MANUAL ANALYSIS OF THE FAT12 FILE SYSTEM

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INTRODUCTION

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In this lab, we are going to analyze how a file system stores its data on disk. Modern file systems are relatively complicated, so we are going to look at how the old file system "FAT12" was used to store files on floppy disks. FAT12 is the predecessor of FAT16 and FAT32 (which is still widely used on USB sticks).

This document does not contain the full specification of FAT12. For a more detailed description of the various structures that are used throughout this filesystem, take a look at the following resources:

- http://www.maverick-os.dk/FileSystemFormats/FAT12_FileSystem.html
- http://www.ntfs.com/fat-systems.htm
- http://en.wikipedia.org/wiki/File_Allocation_Table

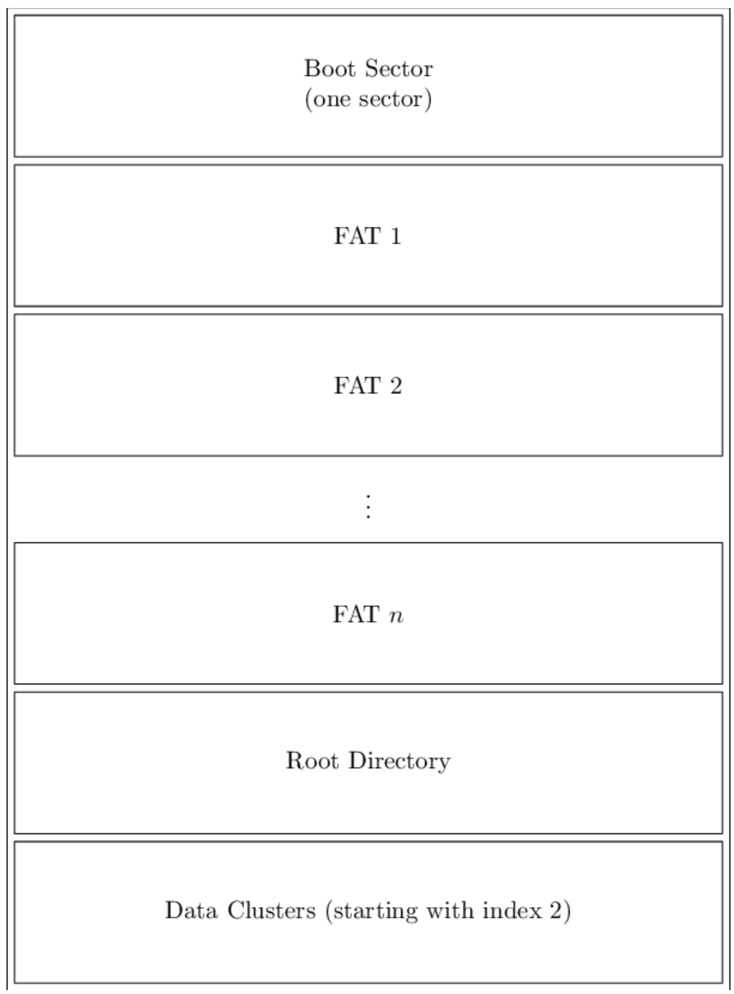
The file fat12.img contains the raw contents of a floppy disk. To view the contents of this file, open it in a hex editor. You can use the free hex editor xvi32, which is also available on the Programs disk (P:). Students with their own laptops can download xvi32, or can download an alternative such as Cygnus, Visual Studio, Hex Fiend, or 0xed.

Take a few moments to get used to your hex editor. In particular, notice that the values of the bytes (in hexadecimal notation) are show in the left column, and the corresponding ASCII value in the right column. The number that precedes the rows is the start offset of the first byte in the row.

OVERVIEW

A disk can be divided into multiple partitioned, with each partition having its own file system. For this course, we will ignore this possibility and just assume a disk contains one single partition which uses the FAT12 file system.

The disk is structured as follows:



We give a short description of each part:

- When given a partition, we cannot assume anything about its contents (e.g. which file system it contains). The boot sector provides this basic information. It also contains the instructions necessary to launch the operating system.
- A single FAT (File Allocation Table) describes how the data making up directories and files is located on the disk. Without this information, one cannot know where to look

for files. Since this information is so crucial, a disk can contain multiple copies of the FAT.
- The root directory contains information about top level files and directories (e.g. under Windows it would describe C:\ or D:\, etc.).
- The data clusters contain information about all subdirectories and files in these subdirectories.

THE BOOT SECTOR

Like any other partition, the first sector of a FAT12 volume is a special sector: the boot sector. It contains information about the partition. The boot sector (the first 512 bytes of the partition) is marked in yellow. The information stored in this sector is defined in the table below. Fill in the bytes values where asked.

Offset	Length in bytes	Description	Bytes
0x00	3	Instruction(s) to jump to the bootstrap code	xx xx xx
0x03	8	Name of the formatting OS	
0x0B	2	Bytes per sector	xx xx
0x0D	1	Sectors per cluster	xx
0x0E	2	Reserved sectors from the start of the volume	
0x10	1	Number of FAT copies	xx
0x11	2	Number of possible root entries	xx xx
0x13	2	Small number of sectors	xx xx
0x15	1	Media descriptor	
0x16	2	Sectors per FAT	xx xx
0x18	2	Sectors per track	xx xx
0x1A	2	Number of heads	xx xx
0x1C	4	Hidden sectors	xx xx xx xx
0x20	4	Large number of sectors (used when volume size exceeds 32MB)	xx xx xx xx
0x24	1	Drive number	
0x25	1	Reserved	

`0x26`	1	Extended boot signature (indicates that the next three fields are available)	
`0x27`	4	Volume serial number	
`0x2B`	11	Volume label (should be the same as in the root directory)	
`0x36`	8	File system type (should be FAT12)	
`0x3E`	448	Bootstrap code	
`0x1FE`	2	Boot sector signature (should be `0xAA55`)	

Use this table to verify the following properties:

- The name of the OS is "`MSDOS5.0`".
- The number of bytes per sector is 512 (or `0x200` in hexadecimal). See the note below.
- There is one reserved sector at the beginning of the partition.
- There is only 1 sector per cluster. This means that for the purpose of this lab, a cluster is the same as a sector.
- The size of the disk is 1.44MB. (Note that one sector is 512 bytes.)
- The file system is indeed "`FAT12`".

Important

Note that if a number is stored in 2 or 4 bytes, you should reverse these bytes!

For example, if you read the bytes `A4 70`, this actually represents the number `0x70A4`. This is because the Intel processor stores integers as little endian (the least-significant byte comes first).

Likewise, `11 22 33 44` corresponds to `0x44332211`.

Convert the following bytes to decimal values:

Bytes	Decimal value
`01`	decimal
`FF 00`	decimal
`00 FF`	decimal
`01 02 03 04`	decimal

PARTITION LAYOUT

After the boot sector, a number of copies of the File Allocation Table (FAT) are stored. Having more than one copy can be useful if one of the copies gets corrupted due to bad disk blocks.

How many copies of the FAT are there in the image? [decimal]

Each FAT has a certain size and thus requires a certain amount of space on disk.

How large is one FAT? [decimal] sectors, which is equal to [decimal] clusters or [decimal] bytes.

After the FATs, the contents of the root directory is stored. This root directory contains references to the files and directories that are stored on the root of the partition (i.e. typically at A:\ in Windows). Each file or directory entry is 32 bytes. The root directory has a maximum size, which is preallocated (meaning it cannot grow or shrink, and is not part of the "normal" data area).

How many file/directory entries can be stored in the root directory (use Table 1)? [decimal]

How large is the root directory, given that each entry is 32 bytes? [decimal] bytes or [decimal] sectors.

All the remaining sectors after the root directory can be used to store folder (or subdirectory) data. Now that you know how large each section is, you should be able to calculate the offsets of each section in the image. Note that each section immediately follows the previous (i.e. there is no wasted space in between).

Compute the offsets of the following sections. Verify with your hex editor that the offsets are correct.

Boot sector	0x0000
FAT 1	0x0200
FAT 2	0x [xxxx]
Root directory	0x [xxxx]
Data section	0x [xxxx]

DIRECTORIES

Each directory (including the root directory) consists of one or more sectors that contain directory entries. A directory entry contains information about a subdirectory or file that is contained in the directory. The structure of one such entry is shown below. Note that the size of an entry is 32 bytes.

Offset	Length in bytes	Description
0x00	8	The filename
0x08	3	The file extension
0x0B	1	File attributes
0x0C	1	Reserved ofr Windows NT
0x0D	1	Creation - Millsecond stamp (actual 100th of a second)
0x0E	2	Creation time
0x10	2	Creation date
0x12	2	Last access date
0x14	2	Reserved for FAT32
0x16	2	Last write time
0x18	2	Last write date
0x1A	2	First logical cluster of the file
0x1C	4	File size in bytes

As an example take the following 32 bytes:

```
54 45 53 54 20 20 20 20 44 44 20 20 00 64 85 1B
5A 33 5A 33 00 00 85 1B 5A 33 03 01 B0 04 00 00
```

Interpreting these as a directory in the FAT12 filesystem gives us the following results.

Name and Extension

```
54 45 53 54 20 20 20 20 44 44 20 20 00 64 85 1B
5A 33 5A 33 00 00 85 1B 5A 33 03 01 B0 04 00 00
```

The first 8 bytes contain the filename. We can look up the corresponding ASCII characters in an ASCII table. The filename becomes "`test    `". The extension (the following three bytes) will be "`dd `". Spaces are used as padding, so the actual filename is `test.dd`.

The first byte of the filename is special and can have different meanings. The following rules apply:

1. A value of `0x00` is interpreted as "stop the search, there are no more entries in this directory".
2. It must not contain the value `0x20` (space).
3. A value of `0xE5` is interpreted as "the entry is free".

Attributes

```
54 45 53 54 20 20 20 20 44 44 20 20 00 64 85 1B
5A 33 5A 33 00 00 85 1B 5A 33 03 01 B0 04 00 00
```

The next byte contains the attributes of the file or directory. A number of attributes can be set. If an attribute is set, a specific bit is set in the value of the byte (this is also called a bit vector). There are 8 possible bits that can be set in the byte, but only the first 6 bits have a specific meaning:

Bit	Description
0	The file is read-only.
1	The file is hidden.
2	The file is a system file.
3	The directory entry contains a volume label.
4	The entry represents a directory (not a file).
5	The File should be archived (used for backup purposes).

Convert `0x20` to binary: 8 bits

The binary value of the byte 20 is `00100000`. Bit 0 is the rightmost bit, bit 7 is the leftmost bit. In this case, only the archive attribute is set for the file.

Time and Date

```
54 45 53 54 20 20 20 20 44 44 20 20 00 64 85 1B
5A 33 5A 33 00 00 85 1B 5A 33 03 01 B0 04 00 00
```

A directory entry contains the creation time, creation date, last access date, last write time, and last write date. Both the time components and the date components use 2 bytes (or 16 bits) each. The bits are used as follows:

The time uses 5 bits to store the hours, 6 bits for the minutes and 5 for the seconds. Note that we cannot store 60 values in the 5 bits that are allocated to the seconds component. This means that we will only store even values, and that the calculated value should be doubled. In the example, the bytes that store the last write time contain the values `85 1B`, which represents the number `0x1B85` or its binary value [0x1B in binary] [0x85 in binary]. From this value, we extract

- the hours: [5 bits], or [decimal]
- the minutes: [6 bits], or [decimal]
- the seconds: [5 bits], or [decimal], which multiplied by 2 gives [decimal]

The 16 bits in the date component are distributed as follows: 7 bits for the amount of years since 1980, 4 bits for the month, and 5 bits for the day. In the example, if we extract the last write date you should get the date [dd] [mm] [yyyy] .

First Cluster

```
54 45 53 54 20 20 20 20 44 44 20 20 00 64 85 1B
5A 33 5A 33 00 00 85 1B 5A 33 03 01 B0 04 00 00
```

This 16-bit value contains the identification number of the first (logical) cluster that contains the data of this file. If the directory entry is a subdirectory (i.e. has the "subdirectory" attribute set), then it points to the first cluster that contains the directory entries of this subdirectory. In the example, the bytes `03 01` represent the value `0x103`, thus the logical cluster 259 contains the first chunk of the file.

File Size

```
54 45 53 54 20 20 20 20 44 44 20 20 00 64 85 1B
5A 33 5A 33 00 00 85 1B 5A 33 03 01 B0 04 00 00
```

The file size is stored in the last 4 bytes of the directory entry. This limits the maximum file size on a partition to 2^{32} bytes or 4Gb. The bytes `B0 04 00 00` represent a filesize of 0x [xxxx] or [decimal] bytes.

Interpret the following directory entry:

```
5A 57 41 52 54 4B 41 53 20 20 20 10 00 00 36 33
5A 33 5A 33 00 00 36 33 5A 33 40 01 00 00 00 00
```

- Filename and extension: [string]
- Attributes (choose between read-only, hidden, system file, system file, volume label, directory and file): [string]

- Last write time: [hh] [mm] [ss]
- Last write date: [dd] [mm] [yyyy]
- First cluster: [decimal]
- File size: [decimal]

List the files and subdirectories of the root directory of fat12.img. Give the name, size and first cluster of each entry. Ignore long file name entries.

- Volume label: [string]
- Directory
  - Name: [string]
  - Size: [decimal]
  - First cluster: [decimal]
- File 1
  - Name: [string]
  - Size: [decimal]
  - First cluster: [decimal]
  - Last write time: [hh] [mm] [ss]
  - Last write date: [dd] [mm] [yyyy]
- File 2
  - Name: [string]
  - Size: [decimal]
  - First cluster: [decimal]
  - Last write time: [hh] [mm] [ss]
  - Last write date: [dd] [mm] [yyyy]

FILE ALLOCATION TABLE

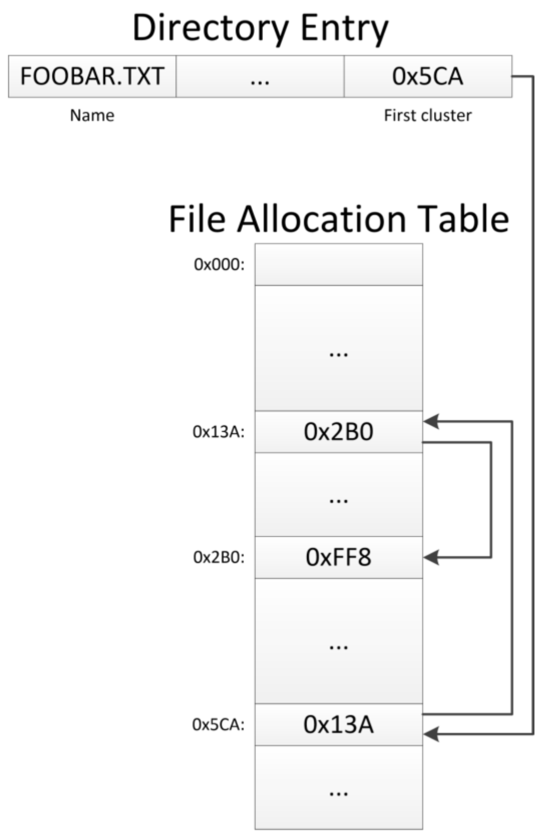
Up until now, we have seen how we can find and interpret the contents of the root directory, and from there on find all the files and subdirectories on the partition. For each file, we know the start cluster, but since a cluster is only 512 bytes, most files will consist of more than one cluster. Hence, we need a mechanism to find the next clusters of a file, given its first cluster.

For this purpose, FAT12 stores a file allocation table at the beginning of the volume. This table is a list of 12-bit entries, with one entry for each cluster in the data section. Because our image consists of 2847 clusters, the file allocation table will contain 2847 12-bit entries, for a total size of 4269 bytes.

The entries in the FAT are actually pointers to the next logical cluster in the data section. Some values have a special meaning:

- `0x000`: Free cluster
- `0x001`, and `0xFF0`-`0xFF6`: Reserved
- `0xFF7`: Bad cluster
- `0xFF8`-`0xFFF`: This is the last cluster of the file

All other values (`0x002` - `0xFEF`) are pointers to the next cluster of the file.



Consider the above figure where a user wants to read the file `foobar.txt`. The operating system finds the correct directory entry that stores the information of this file. From the directory entry, we find that the first logical cluster of the file is cluster `0x5CA`. In order to find the second cluster of the file, we go to the FAT and look up the value that is stored in the FAT entry with index `0x5CA`. We find the value `0x13A`, which is the identification number of the second cluster of the file. The third cluster can be found by looking up the value of FAT entry `0x13A`, which gives us the cluster ID `0x2B0`. Finally, if we look up the value of FAT entry `0x2B0`, we find the value `0xFF8`. This is one of the special values mentioned above, which indicates that this is the last cluster of the file. Putting this all together, we can conclude that the file `foobar.txt` consists of the logical clusters `0x5CA`, `0x13A`, `0x2B0` (in that order).

Every FAT entry is a 12-bit value. This means that one entry cannot be stored in one byte, yet it also does not require the full capacity of two bytes. In order not to waste space, two FAT entries are stored together in 3 bytes (or 24 bits). You can convert from the hexadecimal values of the three bytes to the hexadecimal values of the two FAT entries using the following rule (pay attention to the order!): `UV WX YZ` becomes FAT entries `0xXUV` and `0xYZW`.

Imagine the first 12 bytes of a FAT are `F0 FF FF 00 40 00 05 F0 FF 00 00 00`. Every FAT entry is 12 bits long, which means these 12 bytes contain 8 FAT entries:

0. `0xFF0`
1. 0x xxx
2. 0x xxx
3. 0x xxx
4. 0x xxx
5. 0x xxx
6. 0x xxx
7. 0x xxx

Clusters 0 and 1 are never used in the FAT, so you can ignore them. Which clusters are free? (List them in increasing order)

- decimal
- decimal
- decimal

If the first cluster of a file is cluster 3, its data is spread among clusters decimal , decimal and decimal . The file is at most decimal bytes long. Say the file contains 1200 bytes, then decimal bytes of the last cluster remain unused. This is called slack space and is actually lost space due to internal fragmentation.

Hint To find the correct bytes in the FAT that correspond to a certain cluster ID, you can use this simple formula: (Cluster / 2) × 3. This gives you the byte offset of the first of the three bytes that contain two FAT entries. Keep in mind that this is the byte offset from the start of the FAT; you need to add the offset of the FAT itself to this number as well! If Cluster ID is even, you need the first FAT entry, if it is odd you need the second FAT entry.

How many clusters will the file som.xls occupy (use the file size to calculate this)? decimal

Find all logical clusters of the file som.xls on fat12.img and reconstruct the file.

1. 0x0F0
2. 0x xxx
3. 0x xxx
4. 0x xxx
5. 0x xxx
6. 0x xxx

7. 0x xxx
8. 0x xxx
9. 0x xxx
10. 0x xxx
11. 0x xxx
12. 0x xxx
13. 0x xxx
14. 0x xxx
15. 0x xxx
16. 0x xxx
17. 0x xxx
18. 0x xxx
19. 0x xxx
20. 0x xxx
21. 0x xxx
22. 0x xxx
23. 0x xxx
24. 0x xxx
25. 0x xxx
26. 0x xxx
27. 0x xxx

The cluster IDs that we have been using are logical clusters, meaning that they represent the cluster number starting from the beginning of the data section. The numbers 0 and 1 have a special meaning and are not used as cluster IDs. So the first cluster of the data section has cluster ID 2. If we want to know where exactly a logical cluster is stored on the disk, we need to it into a physical clusters.

We have already calculated that there are 33 clusters before the start of the data section (1 boot cluster, 9 clusters for each FAT, and 14 clusters for the root directory). Using this information, and knowing that the first valid cluster ID is 2, we can deduce the following formula to calculate the physical cluster ID from a given logical cluster ID: physicalID = 33 + logicalID - 2.

Once we know the physical cluster ID, we can calculate the physical location of that cluster on the disk by multiplying the ID with the cluster size (512 bytes).

What is the physical location of the first block of som.xls? 0x xxxxx