Understanding the ELF File Format – Linux Hint

ELF

From Source Code To Binary Code

Programming starts with having a clever idea, and writing source code in a programming language of your choice, for example C, and saving the source code in a file. With the help of an adequate compiler, for example GCC, your source code is translated into object code, first. Eventually, the linker translates the object code into a binary file that links the object code with the referenced libraries. This file contains the single instructions as machine code that are understood by the CPU, and are executed as soon the compiled program is run.

The binary file mentioned above follows a specific structure, and one of the most common ones is named ELF that abbreviates Executable and Linkable Format. It is widely used for executable files, relocatable object files, shared libraries, and core dumps.

Twenty years ago – in 1999 – the 86open project has chosen ELF as the standard binary file format for Unix and Unix-like systems on x86 processors. Luckily, the ELF format had been previously documented in both the System V Application Binary Interface, and the Tool Interface Standard [4]. This fact enormously simplified the agreement on standardization between the different vendors and developers of Unix-based operating systems.

The reason behind that decision was the design of ELF – flexibility, extensibility, and cross-platform support for different endian formats and address sizes. ELF's design is not limited to a specific processor, instruction set, or hardware architecture. For a detailed comparison of executable file formats, have a look here [3].

Since then, the ELF format is in use by several different operating systems. Among others, this includes Linux, Solaris/Illumos, Free-, Net- and OpenBSD, QNX, BeOS/Haiku, and Fuchsia OS [2]. Furthermore, you will find it on mobile devices running Android, Maemo or Meego OS/Sailfish OS as well as on game consoles like the PlayStation Portable, Dreamcast, and Wii.

The specification does not clarify the filename extension for ELF files. In use is a variety of letter combinations, such as .axf, .bin, .elf, .o, .prx, .puff, .ko, .so, and .mod, or none.

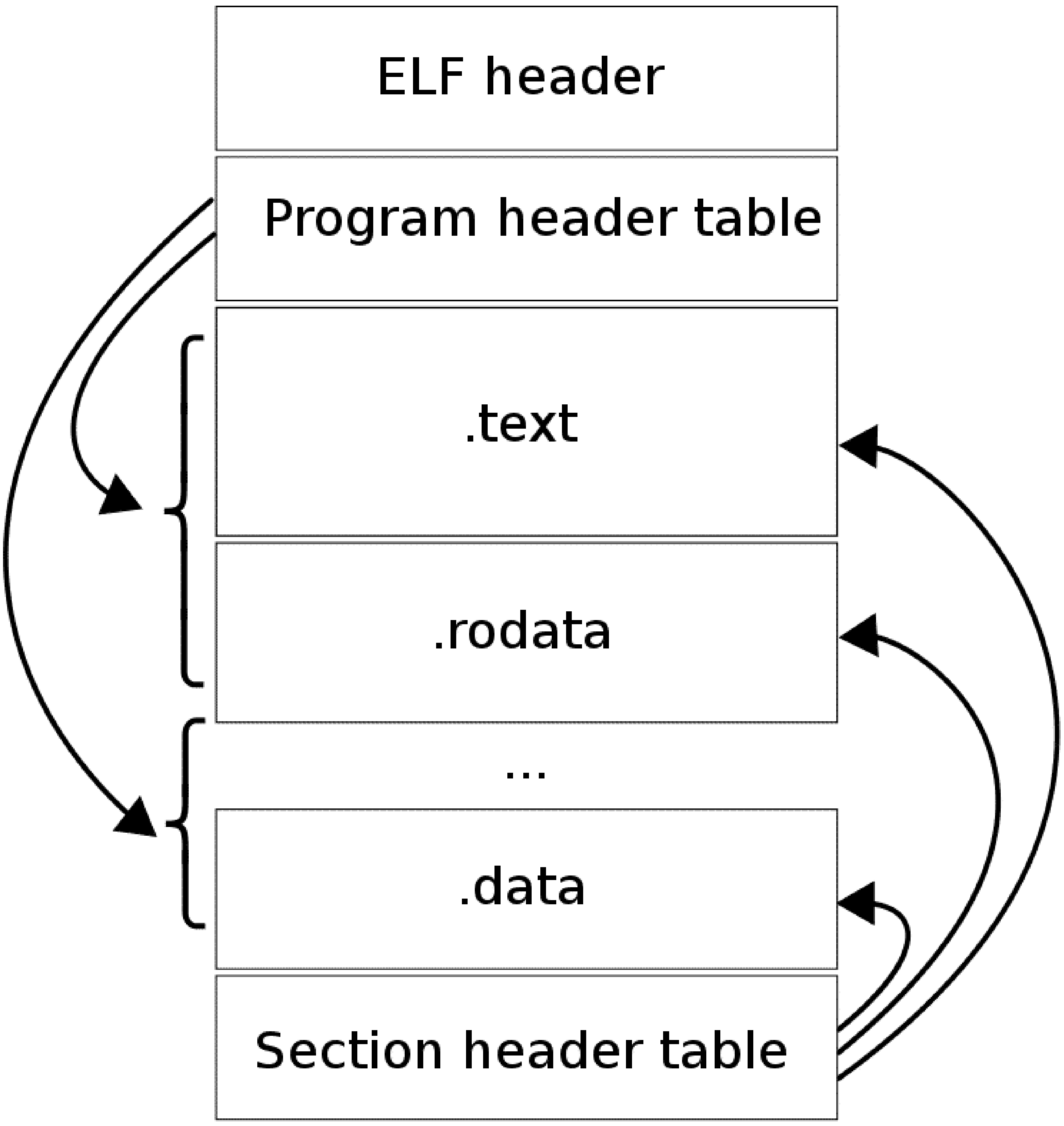
The Structure of an ELF File

On a Linux terminal, the command man elf gives you a handy summary about the structure of an ELF file:

Listing 1: The manpage of the ELF structure

```
$ man elf

ELF(5)                     Linux Programmer's Manual
 ELF(5)

NAME
       elf - format of Executable and Linking Format (ELF) files

SYNOPSIS
       #include <elf.h>

DESCRIPTION
       The  header  file  <elf.h>  defines the format of ELF
executable binary
       files.  Amongst these files are normal  executable  files,
 relocatable
       object files, core files and shared libraries.

       An executable file using the ELF file format consists of an ELF
header,
       followed by a program header table or a section header table,
or  both.
       The  ELF  header  is  always  at  offset zero of the file.  The
program
       header table and the section header table's  offset  in  the
 file  are
       defined  in  the  ELF  header.  The two tables describe the
rest of the
       particularities of the file.

...
```

As you can see from the description above, an ELF file consists of two sections – an ELF header, and file data. The file data section can consist of a program header table describing zero or more segments, a section header table describing zero or more sections, that is followed by data referred to by entries from the program header table, and the section header table. Each segment contains information that is necessary for run-time execution of the file, while sections contain important data for linking and relocation. Figure 1 illustrates this schematically.



The ELF Header

The ELF header is 32 bytes long, and identifies the format of the file. It starts with a sequence of four unique bytes that are 0x7F followed by 0x45, 0x4c, and 0x46 which translates into the three letters E, L, and F. Among other values, the header also indicates whether it is an ELF file for 32 or 64-bit format, uses little or big endianness, shows the ELF version as well as for which operating system the file was compiled for in order to interoperate with the right application binary interface (ABI) and cpu instruction set.

The hexdump of the binary file touch looks as follows:

.Listing 2: The hexdump of the binary file

```
$ hd /usr/bin/touch | head -5
00000000  7f 45 4c 46 02 01 01 00  00 00 00 00 00 00 00 00
 |.ELF............|
00000010  02 00 3e 00 01 00 00 00  e3 25 40 00 00 00 00 00
 |..>......%@.....|
00000020  40 00 00 00 00 00 00 00  28 e4 00 00 00 00 00 00  |@.......
(.......|
00000030  00 00 00 00 40 00 38 00  09 00 40 00 1b 00 1a 00
 |....@.8...@.....|
00000040  06 00 00 00 05 00 00 00  40 00 00 00 00 00 00 00
 |........@.......|
```

Debian GNU/Linux offers the readelf command that is provided in the GNU ‘binutils’ package. Accompanied by the switch -h (short version for “-file-header”) it nicely displays the header of an ELF file. Listing 3 illustrates this for the command touch.

.Listing 3: Displaying the header of an ELF file

```
$ readelf -h /usr/bin/touch
ELF Header:
  Magic:   7f 45 4c 46 02 01 01 00 00 00 00 00 00 00 00 00
  Class:                             ELF64
  Data:                              2's complement, little endian
  Version:                           1 (current)
  OS/ABI:                            UNIX - System V
  ABI Version:                       0
  Type:                              EXEC (Executable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x4025e3
  Start of program headers:          64 (bytes into file)
  Start of section headers:          58408 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         9
  Size of section headers:           64 (bytes)
  Number of section headers:         27
  Section header string table index: 26
```

The Program Header

The program header shows the segments used at run-time, and tells the system how to create a process image. The header from Listing 2 shows that the ELF file consists of 9 program headers that have a size of 56 bytes each, and the first header starts at byte 64.

Again, the readelf command helps to extract the information from the ELF file. The switch -l (short for -program-headers or -segments) reveals more details as shown in Listing 4.

.Listing 4: Display information about the program headers

```
$ readelf -l /usr/bin/touch

Elf file type is EXEC (Executable file)
Entry point 0x4025e3
There are 9 program headers, starting at offset 64

Program Headers:
  Type           Offset             VirtAddr           PhysAddr
                 FileSiz            MemSiz              Flags  Align
  PHDR           0x0000000000000040 0x0000000000400040
0x0000000000400040
                 0x00000000000001f8 0x00000000000001f8  R E    8
  INTERP         0x0000000000000238 0x0000000000400238
0x0000000000400238
                 0x000000000000001c 0x000000000000001c  R      1
      [Requesting program interpreter: /lib64/ld-linux-x86-64.so.2]
  LOAD           0x0000000000000000 0x0000000000400000
0x0000000000400000
                 0x000000000000d494 0x000000000000d494  R E    200000
  LOAD           0x000000000000de10 0x000000000060de10
0x000000000060de10
                 0x0000000000000524 0x0000000000000748  RW     200000
  DYNAMIC        0x000000000000de28 0x000000000060de28
```

```
0x000000000060de28
                 0x00000000000001d0 0x00000000000001d0  RW     8
  NOTE           0x0000000000000254 0x0000000000400254
0x0000000000400254
                 0x0000000000000044 0x0000000000000044  R      4
  GNU_EH_FRAME   0x000000000000bc40 0x000000000040bc40
0x000000000040bc40
                 0x00000000000003a4 0x00000000000003a4  R      4
  GNU_STACK      0x0000000000000000 0x0000000000000000
0x0000000000000000
                 0x0000000000000000 0x0000000000000000  RW     10
  GNU_RELRO      0x000000000000de10 0x000000000060de10
0x000000000060de10
                 0x00000000000001f0 0x00000000000001f0  R      1

 Section to Segment mapping:
  Segment Sections...
   00
   01     .interp
   02     .interp .note.ABI-tag .note.gnu.build-id .gnu.hash .dynsym
.dynstr .gnu.version .gnu.version_r .rela.dyn .rela.plt .init .plt
.text .fini .rodata .eh_frame_hdr .eh_frame
   03     .init_array .fini_array .jcr .dynamic .got .got.plt .data
.bss
   04     .dynamic
   05     .note.ABI-tag .note.gnu.build-id
   06     .eh_frame_hdr
   07
   08     .init_array .fini_array .jcr .dynamic .got
```

The Section Header

The third part of the ELF structure is the section header. It is meant to list the single sections of the binary. The switch -S (short for -section-headers or -sections) lists the different headers. As for the touch command, there are 27 section headers, and Listing 5 shows the first four of them plus the last one, only. Each line covers the section size, the section type as well as its address and memory offset.

.Listing 5: Section details revealed by readelf

```
$ readelf -S /usr/bin/touch
There are 27 section headers, starting at offset 0xe428:
```

```
Section Headers:
  [Nr] Name              Type             Address           Offset
       Size              EntSize          Flags  Link  Info  Align
  [ 0]                   NULL             0000000000000000  00000000
       0000000000000000  0000000000000000           0     0     0
  [ 1] .interp           PROGBITS         0000000000400238  00000238
       000000000000001c  0000000000000000   A       0     0     1
  [ 2] .note.ABI-tag     NOTE             0000000000400254  00000254
       0000000000000020  0000000000000000   A       0     0     4
  [ 3] .note.gnu.build-i NOTE             0000000000400274  00000274
...
...
  [26] .shstrtab         STRTAB           0000000000000000  0000e334
       00000000000000ef  0000000000000000           0     0     1
Key to Flags:
  W (write), A (alloc), X (execute), M (merge), S (strings), l (large)
  I (info), L (link order), G (group), T (TLS), E (exclude), x
(unknown)
  O (extra OS processing required) o (OS specific), p (processor
specific)
```

Tools to Analyze an ELF file

As you may have noted from the examples above, GNU/Linux is fleshed out with a number of useful tools that help you to analyze an ELF file. The first candidate we will have a look at is the file utility.

file displays basic information about ELF files, including the instruction set architecture for which the code in a relocatable, executable, or shared object file is intended. In listing 6 it tells you that /bin/touch is a 64-bit executable file following the Linux Standard Base (LSB), dynamically linked, and built for the GNU/Linux kernel version 2.6.32.

.Listing 6: Basic information using file

```
$ file /bin/touch
/bin/touch: ELF 64-bit LSB executable, x86-64, version 1 (SYSV),
dynamically linked, interpreter /lib64/l,
for GNU/Linux 2.6.32,
BuildID[sha1]=ec08d609e9e8e73d4be6134541a472ad0ea34502, stripped
$
```

The second candidate is readelf. It displays detailed information about an ELF file. The list of switches is comparably long, and covers all the aspects of the ELF format. Using the switch -n (short for -

notes) Listing 7 shows the note sections, only, that exist in the file touch - the ABI version tag, and the build ID bitstring.

.Listing 7: Display Selected sections of an ELF file

```
$ readelf -n /usr/bin/touch

Displaying notes found at file offset 0x00000254 with length
0x00000020:
  Owner                 Data size   Description
  GNU                  0x00000010   NT_GNU_ABI_TAG (ABI version tag)
    OS: Linux, ABI: 2.6.32

Displaying notes found at file offset 0x00000274 with length
0x00000024:
  Owner                 Data size   Description
  GNU                  0x00000014   NT_GNU_BUILD_ID (unique build ID
bitstring)
    Build ID: ec08d609e9e8e73d4be6134541a472ad0ea34502
```

Note that under Solaris and FreeBSD, the utility elfdump [7] corresponds with readelf. As of 2019, there has not been a new release or update since 2003.

Number three is the package named elfutils [6] that is purely available for Linux. It provides alternative tools to GNU Binutils, and also allows validating ELF files. Note that all the names of the utilities provided in the package start with eu for ‘elf utils’.

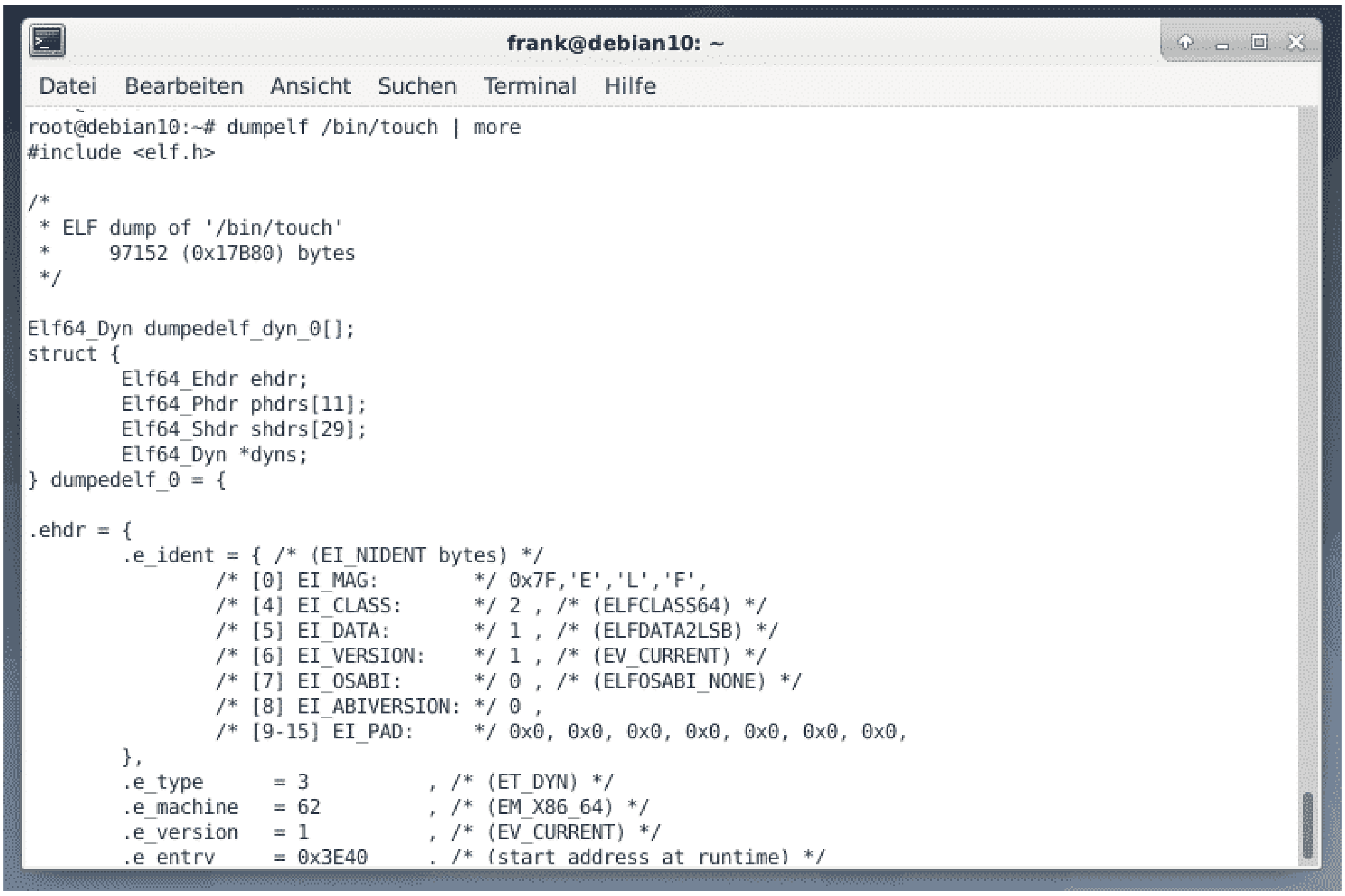
Last but not least we will mention objdump. This tool is similar to readelf but focuses on object files. It provides a similar range of information about ELF files and other object formats.

.Listing 8: File information extracted by objdump

```
$ objdump -f /bin/touch

/bin/touch:     file format elf64-x86-64
architecture: i386:x86-64, flags 0x00000112:
EXEC_P, HAS_SYMS, D_PAGED
start address 0x00000000004025e3

$
```

There is also a software package called ‘elfkickers’ [9] which contains tools to read the contents of an ELF file as well as manipulating it. Unfortunately, the number of releases is rather low, and that’s why we just mention it, and do not show further examples.

As a developer you may have a look at ‘pax-utils’ [10,11], instead. This set of utilities provides a number of tools that help to validate ELF files. As an example, dumpelf analyzes the ELF file, and returns a C header file containing the details – see Figure 2.



```
root@debian10:~# dumpelf /bin/touch | more
#include <elf.h>

/*
 * ELF dump of '/bin/touch'
 *     97152 (0x17B80) bytes
 */

Elf64_Dyn dumpedelf_dyn_0[];
struct {
        Elf64_Ehdr ehdr;
        Elf64_Phdr phdrs[11];
        Elf64_Shdr shdrs[29];
        Elf64_Dyn *dyns;
} dumpedelf_0 = {

.ehdr = {
        .e_ident = { /* (EI_NIDENT bytes) */
                /* [0] EI_MAG:        */ 0x7F,'E','L','F',
                /* [4] EI_CLASS:      */ 2 , /* (ELFCLASS64) */
                /* [5] EI_DATA:       */ 1 , /* (ELFDATA2LSB) */
                /* [6] EI_VERSION:    */ 1 , /* (EV_CURRENT) */
                /* [7] EI_OSABI:      */ 0 , /* (ELFOSABI_NONE) */
                /* [8] EI_ABIVERSION: */ 0 ,
                /* [9-15] EI_PAD:     */ 0x0, 0x0, 0x0, 0x0, 0x0, 0x0, 0x0,
        },
        .e_type      = 3          , /* (ET_DYN) */
        .e_machine   = 62         , /* (EM_X86_64) */
        .e_version   = 1          , /* (EV_CURRENT) */
        .e_entry     = 0x3E40     , /* (start address at runtime) */
```

Conclusion

Thanks to a combination of clever design and excellent documentation the ELF format works very well, and is still in use after 20 years. The utilities shown above allow you an insight view into an ELF file, and let you figure out what a program is doing. These are the first steps for analyzing software – happy hacking!

Links and References

- [1] [Executable and Linkable Format (ELF), Wikipedia]()
- [2] [Fuchsia OS]()
- [3] [Comparison of executable file formats, Wikipedia]()

- [4] Linux Foundation, Referenced Specifications
- [5] Ciro Santilli: ELF Hello World Tutorial
- [6] elfutils Debian package
- [7] elfdump
- [8] Michael Boelen: The 101 of ELF files on Linux: Understanding and Analysis
- [9] elfkickers
- [10] Hardened/PaX Utilities
- [11] pax-utils, Debian package

Acknowledgements

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