1.

ELF stands for “Executable and Linkable Format” and is a standard format for both executable and object code.

```
$ readelf -h test1
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:               0x4010b0
  Start of program headers:          64 (bytes into file)
  Start of section headers:          28928 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           56 (bytes)
  Number of program headers:         13
  Size of section headers:           64 (bytes)
  Number of section headers:         37
  Section header string table index: 36
```

```
$ readelf -h test1.o
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:                              REL (Relocatable file)
  Machine:                           Advanced Micro Devices X86-64
  Version:                           0x1
  Entry point address:               0x0
  Start of program headers:          0 (bytes into file)
  Start of section headers:          5768 (bytes into file)
  Flags:                             0x0
  Size of this header:               64 (bytes)
  Size of program headers:           0 (bytes)
  Number of program headers:         0
  Size of section headers:           64 (bytes)
  Number of section headers:         23
  Section header string table index: 22
```

2.

```
$ gcc -v scan.c main.c parse.c message.c assemble.c symtab.c -o asx20
Using built-in specs.
COLLECT_GCC=gcc
COLLECT_LTO_WRAPPER=/usr/libexec/gcc/x86_64-redhat-linux/12/lto-wrapper
OFFLOAD_TARGET_NAMES=nvptx-none
OFFLOAD_TARGET_DEFAULT=1
Target: x86_64-redhat-linux
Configured with: ../configure --enable-bootstrap --enable-languages=c,c++,fortran,objc,obj-c++,ada,go,d,lto --prefix=/usr
--mandir=/usr/share/man --infodir=/usr/share/info --with-bugurl=http://bugzilla.redhat.com/bugzilla --enable-shared --
enable-threads=posix --enable-checking=release --enable-multilib --with-system-zlib --enable-__cxa_atexit --disable-
libunwind-exceptions --enable-gnu-unique-object --enable-linker-build-id --with-gcc-major-version-only --enable-libstdcxx-
backtrace --with-linker-hash-style=gnu --enable-plugin --enable-initfini-array --with-isl=/builddir/build/BUILD/gcc-
12.3.1-20230508/obj-x86_64-redhat-linux/isl-install --enable-offload-targets=nvptx-none --without-cuda-driver --enable-
offload-defaulted --enable-gnu-indirect-function --enable-cet --with-tune=generic --with-arch_32=i686 --build=x86_64-
redhat-linux --with-build-config=bootstrap-lto --enable-link-serialization=1
```

```
Thread model: posix
Supported LTO compression algorithms: zlib zstd
gcc version 12.3.1 20230508 (Red Hat 12.3.1-1) (GCC)
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 /usr/libexec/gcc/x86_64-redhat-linux/12/cc1 -quiet -v scan.c -quiet -dumpdir asx20- -dumpbase scan.c -dumpbase-ext .c -
mtune=generic -march=x86-64 -version -o /var/tmp/cc2p5yc1.s
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/include-fixed"
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/../../../../x86_64-redhat-linux/include"
#include "..." search starts here:
#include <...> search starts here:
 /usr/lib/gcc/x86_64-redhat-linux/12/include
 /usr/local/include
 /usr/include
End of search list.
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
Compiler executable checksum: 1761180302be05980fb5877562ad4b2f
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 as -v --64 -o /var/tmp/cccZYVCC.o /var/tmp/cc2p5yc1.s
GNU assembler version 2.38 (x86_64-redhat-linux) using BFD version version 2.38-27.fc37
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 /usr/libexec/gcc/x86_64-redhat-linux/12/cc1 -quiet -v main.c -quiet -dumpdir asx20- -dumpbase main.c -dumpbase-ext .c -
mtune=generic -march=x86-64 -version -o /var/tmp/cc2p5yc1.s
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/include-fixed"
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/../../../../x86_64-redhat-linux/include"
#include "..." search starts here:
#include <...> search starts here:
 /usr/lib/gcc/x86_64-redhat-linux/12/include
 /usr/local/include
 /usr/include
End of search list.
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
Compiler executable checksum: 1761180302be05980fb5877562ad4b2f
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 as -v --64 -o /var/tmp/ccUR2Ind.o /var/tmp/cc2p5yc1.s
GNU assembler version 2.38 (x86_64-redhat-linux) using BFD version version 2.38-27.fc37
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 /usr/libexec/gcc/x86_64-redhat-linux/12/cc1 -quiet -v parse.c -quiet -dumpdir asx20- -dumpbase parse.c -dumpbase-ext .c -
mtune=generic -march=x86-64 -version -o /var/tmp/cc2p5yc1.s
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/include-fixed"
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/../../../../x86_64-redhat-linux/include"
#include "..." search starts here:
#include <...> search starts here:
 /usr/lib/gcc/x86_64-redhat-linux/12/include
 /usr/local/include
 /usr/include
End of search list.
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
```

```
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
Compiler executable checksum: 1761180302be05980fb5877562ad4b2f
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 as -v --64 -o /var/tmp/ccKCy9hU.o /var/tmp/cc2p5yc1.s
GNU assembler version 2.38 (x86_64-redhat-linux) using BFD version version 2.38-27.fc37
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 /usr/libexec/gcc/x86_64-redhat-linux/12/cc1 -quiet -v message.c -quiet -dumpdir asx20- -dumpbase message.c -dumpbase-ext
.c -mtune=generic -march=x86-64 -version -o /var/tmp/cc2p5yc1.s
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/include-fixed"
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/../../../../x86_64-redhat-linux/include"
#include "..." search starts here:
#include <...> search starts here:
 /usr/lib/gcc/x86_64-redhat-linux/12/include
 /usr/local/include
 /usr/include
End of search list.
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
Compiler executable checksum: 1761180302be05980fb5877562ad4b2f
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 as -v --64 -o /var/tmp/cc1GpjRN.o /var/tmp/cc2p5yc1.s
GNU assembler version 2.38 (x86_64-redhat-linux) using BFD version version 2.38-27.fc37
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 /usr/libexec/gcc/x86_64-redhat-linux/12/cc1 -quiet -v assemble.c -quiet -dumpdir asx20- -dumpbase assemble.c -dumpbase-
ext .c -mtune=generic -march=x86-64 -version -o /var/tmp/cc2p5yc1.s
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/include-fixed"
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/../../../../x86_64-redhat-linux/include"
#include "..." search starts here:
#include <...> search starts here:
 /usr/lib/gcc/x86_64-redhat-linux/12/include
 /usr/local/include
 /usr/include
End of search list.
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
Compiler executable checksum: 1761180302be05980fb5877562ad4b2f
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 as -v --64 -o /var/tmp/ccbu09JO.o /var/tmp/cc2p5yc1.s
GNU assembler version 2.38 (x86_64-redhat-linux) using BFD version version 2.38-27.fc37
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 /usr/libexec/gcc/x86_64-redhat-linux/12/cc1 -quiet -v symtab.c -quiet -dumpdir asx20- -dumpbase symtab.c -dumpbase-ext .c
-mtune=generic -march=x86-64 -version -o /var/tmp/cc2p5yc1.s
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/include-fixed"
ignoring nonexistent directory "/usr/lib/gcc/x86_64-redhat-linux/12/../../../../x86_64-redhat-linux/include"
#include "..." search starts here:
#include <...> search starts here:
 /usr/lib/gcc/x86_64-redhat-linux/12/include
```

```
 /usr/local/include
 /usr/include
End of search list.
GNU C17 (GCC) version 12.3.1 20230508 (Red Hat 12.3.1-1) (x86_64-redhat-linux)
        compiled by GNU C version 12.3.1 20230508 (Red Hat 12.3.1-1), GMP version 6.2.1, MPFR version 4.1.0-p13, MPC
version 1.2.1, isl version isl-0.24-GMP

GGC heuristics: --param ggc-min-expand=100 --param ggc-min-heapsize=131072
Compiler executable checksum: 1761180302be05980fb5877562ad4b2f
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20-'
 as -v --64 -o /var/tmp/ccEixxjr.o /var/tmp/cc2p5yc1.s
GNU assembler version 2.38 (x86_64-redhat-linux) using BFD version version 2.38-27.fc37
COMPILER_PATH=/usr/libexec/gcc/x86_64-redhat-linux/12/:/usr/libexec/gcc/x86_64-redhat-linux/12/:/usr/libexec/gcc/x86_64-
redhat-linux/:/usr/lib/gcc/x86_64-redhat-linux/12/:/usr/lib/gcc/x86_64-redhat-linux/
LIBRARY_PATH=/usr/lib/gcc/x86_64-redhat-linux/12/:/usr/lib/gcc/x86_64-redhat-
linux/12/../../../../lib64/:/lib/../lib64/:/usr/lib/../lib64/:/usr/lib/gcc/x86_64-redhat-
linux/12/../../../:/lib/:/usr/lib/
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20.'
 /usr/libexec/gcc/x86_64-redhat-linux/12/collect2 -plugin /usr/libexec/gcc/x86_64-redhat-linux/12/liblto_plugin.so -
plugin-opt=/usr/libexec/gcc/x86_64-redhat-linux/12/lto-wrapper -plugin-opt=-fresolution=/var/tmp/ccIFgoTy.res -plugin-
opt=-pass-through=-lgcc -plugin-opt=-pass-through=-lgcc_s -plugin-opt=-pass-through=-lc -plugin-opt=-pass-through=-lgcc -
plugin-opt=-pass-through=-lgcc_s --build-id --no-add-needed --eh-frame-hdr --hash-style=gnu -m elf_x86_64 -dynamic-linker
/lib64/ld-linux-x86-64.so.2 -o asx20 /usr/lib/gcc/x86_64-redhat-linux/12/../../../../lib64/crt1.o /usr/lib/gcc/x86_64-
redhat-linux/12/../../../../lib64/crti.o /usr/lib/gcc/x86_64-redhat-linux/12/crtbegin.o -L/usr/lib/gcc/x86_64-redhat-
linux/12 -L/usr/lib/gcc/x86_64-redhat-linux/12/../../../../lib64 -L/lib/../lib64 -L/usr/lib/../lib64 -
L/usr/lib/gcc/x86_64-redhat-linux/12/../../../.. /var/tmp/cccZYVCC.o /var/tmp/ccUR2Ind.o /var/tmp/ccKCy9hU.o
/var/tmp/cc1GpjRN.o /var/tmp/ccbu09JO.o /var/tmp/ccEixxjr.o -lgcc --push-state --as-needed -lgcc_s --pop-state -lc -lgcc -
-push-state --as-needed -lgcc_s --pop-state /usr/lib/gcc/x86_64-redhat-linux/12/crtend.o /usr/lib/gcc/x86_64-redhat-
linux/12/../../../../lib64/crtn.o
COLLECT_GCC_OPTIONS='-v' '-o' 'asx20' '-mtune=generic' '-march=x86-64' '-dumpdir' 'asx20.'
```

3.

The parent thread would create a single child thread for each file on the command line. Each thread is given work for a file provided on the command line. The work consists of opening and reading a file, separating the file into individual words (symbols), adding each unique word to the symbol table, and counting the occurrence of each unique word. Each node of the table would have a member indicating its frequency. The child threads would lock (mutex) the symbol table while the unique word is being inserted as well as for increasing the frequency. When all child threads are complete, a conditional variable would send a signal to the parent thread to wake it up and display the results.

4.

```
        .file   "factorial.c"
        .text
        .globl  factorial
        .type   factorial, @function
factorial:
.LFB0:
        .cfi_startproc
        pushq   %rbp                        // old frame pointer
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq    %rsp, %rbp                  // new frame pointer
        .cfi_def_cfa_register 6
        pushq   %rbx
        subq    $24, %rsp                   // Allocate one local
        .cfi_offset 3, -24
        movl    %edi, -20(%rbp)
        cmpl    $0, -20(%rbp)               // test n against 0
        jne     .L2                         // branch to .L2 if n != 0
        movl    $1, %eax                    // save 1
        jmp     .L3                         // unconditional jump to .L3
.L2:
        movl    -20(%rbp), %eax             // save n into the local
```

```
        movslq  %eax, %rbx
        movl    -20(%rbp), %eax
        subl    $1, %eax                    // compute (n – 1)
        movl    %eax, %edi
        call    factorial                   // recursive call
        imulq   %rbx, %rax                  // compute n * factorial(n – 1)
.L3:
        movq    -8(%rbp), %rbx              // deallocate the local
        leave
        .cfi_def_cfa 7, 8
        ret                                 // return to caller
        .cfi_endproc
.LFE0:
        .size   factorial, .-factorial
        .section        .rodata
.LC0:
        .string "%ld\n"                     // printf()
        .text
        .globl  main
        .type   main, @function
main:
.LFB1:
        .cfi_startproc
        pushq   %rbp                        // old frame pointer
        .cfi_def_cfa_offset 16
        .cfi_offset 6, -16
        movq    %rsp, %rbp                  // new frame pointer
        .cfi_def_cfa_register 6
        subq    $16, %rsp                   // subtract 16 from the stack pointer
        movl    $9, -4(%rbp)
        movl    -4(%rbp), %eax
        movl    %eax, %edi
        call    factorial                   // recursive call
        movq    %rax, %rsi                  // pass return value from fact as arg 2
        movl    $.LC0, %edi                 // pass format string as arg 1
        movl    $0, %eax
        call    printf                      // calls printf()
        nop
        leave
        .cfi_def_cfa 7, 8
        ret                                 // return to caller
        .cfi_endproc
.LFE1:
        .size   main, .-main
        .ident  "GCC: (GNU) 12.2.1 20220819 (Red Hat 12.2.1-1)"
        .section        .note.GNU-stack,"",@progbits5.
```

5.

Typing more than 15 characters will result in a segmentation fault. This is because it is a buffer overflow

6.

```
Result:
       Word 0               00000000
Mainx20:
       Addi   fp, sp        0000ed0b
       Ldimm  r0, 4         00004003
       Subi   sp, r0        00000e0c
       Call   get44         000d000f
       Ldind  r0, -1(fp)    ffffd005
       Call   get42         000e000f
       Ldind  r1, -1(fp)    ffffd105
```

```
       Addi   r0, r1         0000100b
       Call   get44          0008000f
       Ldind  r1, -1(fp)     ffffd105
       Addi   r0, r1         0000100b
       Call   get42          0008000f
       Ldind  r1, -1(fp)     ffffd105
       Addi   r0, r1         0000100b
       Store  r0, result     ffff0002
       Halt                  00000000
Get44:
       Ldimm  r7, 44         0002c703
       Stind  r7, -1(fp)     ffffd706
       Ret                   00000010
Get42:
       Ldimm  r7, 42         0002a703
       Stind  r7, -1(fp)     ffffd706
       Ret                   00000010
```

7.

```
[00007ffd96048e28] 0000000000401190        // saved %rip
[00007ffd96048e30] 0000020000000100        // n.y and n.x
[00007ffd96048e38] 0000000000000000        // n.d1
[00007ffd96048e40] 676e69727473796d        // n.str
[00007ffd96048e48] 0000000000000000        // n.str
[00007ffd96048e50] c014000000000000        // n.f1
[00007ffd96048e58] 0000000000000000        // n.f1
[00007ffd96048e60] 00007ffd96048e80        // go to next frame
```

8.

The compiler may add some extra bytes between the members or at the end of the struct to align them properly in memory. Called padding.

```
Structa_t      0xcc 0xssss
               → 0x00cc 0xssss
               → 00 cc ss ss
               → 4

Structb_t      0xssss 0xcc 0xiiiiiiii
               → 0x0000ssss 0x000000cc 0xiiiiiiii
               → ss ss 00 cc ii ii ii ii
               → 8

Structc_t      0xcc 0xddddddddd 0xddddddddd 0xiiiiiiii
               → 0x00000000000000cc 0xddddddddddddddddd 0xiiiiiiii
               → 00 00 00 00 00 00 00 00 00 00 00 00 cc dd dd dd dd dd dd dd dd ii ii ii ii
               → 24

Structd_t      0xddddddddd 0xddddddddd 0xiiiiiiii 0xcc
               → 0xddddddddddddddddd 0xiiiiiiii 0x000000cc
               → dd dd dd dd dd dd dd dd ii ii ii ii 00 00 00 cc
               → 16
```