Operating Systems

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Ch10, part 1
Details of FAT32

Topics in Ch10

- Case study

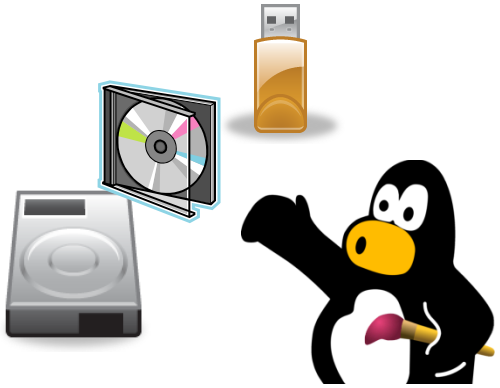
Details of FAT32
File attributes and directory entries, file operations

Details of Ext2/3/4
Detailed layout, detailed inode structure (file attributes), FS operations…

Details of FAT32

- **Introduction**
- Directory and File Attributes
- File Operations
  - Read files
  - Write files
  - Delete files
  - Recover deleted files

Microsoft Extensible Firmware Initiative FAT32 File System Specification (FAT: General Overview of On-Disk Format), Version 1.03, December 6, 2000, hardware white papers @ Microsoft Corporation.

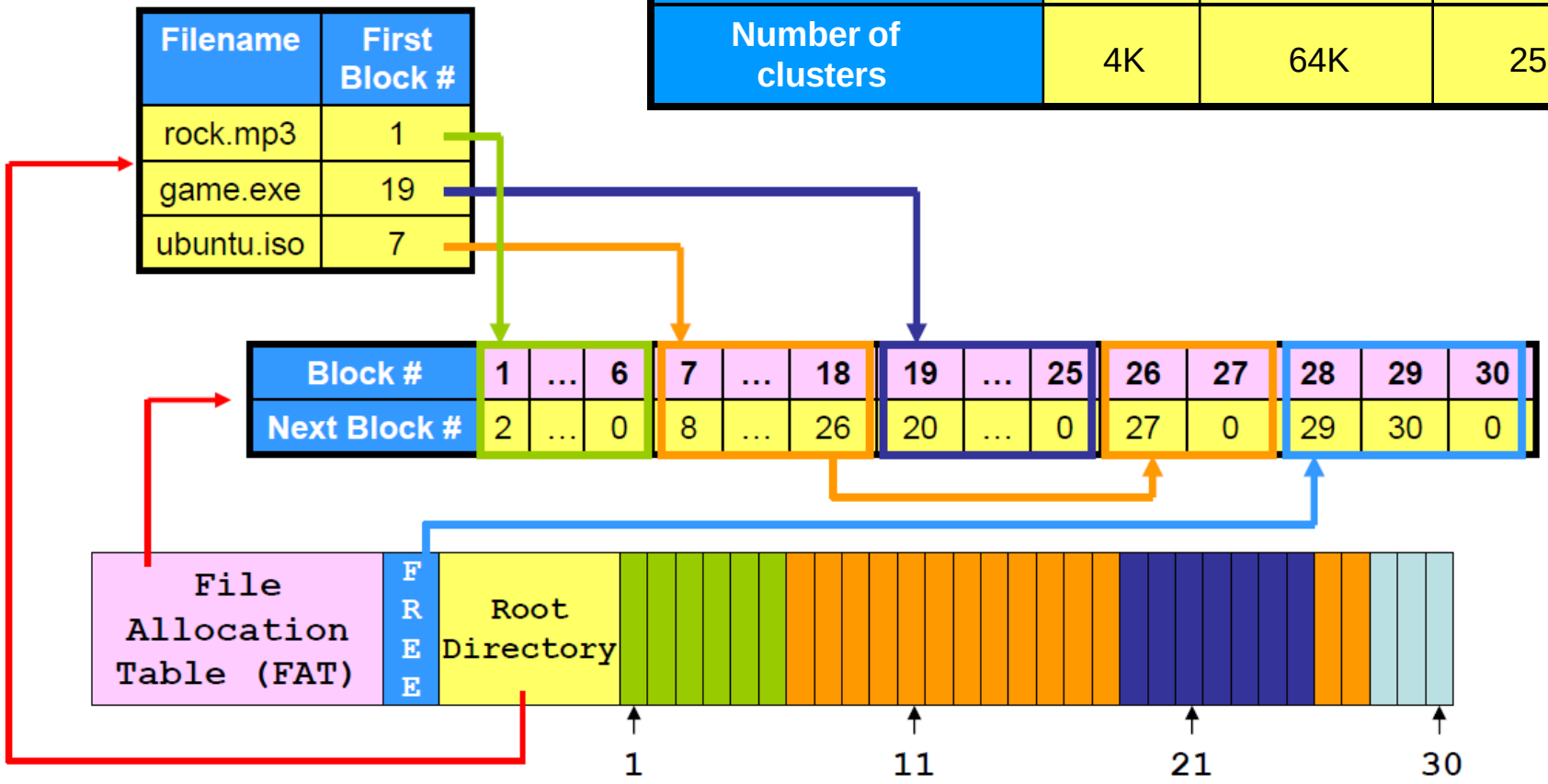


Recall on FAT allocation

- The layout

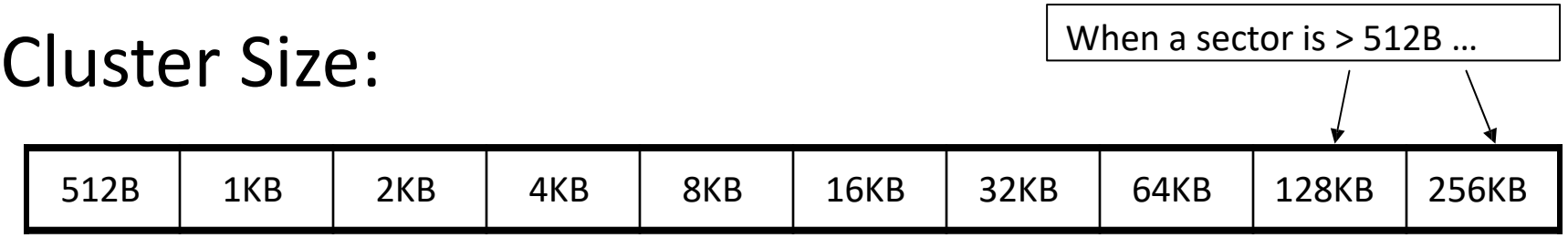
A block is named a **cluster**.

File System	FAT12	FAT16	FAT32
Cluster addr length	12 bits	16 bits	32 bits (28?)
Number of clusters	4K	64K	256M



Trivia

- Cluster Size:



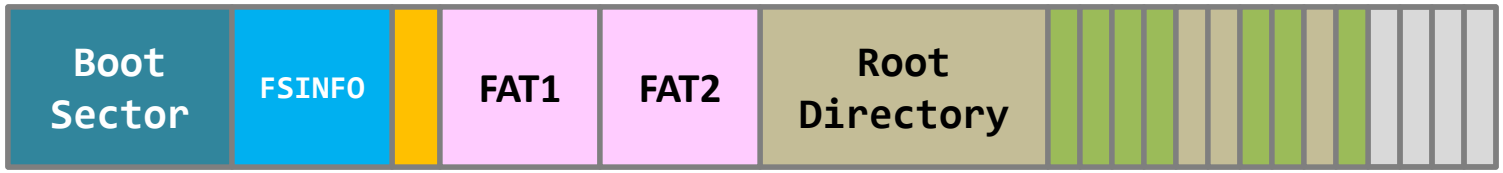
  – Try typing "help format" in the command prompt in Windows.

- Calculating the maximum partition size
  – with the cluster size = 32KB…

$$(32 \times 2^{10}) \times 2^{28} = 2^{43}\ (8TB)$$

Typical layout of a FAT32 partition

	Propose	Size
Boot sector	Store FS-specific parameters	1 sector, 512 bytes
FSINFO	Free-space management	1 sector, 512 bytes
Reserved sectors	**Don’t ask me, ask Micro$oft!**	Variable, can be changed during format.
FAT (2 pieces)	A **robust design**: if “**FAT 1**” is corrupted or containing bad sectors, then “**FAT 2**” can act as a backup.	Variable, depends on disk size and cluster size.
Root directory	Start of the directory tree.	At least one cluster, depend on the number of director entries.



Typical layout of a FAT32 partition

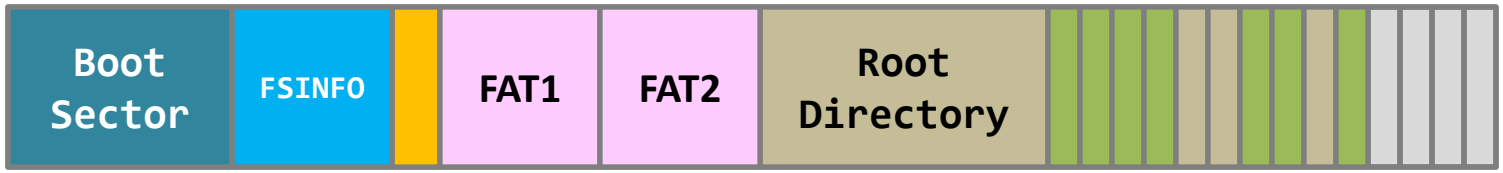
```
$ sudo mkfs.vfat -F32 /dev/ram0
mkfs.fat 3.0.28 (2015-05-16)
......
$ sudo dosfsck -v /dev/ram0
```

Format the disk, “-F32” means FAT32.

Read the information stored in the boot sector.

Running “**dosfsck**”, *DOS file system check*, on a FAT32 FS.

This program reads details from the **Boot Sector**.



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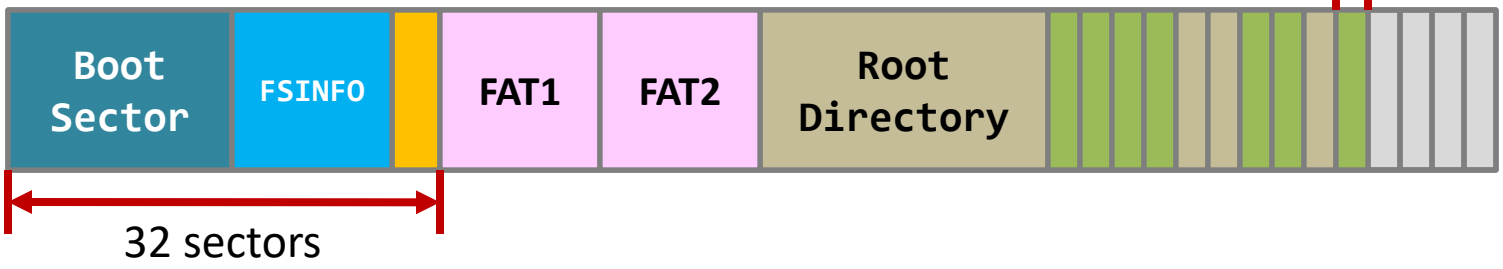
mkfs.fat 3.0.28 (2015-05-16)
......
$ sudo dosfsck -v /dev/ram0
fsck.fat 3.0.28 (2015-05-16)

Checking we can access the last sector of the filesystem
Boot sector contents:
System ID "mkfs.fat"
Media byte 0xf8 (hard disk)
       512 bytes per logical sector
       512 bytes per cluster
        32 reserved sectors
First FAT starts at byte 16384 (sector 32)
         2 FATs, 32 bit entries
    516608 bytes per FAT (= 1009 sectors)
Root directory start at cluster 2 (arbitrary size)
Data area starts at byte 1049600 (sector 2050)
    129022 data clusters (66059264 bytes)
......
```

Details of the **Boot Sector**

The boot sector says:
A cluster is made of 1 sector.

One cluster size: 512 bytes in this case



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......
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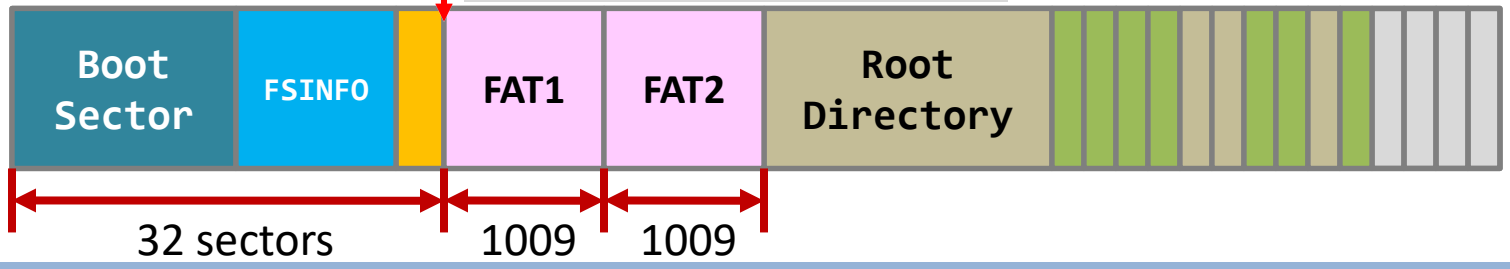
fsck.fat 3.0.28 (2015-05-16)

Checking we can access the last sector of the filesystem
Boot sector contents:
System ID "mkdosfs"
Media byte 0xf8 (hard disk)
       512 bytes per logical sector
       512 bytes per cluster
        32 reserved sectors
First FAT starts at byte 16384 (sector 32)
         2 FATs, 32 bit entries
    516608 bytes per FAT (= 1009 sectors)
Root directory start at cluster 2 (arbitrary size)
Data area starts at byte 1049600 (sector 2050)
    129022 data clusters (66059264 bytes)
......
```

The boot sector says:
2 FATs and each of them is of size **516,608 bytes**.

Number of FATs and the length of each entry in a FAT.

Good! No slack space between reserved sectors of the first FAT.



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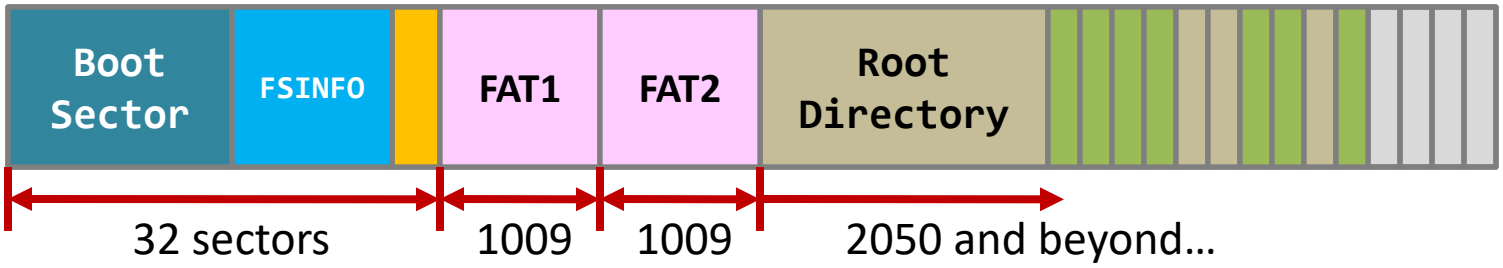
    129022 data clusters (66059264 bytes)
......
```

The first data cluster is **Cluster #2** and it is usually, not always, the root directory.

Cluster #0 & #1 are reserved.

`32 + 1009 x 2 = 2050`



Details of FAT32

- Introduction
- **Directory and File Attributes**
- File Operations
  - Read files
  - Write files
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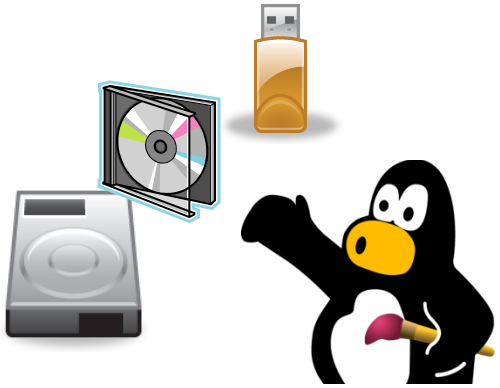


Directory Traversal

Step (1) Read the directory file of the root directory starting from **Cluster #2**.

"**C:\windows**" starts from Cluster #123.

```
c:\> dir c:\windows
……
06/13/2012  2,033,216   explorer.exe
08/04/2015    169,120   notepad.exe
……
c:\> _
```

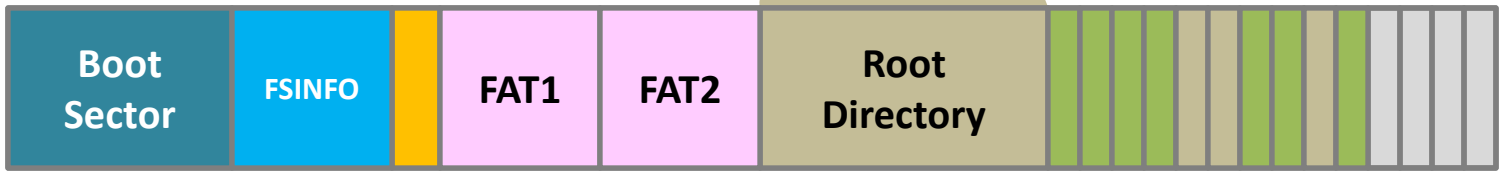
How does this work?

Cluster #2		
Filename	Attributes	Cluster #
.	……	?
..	……	?
……	……	……
windows	……	123

A directory entry

Check this out by yourself.

Whether those two directory entries exist or not.



Directory Traversal

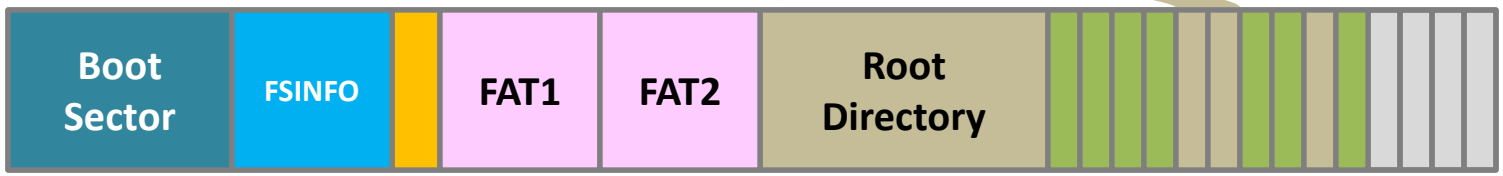
Step (2) Read the directory file of the "**C:\windows**" starting from **Cluster #123**.

```
c:\> dir c:\windows
.....
06/13/2012  2,033,216    explorer.exe
08/04/2015    169,120    notepad.exe
.....
c:\> _
```

How does this work?

Cluster #123		
Filename	**Attributes**	**Cluster #**
.	.....	?
..	.....	?
.....	.....	.....
notepad.exe	.....	456

But, where are the information, e.g., file size, modification time, etc?



Directory entry

- Directory entry is just a structure.

Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
1-10	7+3 characters of filename + extension.
11-11	File attributes (e.g., read only, hidden)
12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and FAT12).
22-25	Written time information.
26-27	Low 2 bytes of first cluster address.
28-31	File size.

what?

Filename	Attributes	Cluster #
explorer.exe	.....	32

How?

0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
24	…	…	20	00	00	C4	0F	00	31

Note. This is the 8+3 naming convention.

8 characters for name +
3 characters for file extension

Directory entry

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what?

Filename	Attributes	Cluster #
explorer.exe	.....	32

How?

0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
24	…	…	20	00	00	C4	0F	00	31

How to calculate the first cluster address?

Directory entry

- Directory entry is just a structure.

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what?

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How?

0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
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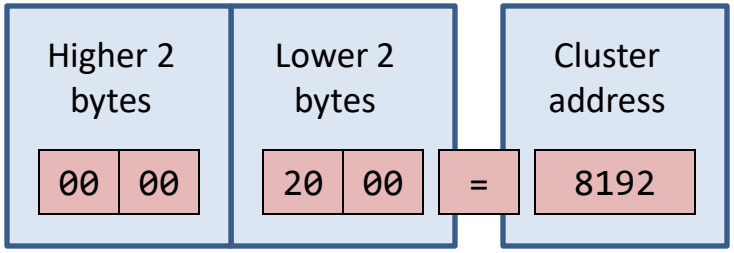
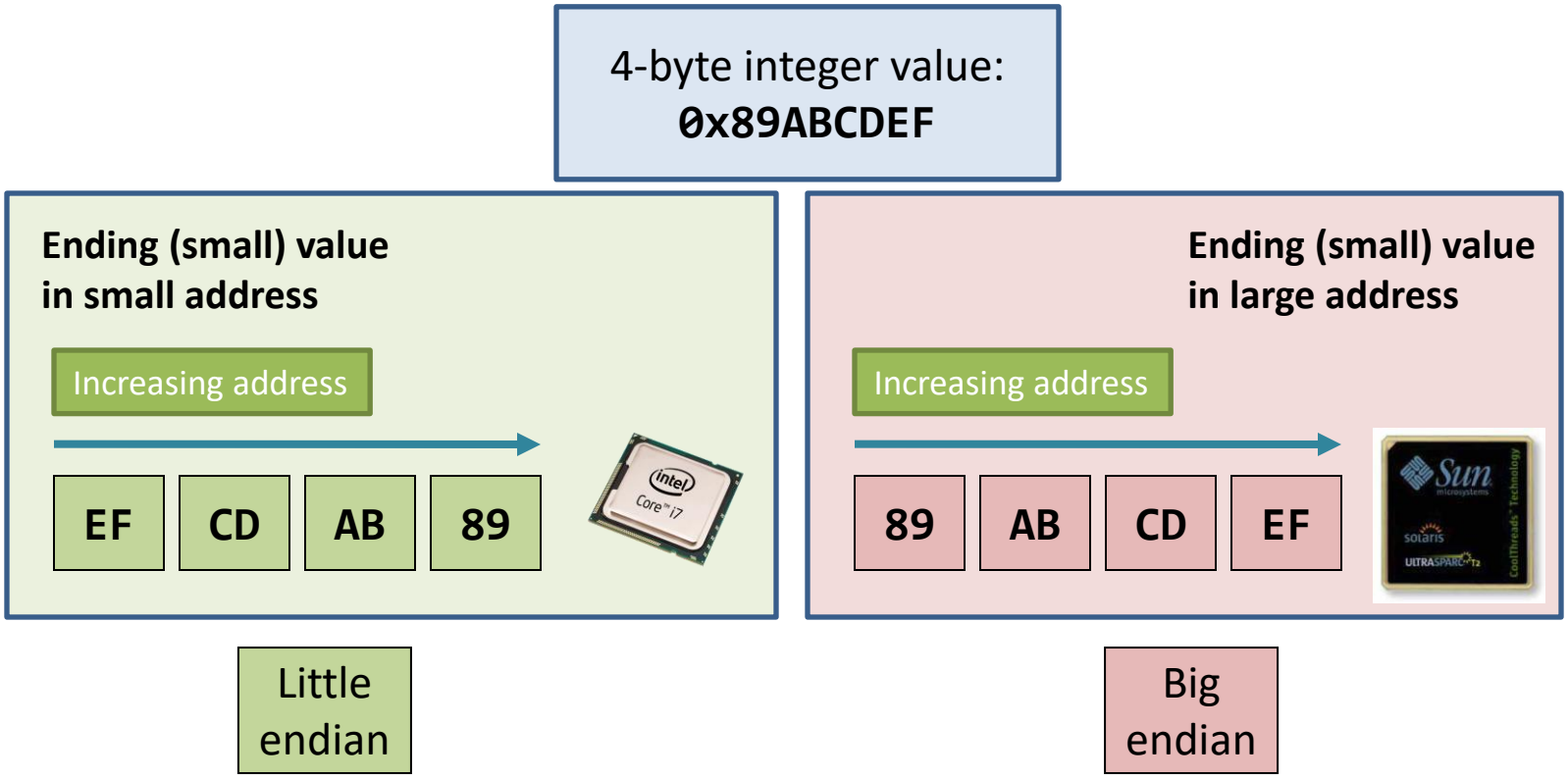


It is not 32, why?

Big Endian vs Little Endian

- Endian-ness is about byte ordering.
  - It means the way that a machine (we mean the entire computer architecture) orders the bytes.



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0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
24	…	…	20	00	00	C4	0F	00	31

Big endian	00	00	20	00	=	8192
Little endian	00	00	00	20	=	32

The FAT is defined to use little-endian byte ordering, as its original implementation was on the Intel x86 platform

The file size…

Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
1-10	7+3 characters of filename + extension.
11-11	File attributes (e.g., read only, hidden)
12-12	Reserved.
13-19	Creation and access time information.
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what?

Filename	Attributes	Cluster #
explorer.exe	.....	32

How?

0	e	x	p	l	o	r	e	r	7
8	e	x	e	…	…	…	…	…	15
16	…	…	…	…	00	00	…	…	23
24	…	…	20	00	00	C4	0F	00	31

So, what is the largest size of a file?

4G – 1 bytes

Directory entry

- Any problem with this design?

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12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and FAT12).
22-25	Written time information.
26-27	Low 2 bytes of first cluster address.
28-31	File size.

Note. This is the 8+3 naming convention.

8 characters for name +
3 characters for file extension

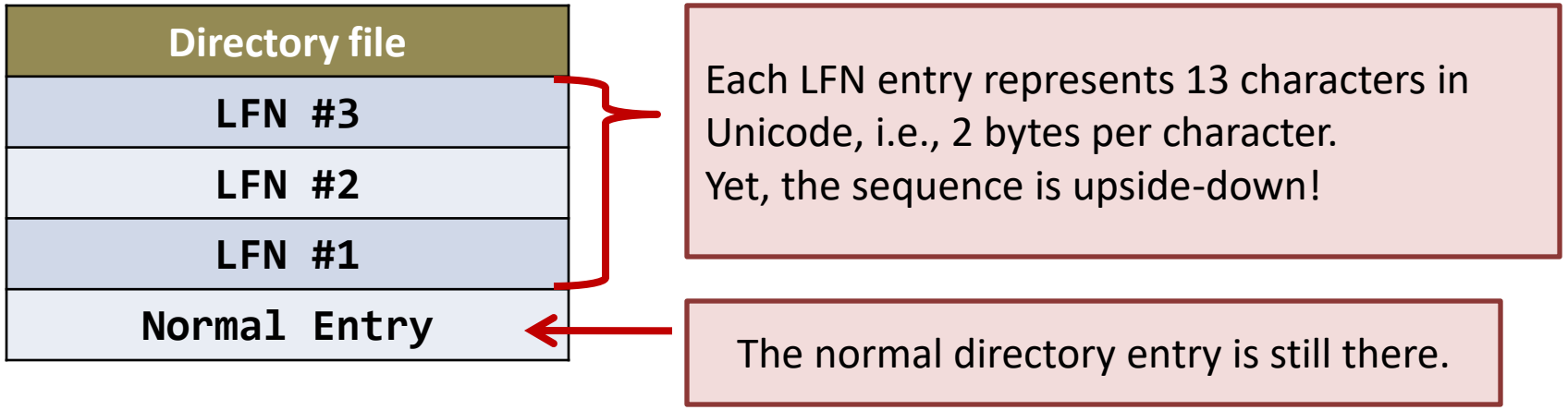
Example:

How to store the file:
`"I_love_the_operating_system_course.txt"`

How to store long filename?

FAT series – LFN directory entry

- LFN: Long File Name.
  - In FAT32, the 8+3 naming convention is removed by…
  - Adding more entries to represent the filename



FAT series – LFN directory entry

Normal entry

Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)
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12-12	Reserved.
13-19	Creation and access time information.
20-21	High 2 bytes of the first cluster address (0 for FAT16 and FAT12).
22-25	Written time information.
26-27	Low 2 bytes of first cluster address.
28-31	File size.

LFN entry

Bytes	Description
0-0	Sequence Number
1-10	File name characters (5 characters in Unicode)
11-11	File attributes - always 0x0F
12-12	Reserved.
13-13	Checksum
14-25	File name characters (6 characters in Unicode)
26-27	Reserved
28-31	File name characters (2 characters in Unicode)

FAT series – LFN directory entry

- Filename:
  “**I_love_the_operating_system_course.txt**”.

FAT series – LFN directory entry

This is the sequence number, and they are arranged in descending order.

The terminating directory entry has the sequence number **OR-ed with 0x40**.

Directory file
LFN #3: “m_cou” “rse.tx” “t”
LFN #2: “erati” “ng_sys” “te”
LFN #1: “I_lov” “e_the_” “op”
Normal Entry

LFN #3	43	6d 005f	0063	006f	0075	000f	0040	7200	Cm._.c.o.u...@r.
	7300	6500	2e00	7400	7800	0000	7400	0000	s.e...t.x...t...
LFN #2	02	65 0072	0061	0074	0069	000f	0040	6e00	.e.r.a.t.i...@n.
	6700	5f00	7300	7900	7300	0000	7400	6500	g._.s.y.s...t.e.
LFN #1	01	49 005f	006c	006f	0076	000f	0040	6500	.I._.l.o.v...@e.
	5f00	7400	6800	6500	5f00	0000	6f00	7000	_.t.h.e._...o.p.
Normal	495f	4c4f	5645	7e31	5458	5420	0064	b99e	I_LOVE~1TXT .d..
	773d	773d	0000	b99e	773d	0000	0000	0000	w=w=....w=......

FAT series – directory entry: a short summary

- A directory is an extremely important part of a FAT-like file system.
  - It stores the **start of the content**, i.e., the start cluster number.
  - It stores the **end of the content**, i.e., the **file size**; without the file size, how can you know when you should stop reading a cluster?
  - It stores **all file attributes**.

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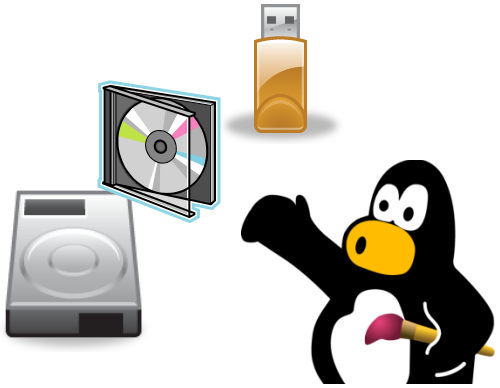


How to read a file?

Task: read "C:\windows\explorer.exe" sequentially.

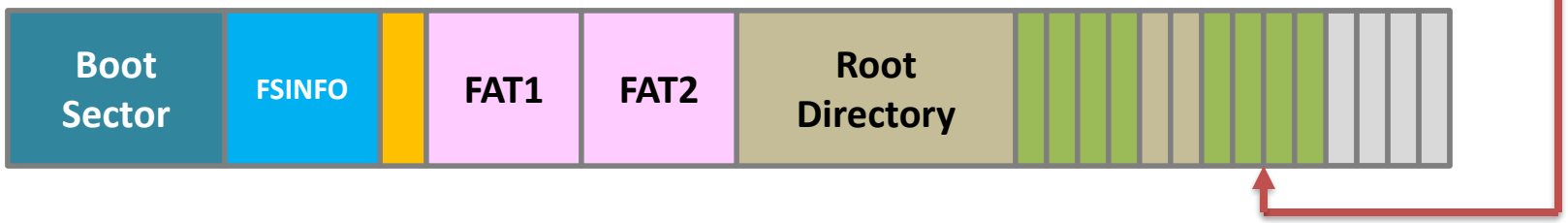
Suppose we already read out the directory entry…

You know the process of directory traversal, right?

Filename	Attributes	Cluster #
explorer.exe	.....	32

Step 1. Read the content from Cluster #32.

Note. The **file size** may also help determine if the last cluster is reached (remember where it is stored?)



How to read a file?

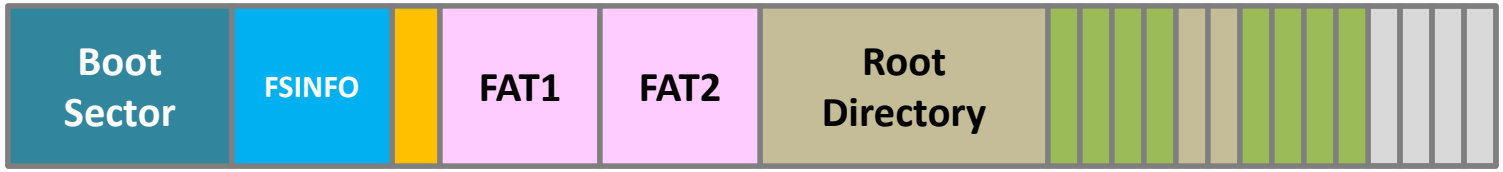
Task: read "C:\windows\explorer.exe" sequentially.

0	…
1	…
…	…
32	**33**
33	**EOF**
34	**0**
35	**0**

Filename	Attributes	Cluster #
explorer.exe	.....	32

Step 1. Read the content from Cluster #32.
Note. The **file size** may also help determining if the last cluster is reached.

Step 2. Look for the next cluster and it is Cluster #33 (from the **FAT** table)



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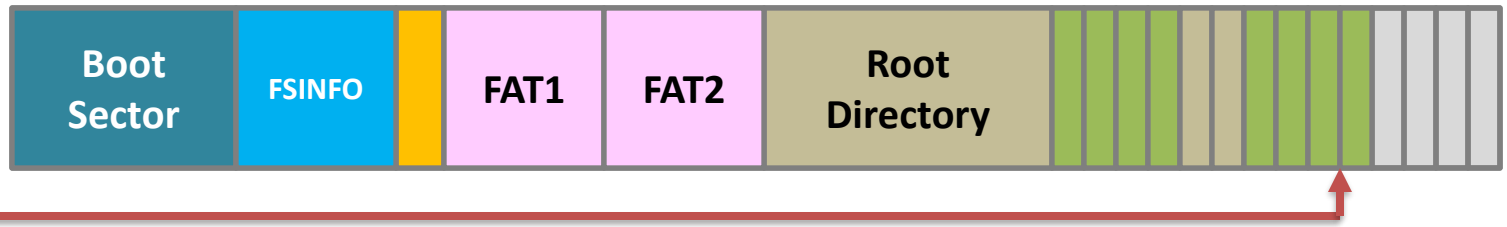
0	…
1	…
…	…
32	**33**
33	**EOF**
34	**0**
35	**0**

Filename	Attributes	Cluster #
explorer.exe	.....	32

FAT entry structure??
Remember: 28bits are used to represent cluster number for FAT32

Step 3. Since the FAT has marked "EOF", we have reached the last cluster.

Note. The file size help determine **how many bytes to read** from the last cluster.



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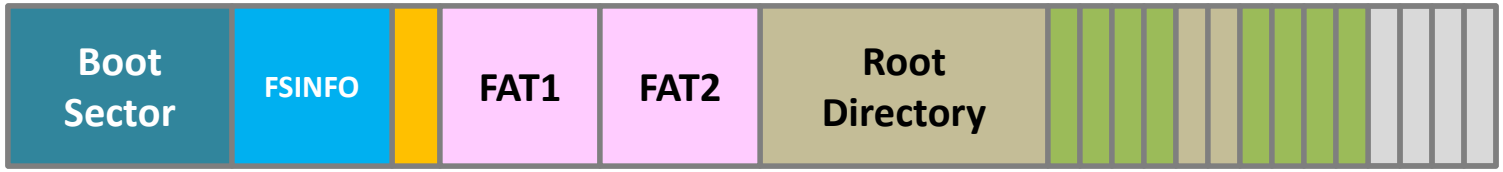
0	…
1	…
…	…
32	**33**
33	**EOF**
34	**0**
35	**0**

Filename	Attributes	Cluster #
explorer.exe	.....	32

Damaged = 0x0ffffff7
EOF >= 0x0ffffff8
Unallocated = 0x0

Step 3. Since the FAT has marked "EOF", we have reached the last cluster.

Note. The file size help determine **how many bytes to read** from the last cluster.



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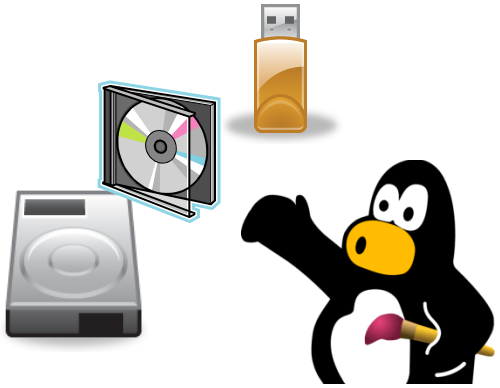


How to write a file?

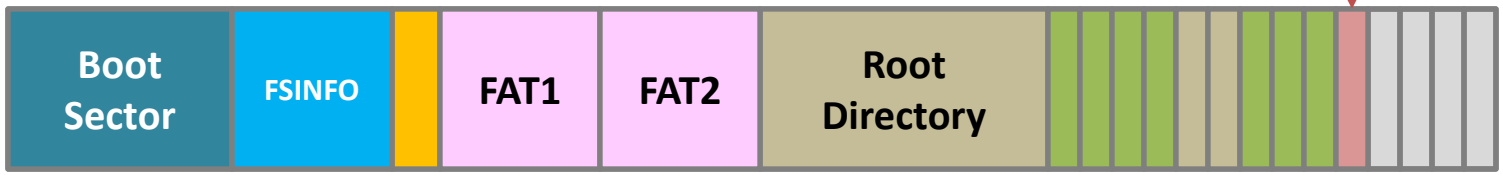
Task: append data to "C:\windows\explorer.exe".

0	…
1	…
…	…
32	**33**
33	**EOF**
34	**0**
35	**0**

Filename	Attributes	Cluster #
explorer.exe	.....	32

Step 1. Locate the last cluster.

Step 2. Start writing to the non-full cluster.



How to write a file?

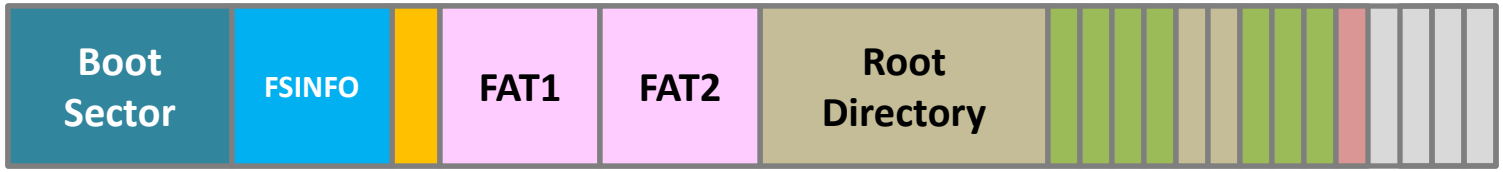
Task: append data to “C:\windows\explorer.exe”.

0	…
1	…
…	…
32	**33**
33	**EOF**
34	**0**
35	**0**

Filename	Attributes	Cluster #
explorer.exe	.....	32

What is stored in FSINFO?
How to allocate?

Step 3. Allocate the next cluster through FSINFO.



How to write a file?

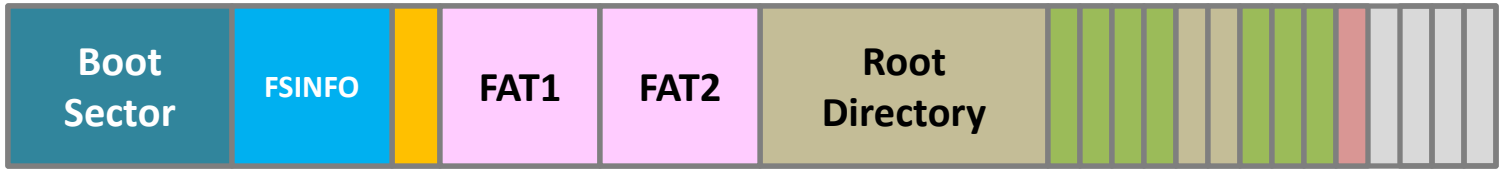
Task: append data to “C:\windows\explorer.exe”.

0	…
1	…
…	…
32	**33**
33	**EOF**
34	**0**
35	**0**

Filename	**Attributes**	**Cluster #**
`explorer.exe`	`......`	**32**

FSINFO	
# of free clusters	4
Next free cluster #	34

Step 3. Allocate the next cluster through FSINFO.



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0	…
1	…
…	…
32	**33**
33	**34**
34	**EOF**
35	**0**

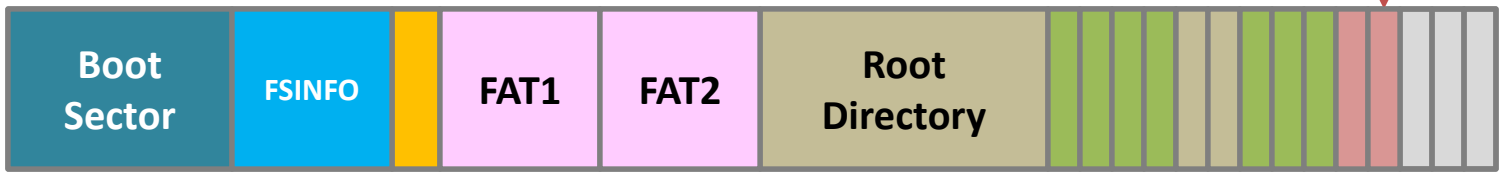
Filename	Attributes	Cluster #
explorer.exe	.....	32

FSINFO	
# of free clusters	3
Next free cluster #	35

Step 3. Allocate the next cluster through FSINFO.

Step 4. Update the FATs and FSINFO.

Step 5. When write finishes, update the file size.



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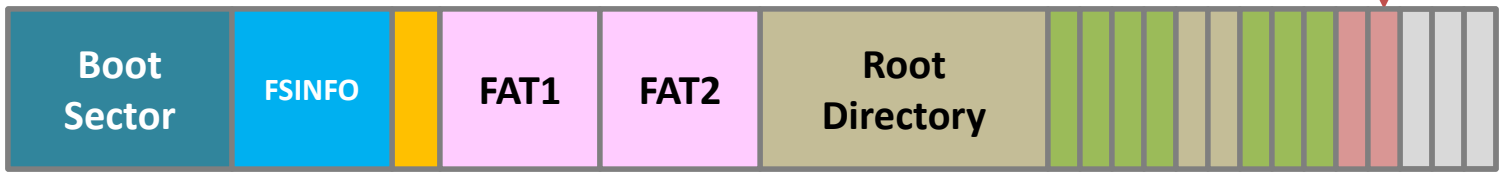
Task: append data to "C:\windows\explorer.exe".

0	…
1	…
…	…
32	33
33	34
34	EOF
35	0

Filename	Attributes	Cluster #
explorer.exe	.....	32

FSINFO	
# of free clusters	3
Next free cluster #	35

Q: How to obtain the next free cluster?



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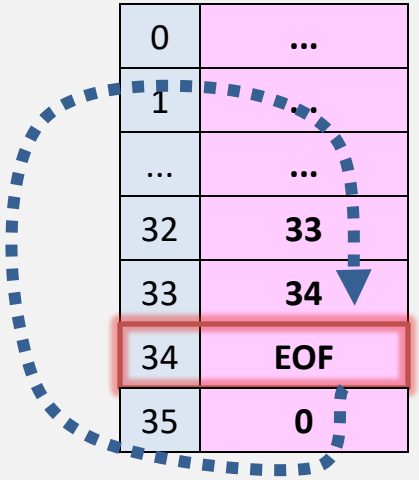


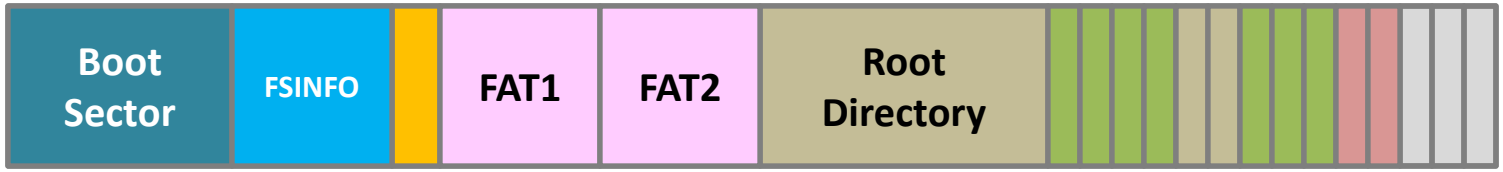
FSINFO	
# of free clusters	3
Next free cluster #	35

Filename	Attributes	Cluster #
explorer.exe	.....	32

The search for the next free cluster is a **circular, next-available** search.

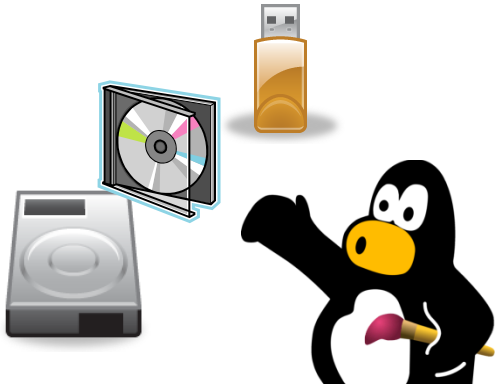
Why implementing next-available?
Principle of locality

Why circular?
To find out every free block



Details of FAT32

- Introduction
- Directory and File Attributes
- File Operations
  - Read files
  - Write files
  - **Delete files**
  - Recover deleted files



How to delete a file?

Task: delete "C:\windows\explorer.exe".

0	…
1	…
…	…
32	**33**
33	**34**
34	**EOF**
35	**0**

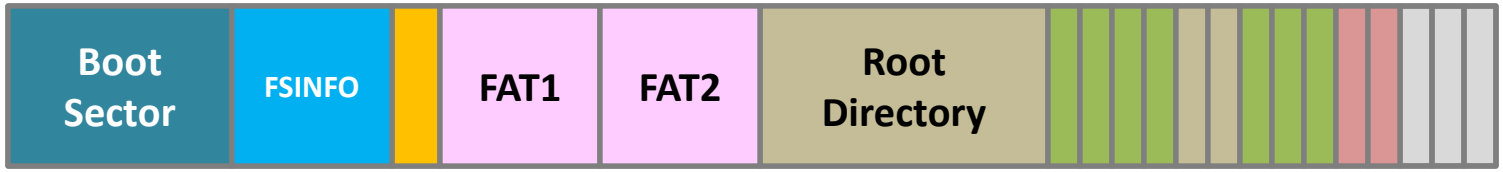
0	…
1	…
…	…
32	**0**
33	**0**
34	**0**
35	**0**

Filename	Attributes	Cluster #
explorer.exe	.....	32

Step 1. De-allocate all the blocks involved. Update FSINFO and FATs.

FSINFO	
# of free clusters	3
Next free cluster #	35

FSINFO	
# of free clusters	6
Next free cluster #	32

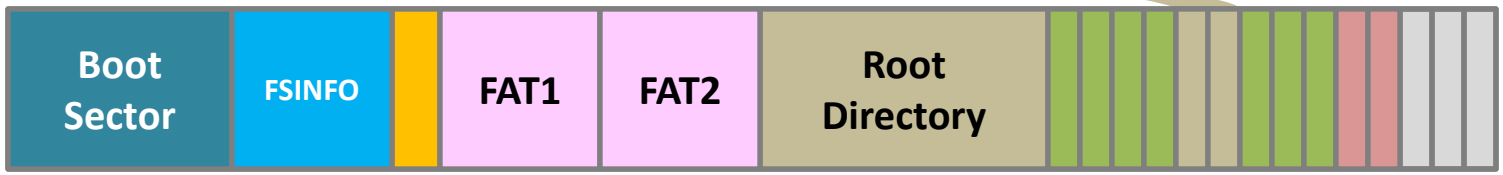


How to delete a file?

Task: delete “C:\windows\explorer.exe”.

How about the directory entry

Cluster #123		
Filename	**Attributes**	**Cluster #**
.	.....	?
..	.....	?
explorer.exe	.....	32
notepad.exe	.....	456



How to delete a file?

Task: delete "C:\windows\explorer.exe".

Bytes	Description
0-0	1st character of the filename (0x00 or 0xe5 means unallocated)

The first character becomes "0xE5".

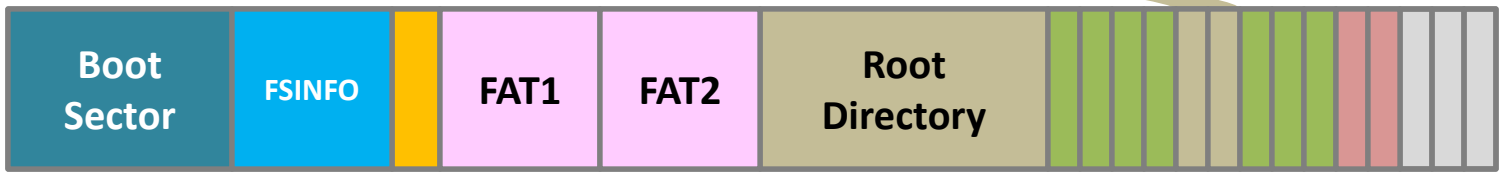
Cluster #123		
Filename	**Attributes**	**Cluster #**
.	.....	?
..	.....	?
_xplorer.exe	.....	32
notepad.exe	.....	456

How about the directory entry

Step 2. Change the first byte of the directory entry to 0xE5.

LFN entries also receive the same treatment.

That's the end of deletion!



Really delete a file?

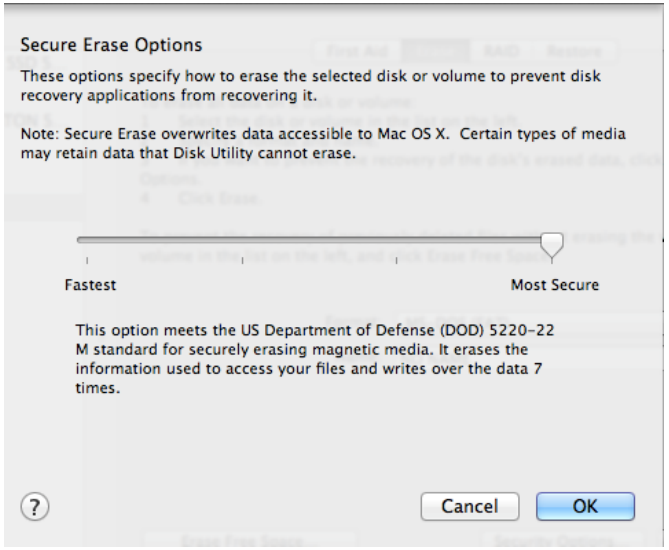
- Can you see that: **the file is not really removed from the FS layout?**
  - Perform a search in all the free space. Then, you will find all deleted file contents.

- "*Deleted data*" persists until the de-allocated clusters **are reused**.
  - This is an issue between performance (during deletion) and security.

- Any way(s) to delete a file **securely**?

How to delete a file “securely”?

Mac OS X Secure Disk Erase



Brute Force?

http://www.ohgizmo.com/2009/06/01/manual-hard-drive-destroyer-looks-like-fun/

What will the research community tell you?

http://cdn.computerscience1.net/2006/fall/lectures/8/articles8.pdf

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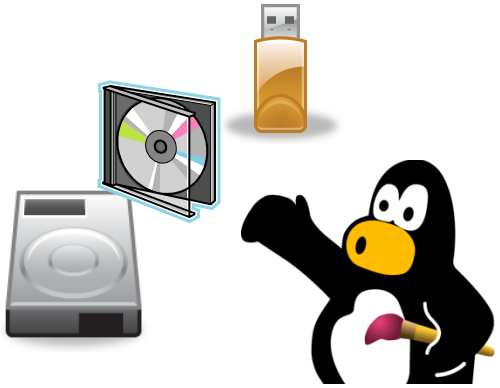
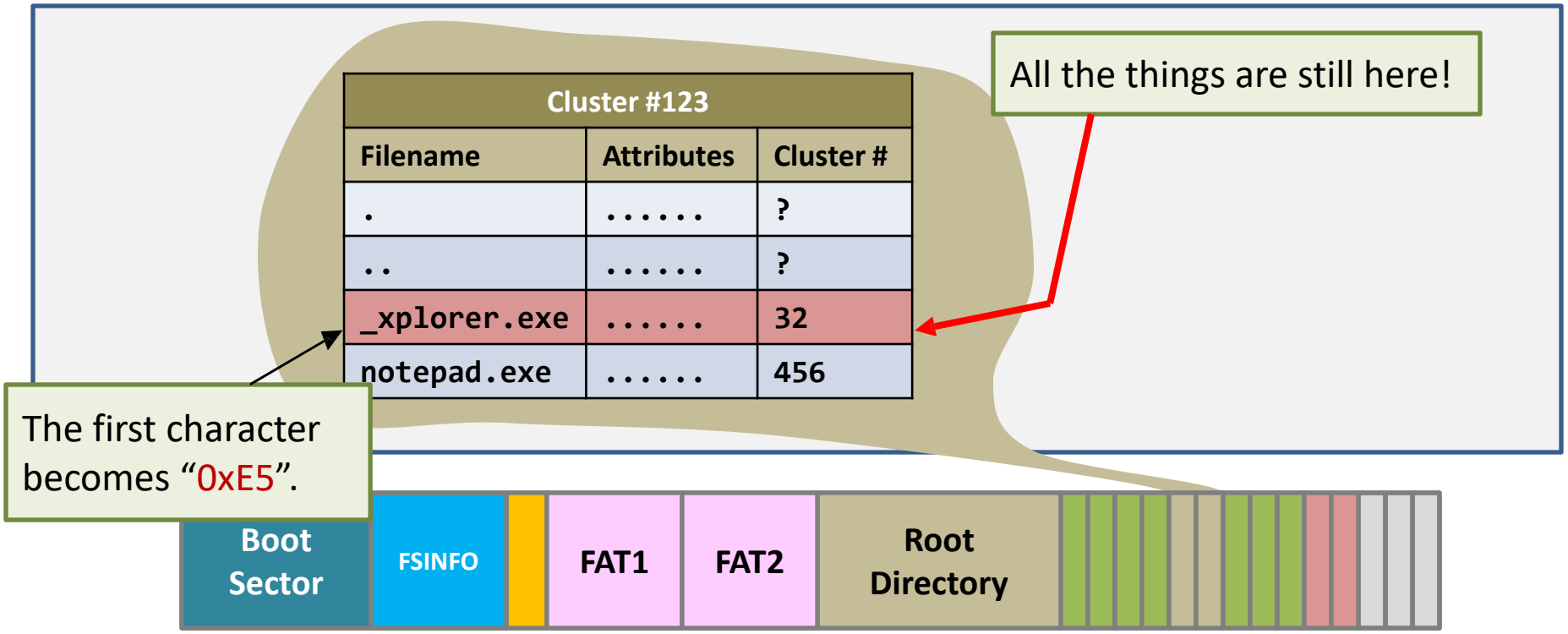
  - Write files
  - Delete files
  - **Recover deleted files**



How to "*rescue*" a deleted file?

- If you're really care about the deleted file, then…
  - **PULL THE POWER PLUG AT ONCE!**
  - Pulling the power plug stops the target clusters from being over-written.



How to "*rescue*" a deleted file?

- If you're really care about the deleted file, then…
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Principle of "rescue" deleted file

Data persists unless the sectors are reallocated and overwritten.

File size <= 1 cluster	Because **the first cluster address** is still readable, the recovery is having a very high successful rate. Note that filenames with **the same postfix** may also be found.

How to "*rescue*" a deleted file?

- If you're really care about the deleted file, then…
  - **PULL THE POWER PLUG AT ONCE!**
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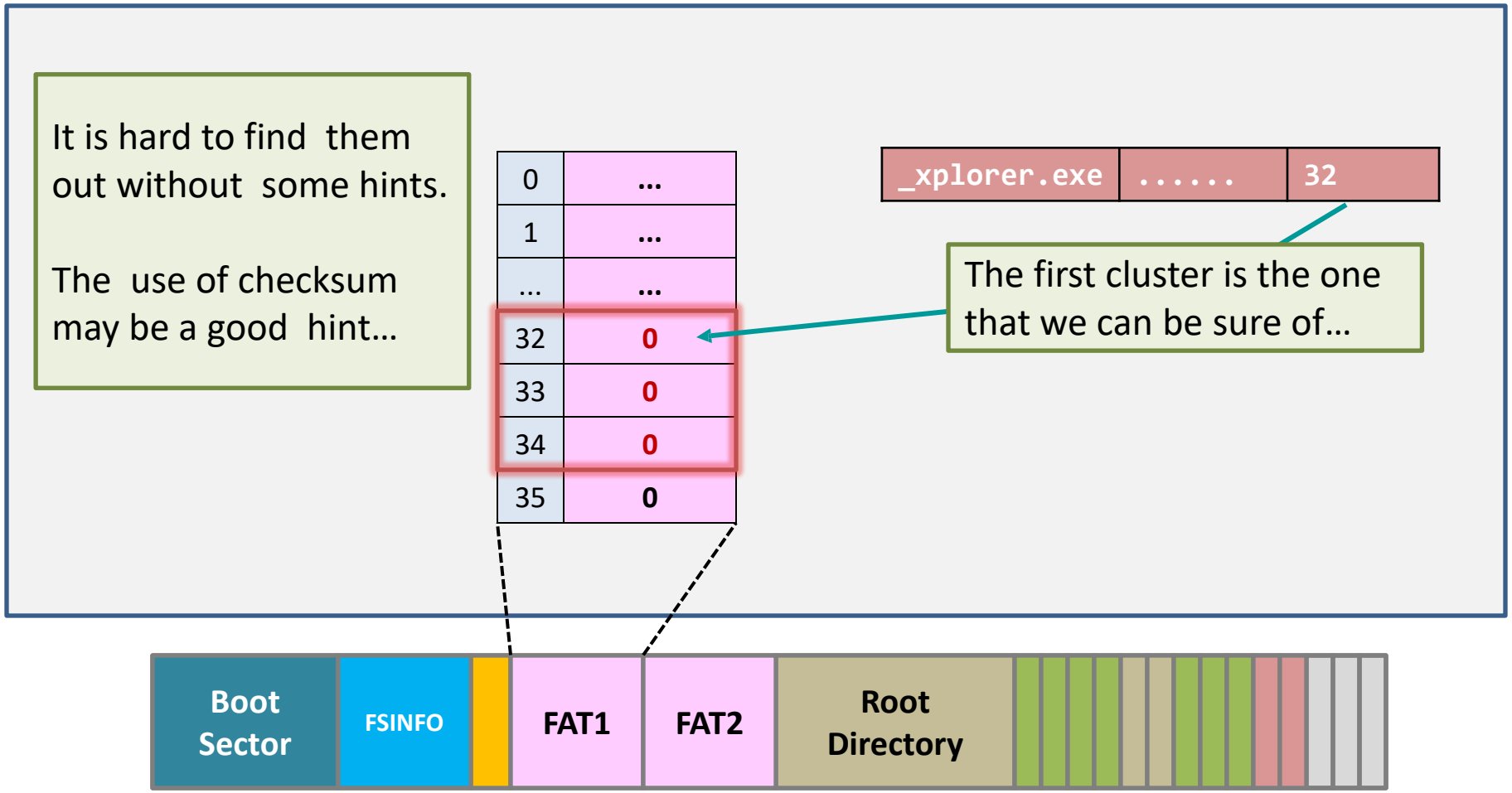
Principle of "rescue" deleted file

Data persists unless the sectors are reallocated and overwritten.

File size > 1 cluster	It is still possible as the clusters of a file are likely to be contiguously allocated. The next-available search provides a hint in looking for deleted blocks. If not, you'd better have the **checksum** and **the exact file size** beforehand, so that you can use a ***brute-force method*** to recover the file.

How to "*rescue*" a deleted file?

- What if the value of the 32nd cluster is not 0?



FAT series – conclusion

- It is a “nice” file system:
  - Space efficient: 4 bytes overhead (FAT entry) per data cluster.
- Deletion problem:
  - This is a lazy yet fast implementation.
  - Need extra protection for deleted data.
- Deployment:
  - It is everywhere: SD cards, USB drives, disks…