4 inode (extent-based addressing)
...
Extent-Header
Extent-Index 1
Extent-Index 2
Extent-Index 3
Extent-Index 4
Start of the area in the file (cluster number)
Number of clusters
48 Bits large number of the first cluster on the storage device
32 Bits (4 Bytes)
Cluster numbers (content of the file)
1
...
32768
32769
...
65536
65537
...
98304
98305
...
131072
2^{15} clusters can be directly addressed per extent
Extent 1 max. 128 MB
Extent 2 max. 128 MB
Extent 3 max. 128 MB
Extent 4 max. 128 MB
max. 512 MB can be addressed directly (with cluster size 4 kB)

Extents cannot become larger than 128 MB (2^{15} bits) because ext4, just like its predecessors ext2 and ext3, organizes the file system clusters into so-called block groups (see slide 10) with a maximum size of 128 MB.

Maximum partition size of ext4: 2^{48} cluster numbers $\times$ 4096 Byte cluster size = 1 Exabyte

Benefit of Extents using the Example ext4

- With a maximum of 12 clusters, an ext3/4 inode can directly address 48 kB (at 4 kB cluster size)
- With 4 extents, an ext4 inode can directly address 512 MB
- If the size of a file is $>$ 512 MB, ext4 creates a tree of extents
  - The principle is analogous to indirect block addressing



Helpful descriptions of Extents in ext4...

`https://ext4.wiki.kernel.org/index.php/Ext4_Disk_Layout#Extent_Tree`
`https://www.sans.org/blog/understanding-ext4-part-3-extent-trees/`
`https://metebalci.com/blog/a-minimum-complete-tutorial-of-linux-ext4-file-system/`
An analysis of Ext4 for digital forensics: `https://www.sciencedirect.com/science/article/pii/S1742287612000357`

NTFS – **N**ew **T**echnology **F**ile **S**ystem

Several different versions of the NTFS file system exist

- NTFS 1.0: Windows NT 3.1 (released in 1993)
- NTFS 1.1: Windows NT 3.5/3.51
- NTFS 2.x: Windows NT 4.0 bis SP3
- NTFS 3.0: Windows NT 4.0 ab SP3/2000
- NTFS 3.1: Windows XP/2003/Vista/7/8/10

Recent versions of NTFS offer additional features as...

- support for quotas since version 3.x
- transparent compression
- transparent encryption (Triple-DES and AES) since version 2.x

- Cluster size: 512 Bytes to 64 kB
- NTFS offers, compared with its predecessor FAT, among others:
  - Maximum file size: 16 TB ($\Longrightarrow$ extents)
  - Maximum partition size: 256 TB ($\Longrightarrow$ extents)
  - Security features on file and directory level
- Equal to VFAT...
  - implements NTFS file names up a length of 255 Unicode characters
  - implements NTFS interoperability with the MS-DOS operating system family by storing a unique file name in the format 8.3 for each file

Structure of NTFS (1/2)

- The file system contains a **Master File Table** (MFT)
  - It contains the references of the files to the clusters
  - Also contains the metadata of the files (file size, file type, date of creation, date of last modification and possibly the file content)
    - The content of small files $\leq$ 900 Bytes is stored directly in the MFT

Source: **How NTFS Works**. Microsoft. 2003. https://technet.microsoft.com/en-us/library/cc781134(v=ws.10).aspx

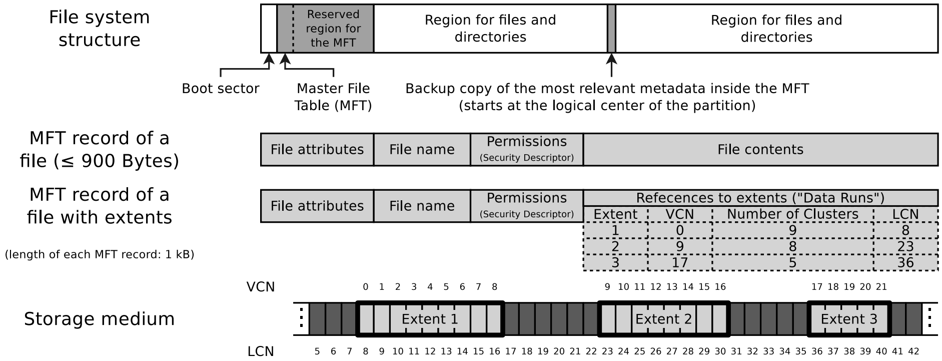
- When a partition is formatted as, a fixed space is reserved for the MFT
  - 12.5% of the partition size is reserved for the MFT by default
  - If the MFT area has no more free capacity, the file system uses additional free space in the partition for the MFT
    - This may cause fragmentation of the MFT (but has no negative effects for flash memory)

Partition size	Cluster size
< 16 TB	4 kB
16 TB - 32 TB	8 kB
32 TB - 64 TB	16 kB
64 TB - 128 TB	32 kB
128 TB - 256 TB	64 kB

The table contains default cluster sizes of Windows 2000/XP/Vista/7/8/10. The cluster size can be specified when the file system is created

Source: http://support.microsoft.com/kb/140365/de

Structure of NTFS (2/2)


File system structure
Reserved region for the MFT
Region for files and directories
Region for files and directories
Boot sector
Master File Table (MFT)
Backup copy of the most relevant metadata inside the MFT (starts at the logical center of the partition)
MFT record of a file (≤ 900 Bytes)
File attributes
File name
Permissions (Security Descriptor)
File contents
MFT record of a file with extents
File attributes
File name
Permissions (Security Descriptor)
Refecences to extents ("Data Runs")
(length of each MFT record: 1 kB)
VCN
0 1 2 3 4 5 6 7 8
9 10 11 12 13 14 15 16
17 18 19 20 21
Storage medium
Extent 1
Extent 2
Extent 3
LCN
5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42

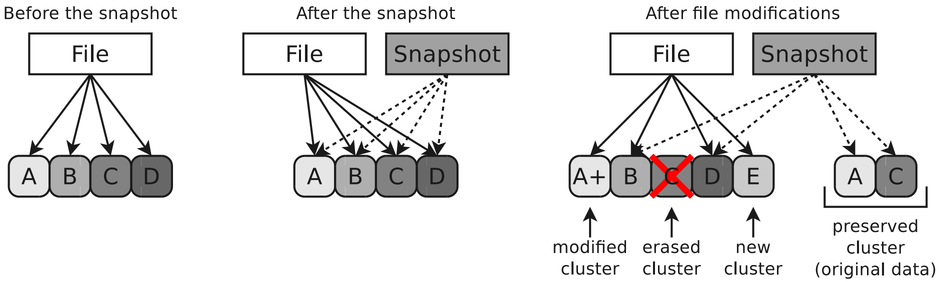
Extent	VCN	Number of Clusters	LCN
1	0	9	8
2	9	8	23
3	17	5	36

If an MFT entry refers to extents (so called „Data Runs“), it stores 3 values per extent

- Start (cluster number) of the area (extent) in the file $\Longrightarrow$ **Virtual Cluster Number (VCN)**
- Size of the area in the file (in clusters) $\Longrightarrow$ **number of clusters**
- Number of the first cluster on the storage device $\Longrightarrow$ **Logical Cluster Number (LCN)**

Also a directory is a file (MFT entry) whose file contents are the numbers of the MFT entries (files) associated with the directory

Most advanced Concept: Copy-on-write



- Write operations do not modify/erase file system contents
  - Modified data is written into free clusters
  - Afterward, the metadata is modified for the new file
- Older file versions are preserved and can be restored
  - Data security is better compared with journaling file systems
  - Snapshots can be created without delay (just metadata modification)
- Examples: ZFS, btrfs and ReFS (Resilient File System)

Accelerating Data Access with a Cache (1/2)

- Modern operating systems accelerate the access to stored data with a **Page Cache** (called *Buffer Cache*) in the main memory
  - If a file is requested for reading, the kernel first tries to allocate the file in the cache
    - If the file is not present in the cache, it is loaded into the cache
- The page cache is never as big as the amount of data on the system
  - That is why rarely requested files must be replaced
    - If data in the cache was modified, the modification must be passed down (written back) at some point in time
    - Optimal use of the cache is impossible because data accesses are non-deterministic (unpredictable)
- Modern operating systems usually do not pass down write accesses immediately ($\Longrightarrow$ **write-back**)
  - Benefit: Better system performance
  - Drawback: System crashes may cause inconsistencies

Accelerating Data Access with a Cache (2/2)

- DOS and Windows up to version 3.11 use the *Smartdrive* utility to implement a page cache
  - All later versions of Windows also contain a *Cache Manager* that implements a page cache
- Linux automatically buffers as much data as there is free space in main memory
  - The command `free -m` returns an overview of the memory usage
    - The `buff/cache` column indicates how much main memory is currently used for the page cache

```
$ free -m
             total        used        free      shared  buff/cache   available
Mem:         15540        5774        1609         785        8156        8650
Swap:        10689           1       10688
```

Good sources regarding the page cache under Linux and how to empty it manually

https://askubuntu.com/questions/770108/what-do-the-changes-in-free-output-from-14-04-to-16-04-mean
http://www.thomas-krenn.com/de/wiki/Linux_Page_Cache
http://unix.stackexchange.com/questions/87908/how-do-you-empty-the-buffers-and-cache-on-a-linux-system
http://serverfault.com/questions/85470/meaning-of-the-buffers-cache-line-in-the-output-of-free

Howto implement Write-through mode? (1/3)

- The **Write-back** policy is standard in many hardware and operating system components (see slide sets 3, 5, and 6)
  - How is it possible to switch to **Write-through** write policy?
- In **Linux**, it is impossible to turn off the page cache globally
  - But it can be done on application and sometimes on file system level
    - However, it is only useful in some cases, like using an application with a dedicated cache in userspace (e.g., a DBMS), using memory-like storage devices or ramdisks or doing performance testing of devices
- The **Linux function call** `open` (`fcntl.h`) for creating or opening a file offers the flags `O_DIRECT` and `O_SYNC`
  - Setting them both specifies that write operations to this file bypass the Linux page cache and is immediately flushed to the drive

`https://man7.org/linux/man-pages/man2/open.2.html`
`https://pubs.opengroup.org/onlinepubs/9699919799.2018edition/functions/open.html`

Howto implement Write-through mode? (2/3)

- The **mount option** `-o sync` bypasses the page cache when using the file systems ext2, ext3, FAT, VFAT, and UFS (Universal Flash Storage)

https://linux.die.net/man/8/mount

- The **mount option** `dax` bypasses the page cache when using the file systems ext2, ext4, and XFS
  - Requires memory-like block devices like Persistent Memory (pmem)

https://www.kernel.org/doc/Documentation/filesystems/dax.txt
https://lwn.net/Articles/787233/

- File systems that make use of the **FUSE** (Filesystem in Userspace) module offer `direct-io` mode where the page cache is bypassed

https://www.kernel.org/doc/Documentation/filesystems/fuse-io.txt

Howto implement Write-through mode? (3/3)

- The **Windows** function call `CreateFileA` (`fileapi.h`) for creating or opening a file offers the flags `FILE_FLAG_WRITE_THROUGH` and `FILE_FLAG_WRITE_THROUGH`
  - Setting them both specifies that write operations bypass the windows system cache and are immediately flushed to the drive

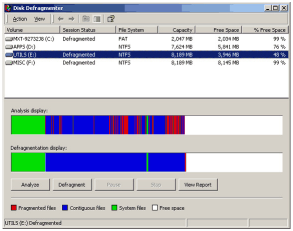
https://devblogs.microsoft.com/oldnewthing/20210729-00/?p=105494
https://learn.microsoft.com/en-us/windows/win32/api/fileapi/nf-fileapi-createfilea

Additional information about how to enable write-through in different operating systems

https://github.com/ronomon/direct-io
https://ext4.wiki.kernel.org/index.php/Clarifying_Direct_IO%27s_Semantics

Fragmentation

- A cluster can only be assigned to a single file
  - If a file is bigger than a cluster, the file is split and stored in several clusters
    - **Fragmentation** means that logically related clusters are not located physically next to each other
  - Objective: Avoid frequent movements of the HDDs arms
    - If the clusters of a file are distributed over the HDD, the heads need to perform more time-consuming position changes when accessing the file
    - For SSDs the position of the clusters is irrelevant for the latency

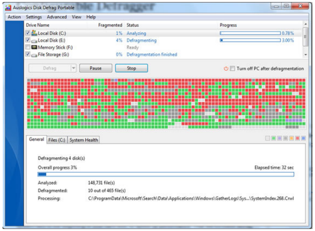


Volume	Session Status	File System	Capacity	Free Space	% Free Space
MXT-9273238 (C:)	Defragmented	FAT	2,047 MB	2,034 MB	99 %
APPS (D:)		NTFS	7,624 MB	5,841 MB	76 %
UTILS (E:)	Defragmented	NTFS	8,189 MB	3,946 MB	48 %
MISC (F:)	Defragmented	NTFS	8,189 MB	8,145 MB	99 %

🟥 Fragmented files 🟦 Contiguous files 🟩 System files ⬜ Free space

UTILS (E:) Defragmented

Image source: http://windowsitpro.com



Drive Name	Fragmented	Status	Progress
✓ Local Disk (C:)	1%	Analyzing	0.78%
✓ Local Disk (E:)	4%	Defragmenting	3.00%
Memory Stick (F:)		Ready	
✓ File Storage (G:)	0%	Defragmentation finished	

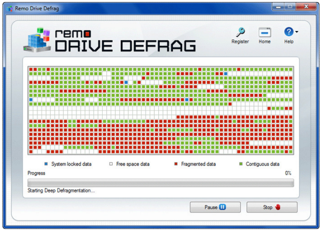
Turn off PC after defragmentation

Defragmenting 4 disk(s)

Overall progress 3% Elapsed time: 32 sec

Analyzed:	148,731 file(s)
Defragmented:	10 out of 465 file(s)
Processing:	C:\ProgramData\Microsoft\Search\Data\Applications\Windows\GatherLogs\Sys...\SystemIndex.268.Crwl

Image source: http://www.teknobites.com



🟦 System locked data ⬜ Free space data 🟥 Fragmented data 🟩 Contiguous data

Progress 0%

Starting Deep Defragmentation...

Image s.: http://www.remosoftware.com

Defragmentation (1/3)

- These questions are frequently asked:
  - Why is it for Linux/UNIX not common to defragment?
  - Does fragmentation occur with Linux/UNIX?
  - Is it possible to defragment with Linux/UNIX?
- First of all, we need to answer: What do we want to achieve with **defragmentation**?
  - Writing data to a drive, always leads to fragmentation
    - The data is no longer contiguously arranged
  - A continuous arrangement would maximum accelerate the **continuous forward reading** of the data because no more seek times occur
  - Only if the seek times are huge, defragmentation makes sense
    - With operating systems, which use only a little amount of main memory for caching HDD accesses, high seek times are very negative

Discovery 1: Defragmentation accelerates mainly the continuous forward reading

Defragmentation (2/3)

- Singletasking operating systems (e.g. MS-DOS)
  - Only a single application can be executed
    - If this application often hangs, because it waits for the results of read/write requests, this causes a poor system performance

Discovery 2: Defragmentation may be useful for singletasking operating systems.
In practice, however, single-tasking operating systems are used seldom

- Multitasking operating systems
  - Multiple programs are executed at the same time
    - **Applications can almost never read large amounts of data in a row, without other applications in between, requesting r/w operations**
- In order to prevent that programs, which are executed at the same time, do interfere each other, operating systems read more data than requested
  - The system reads a stock of data into the **cache**, even if no requests for these data exist

Discovery 3: In multitasking operating systems, applications can almost never read large amounts of data in a row

Defragmentation (3/3)

- Linux systems automatically hold data in the cache, which is frequently accessed by the processes
  - **The impact of the cache greatly exceeds the short-term benefits, which can be achieved by defragmentation**

Discovery 4: Defragmenting has mainly a benchmark effect
Discovery 5: Enlarge the file system cache brings better results than defragmentation

- Defragmenting has mainly a **benchmark effect**
  - In practice, defragmentation (in Linux!) causes almost no positive impact
  - Tools like `defragfs` can be used for Linux file system defragmentation
    - Using these tools is often not recommended and useful

Helpful source of information: `http://www.thomas-krenn.com/de/wiki/Linux_Page_Cache`