Project 3: FAT32 File System

Project Overview

- FAT32 is a file system
- What does that actually mean?
- A storage device (e.g. hard drive) is simply a place to store a bunch of bytes
- Given a device, how do you find a specific file in that large bunch of bytes?
- File systems organize the space available on a storage device into an accessible and navigable format

Implementation Overview

- Implemented in C
- No more kernel programming
  - Program will run as a normal executable
- Given an image file containing raw bytes
  - Open image file
  - Read user input
  - Manipulate image file according to input

Getting Started

- First, explore the provided fat32 image file

2 options:

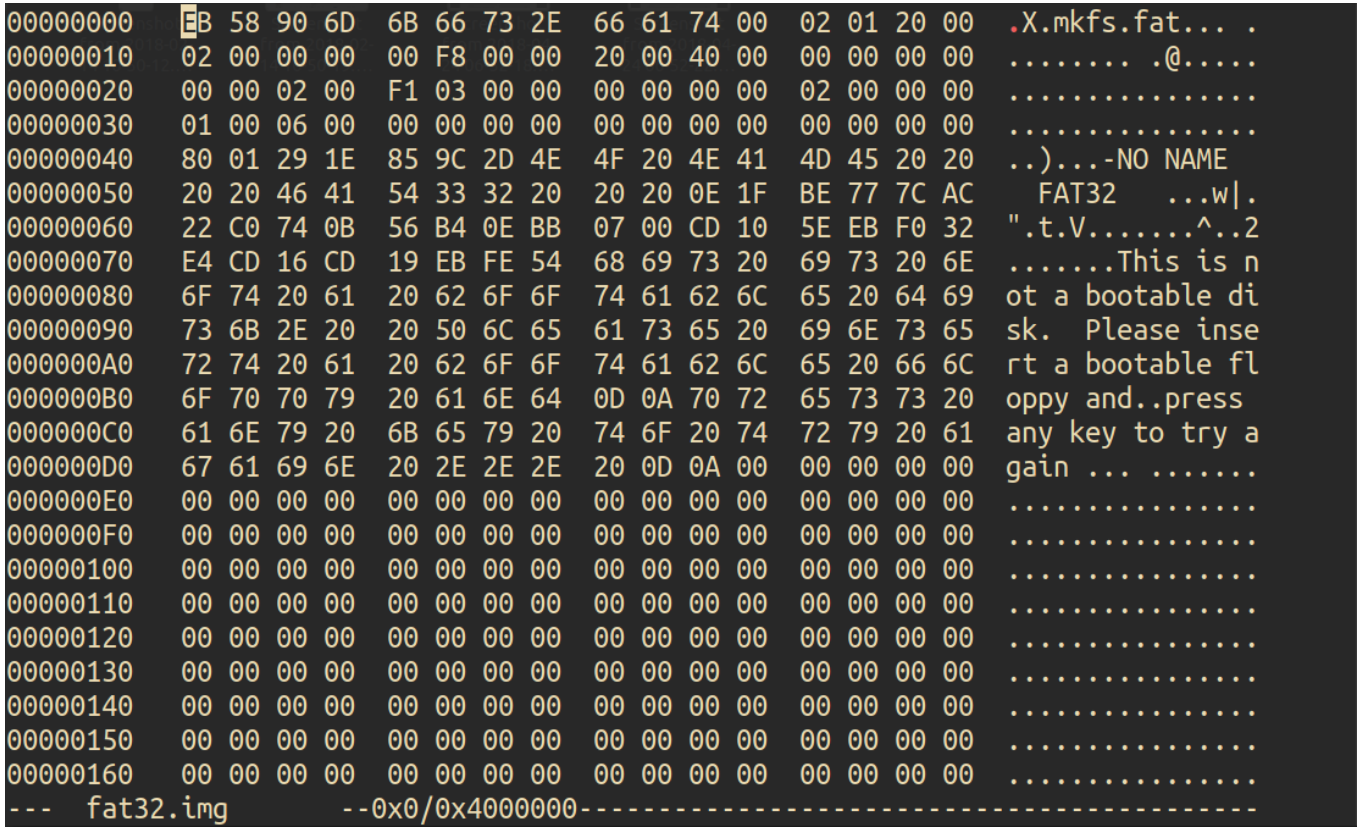
  - Hexedit
  - Mount

Hexedit

- Hexedit often included in Linux distributions
- Free downloads for hex viewers available online
- Allow you to view raw data content of an image file
- Even if you use hexedit, make sure to test your project via mounting before submission and vice versa

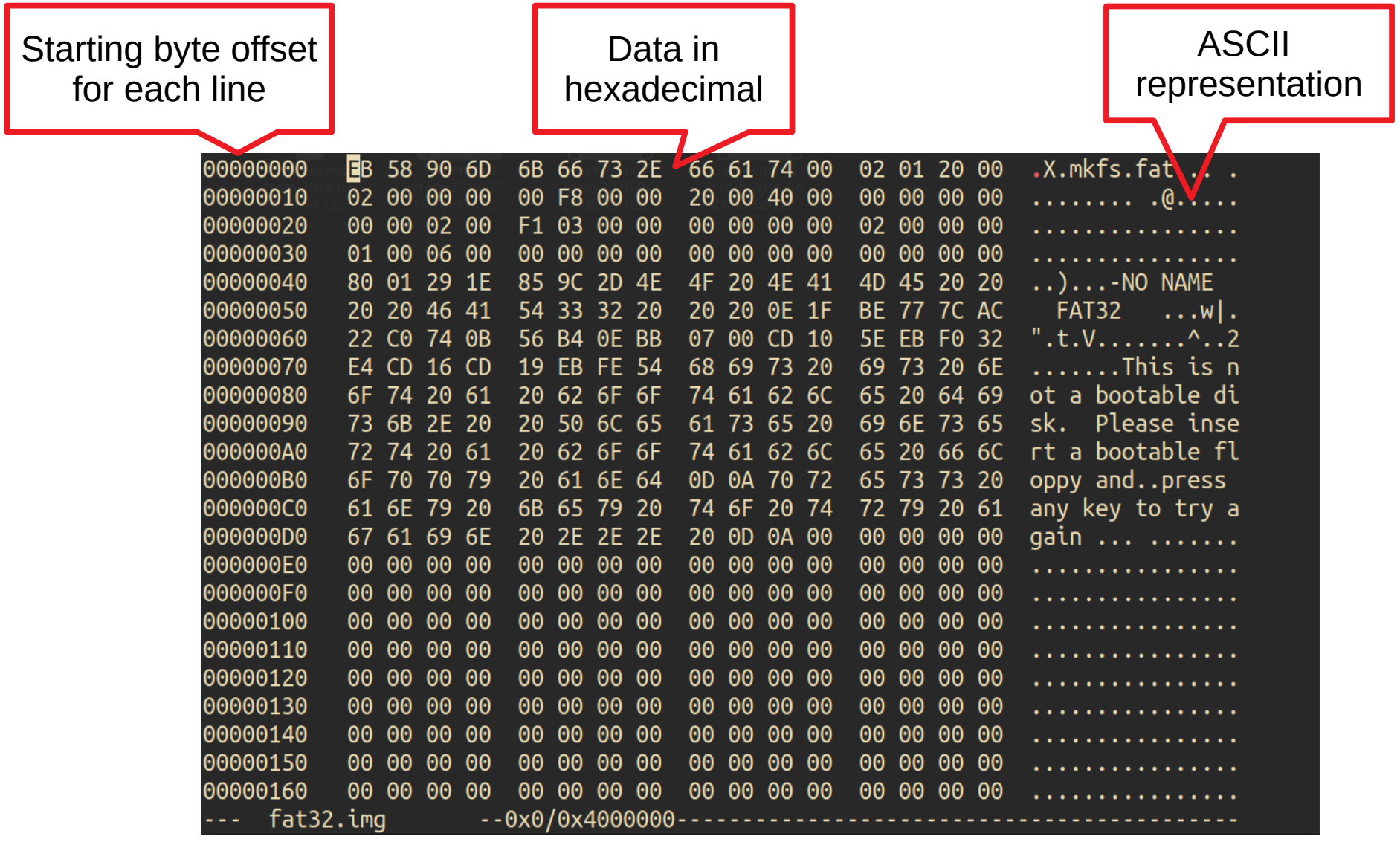
Hexedit

```
$ hexedit fat32.img
```



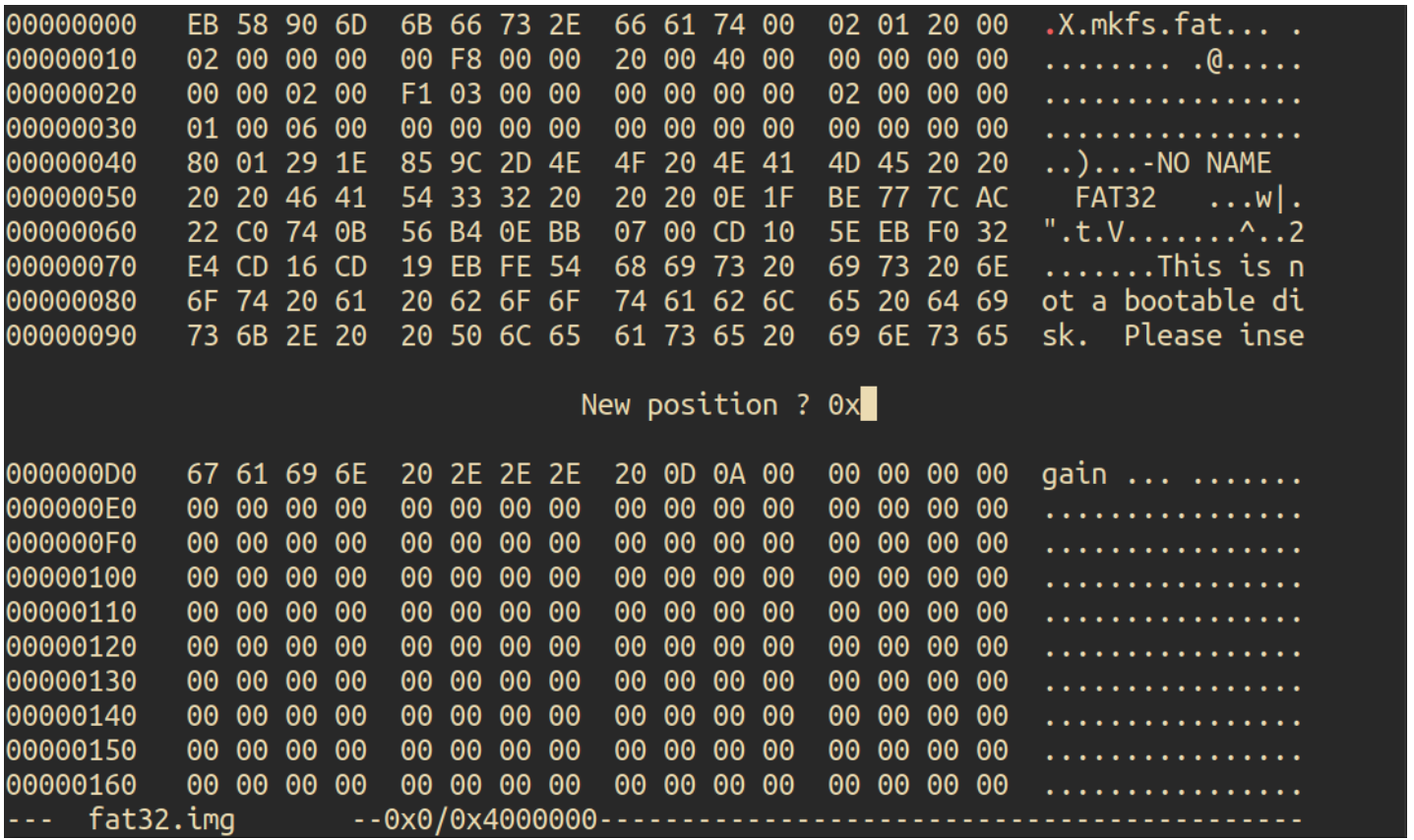
Hexedit

- Data and line numbers shown in hexadecimal
- When possible, the ASCII representation of the data will be shown on the right


Starting byte offset for each line
Data in hexadecimal
ASCII representation
00000000 EB 58 90 6D 6B 66 73 2E 66 61 74 00 02 01 20 00 .X.mkfs.fat .. .
00000010 02 00 00 00 00 F8 00 00 20 00 40 00 00 00 00 00 ....@.....
00000020 00 00 02 00 F1 03 00 00 00 00 00 00 02 00 00 00 ....
00000030 01 00 06 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000040 80 01 29 1E 85 9C 2D 4E 4F 20 4E 41 4D 45 20 20 ..)...-NO NAME
00000050 20 20 46 41 54 33 32 20 20 20 0E 1F BE 77 7C AC FAT32 ...w|.
00000060 22 C0 74 0B 56 B4 0E BB 07 00 CD 10 5E EB F0 32 ".t.V.......^..2
00000070 E4 CD 16 CD 19 EB FE 54 68 69 73 20 69 73 20 6E ....This is n
00000080 6F 74 20 61 20 62 6F 6F 74 61 62 6C 65 20 64 69 ot a bootable di
00000090 73 6B 2E 20 20 50 6C 65 61 73 65 20 69 6E 73 65 sk. Please inse
000000A0 72 74 20 61 20 62 6F 6F 74 61 62 6C 65 20 66 6C rt a bootable fl
000000B0 6F 70 70 79 20 61 6E 64 0D 0A 70 72 65 73 73 20 oppy and..press
000000C0 61 6E 79 20 6B 65 79 20 74 6F 20 74 72 79 20 61 any key to try a
000000D0 67 61 69 6E 20 2E 2E 2E 20 0D 0A 00 00 00 00 00 gain ... .
000000E0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
000000F0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000100 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000110 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000120 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000130 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000140 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000150 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
00000160 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ....
--- fat32.img --0x0/0x4000000----------

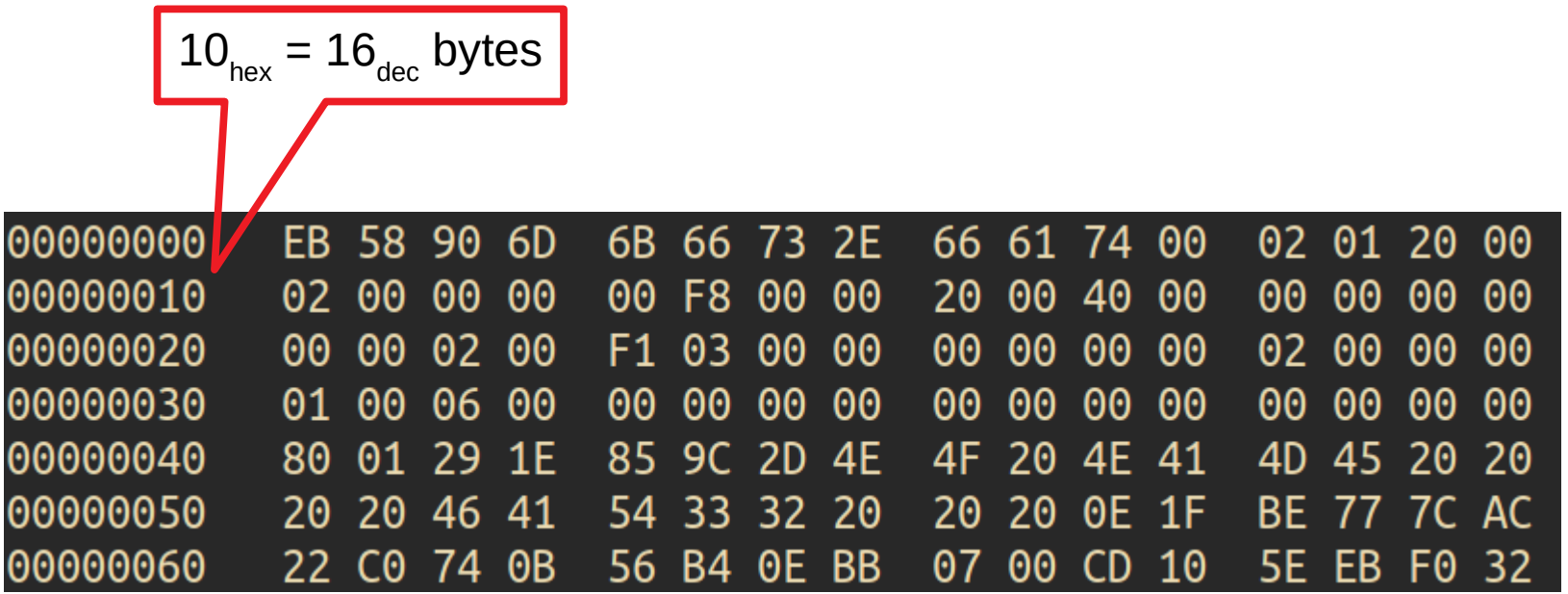
Hexedit

- Use ctrl-g or F4 to jump to a new line:



Hexedit

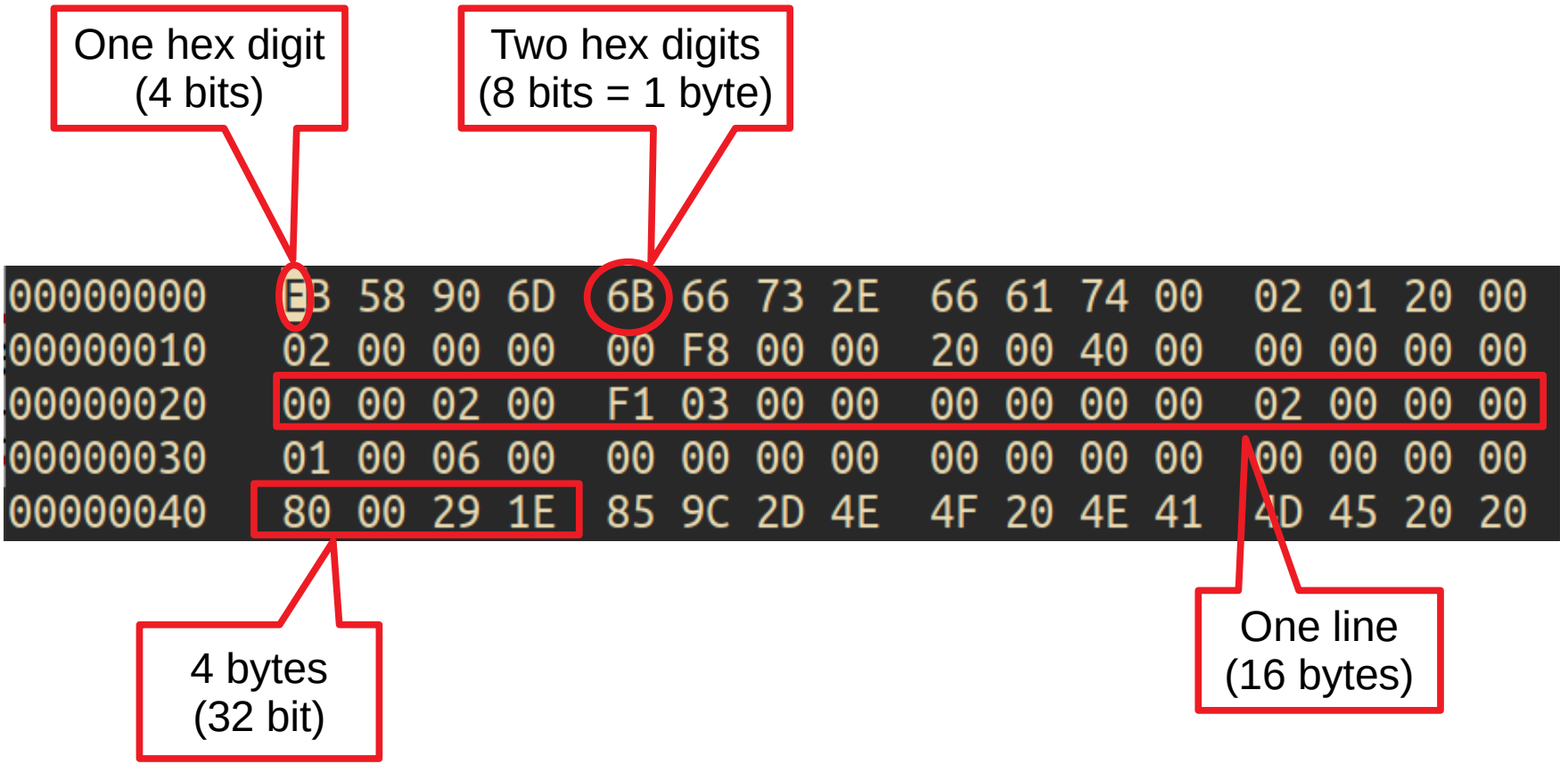
- To make things easier to read, set each line to 16 bytes



Hexadecimal Refresher

- Represented by 0-9 A-F
- Base 16: each digit ranges from 0 – 15
- Binary 0000 to 1111 = 0 to 15
  - Need 4 bits to represent one hexadecimal digit
  - 2 hexadecimal digits = 8 bits = 1 byte

Hexedit


One hex digit
(4 bits)
Two hex digits
(8 bits = 1 byte)
00000000 EB 58 90 6D 6B 66 73 2E 66 61 74 00 02 01 20 00
00000010 02 00 00 00 00 F8 00 00 20 00 40 00 00 00 00 00
00000020 00 00 02 00 F1 03 00 00 00 00 00 00 02 00 00 00
00000030 01 00 06 00 00 00 00 00 00 00 00 00 00 00 00 00
00000040 80 00 29 1E 85 9C 2D 4E 4F 20 4E 41 4D 45 20 20
4 bytes
(32 bit)
One line
(16 bytes)

Hexedit

- For further help, press F1 to bring up a list of commands and their descriptions

Mount

- To mount in Linux environment:

```
$ mkdir -p mnt_pnt
$ sudo mount -o loop /path/to/image mnt_pnt
$ cd mnt_pnt
```

- Now you can access the contents of the image file through the mount point
- To remove:

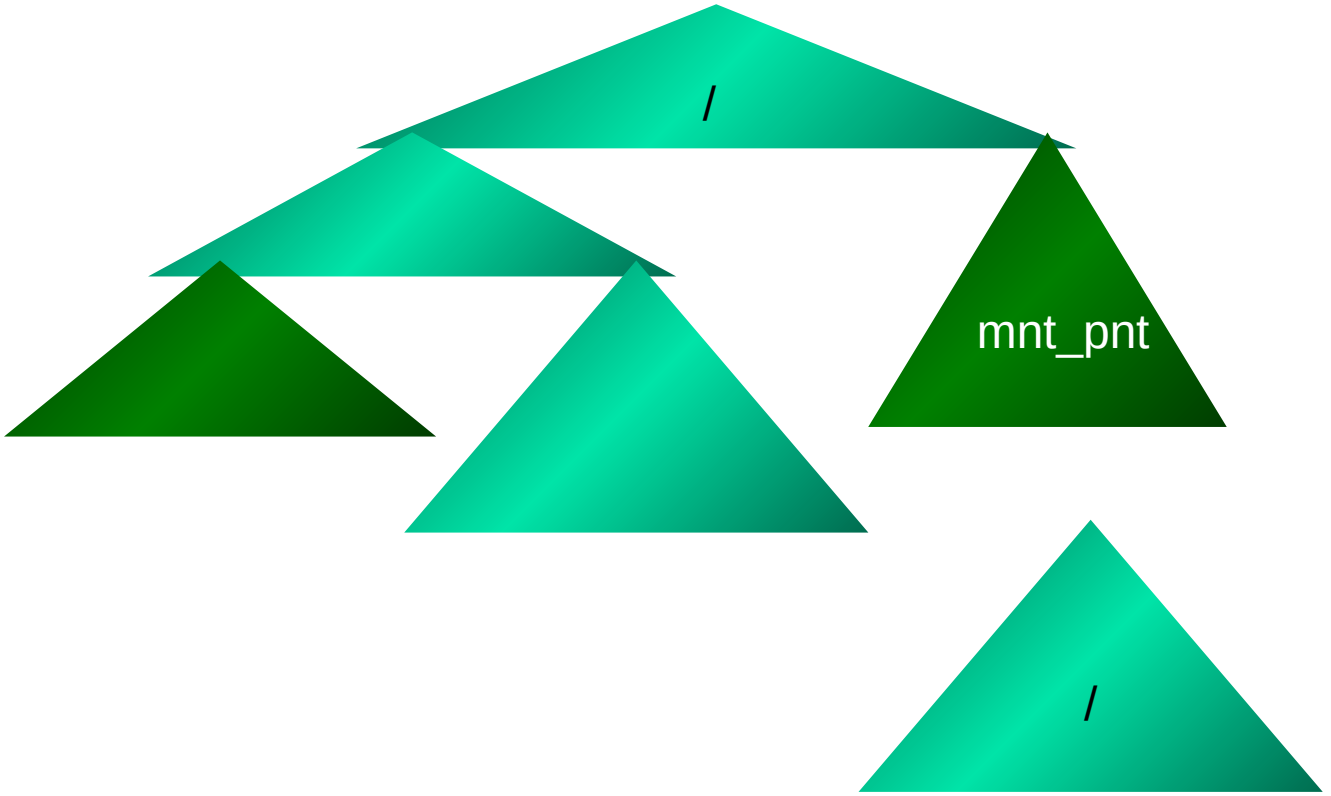
```
$ sudo umount mnt_pnt
```

Mount

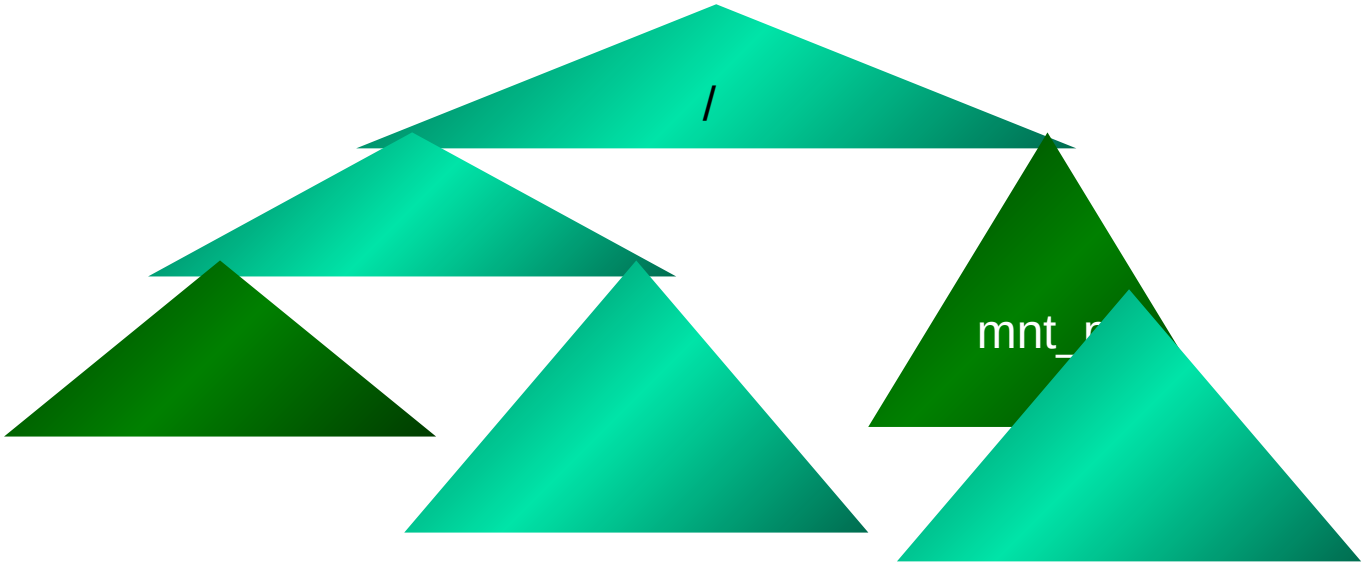
Example

```
vagrant@ubuntu-bionic:~$ mkdir -p mnt
vagrant@ubuntu-bionic:~$ ls mnt/
vagrant@ubuntu-bionic:~$ sudo mount -o loop fat32.img mnt/
vagrant@ubuntu-bionic:~$ ls mnt/
blue  green  hello  longfile  red
vagrant@ubuntu-bionic:~$ sudo umount mnt/
vagrant@ubuntu-bionic:~$ ls mnt/
vagrant@ubuntu-bionic:~$
```

Mount



Mount



Terms

- **Byte –** 8 bits of data, the smallest addressable unit in modern processors
- **Sector –** Smallest addressable unit on a *storage device*, usually this is 512 bytes
- **Cluster –** FAT32-specific term. A group of sectors representing a chunk of data
- **FAT –** Stands for **F**ile **A**llocation **T**able and is a map of files to data
- A set of bytes make up a sector and a set of sectors make up a cluster, FAT entries are in terms of clusters

FAT32 Data Layout

- **Reserved Region –** Includes the boot sector, the extended boot sector, the file system information sector, and a few other reserved sectors
- **FAT Region –** Contains the FAT: basically a guide for traversing the data region. Groups of cluster locations are chained together in the FAT
- **Data Region –** Contains the actual data for files and directories

Reserved Region

- Contains information about the file system itself
- When a FAT file system is mounted, the machine reads the reserved region to determine the type of file system and the characteristics associated with the file system
- For example,
  - Size of clusters
  - Number of FATs
  - etc

FAT

- Data is organized into clusters – a cluster is the smallest addressable unit for the File Allocation Table (FAT)
- Each cluster in the data region is represented in the FAT
- The FAT keeps track of which clusters belong to which files
- To access a file, you must know its first cluster
- Then, you can find subsequent clusters using the FAT

FAT

xxxxxxxx	xxxxxxxx	00000009	00000004
00000005	00000007	00000000	00000008
FFFFFFFF	0000000A	0000000B	00000011
0000000D	0000000E	FFFFFFFF	00000010
00000012	FFFFFFFF	00000013	00000014
00000015	00000016	FFFFFFFF	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000

Root Directory:
2, 9, A, B, 11

https://www.pjrc.com/tech/8051/ide/fat32.html

FAT

xxxxxxxx	xxxxxxxx	00000009	00000004
00000005	00000007	00000000	00000008
FFFFFFFF	0000000A	0000000B	00000011
0000000D	0000000E	FFFFFFFF	00000010
00000012	FFFFFFFF	00000013	00000014
00000015	00000016	FFFFFFFF	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000

Root Directory:
2, 9, A, B, 11

File #1:
3, 4, 5, 7, 8

File #2:
C, D, E

File #3:
F, 10, 12, 13, 14, 15, 16

https://www.pjrc.com/tech/8051/ide/fat32.html

Data Region

- Data in the data region can be of two types: directory (folder) data or file data

Data Region

Directory data:

- Each directory contains directory (DIR) entries
- A directory's data in the data region is a list of DIR entries where each DIR entry represents an item in the directory (ie files and/or other directories)

Data Region

Directory data:

- For example,
  - Directory my_dir contains files a.txt and b.txt and directory my_child_dir
  - The portion of the data region corresponding to my_dir would contain DIR entries for a.txt, b.txt, and my_child_dir
- Therefore, ***every*** file and directory will have a DIR entry (except for the root directory)

Data Region

Directory data:

- DIR entries
  - Fixed sized data structures which contain fixed sized fields containing information about the entry
    - Name
    - Size
    - attributes
    - ***First cluster number***
  - Check FATspec for all fields
  - Read in using a struct with corresponding fields

Data Region

Directory data:

- Example: Root Directory

```
vagrant@ubuntu-bionic:~/mnt$ ls
blue  green  hello  longfile  red
vagrant@ubuntu-bionic:~/mnt$
```

- In the data region for the root directory, there will be DIR entries for blue, green, and red directories, and hello, longfile files

Data Region

Directory data:

- Example: Root Directory

```
001003F0   00 00 00 00  00 00 00 00  00 00 00 00  00 00 00 00  ................
00100400   41 6C 00 6F  00 6E 00 67  00 66 00 0F  00 97 69 00  Al.o.n.g.f....i.
00100410   6C 00 65 00  00 00 FF FF  FF FF 00 00  FF FF FF FF  l.e.............
00100420   4C 4F 4E 47  46 49 4C 45  20 20 20 20  00 64 04 8E  LONGFILE    .d..
00100430   78 4E 49 4F  00 00 04 8E  78 4E 03 00  76 5B 03 00  xNIO....xN..v[..
00100440   41 68 00 65  00 6C 00 6C  00 6F 00 0F  00 14 00 00  Ah.e.l.l.o......
00100450   FF FF FF FF  FF FF FF FF  FF FF 00 00  FF FF FF FF  ................
00100460   48 45 4C 4C  4F 20 20 20  20 20 20 20  00 64 04 8E  HELLO       .d..
00100470   78 4E 49 4F  00 00 04 8E  78 4E B1 01  0A 00 00 00  xNIO....xN......
00100480   41 62 00 6C  00 75 00 65  00 00 00 0F  00 55 FF FF  Ab.l.u.e.....U..
00100490   FF FF FF FF  FF FF FF FF  FF FF 00 00  FF FF FF FF  ................
001004A0   42 4C 55 45  20 20 20 20  20 20 20 10  00 64 04 8E  BLUE        ..d..
001004B0   78 4E 78 4E  00 00 04 8E  78 4E B2 01  00 00 00 00  xNxN....xN......
001004C0   41 67 00 72  00 65 00 65  00 6E 00 0F  00 42 00 00  Ag.r.e.e.n...B..
001004D0   FF FF FF FF  FF FF FF FF  FF FF 00 00  FF FF FF FF  ................
001004E0   47 52 45 45  4E 20 20 20  20 20 20 10  00 64 04 8E  GREEN       ..d..
001004F0   78 4E 78 4E  00 00 04 8E  78 4E B3 01  00 00 00 00  xNxN....xN......
00100500   41 72 00 65  00 64 00 00  00 FF FF 0F  00 37 FF FF  Ar.e.d.......7..
00100510   FF FF FF FF  FF FF FF FF  FF FF 00 00  FF FF FF FF  ................
00100520   52 45 44 20  20 20 20 20  20 20 20 10  00 00 05 8E  RED         .....
00100530   78 4E 78 4E  00 00 05 8E  78 4E B4 01  00 00 00 00  xNxN....xN......
00100540   00 00 00 00  00 00 00 00  00 00 00 00  00 00 00 00  ................
00100550   00 00 00 00  00 00 00 00  00 00 00 00  00 00 00 00  ................
---  fat32.img       --0x100550/0x4000000-----------------------------------
```

Corresponding long dir name entries (safe to ignore)

DIR entry for hello

DIR entry for green directory

Data Region

Directory data:

- All DIR entries (except for . and ..) will be preceeded by a single long directory (LDIR) entry
- All directories will have a “.” and “..” DIR entry except for the root directory

Data Region

File Data:

- In the data region, file data is simply the contents of the file
- If the file is a text file, clusters in the data region allocated to the text file is simply the text contents

Data Region

File data example

- longfile contents:
  this is a loooong file
  this is a loooong file
  this is a loooong file
  this is a loooong file
  this is a loooong file
  ...

```
001005D0   00 00 00 00  00 00 00 00  00 00 00 00  00 00 00 00  ................
001005E0   00 00 00 00  00 00 00 00  00 00 00 00  00 00 00 00  ................
001005F0   00 00 00 00  00 00 00 00  00 00 00 00  00 00 00 00  ................
00100600   74 68 69 73  20 69 73 20  61 20 6C 6F  6F 6F 6E 67  this is a looong
00100610   20 66 69 6C  65 0A 74 68  69 73 20 69  73 20 61 20   file.this is a
00100620   6C 6F 6F 6F  6E 67 20 66  69 6C 65 0A  74 68 69 73  looong file.this
00100630   20 69 73 20  61 20 6C 6F  6F 6F 6E 67  20 66 69 6C   is a looong fil
00100640   65 0A 74 68  69 73 20 69  73 20 61 20  6C 6F 6F 6F  e.this is a looo
00100650   6E 67 20 66  69 6C 65 0A  74 68 69 73  20 69 73 20  ng file.this is
00100660   61 20 6C 6F  6F 6F 6E 67  20 66 69 6C  65 0A 74 68  a looong file.th
00100670   69 73 20 69  73 20 61 20  6C 6F 6F 6F  6E 67 20 66  is is a looong f
00100680   69 6C 65 0A  74 68 69 73  20 69 73 20  61 20 6C 6F  ile.this is a lo
00100690   6F 6F 6E 67  20 66 69 6C  65 0A 74 68  69 73 20 69  oong file.this i
001006A0   73 20 61 20  6C 6F 6F 6F  6E 67 20 66  69 6C 65 0A  s a looong file.
001006B0   74 68 69 73  20 69 73 20  61 20 6C 6F  6F 6F 6E 67  this is a looong
001006C0   20 66 69 6C  65 0A 74 68  69 73 20 69  73 20 61 20   file.this is a
001006D0   6C 6F 6F 6F  6E 67 20 66  69 6C 65 0A  74 68 69 73  looong file.this
001006E0   20 69 73 20  61 20 6C 6F  6F 6F 6E 67  20 66 69 6C   is a looong fil
001006F0   65 0A 74 68  69 73 20 69  73 20 61 20  6C 6F 6F 6F  e.this is a looo
00100700   6E 67 20 66  69 6C 65 0A  74 68 69 73  20 69 73 20  ng file.this is
00100710   61 20 6C 6F  6F 6F 6E 67  20 66 69 6C  65 0A 74 68  a looong file.th
00100720   69 73 20 69  73 20 61 20  6C 6F 6F 6F  6E 67 20 66  is is a looong f
---  fat32.img       --0x1005D0/0x4000000-------------------------------------
```

Function: exit

- Close program and free up any allocated resources

Function: info

- Print important meta data about the file system
- Boot block is the first 512 bytes (1st sector) of the image disk
- All the vital parameters of the file system are contained here
- Fields in this block can be found in the FATSpec.pdf

Function: info

- Read all FAT32 fields into a struct – you will need these values throughout your program
- Within your struct, make a corresponding variable for each field
  - Make sure the byte size of the variable matches the size of the field as specified in the FATspec!
  - Make sure the struct variables are listed in the same order as shown in the FATspec
- Check your values make sense
  - watch out for endian issues!

Endianness

- Endianess describes the order in which *bytes* are stored in memory
- One hex value represents 16 bits
  - Two hex values represent a byte
- Given an integer 0x0A0B0C
  - Big endian systems would represent integer as 0A | 0B | 0C
    - Most significant byte first
  - Little endian systems would represent integer as 0C | 0B | 0A
    - Least significant byte first
- FAT32 uses little endian
- (characters are single bytes → no reordering necessary)

Function: info

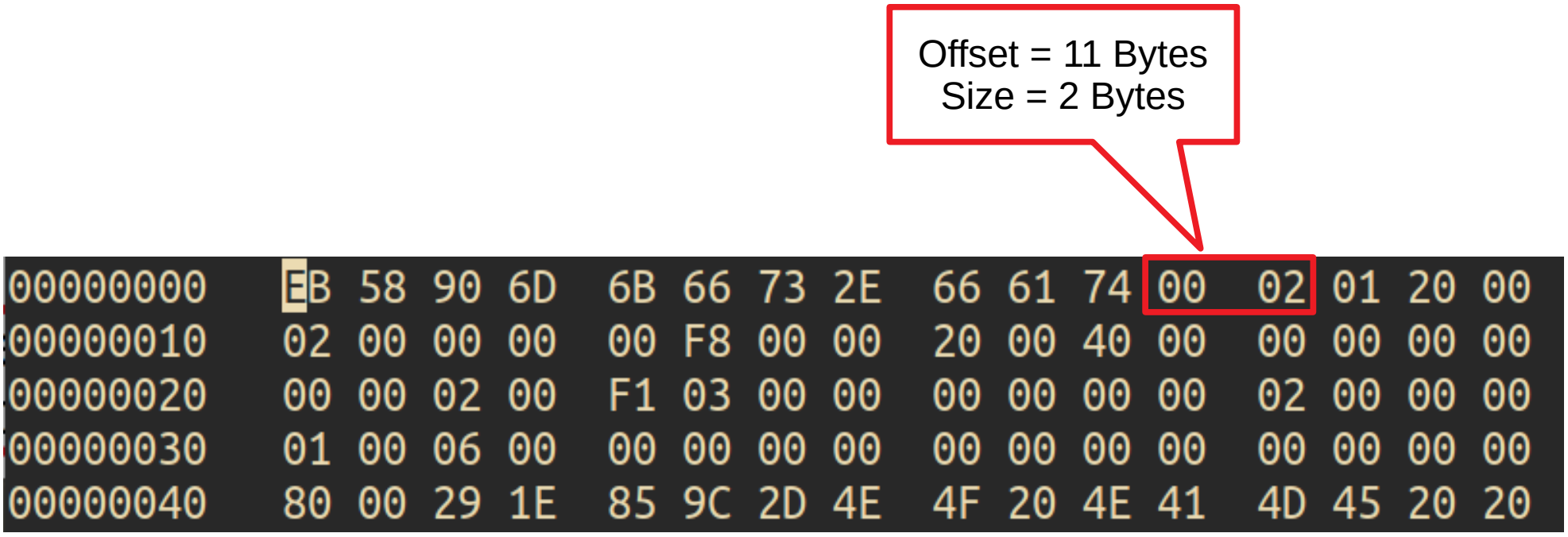
ex) Finding the BPB_BytesPerSec

FATspec

- Field Name: BPB_BytesPerSec
- Offset (byte): 11
- Size (byte): 2

Boot Sector and BPB Structure

Name	Offset (byte)	Size (bytes)	Description
BS_jmpBoot	0	3	Jump instruction to boot code. This field has two allowed forms: **jmpBoot[0] = 0xEB, jmpBoot[1] = 0x??, jmpBoot[2] = 0x90** and **jmpBoot[0] = 0xE9, jmpBoot[1] = 0x??, jmpBoot[2] = 0x??** **0x??** indicates that any 8-bit value is allowed in that byte. What this forms is a three-byte Intel x86 unconditional branch (jump) instruction that jumps to the start of the operating system bootstrap code. This code typically occupies the rest of sector 0 of the volume following the BPB and possibly other sectors. Either of these forms is acceptable. **JmpBoot[0] = 0xEB** is the more frequently used format.
BS_OEMName	3	8	"MSWIN4.1" There are many misconceptions about this field. It is only a name string. Microsoft operating systems don't pay any attention to this field. Some FAT drivers do. This is the reason that the indicated string, "MSWIN4.1", is the recommended setting, because it is the setting least likely to cause compatibility problems. If you want to put something else in here, that is your option, but the result may be that some FAT drivers might not recognize the volume. Typically this is some indication of what system formatted the volume.
BPB_BytsPerSec	11	2	Count of bytes per sector. This value may take on only the following values: 512, 1024, 2048 or 4096. If maximum compatibility with old implementations is desired, only the value 512 should be used. There is a lot of FAT code in the world that is basically "hard wired" to 512 bytes per sector and doesn't bother to check this field to make sure it is 512. Microsoft operating systems will properly support 1024, 2048, and 4096. **Note:** Do not misinterpret these statements about maximum compatibility. If the media being recorded has a physical sector size N, you must use N and this must still be less than or equal to 4096. Maximum compatibility is achieved by only using media with specific sector sizes.



- 00 02 little endian = 02 00 big endian
- $0200_{hex} = 512_{dec} \rightarrow$ 512 bytes per sector

Endianness

- Use `__attribute__((packed))` on structs
  - Makes sure structs don’t pad members to fit into a certain alignment
  - This resolves alignment issues
  - Whenever you read in a new type of value from FAT, make sure the endianness is correct

```
struct A {
    short small;
    int large;
};
struct B {
    short small;
    int large;
} __attribute__((packed));

int main() {
    //prints 8
    printf("A: %d\n", sizeof(struct A));
    //prints 6
    printf("B: %d\n", sizeof(struct B));
    return 0;
}
```

Function: ls DIRNAME

- Print the contents of the desired directory (DIRNAME)
- First, need to find DIRNAME via file system traversal

Function: info

- Note: one of the fields in the boot block is the BPB_RootClus
  - This field tells you the cluster number of the root directory
  - This field is usually = 2

ls DIRNAME

- Let’s first try running ls at the root
- Start at root directory – cluster number given in the boot sector
- Index into the FAT using this cluster number
- Value at this location in FAT table will either contain an end of cluster marker or a new index
- FAT entries form a chain of indices for a given file

ls DIRNAME

- Running ls on other directories is the exact same process except the starting cluster will be different
- If no argument given, use current working directory’s cluster
- If DIRNAME given, start at the first cluster number of DIRNAME (given in DIRNAME’s DIR entry)

FAT Entries

- FAT[current_cluster_number] = next_cluster_number → file continues at next_cluster_number
- FAT[current_cluster_number] = 0x0FFFFFF8 or 0x0FFFFFFF → end of cluster marker, current_cluster_number is the last cluster in the file
- FAT[current_cluster_number] = 0 → you are at an empty cluster

FAT

xxxxxxxx	xxxxxxxx	00000009	00000004
00000005	00000007	00000000	00000008
FFFFFFFF	0000000A	0000000B	00000011
0000000D	0000000E	FFFFFFFF	00000010
00000012	FFFFFFFF	00000013	00000014
00000015	00000016	FFFFFFFF	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000
00000000	00000000	00000000	00000000

Root Directory:
2, 9, A, B, 11

File #1:
3, 4, 5, 7, 8

File #2:
C, D, E

File #3:
F, 10, 12, 13, 14, 15, 16

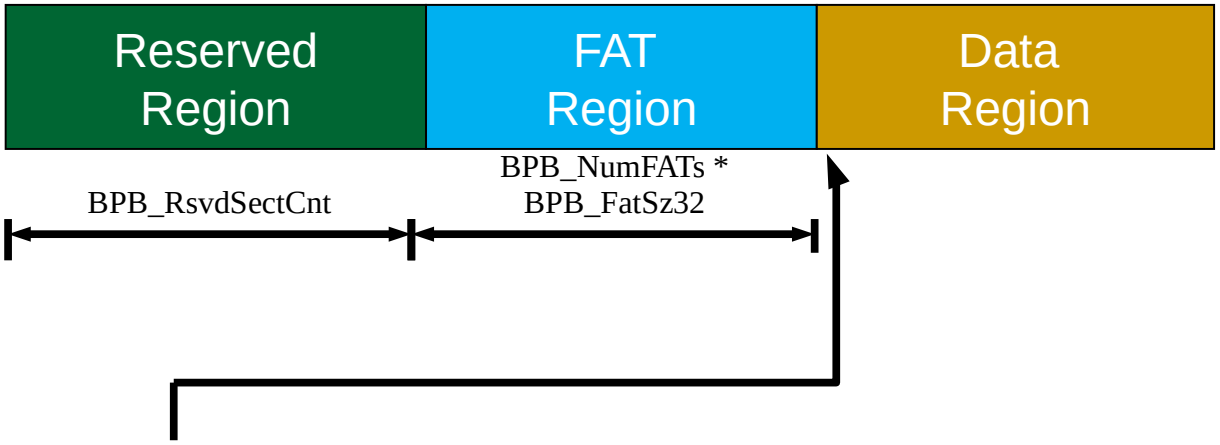
- So, the root directory contents are located in *cluster* numbers 2, 9, A, B, and 11

https://www.pjrc.com/tech/8051/ide/fat32.html

FAT Traversal

- FAT table shows *cluster number* of file contents!
- Must go to that cluster number in the data region to find the file’s actual contents

Finding a File's Contents



- FirstDataSector = BPB_RsvdSectCnt + (BPB_NumFATs*BPB_FatSz32)
- FirstDataSector is the Sector where data region starts (should be somewhere around 0x100400 in the example image)

Finding a File's Contents

- FirstSectorofCluster =

  FirstDataSector + ((N - 2)*BPB_SecPerClus)

Start of Data Region

This term is equal to the offset of the data from the beginning of the data region

Sectors per cluster * number of clusters = offset in terms of sector

(use cluster number – 2 because we start indexing clusters with N=2, remember how root started at 2?)

FAT32 Directories

- Similar to Boot Sector, make a struct with the fields corresponding to the entries in the directory structure
  - Check FATspec for details
- You do not have to support long entries → directory consists of second long directory entry and short entry
  - But they may exist in the image file, you can safely skip over them

FAT32 Directories

- The first byte of the entry will determine if the entry is taken, empty, and/or the end
  - 0x00: entry is empty and no other entry after it
  - 0xE5: entry is empty but more entries after it
  - Any other legal character: entry is taken

Function: cd DIRNAME

- Similar to ls, but instead of printing filenames, compare filenames to DIRNAME
- If DIRNAME is found and DIR_attr = 0x10, construct DIRNAME's location using DIR_FstClusHI and DIR_FstClusLO and set it as the present working directory (simply store it in your program, do not change environment variables)

Functions: size

- Same as cd except you are looking for DIR_Size upon match of filename

When in doubt, check the FATspec!