CPE 323
Introduction to Software Reverse Engineering in Embedded Computer Systems

Aleksandar Milenković
Email: milenka@uah.edu
Web: http://www.ece.uah.edu/~milenka

Objective:
Introduce tools and methods for software reverse engineering in embedded systems

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1 Introduction

In this section we will introduce basic concepts, tools, and techniques for software reverse engineering with a special emphasis on embedded computer systems.

Reverse engineering in general is a process of deconstructing man-made artifacts with a goal to reveal their designs and architecture or to extract knowledge. It is widely used in many areas of engineering, but here we are focusing on software reverse engineering. Note: hardware reverse engineering is another topic that may be of interest for electrical and computer engineers, but it is out of scope in this tutorial.

Software reverse engineering refers to a process of analyzing a software system in order to identify its components and their interrelationships and to create representations of the system in another form, typically at a higher level of abstraction. Two main components of software reverse engineering are *re-documentation* and *design recovery*. Re-documentation is a process of creating a new representation of the computer code that is easier to understand, often given at a higher level of abstraction. Design recovery is the use of deduction or reasoning from personal experience of the software system to understand its functionality. Software reverse engineering can be used even when the source code is available with the goal to uncover aspects of the program that may be poorly documented or are documented but no longer valid. More often though, software reverse engineering is used when source code is not available.

Software reverse engineering is used for the purpose of:
- Analyzing malware;
- Analyzing closed-source software to uncover vulnerabilities or interoperability issues;
- Analyzing compiler-generated code to validate performance and/or correctness;
- Debugging programs;

This tutorial focuses on reverse engineering of code written for the TI's MSP430 family of microcontrollers. It covers the following topics:
- Format of Executable Files
- GNU binary utilities typically used in software reverse engineering to understand executable files and disassemble executable programs;
- Extracting useful information from binaries;
- Retrieving programs from embedded platforms and analyzing them.

2 Format of Executable Files

In this section we will take a look at the format of executable files. Figure 1 illustrates a generalized flow of source code translation. User created source code written in high-level programming languages or an assembly language is translated into object files that are further linked with library files into executable files that are then loaded onto the target platform.

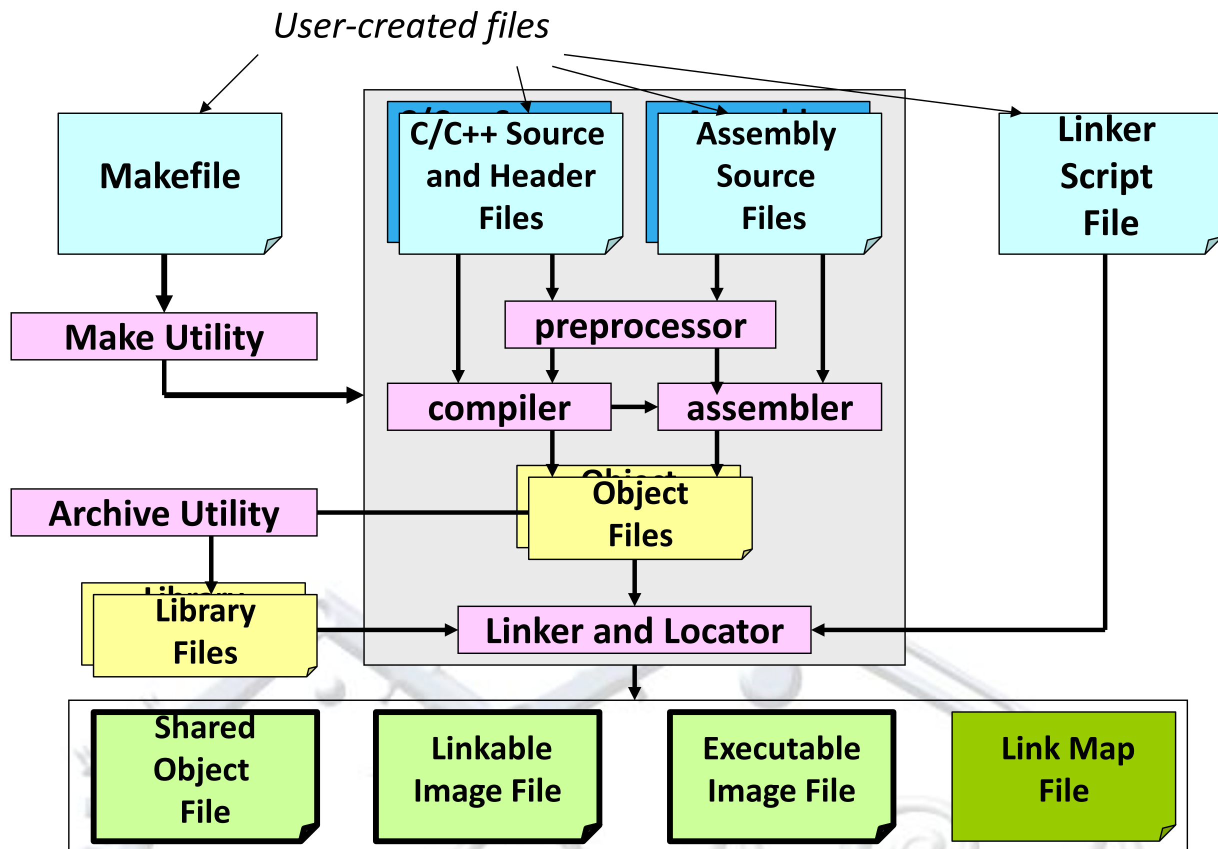


Figure 1. Source Translation Process.

Executable and Linkable File (ELF) format is a common standard file format used for executable files, object files, shared libraries, and core dumps. TI Code Composer Studio produces executable files in the ELF format, regardless of the compiler used (TI compiler or GNU MSP430 GCC compiler). The ELF format is not bound by the Instruction Set Architecture or operating systems. It defines the structure of the file, specifically the headers which describe actual binary content of the file. The structure of the ELF file is well defined and more information can be found at https://en.wikipedia.org/wiki/Executable_and_Linkable_Format. In brief, it is important to recognize the concept of segments and sections. The segments contain information that is needed for run-time execution of the program, while sections contain important data needed for linking and relocation.

Figure 2 illustrates two views of ELF files: linkable and executable file formats. ELF files contain the following components:

- ELF file header
- Program header table: Describes zero or more memory segments; It tells loader how to create a process image in memory;
- Section header table: Describes zero or more sections that contain data referred to by entries in the program header tables and section header tables;
- Segments: contain info needed for run-time execution;

- Sections: contain info for linking and relocation.

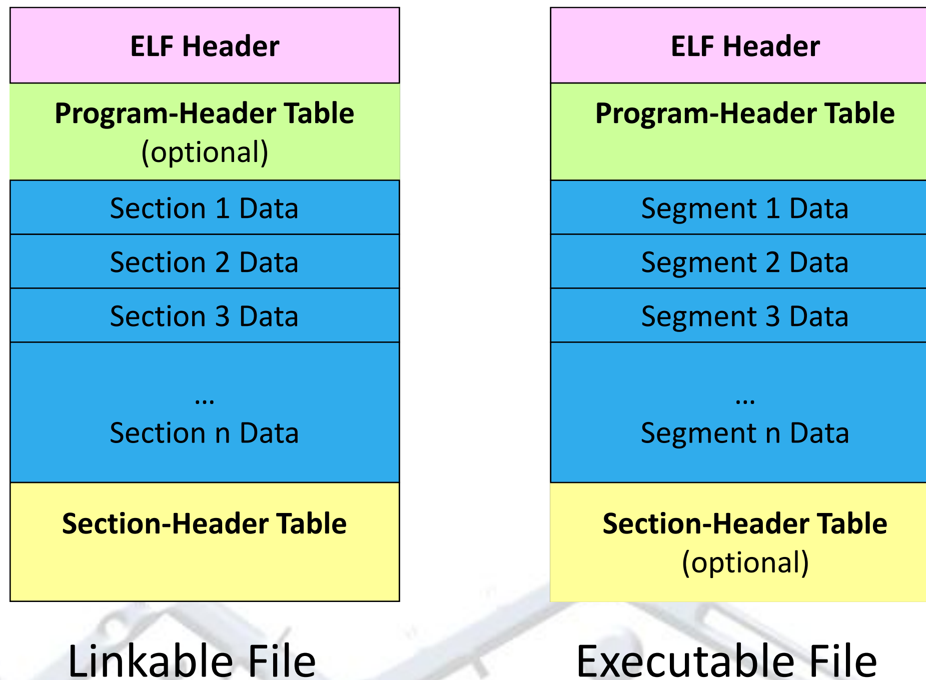


Figure 2. Linkable and Executable Views of ELF Files.

ELF linkable files are divided into a collection of sections. Each section contains a single type of information and can contain flags (writable data, memory space during execution or executable machine instructions). Sections have:

- Name and type
- Requested memory location at run time
- Permissions (R, W, X).

Table 1 shows common sections of ELF linkable files.

Table 1. ELF Linking View: Common Sections.

Sections	Description
.interp	Path name of program interpreter
.text	Code (executable instructions) of a program; Typically stored in read-only memory.
.data	Initialized read/write data (global, static)
.bss	Uninitialized read/write data (global, static) Often it is initialized by the start-up code
.const/.rodata	Read-only data; typically stored in Flash memory

.init	Executable instructions for process initialization
.fini	Executable instructions for process termination
.ptl	Holds the procedure linkage table
.re.[x]	Relocation information for section [x]
.dynamic	Dynamic linking information
.symtab, .dynsym	Symbols (static/dynamic)
.strtab, .dynstr	String table
.stack	Stack

Linker is a utility program that takes one or more object files generated by a compiler and combines them into a single executable file, library file, or another object file. Figure 3 illustrates linking multiple object files into a single executable file. The linker script defines the memory map of the device with respect to the compiled code sections. The linker needs to know where in memory to locate each of the sections of code, based on the type of section and its attributes. Sometimes, these linker scripts can be modified by the developer to add custom sections for very specific purposes, but typically they are provided by software development environments.

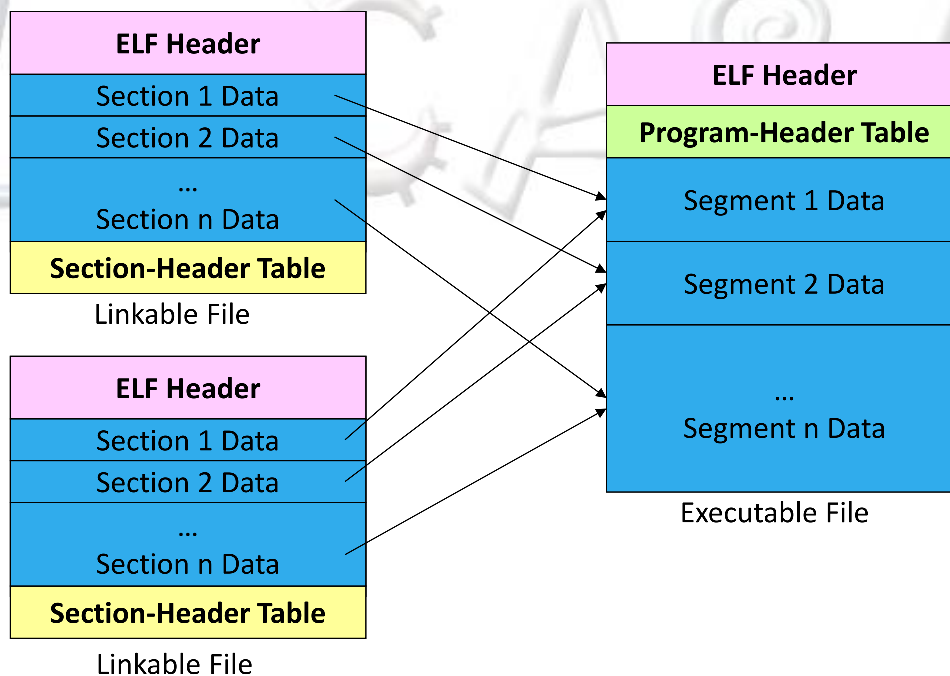


Figure 3. Linking Object Files into an Executable File.

The executable ELF file consists of segments. All loadable sections are packed into segments. Segments are parts with code and data that are loaded into memory at run-time. Utility

programs that load executable files into memory and start program execution are called loaders. Segments have:

- Type
- Requested memory location
- Permissions (R, W, X)
- Size (in file and in memory)

Table 2 shows common segments in ELF executable files.

Table 2. ELF Executable View: Common Segments.

Common Segments	Description
LOAD	Portion of file to be loaded into memory
INTERP	Pointer to dynamic linker for this executable (.interp section)
DYNAMIC	Pointer to dynamic linking information (.dynamic section)

3 GNU Utilities

In this section we will give a brief introduction to GNU Binary Utilities, also known as binutils. Binutils is a set of programming tools for creating and managing binary programs, object files, profile data, and assembly source code. Table 3 shows a list of commonly used binutils.

Table 3. Common GNU utilities

Utility	Description
as	Assembler
elfedit	Edit ELF files
gdb	Debugger
gprof	Profiler
ld	Linker
objcopy	Copy object files, possibly making changes
objdump	Dump information about object files
nm	List symbols from object files
readelf	Display content of ELF files
strings	List printable strings
size	List total and section sizes

strip	Remove symbols from an object file

Texas Instruments partnered with a third party company to support open-source compiler called MSP430 GCC that originated from a community-driven MSPGCC. MSP430 GCC can be used as a stand-alone package or it can be used within Code Composer Studio (CCS) IDE v6.0 or later as an Add-On through the CCS's App Center.
You can locate various MSP430 GNU utilities from a Windows Command Prompt as shown in Figure 4. To learn more about each utility, run each of them with `--help` switch. Here we will take a closer look at several of these utilities of interest for software reverse engineering tasks:

- msp430-elf-readelf: displays information about executable files (Figure 5);
- msp430-elf-objdump: disassembler (Figure 6);
- msp430-elf-strings: displays printable strings (Figure 7).

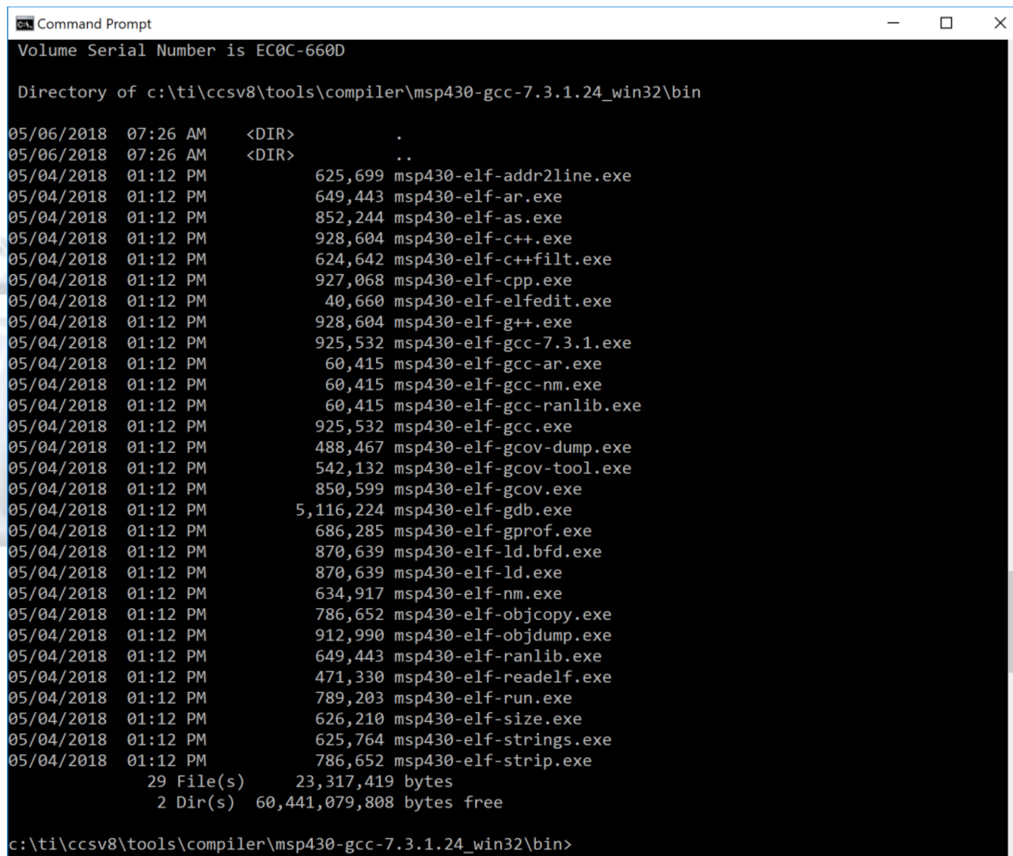


Figure 4. Windows Command Prompt: List of GNU Utilities

```
1   c:\ti\ccsv8\tools\compiler\msp430-gcc-7.3.1.24_win32\bin>msp430-elf-readelf.exe --help
2   Usage: readelf <option(s)> elf-file(s)
3    Display information about the contents of ELF format files
4    Options are:
5     -a --all               Equivalent to: -h -l -S -s -r -d -V -A -I
6     -h --file-header       Display the ELF file header
7     -l --program-headers   Display the program headers
```

```
8         --segments          An alias for --program-headers
9      -S --section-headers   Display the sections' header
10        --sections          An alias for --section-headers
11     -g --section-groups    Display the section groups
12     -t --section-details   Display the section details
13     -e --headers           Equivalent to: -h -l -S
14     -s --syms              Display the symbol table
15        --symbols           An alias for --syms
16     --dyn-syms             Display the dynamic symbol table
17     -n --notes             Display the core notes (if present)
18     -r --relocs            Display the relocations (if present)
19     -u --unwind            Display the unwind info (if present)
20     -d --dynamic           Display the dynamic section (if present)
21     -V --version-info      Display the version sections (if present)
22     -A --arch-specific     Display architecture specific information (if any)
23     -c --archive-index     Display the symbol/file index in an archive
24     -D --use-dynamic       Use the dynamic section info when displaying symbols
25     -x --hex-dump=<number|name>
26                            Dump the contents of section <number|name> as bytes
27     -p --string-dump=<number|name>
28                            Dump the contents of section <number|name> as strings
29     -R --relocated-dump=<number|name>
30                            Dump the contents of section <number|name> as relocated bytes
31     -z --decompress        Decompress section before dumping it
32     -w[lLiaprmfFsoRt] or
33     --debug-dump[=rawline,=decodedline,=info,=abbrev,=pubnames,=aranges,=macro,=frames,
34                  =frames-interp,=str,=loc,=Ranges,=pubtypes,
35                  =gdb_index,=trace_info,=trace_abbrev,=trace_aranges,
36                  =addr,=cu_index]
37                            Display the contents of DWARF2 debug sections
38     --dwarf-depth=N        Do not display DIEs at depth N or greater
39     --dwarf-start=N        Display DIEs starting with N, at the same depth
40                            or deeper
41     -I --histogram         Display histogram of bucket list lengths
42     -W --wide              Allow output width to exceed 80 characters
43     @<file>                Read options from <file>
44     -H --help              Display this information
45     -v --version           Display the version number of readelf
46   Report bugs to <http://www.sourceware.org/bugzilla/>
47
```

Figure 5. msp430-elf-readelf Utility: Help System.

```
1    c:\ti\ccsv8\tools\compiler\msp430-gcc-7.3.1.24_win32\bin>msp430-elf-objdump.exe --help
2    Usage: msp430-elf-objdump.exe <option(s)> <file(s)>
3     Display information from object <file(s)>.
4     At least one of the following switches must be given:
5      -a, --archive-headers    Display archive header information
6      -f, --file-headers       Display the contents of the overall file header
7      -p, --private-headers    Display object format specific file header contents
8      -P, --private=OPT,OPT... Display object format specific contents
9      -h, --[section-]headers  Display the contents of the section headers
10     -x, --all-headers        Display the contents of all headers
11     -d, --disassemble        Display assembler contents of executable sections
12     -D, --disassemble-all    Display assembler contents of all sections
13     -S, --source             Intermix source code with disassembly
14     -s, --full-contents      Display the full contents of all sections requested
15     -g, --debugging          Display debug information in object file
16     -e, --debugging-tags     Display debug information using ctags style
17     -G, --stabs              Display (in raw form) any STABS info in the file
```

```
18      -W[lLiaprmfFsoRt] or
19      --dwarf[=rawline,=decodedline,=info,=abbrev,=pubnames,=aranges,=macro,=frames,
20              =frames-interp,=str,=loc,=Ranges,=pubtypes,
21              =gdb_index,=trace_info,=trace_abbrev,=trace_aranges,
22              =addr,=cu_index]
23                               Display DWARF info in the file
24      -t, --syms               Display the contents of the symbol table(s)
25      -T, --dynamic-syms       Display the contents of the dynamic symbol table
26      -r, --reloc              Display the relocation entries in the file
27      -R, --dynamic-reloc      Display the dynamic relocation entries in the file
28      @<file>                  Read options from <file>
29      -v, --version            Display this program's version number
30      -i, --info               List object formats and architectures supported
31      -H, --help               Display this information
32
33     The following switches are optional:
34      -b, --target=BFDNAME           Specify the target object format as BFDNAME
35      -m, --architecture=MACHINE     Specify the target architecture as MACHINE
36      -j, --section=NAME             Only display information for section NAME
37      -M, --disassembler-options=OPT Pass text OPT on to the disassembler
38      -EB --endian=big               Assume big endian format when disassembling
39      -EL --endian=little            Assume little endian format when disassembling
40          --file-start-context       Include context from start of file (with -S)
41      -I, --include=DIR              Add DIR to search list for source files
42      -l, --line-numbers             Include line numbers and filenames in output
43      -F, --file-offsets             Include file offsets when displaying information
44      -C, --demangle[=STYLE]         Decode mangled/processed symbol names
45                                      The STYLE, if specified, can be `auto', `gnu',
46                                      `lucid', `arm', `hp', `edg', `gnu-v3', `java'
47                                      or `gnat'
48      -w, --wide                     Format output for more than 80 columns
49      -z, --disassemble-zeroes       Do not skip blocks of zeroes when disassembling
50          --start-address=ADDR       Only process data whose address is >= ADDR
51          --stop-address=ADDR        Only process data whose address is <= ADDR
52          --prefix-addresses         Print complete address alongside disassembly
53          --[no-]show-raw-insn       Display hex alongside symbolic disassembly
54          --insn-width=WIDTH         Display WIDTH bytes on a single line for -d
55          --adjust-vma=OFFSET        Add OFFSET to all displayed section addresses
56          --special-syms             Include special symbols in symbol dumps
57          --prefix=PREFIX            Add PREFIX to absolute paths for -S
58          --prefix-strip=LEVEL       Strip initial directory names for -S
59          --dwarf-depth=N        Do not display DIEs at depth N or greater
60          --dwarf-start=N        Display DIEs starting with N, at the same depth
61                                 or deeper
62          --dwarf-check          Make additional dwarf internal consistency checks.
63
64    msp430-elf-objdump.exe: supported targets: elf32-msp430 elf32-msp430 elf32-little elf32-big
65    plugin srec symbolsrec verilog tekhex binary ihex
66    msp430-elf-objdump.exe: supported architectures: msp:14 MSP430 MSP430x11x1 MSP430x12 MSP430x13
67    MSP430x14 MSP430x15 MSP430x16 MSP430x20 MSP430x21 MSP430x22 MSP430x23 MSP430x24 MSP430x26
68    MSP430x31 MSP430x32 MSP430x33 MSP430x41 MSP430x42 MSP430x43 MSP430x44 MSP430x46 MSP430x47
69    MSP430x54 MSP430X plugin
70    Report bugs to <http://www.sourceware.org/bugzilla/>.
```

Figure 6. msp430-elf-objdump Utility: Help System.

```
1     c:\ti\ccsv8\tools\compiler\msp430-gcc-7.3.1.24_win32\bin>msp430-elf-strings.exe --help
2     Usage: msp430-elf-strings.exe [option(s)] [file(s)]
3      Display printable strings in [file(s)] (stdin by default)
4      The options are:
```

```
5     -a - --all                 Scan the entire file, not just the data section [default]
6     -d --data                  Only scan the data sections in the file
7     -f --print-file-name       Print the name of the file before each string
8     -n --bytes=[number]        Locate & print any NUL-terminated sequence of at
9     -<number>                    least [number] characters (default 4).
10    -t --radix={o,d,x}         Print the location of the string in base 8, 10 or 16
11    -w --include-all-whitespace Include all whitespace as valid string characters
12    -o                         An alias for --radix=o
13    -T --target=<BFDNAME>      Specify the binary file format
14    -e --encoding={s,S,b,l,B,L} Select character size and endianness:
15                               s = 7-bit, S = 8-bit, {b,l} = 16-bit, {B,L} = 32-bit
16    -s --output-separator=<string> String used to separate strings in output.
17    @<file>                    Read options from <file>
18    -h --help                  Display this information
19    -v -V --version            Print the program's version number
20  msp430-elf-strings.exe: supported targets: elf32-msp430 elf32-msp430 elf32-little elf32-big
21  plugin srec symbolsrec verilog tekhex binary ihex
22  Report bugs to <http://www.sourceware.org/bugzilla/>
```

Figure 7. msp430-elf-strings Utility: Help System.

4 Deconstructing Executable Files: An Example

To demonstrate software reverse engineering in practice, let us start from a C program described in Figure 8. This program toggles the LEDs connected to ports P2.1 and P2.2 on the TI Experimenter's board. Our first step is to compile this program using GNU C compiler that comes as an Add-on in TI's Code Composer Studio. To compile this program we select the GNU C compiler and set appropriate compilation flags as shown in Figure 9.

```
1   /******************************************************************************
2    *   File:        ToggleLEDs.c
3    *   Description: Program toggles LED1 and LED2 by
4    *                xoring port pins inside of an infinite loop.
5    *   Board:       MSP430FG461x/F20xx Experimenter Board
6    *   Clocks:      ACLK = 32.768kHz, MCLK = SMCLK = default DCO
7    *
8    *                 MSP430FG461x
9    *             -----------------
10   *         /|\|                 |
11   *          | |                 |
12   *          --|RST              |
13   *            |                 |
14   *            |             P2.1|--> LED2
15   *            |             P2.2|--> LED1
16   *
17   *   Author: Alex Milenkovich, milenkovic@computer.org
18   *   Date:   September 2010
19  ******************************************************************************/
20  #include  <msp430.h>
21
22  int main(void) {
23     WDTCTL = WDTPW + WDTHOLD;     // Stop watchdog timer
24     P2DIR |= (BIT1 | BIT2);       // Set P2.1 and P2.2 to output direction (0000_0110)
25     P2OUT = 0x00;                 // Clear output port P2, P2OUT=0000_0000b
26     for (;;) {
```

```
27          unsigned int i;
28          P2OUT ^= (BIT1 | BIT2);     // Toggle P2.1 and P2.2 using exclusive-OR
29          for(i = 0; i < 50000; i++); // Software delay (13 cc per iteration)
30          /* Total delay on average 13 cc*50,000 = 750,000; 750,000 * 1us = 0.75 s */
31        }
32        return 0;
33    }
```

Figure 8. ToggleLEDs Source Code.

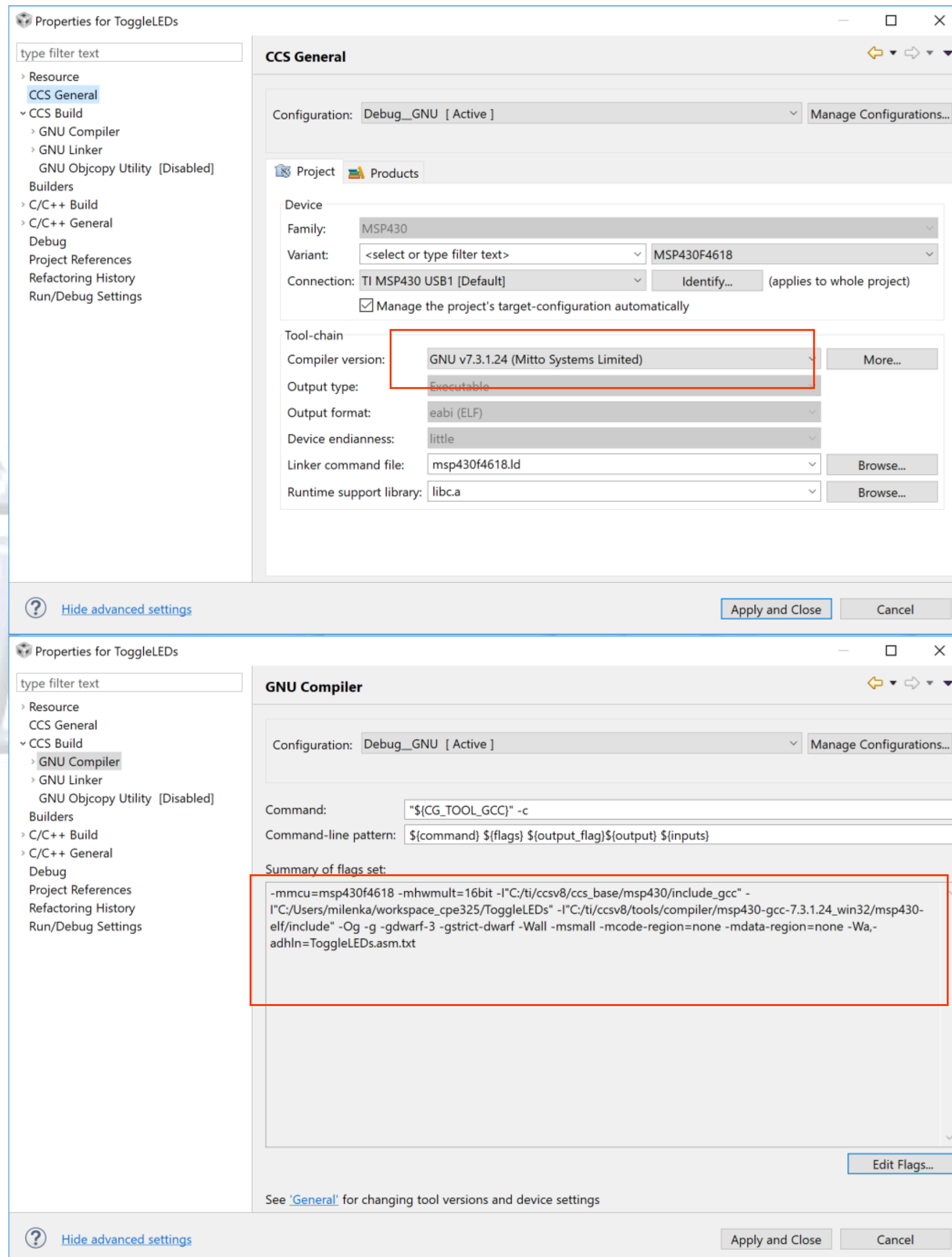


Figure 9. Settings for GNU C Compiler.

As the result of compilation you will notice ToggleLEDs.o (object file), ToggleLEDs.out (executable file), and ToggleLEDs.asm.txt (assembly code created by the compiler switches –Wa,-adhln=ToggleLEDs.asm.txt). Figure 10 shows the output list file with assembly code for each line of the source code in C.

```
1      1                   .file  "ToggleLEDs.c"
2      2                   .text
3      3                   .Ltext0:
4      4                   .balign 2
5      5                   .globalmain
6      7                    main:
7      8                   .LFB0:
8      9                   .file 1 "../ToggleLEDs.c"
9      1:../ToggleLEDs.c ****
10   /*****************************************************************************
11     2:../ToggleLEDs.c ****  *   File:        ToggleLEDs.c
12     3:../ToggleLEDs.c ****  *   Description: Program toggles LED1 and LED2 by
13     4:../ToggleLEDs.c ****  *                xoring port pins inside of an infinite loop.
14     5:../ToggleLEDs.c ****  *   Board:       MSP430FG461x/F20xx Experimenter Board
15     6:../ToggleLEDs.c ****  *   Clocks:      ACLK = 32.768kHz, MCLK = SMCLK = default DCO
16     7:../ToggleLEDs.c ****  *
17     8:../ToggleLEDs.c ****  *                 MSP430FG461x
18     9:../ToggleLEDs.c ****  *             -----------------
19    10:../ToggleLEDs.c ****  *         /|\|                 |
20    11:../ToggleLEDs.c ****  *          | |                 |
21    12:../ToggleLEDs.c ****  *          --|RST              |
22    13:../ToggleLEDs.c ****  *            |                 |
23    14:../ToggleLEDs.c ****  *            |             P2.1|--> LED2
24    15:../ToggleLEDs.c ****  *            |             P2.2|--> LED1
25    16:../ToggleLEDs.c ****  *
26    17:../ToggleLEDs.c ****  *   Author: Alex Milenkovich, milenkovic@computer.org
27    18:../ToggleLEDs.c ****  *   Date:   September 2010
28    19:../ToggleLEDs.c ****
29   *****************************************************************************/
30    20:../ToggleLEDs.c **** #include  <msp430.h>
31    21:../ToggleLEDs.c ****
32    22:../ToggleLEDs.c **** int main(void)
33    23:../ToggleLEDs.c **** {
34    10                   .loc 1 23 0
35    11                   ; start of function
36    12                   ; framesize_regs:     0
37    13                   ; framesize_locals:   0
38    14                   ; framesize_outgoing: 0
39    15                   ; framesize:          0
40    16                   ; elim ap -> fp       2
41    17                   ; elim fp -> sp       0
42    18                   ; saved regs:(none)
43    19                   ; start of prologue
44    20                   ; end of prologue
45    24:../ToggleLEDs.c ****    WDTCTL = WDTPW + WDTHOLD;    // Stop watchdog timer
46    21                   .loc 1 24 0
47    22 0000 B240 805A    MOV.W #23168, &WDTCTL
48    22      0000
49    25:../ToggleLEDs.c ****    P2DIR |= (BIT1 | BIT2);      // Set P2.1 and P2.2 to output
50   direction (0000_0110)
51    23                    .loc 1 25 0
52    24 0006 F2D0 0600     BIS.B #6, &P2DIR
53    24      0000
```

```
54    26:../ToggleLEDs.c ****    P2OUT = 0x00;                // Clear output port P2,
55  P2OUT=0000_0000b
56    25                     .loc 1 26 0
57    26 000c C243 0000     MOV.B #0, &P2OUT
58    27 0010 3040 0000     BR #.L4
59    28                     .LVL0:
60    29                     .L3:
61    30                     .LBB2:
62    27:../ToggleLEDs.c ****    for (;;) {
63    28:../ToggleLEDs.c ****      unsigned int i;
64    29:../ToggleLEDs.c ****      P2OUT ^= (BIT1 | BIT2);    // Toggle P2.1 and P2.2 using
65  exclusive-OR
66    30:../ToggleLEDs.c ****      for(i = 0; i < 50000; i++); // Software delay (13 cc per
67  iteration)
68    31                      .loc 1 30 0
69    32 0014 1C53            ADD.W #1, R12
70    33                    .LVL1:
71    34                    .L2:
72    35                     .loc 1 30 0 is_stmt 0
73    36 0016 3D40 4FC3    MOV.W #-15537, R13
74    37 001a 0D9C 002C    CMP.W R12, R13 { JHS .L3
75    38                    .LVL2:
76    39                    .L4:
77    29:../ToggleLEDs.c ****      for(i = 0; i < 50000; i++); // Software delay (13 cc per
78  iteration)
79    40                     .loc 1 29 0 is_stmt 1
80    41 001e F2E0 0600     XOR.B #6, &P2OUT
81    41      0000
82    42                     .LVL3:
83    43                     .loc 1 30 0
84    44 0024 4C43          MOV.B #0, R12
85    45 0026 3040 0000     BR #.L2
86    46                   .LBE2:
87    47                   .LFE0:
88    75                   .Letext0:
89    76                    .file 2 "C:/ti/ccsv8/ccs_base/msp430/include_gcc/msp430f4618.h"
```

Figure 10. Output Assembly Code Generated by GNU GCC Compiler

For the moment, let us assume that we are given the executable file and that we have no prior knowledge what that executable code is doing. Here we will demonstrate steps we can take to deconstruct or reverse engineer code from the executable file.

Step #1: **Examine ELF header to determine type of machine code, data representation, entry points and more**. We can use msp430-elf-readelf to learn more about the executable file. Switch *--file-header* displays information about the ELF header: this is an ELF32 executable file, containing code for MSP430 microcontroller, the entry program point is at address 0x310c, and so on (see Figure 11).

```
1  C:\Users\milenka\workspace_cpe325\ToggleLEDs\Debug__GNU>msp430-elf-readelf -h ToggleLEDs.out
2  ELF Header:
3    Magic:   7f 45 4c 46 01 01 01 ff 00 00 00 00 00 00 00 00
4    Class:                             ELF32
5    Data:                              2's complement, little endian
6    Version:                           1 (current)
7    OS/ABI:                            Standalone App
```

```
 8      ABI Version:                       0
 9      Type:                              EXEC (Executable file)
10      Machine:                           Texas Instruments msp430 microcontroller
11      Version:                           0x1
12      Entry point address:               0x310c
13      Start of program headers:          52 (bytes into file)
14      Start of section headers:          12920 (bytes into file)
15      Flags:                             0x2d: architecture variant: MSP430X
16      Size of this header:               52 (bytes)
17      Size of program headers:           32 (bytes)
18      Number of program headers:         5
19      Size of section headers:           40 (bytes)
20      Number of section headers:         25
21      Section header string table index: 22
```

Figure 11. msp430-elf-readelf –file-header (-h): ELF Header Content for ToggleLEDs.out

Step #2. **Examine ELF file sections**.

We can use msp430-elf-readelf utility with --section-headers switch to display information about all sections. Figure 12 shows the output of this command for ToggleLEDs.out. A similar information can be obtained using objdump utility with –h switch as shown in Figure 13. The list of sections includes the section name, the starting addresses (VMA – virtual and LMA – load memory address), the offset of the section in the actual file, the size of the section, the section attributes, and the alignment in memory.

The __reset_vector, .rodata, and .text sections reside in the Flash memory (read only). The .rodata2 starts at the address 0x3100 and the size is 12 bytes (0x000c). The .lowtext starts at 0x310c (right after that) and has the size of 0x66 bytes (102 bytes). It is followed by the .text section that starts at 0x3172 and contain 0x146 bytes. The RAM memory region consists of .data and .bss sections. The .bss section starts at address 0x1100 and occupies 0x12 (18) bytes, followed by the .heap section at 0x1112. Another noteworthy entry is __reset_vector that sits at the address 0xFFFE.

```
 1  C:\Users\milenka\workspace_cpe325\ToggleLEDs\Debug__GNU>msp430-elf-readelf --section-headers
 2  ToggleLEDs.out
 3  There are 25 section headers, starting at offset 0x3278:
 4
 5  Section Headers:
 6    [Nr] Name              Type            Addr     Off    Size   ES Flg Lk Inf Al
 7    [ 0]                   NULL            00000000 000000 000000 00      0   0  0
 8    [ 1] __reset_vector    PROGBITS        0000fffe 00028e 000002 00   A  0   0  1
 9    [ 2] .lower.rodata     PROGBITS        00003100 000290 000000 00   W  0   0  1
10    [ 3] .rodata           PROGBITS        00003100 000290 000000 00  WA  0   0  1
11    [ 4] .rodata2          PROGBITS        00003100 0000d4 00000c 00  WA  0   0  4
12    [ 5] .data             PROGBITS        00001100 000290 000000 00  WA  0   0  1
13    [ 6] .bss              NOBITS          00001100 0000e0 000012 00  WA  0   0  2
14    [ 7] .noinit           PROGBITS        00001112 000290 000000 00   W  0   0  1
15    [ 8] .heap             NOBITS          00001112 0000e2 000004 00  WA  0   0  1
16    [ 9] .lowtext          PROGBITS        0000310c 0000e0 000066 00  AX  0   0  1
17    [10] .lower.text       PROGBITS        00003172 000290 000000 00   W  0   0  1
18    [11] .text             PROGBITS        00003172 000146 000146 00  AX  0   0  2
19    [12] .upper.text       PROGBITS        00010000 000290 000000 00   W  0   0  1
20    [13] .MSP430.attribute MSP430_ATTRIBUT 00000000 000290 000017 00      0   0  1
21    [14] .comment          PROGBITS        00000000 0002a7 000039 01  MS  0   0  1
22    [15] .debug_aranges    PROGBITS        00000000 0002e0 000020 00      0   0  1
```

```
23     [16] .debug_info       PROGBITS        00000000 000300 000d42 00      0   0  1
24     [17] .debug_abbrev     PROGBITS        00000000 001042 0000a6 00      0   0  1
25     [18] .debug_line       PROGBITS        00000000 0010e8 0000a5 00      0   0  1
26     [19] .debug_frame      PROGBITS        00000000 001190 000024 00      0   0  4
27     [20] .debug_str        PROGBITS        00000000 0011b4 0007f8 01  MS  0   0  1
28     [21] .debug_loc        PROGBITS        00000000 0019ac 000013 00      0   0  1
29     [22] .shstrtab         STRTAB          00000000 003187 0000ef 00      0   0  1
30     [23] .symtab           SYMTAB          00000000 0019c0 000f20 10     24 196  4
31     [24] .strtab           STRTAB          00000000 0028e0 0008a7 00      0   0  1
32   Key to Flags:
33     W (write), A (alloc), X (execute), M (merge), S (strings)
34     I (info), L (link order), G (group), T (TLS), E (exclude), x (unknown)
35     O (extra OS processing required) o (OS specific), p (processor specific)
```

Figure 12. msp430-elf-readelf –section-headers (-S): ELF section headers for ToggleLEDs.out

```
1    C:\Users\milenka\workspace_cpe325\ToggleLEDs\Debug__GNU>msp430-elf-objdump -h ToggleLEDs.out
2
3    ToggleLEDs.out:     file format elf32-msp430
4
5    Sections:
6    Idx Name          Size      VMA       LMA       File off  Algn
7      0 __reset_vector 00000002  0000fffe  0000fffe  0000028e  2**0
8                      CONTENTS, ALLOC, LOAD, READONLY, DATA
9      1 .lower.rodata 00000000  00003100  00003100  00000290  2**0
10                     CONTENTS
11     2 .rodata       00000000  00003100  00003100  00000290  2**0
12                     CONTENTS, ALLOC, LOAD, DATA
13     3 .rodata2      0000000c  00003100  00003100  000000d4  2**2
14                     CONTENTS, ALLOC, LOAD, DATA
15     4 .data         00000000  00001100  00001100  00000290  2**0
16                     CONTENTS, ALLOC, LOAD, DATA
17     5 .bss          00000012  00001100  0000310c  000000e0  2**1
18                     ALLOC
19     6 .noinit       00000000  00001112  00001112  00000290  2**0
20                     CONTENTS
21     7 .heap         00000004  00001112  0000310c  000000e2  2**0
22                     ALLOC
23     8 .lowtext      00000066  0000310c  0000310c  000000e0  2**0
24                     CONTENTS, ALLOC, LOAD, READONLY, CODE
25     9 .lower.text   00000000  00003172  00003172  00000290  2**0
26                     CONTENTS
27    10 .text         00000146  00003172  00003172  00000146  2**1
28                     CONTENTS, ALLOC, LOAD, READONLY, CODE
29    11 .upper.text   00000000  00010000  00010000  00000290  2**0
30                     CONTENTS
31    12 .MSP430.attributes 00000017  00000000  00000000  00000290  2**0
32                     CONTENTS, READONLY
33    13 .comment      00000039  00000000  00000000  000002a7  2**0
34                     CONTENTS, READONLY
35    14 .debug_aranges 00000020  00000000  00000000  000002e0  2**0
36                     CONTENTS, READONLY, DEBUGGING
37    15 .debug_info   00000d42  00000000  00000000  00000300  2**0
38                     CONTENTS, READONLY, DEBUGGING
39    16 .debug_abbrev 000000a6  00000000  00000000  00001042  2**0
40                     CONTENTS, READONLY, DEBUGGING
41    17 .debug_line   000000a5  00000000  00000000  000010e8  2**0
42                     CONTENTS, READONLY, DEBUGGING
43    18 .debug_frame  00000024  00000000  00000000  00001190  2**2
44                     CONTENTS, READONLY, DEBUGGING
```

```
45   19 .debug_str    000007f8  00000000  00000000  000011b4  2**0
46                    CONTENTS, READONLY, DEBUGGING
47   20 .debug_loc    00000013  00000000  00000000  000019ac  2**0
48                    CONTENTS, READONLY, DEBUGGING
```

Figure 13. msp430-elf-objdump –h: ELF section headers for ToggleLEDs.out

Step #3. **Display ELF symbols**.

We use msp430-elf-readelf utility with --symbols switch (or –s) to display all symbols in the ELF file. Figure 15 shows a filtered output of this utility for ToggleLEDs.out (the full list contains 241 symbols). A similar output can be obtained by using msp430-elf-objdump utility with switch –t or by using a separate binutils utility msp430-elf-nm. By searching the output you can identify important symbols such as '_start', '__stack', '__heap_start__', '_bssstart', 'main', and others. These sections and their locations are defined in the linker script file for the given microcontroller as the placement is a function of the size and mapping of Flash and RAM memory.

```
1
2   Symbol table '.symtab' contains 242 entries:
3      Num:    Value  Size Type    Bind   Vis      Ndx Name
4        0: 00000000     0 NOTYPE  LOCAL  DEFAULT  UND
5        1: 0000fffe     0 SECTION LOCAL  DEFAULT    1
6        2: 00003100     0 SECTION LOCAL  DEFAULT    2
7        3: 00003100     0 SECTION LOCAL  DEFAULT    3
8   .....
9      195: 0000310c     0 NOTYPE  LOCAL  DEFAULT    9 _start
10     196: 0000323e    56 FUNC    GLOBAL DEFAULT   11 memmove
11     197: 000032b8     0 OBJECT  GLOBAL HIDDEN    11 __TMC_END__
12     198: 0000310a     0 OBJECT  GLOBAL HIDDEN     4 __DTOR_END__
13     199: 00003100     0 NOTYPE  GLOBAL DEFAULT    3 __fini_array_end
14     200: 0000002a     0 NOTYPE  GLOBAL DEFAULT  ABS P2DIR
15     201: 00000120     0 NOTYPE  GLOBAL DEFAULT  ABS WDTCTL
16     202: 0000310c     4 FUNC    GLOBAL DEFAULT    9 __crt0_start
17     203: 00001116     0 NOTYPE  GLOBAL DEFAULT    8 __HeapLimit
18     204: 00001116     0 NOTYPE  GLOBAL DEFAULT    8 __heap_end__
19     205: 00003110    14 FUNC    GLOBAL DEFAULT    9 __crt0_init_bss
20     206: 00000012     0 NOTYPE  GLOBAL DEFAULT  ABS __bsssize
21     207: 00003132    10 FUNC    GLOBAL DEFAULT    9 __crt0_call_init_then_mai
22     208: 00000000     0 NOTYPE  WEAK   DEFAULT  UND __deregister_frame_info
23     209: 00000000     0 NOTYPE  WEAK   DEFAULT  UND _ITM_registerTMCloneTable
24     210: 00003154     0 FUNC    GLOBAL DEFAULT    9 _msp430_run_fini_array
25     211: 00000000     0 NOTYPE  GLOBAL DEFAULT  ABS __romdatacopysize
26     212: 00000029     0 NOTYPE  GLOBAL DEFAULT  ABS P2OUT
27     213: 00000000     0 NOTYPE  WEAK   DEFAULT  UND _ITM_deregisterTMCloneTab
28     214: 00003100     0 NOTYPE  GLOBAL DEFAULT    3 __fini_array_start
29     215: 00000000     0 NOTYPE  WEAK   DEFAULT  ABS __rom_highdatacopysize
30     216: 0000329c     0 NOTYPE  GLOBAL DEFAULT   11 __msp430_init
31     217: 00003272    20 FUNC    GLOBAL DEFAULT   11 memset
32     218: 00003218    42 FUNC    GLOBAL DEFAULT   11 main
33     219: 00003100     0 NOTYPE  GLOBAL DEFAULT    3 __init_array_end
34     220: 00001112     0 NOTYPE  GLOBAL DEFAULT    8 __heap_start__
35     221: 00000000     0 NOTYPE  WEAK   DEFAULT  ABS __high_bsssize
36     222: 00000000     0 NOTYPE  WEAK   DEFAULT  ABS __rom_highdatastart
37     223: 000032b8     0 NOTYPE  GLOBAL DEFAULT   11 __msp430_fini_end
38     224: 0000310c     0 NOTYPE  GLOBAL DEFAULT  ABS __romdatastart
39     225: 0000313c     0 FUNC    GLOBAL DEFAULT    9 _msp430_run_init_array
```

```
40      226: 00003100     0 NOTYPE  GLOBAL DEFAULT    3 __preinit_array_end
41      227: 00000000     0 NOTYPE  WEAK   DEFAULT  ABS __high_datastart
42      228: 00000000     0 NOTYPE  WEAK   DEFAULT  ABS __upper_data_init
43      229: 00001100     0 NOTYPE  GLOBAL DEFAULT    6 __bssstart
44      230: 00003100     0 NOTYPE  GLOBAL DEFAULT    8 __stack
45      231: 00001100     0 NOTYPE  GLOBAL DEFAULT    5 _edata
46      232: 00001112     0 NOTYPE  GLOBAL DEFAULT    8 _end
47      233: 000032ae     0 NOTYPE  GLOBAL DEFAULT   11 __msp430_init_end
48      234: 00000000     0 NOTYPE  WEAK   DEFAULT  ABS __high_bssstart
49      235: 00003100     0 NOTYPE  GLOBAL DEFAULT    3 __init_array_start
50      236: 00001100     0 NOTYPE  GLOBAL DEFAULT    5 __datastart
51      237: 00003100     0 NOTYPE  GLOBAL DEFAULT    3 __preinit_array_start
52      238: 0000311e    20 FUNC    GLOBAL DEFAULT    9 __crt0_movedata
53      239: 00000000     0 NOTYPE  WEAK   DEFAULT  UND __register_frame_info
54      240: 00003148     0 FUNC    GLOBAL DEFAULT    9 _msp430_run_preinit_array
55      241: 000032ae     0 NOTYPE  GLOBAL DEFAULT   11 __msp430_fini
```

Figure 14. msp430-elf-readelf --symbols: ELF symbols for ToggleLEDs.out

Step #4. **Display ELF segments**.

We use msp430-elf-readelf utility with --program-headers switch (or –segments) to display all segments that are loadable into the memory. Figure 15 shows the output of this utility for ToggleLEDs.out. It shows information about loadable segments in the memory, namely .rodata2 (Flash memory), .bss and .heap (RAM memory), and .text and __reset_vector (Flash memory).

```
1   C:\Users\milenka\workspace_cpe325\ToggleLEDs\Debug__GNU>msp430-elf-readelf --program-headers
2   ToggleLEDs.out
3
4   Elf file type is EXEC (Executable file)
5   Entry point 0x310c
6   There are 5 program headers, starting at offset 52
7
8   Program Headers:
9     Type           Offset   VirtAddr   PhysAddr   FileSiz MemSiz  Flg Align
10    LOAD           0x000000 0x0000302c 0x0000302c 0x000e0 0x000e0 RW  0x4
11    LOAD           0x0000e0 0x00001100 0x0000310c 0x00000 0x00012 RW  0x4
12    LOAD           0x0000e2 0x00001112 0x0000310c 0x00000 0x00004 RW  0x4
13    LOAD           0x0000e0 0x0000310c 0x0000310c 0x001ac 0x001ac R E 0x4
14    LOAD           0x00028e 0x0000fffe 0x0000fffe 0x00002 0x00002 R   0x4
15
16   Section to Segment mapping:
17    Segment Sections...
18     00     .rodata2
19     01     .bss
20     02     .heap
21     03     .lowtext .text
22     04     __reset_vector
```

Figure 15. msp430-elf-readelf: ELF Program Headers or Segments for ToggleLEDs.out (-l or –program-headers)

Step #5. **Disassemble the code**.

Now we are ready to take additional steps toward deconstructing the text segment that contains the code. We use msp430-elf-objdump –S to dump source code together with disassembly. Note: this is a slight deviation from our assumption that source code is not available. Similar results can be obtained using –d (disassembly) that does not assume that

source code is present. Figure 16 shows the result of disassembling operation of the text segment of ToggleLEDs.out executable file. The first thing we can notice is that the first instruction differs from the one shown in Figure 10. The entry point in the program is as expected 0x310c, but the first instruction is the one to initialize the stack pointer, rather than to stop the watchdog timer. This is because the compiler inserts so-called start-up code that proceeds the main code. Thus, first instruction is actually moving the symbol that corresponds to the label __stack (the location above physical RAM) into R1 (stack pointer). Then comes the first label '__crt0_init_bss'. The code following this label does three things, moves __bssstart to R12, clears R13, and then moves __bsssize to R14. Next the subroutine at #0x3272 is called. Can you find what symbol is associated with that address?
This is the memset function. Its prototype is as follows:

```
int memset(void *ptr, int fill, size_t nbytes)
```

We can deduce that the memset is called with the following parameters:

```
int memset(__bssstart, 0, __bsssize)
```

Thus, this function clears the .bss section, as the function name indicates.

Next we have the label '__crt0_movedata'. The symbol __datastart is moved to r12, __romdatastart is moved into r13 and __romdatacopysize is moved into r14. Then memmove is called that will copy the data section from Flash to RAM, so it can be accessed and modified as required. The memmove is called with the following parameters:

```
memmove(__datastart, __romdatastart, __romdatacopysize);
```

Next, '__crt0_call_init_then_main' is called, which sets up some C++ exception handlers or may perform initialization of the standard C library tasks. Finally, the main function is executed, starting at the address 0x3218.

```
1
2   ToggleLEDs.out:     file format elf32-msp430
3
4
5   Disassembly of section .lowtext:
6
7   0000310c <__crt0_start>:
8       310c:      31 40 00 31    mov    #12544, r1     ;#0x3100
9
10  00003110 <__crt0_init_bss>:
11      3110:      3c 40 00 11    mov    #4352, r12    ;#0x1100
12
13  00003114 <.Loc.74.1>:
14      3114:      0d 43          clr    r13           ;
15
16  00003116 <.Loc.75.1>:
17      3116:      3e 40 12 00    mov    #18,   r14    ;#0x0012
18
```

```
19   0000311a <.Loc.79.1>:
20       311a:      b0 12 72 32    call    #12914         ;#0x3272
21
22   0000311e <__crt0_movedata>:
23       311e:      3c 40 00 11    mov     #4352, r12     ;#0x1100
24
25   00003122 <.Loc.116.1>:
26       3122:      3d 40 0c 31    mov     #12556,r13     ;#0x310c
27
28   00003126 <.Loc.119.1>:
29       3126:      0d 9c          cmp     r12,   r13     ;
30
31   00003128 <.Loc.120.1>:
32       3128:      04 24          jz      $+10           ;abs 0x3132
33
34   0000312a <.Loc.122.1>:
35       312a:      3e 40 00 00    mov     #0,    r14     ;
36
37   0000312e <.Loc.124.1>:
38       312e:      b0 12 3e 32    call    #12862         ;#0x323e
39
40   00003132 <__crt0_call_init_then_main>:
41       3132:      b0 12 9c 32    call    #12956         ;#0x329c
42
43   00003136 <.Loc.196.1>:
44       3136:      0c 43          clr     r12            ;
45
46   00003138 <.Loc.197.1>:
47       3138:      b0 12 18 32    call    #12824         ;#0x3218
48
49   0000313c <_msp430_run_init_array>:
50       313c:      34 40 00 31    mov     #12544,r4      ;#0x3100
51
52   00003140 <.Loc.224.1>:
53       3140:      35 40 00 31    mov     #12544,r5      ;#0x3100
54
55   00003144 <.Loc.225.1>:
56       3144:      26 43          mov     #2,    r6      ;r3 As==10
57
58   00003146 <.Loc.226.1>:
59       3146:      0d 3c          jmp     $+28           ;abs 0x3162
60
61   00003148 <_msp430_run_preinit_array>:
62       3148:      34 40 00 31    mov     #12544,r4      ;#0x3100
63
64   0000314c <.Loc.232.1>:
65       314c:      35 40 00 31    mov     #12544,r5      ;#0x3100
66
67   00003150 <.Loc.233.1>:
68       3150:      26 43          mov     #2,    r6      ;r3 As==10
69
70   00003152 <.Loc.234.1>:
71       3152:      07 3c          jmp     $+16           ;abs 0x3162
72
73   00003154 <_msp430_run_fini_array>:
74       3154:      34 40 00 31    mov     #12544,r4      ;#0x3100
75
76   00003158 <.Loc.240.1>:
77       3158:      35 40 00 31    mov     #12544,r5      ;#0x3100
78
79   0000315c <.Loc.241.1>:
```

```
80       315c:      36 40 fe ff    mov     #65534, r6     ;#0xfffe
81
82   00003160 <.Loc.242.1>:
83       3160:      00 3c          jmp     $+2            ;abs 0x3162
84
85   00003162 <_msp430_run_array>:
86       3162:      05 94          cmp     r4,    r5      ;
87
88   00003164 <.Loc.246.1>:
89       3164:      05 24          jz      $+12           ;abs 0x3170
90
91   00003166 <.Loc.247.1>:
92       3166:      27 44          mov     @r4,   r7      ;
93
94   00003168 <.Loc.248.1>:
95       3168:      04 56          add     r6,    r4      ;
96
97   0000316a <.Loc.249.1>:
98       316a:      a7 12          call    @r7            ;
99
100  0000316c <.Loc.250.1>:
101      316c:      10 40 f4 ff    br      0xfff4         ;PC rel. 0x3162
102
103  00003170 <_msp430_run_done>:
104      3170:      30 41          ret
105
106  Disassembly of section .text:
107
108  00003172 <deregister_tm_clones>:
109      3172:      3c 40 b8 32    mov     #12984, r12    ;#0x32b8
110      3176:      3c 90 b8 32    cmp     #12984, r12    ;#0x32b8
111      317a:      07 24          jz      $+16           ;abs 0x318a
112      317c:      3d 40 00 00    mov     #0,    r13     ;
113      3180:      0d 93          cmp     #0,    r13     ;r3 As==00
114      3182:      03 24          jz      $+8            ;abs 0x318a
115      3184:      3c 40 b8 32    mov     #12984, r12    ;#0x32b8
116      3188:      8d 12          call    r13            ;
117
118  0000318a <.L1>:
119      318a:      30 41          ret
120
121  0000318c <register_tm_clones>:
122      318c:      3d 40 b8 32    mov     #12984, r13    ;#0x32b8
123      3190:      3d 80 b8 32    sub     #12984, r13    ;#0x32b8
124      3194:      0d 11          rra     r13            ;
125      3196:      0c 4d          mov     r13,   r12     ;
126      3198:      5c 03          rrum    #1,    r12     ;
127      319a:      4d 18 0c 11    rpt #14 { rrax.w      r12             ;
128      319e:      0d 5c          add     r12,   r13     ;
129      31a0:      0d 11          rra     r13            ;
130      31a2:      0d 93          cmp     #0,    r13     ;r3 As==00
131      31a4:      07 24          jz      $+16           ;abs 0x31b4
132      31a6:      3e 40 00 00    mov     #0,    r14     ;
133      31aa:      0e 93          cmp     #0,    r14     ;r3 As==00
134      31ac:      03 24          jz      $+8            ;abs 0x31b4
135      31ae:      3c 40 b8 32    mov     #12984, r12    ;#0x32b8
136      31b2:      8e 12          call    r14            ;
137
138  000031b4 <.L9>:
139      31b4:      30 41          ret
140
```

```
141  000031b6 <__do_global_dtors_aux>:
142      31b6:      1a 15          pushm   #2,     r10     ;16-bit words
143      31b8:      c2 93 00 11    cmp.b   #0,     &0x1100;r3 As==00
144      31bc:      17 20          jnz     $+48            ;abs 0x31ec
145      31be:      3a 40 0a 31    mov     #12554, r10     ;#0x310a
146      31c2:      3a 80 08 31    sub     #12552, r10     ;#0x3108
147      31c6:      0a 11          rra     r10             ;
148      31c8:      3a 53          add     #-1,    r10     ;r3 As==11
149      31ca:      39 40 08 31    mov     #12552, r9      ;#0x3108
150
151  000031ce <.L19>:
152      31ce:      1c 42 02 11    mov     &0x1102,r12     ;0x1102
153      31d2:      0c 9a          cmp     r10,    r12     ;
154      31d4:      0d 28          jnc     $+28            ;abs 0x31f0
155      31d6:      b0 12 72 31    call    #12658          ;#0x3172
156      31da:      3d 40 00 00    mov     #0,     r13     ;
157      31de:      0d 93          cmp     #0,     r13     ;r3 As==00
158      31e0:      03 24          jz      $+8             ;abs 0x31e8
159      31e2:      3c 40 00 31    mov     #12544, r12     ;#0x3100
160      31e6:      8d 12          call    r13             ;
161
162  000031e8 <.L21>:
163      31e8:      d2 43 00 11    mov.b   #1,     &0x1100;r3 As==01
164
165  000031ec <.L17>:
166      31ec:      19 17          popm    #2,     r10     ;16-bit words
167      31ee:      30 41          ret
168
169  000031f0 <.L20>:
170      31f0:      1c 53          inc     r12             ;
171      31f2:      82 4c 02 11    mov     r12,    &0x1102;
172      31f6:      0c 5c          rla     r12             ;
173      31f8:      0c 59          add     r9,     r12     ;
174      31fa:      2c 4c          mov     @r12,   r12     ;
175      31fc:      8c 12          call    r12             ;
176      31fe:      e7 3f          jmp     $-48            ;abs 0x31ce
177
178  00003200 <frame_dummy>:
179      3200:      3e 40 00 00    mov     #0,     r14     ;
180      3204:      0e 93          cmp     #0,     r14     ;r3 As==00
181      3206:      05 24          jz      $+12            ;abs 0x3212
182      3208:      3d 40 04 11    mov     #4356,  r13     ;#0x1104
183      320c:      3c 40 00 31    mov     #12544, r12     ;#0x3100
184      3210:      8e 12          call    r14             ;
185
186  00003212 <.L27>:
187      3212:      b0 12 8c 31    call    #12684          ;#0x318c
188      3216:      30 41          ret
189
190  00003218 <main>:
191  ********************************************************************************/
192  #include  <msp430.h>
193
194  int main(void)
195  {
196     WDTCTL = WDTPW + WDTHOLD;    // Stop watchdog timer
197      3218:      b2 40 80 5a    mov     #23168,&0x0120;#0x5a80
198      321c:      20 01
199
200  0000321e <.Loc.25.1>:
201     P2DIR |= (BIT1 | BIT2);      // Set P2.1 and P2.2 to output direction (0000_0110)
```

```
202       321e:      f2 d0 06 00    bis.b   #6,    &0x002a;
203       3222:      2a 00
204
205   00003224 <.Loc.26.1>:
206      P2OUT = 0x00;                // Clear output port P2, P2OUT=0000_0000b
207       3224:      c2 43 29 00    mov.b   #0,    &0x0029;r3 As==00
208       3228:      05 3c          jmp     $+12           ;abs 0x3234
209
210   0000322a <.L3>:
211      for (;;) {
212        unsigned int i;
213        P2OUT ^= (BIT1 | BIT2);    // Toggle P2.1 and P2.2 using exclusive-OR
214        for(i = 0; i < 50000; i++); // Software delay (13 cc per iteration)
215       322a:      1c 53          inc     r12            ;
216
217   0000322c <.L2>:
218       322c:      3d 40 4f c3    mov     #49999,r13     ;#0xc34f
219       3230:      0d 9c          cmp     r12,   r13     ;
220       3232:      fb 2f          jc      $-8            ;abs 0x322a
221
222   00003234 <.L4>:
223      WDTCTL = WDTPW + WDTHOLD;    // Stop watchdog timer
224      P2DIR |= (BIT1 | BIT2);      // Set P2.1 and P2.2 to output direction (0000_0110)
225      P2OUT = 0x00;                // Clear output port P2, P2OUT=0000_0000b
226      for (;;) {
227        unsigned int i;
228        P2OUT ^= (BIT1 | BIT2);    // Toggle P2.1 and P2.2 using exclusive-OR
229       3234:      f2 e0 06 00    xor.b   #6,    &0x0029;
230       3238:      29 00
231
232   0000323a <.Loc.30.1>:
233        for(i = 0; i < 50000; i++); // Software delay (13 cc per iteration)
234       323a:      4c 43          clr.b   r12            ;
235       323c:      f7 3f          jmp     $-16           ;abs 0x322c
236
237   0000323e <memmove>:
238       323e:      0d 9c          cmp     r12,   r13     ;
239       3240:      09 28          jnc     $+20           ;abs 0x3254
240
241   00003242 <L0>:
242       3242:      0f 4c          mov     r12,   r15     ;
243       3244:      0e 5c          add     r12,   r14     ;
244
245   00003246 <.L3>:
246       3246:      0e 9f          cmp     r15,   r14     ;
247       3248:      0c 24          jz      $+26           ;abs 0x3262
248
249   0000324a <.LVL3>:
250       324a:      ef 4d 00 00    mov.b   @r13,  0(r15) ;
251       324e:      1f 53          inc     r15            ;
252
253   00003250 <.LVL4>:
254       3250:      1d 53          inc     r13            ;
255       3252:      f9 3f          jmp     $-12           ;abs 0x3246
256
257   00003254 <.L2>:
258       3254:      0f 4d          mov     r13,   r15     ;
259       3256:      0f 5e          add     r14,   r15     ;
260       3258:      0c 9f          cmp     r15,   r12     ;
261       325a:      f3 2f          jc      $-24           ;abs 0x3242
262
```

```
263  0000325c <.L4>:
264      325c:      3e 53          add     #-1,    r14     ;r3 As==11
265
266  0000325e <.LVL7>:
267      325e:      3e 93          cmp     #-1,    r14     ;r3 As==11
268      3260:      01 20          jnz     $+4             ;abs 0x3264
269
270  00003262 <.L10>:
271      3262:      30 41          ret
272
273  00003264 <.L6>:
274      3264:      0b 4c          mov     r12,    r11     ;
275      3266:      0b 5e          add     r14,    r11     ;
276      3268:      0f 4d          mov     r13,    r15     ;
277      326a:      0f 5e          add     r14,    r15     ;
278      326c:      eb 4f 00 00    mov.b   @r15,   0(r11)  ;
279      3270:      f5 3f          jmp     $-20            ;abs 0x325c
280
281  00003272 <memset>:
282      3272:      0f 4c          mov     r12,    r15     ;
283      3274:      0e 5c          add     r12,    r14     ;
284
285  00003276 <L0>:
286      3276:      0f 9e          cmp     r14,    r15     ;
287      3278:      01 20          jnz     $+4             ;abs 0x327c
288
289  0000327a <.Loc.104.1>:
290      327a:      30 41          ret
291
292  0000327c <.L3>:
293      327c:      cf 4d 00 00    mov.b   r13,    0(r15)  ;
294      3280:      1f 53          inc     r15             ;
295
296  00003282 <.LVL4>:
297      3282:      f9 3f          jmp     $-12            ;abs 0x3276
298
299  00003284 <__do_global_ctors_aux>:
300      3284:      0a 15          pushm   #1,     r10     ;16-bit words
301
302  00003286 <L0>:
303      3286:      3a 40 04 31    mov     #12548, r10     ;#0x3104
304
305  0000328a <.L2>:
306      328a:      2c 4a          mov     @r10,   r12     ;
307      328c:      3c 93          cmp     #-1,    r12     ;r3 As==11
308      328e:      02 20          jnz     $+6             ;abs 0x3294
309      3290:      0a 17          popm    #1,     r10     ;16-bit words
310      3292:      30 41          ret
311
312  00003294 <.L3>:
313      3294:      8c 12          call    r12             ;
314      3296:      3a 50 fe ff    add     #65534, r10     ;#0xfffe
315      329a:      f7 3f          jmp     $-16            ;abs 0x328a
316
317  0000329c <__msp430_init>:
318      329c:      b0 12 00 32    call    #12800          ;#0x3200
319      32a0:      b0 12 84 32    call    #12932          ;#0x3284
320
321  000032a4 <L0>:
322      32a4:      b0 12 48 31    call    #12616          ;#0x3148
323
```

```
324  000032a8 <.Loc.19.1>:
325      32a8:      b0 12 3c 31     call    #12604          ;#0x313c
326
327  000032ac <.Loc.20.1>:
328      32ac:      30 41           ret
329
330  000032ae <__msp430_fini>:
331      32ae:      b0 12 54 31     call    #12628          ;#0x3154
332
333  000032b2 <L0>:
334      32b2:      b0 12 b6 31     call    #12726          ;#0x31b6
335
336  000032b6 <L0>:
337      32b6:      30 41           ret
```

Figure 16. msp430-elf-objdump –S for ToggleLEDs.out.

By analyzing the sequence of instructions in the main code, we should deduce what our program is doing. Figure 17 shows the disassembled code for the main code using msp430-objdump –d (there is no C statements displayed in the disassembled code). We can walk through the code one by one instruction, write comments, and then tie everything together into a functional description of what this code does. Line 2 is a MOV instruction that moves immediate #0x5a80 into the address 0x0120 in the address space. This address represents the control register of the watchdog timer. By analyzing the format of this register we can deduce that this instruction stops the watchdog timer. The next instruction is bis.b #6, &0x002a. At the address 0x002a we have a P2DIR register, and this instruction will set port pins at bit positions 1 and 2 to be outputs. The next instruction at 0x3224 clears a byte at the address 0x0029, which represents P2OUT. The following instruction is an unconditional jump to address 0x3234, where an XOR instruction performs a logical XOR operation on P2OUT (effectively toggling bits BIT1 and BIT2 of P2OUT). Then, R13 is cleared and a jump performed to 0x322c, where a loop is executed for 50,000 iterations to implement a software delay. After that P2OUT is toggled again and the entire sequence repeats. Thus, we can finally deduce that this code periodically toggles port pins P2.1 and P2.2.

```
1   00003218 <main>:
2       3218:      b2 40 80 5a     mov     #23168,&0x0120;#0x5a80
3       321c:      20 01
4
5   0000321e <.Loc.25.1>:
6       321e:      f2 d0 06 00     bis.b   #6,     &0x002a;
7       3222:      2a 00
8
9   00003224 <.Loc.26.1>:
10      3224:      c2 43 29 00     mov.b   #0,     &0x0029;r3 As==00
11      3228:      05 3c           jmp     $+12            ;abs 0x3234
12
13  0000322a <.L3>:
14      322a:      1c 53           inc     r12             ;
15
16  0000322c <.L2>:
17      322c:      3d 40 4f c3     mov     #49999,r13      ;#0xc34f
18      3230:      0d 9c           cmp     r12,    r13     ;
19      3232:      fb 2f           jc      $-8             ;abs 0x322a
```

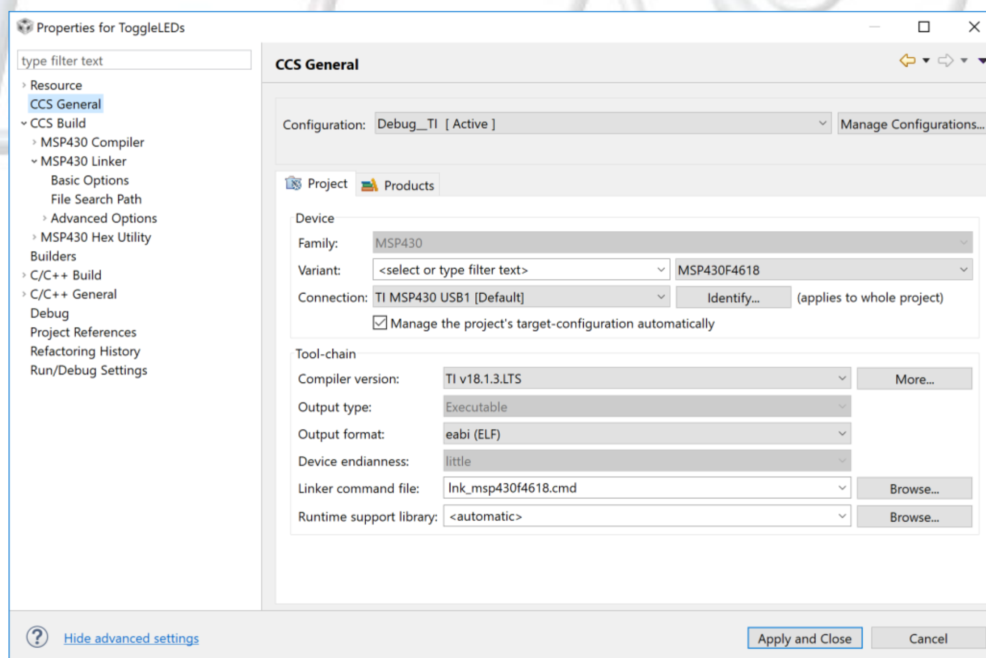
```
20
21  00003234 <.L4>:
22      3234:      f2 e0 06 00    xor.b   #6,     &0x0029;
23      3238:      29 00
24
25  0000323a <.Loc.30.1>:
26      323a:      4c 43          clr.b   r12             ;
27      323c:      f7 3f          jmp     $-16            ;abs 0x322c
```

Figure 17. msp430-elf-objdump –d for ToggleLEDs.out (main section)

A useful exercise is to select the TI compiler instead of MSP430 GCC, create a new executable file, and repeat the analysis of the executable using utilities discussed above: msp430-elf-readelf, msp430-elf-nm, msp430-elf-symbols, and msp430-elf-objdump. What insights can you glean from your analysis?

5 Working with HEX Files and MSP430Flasher Utility

In this section we use ToggleLEDs.c program to demonstrate how to create a HEX file with executable and how to flash it on the target platform using TI's MSP430Flasher utility program. We select the TI compiler in the CCS, enable MSP430 HEX Utility, set General Options and Output Format Options as shown in Figure 18. An output HEX file is created (ToggleLEDs.txt) and its content is shown in Figure 19. This file can be downloaded on the target platform using a TI utility called MSP430Flasher as shown in Figure 20. If everything goes all right, we should see the green and yellow LEDs flashing together.



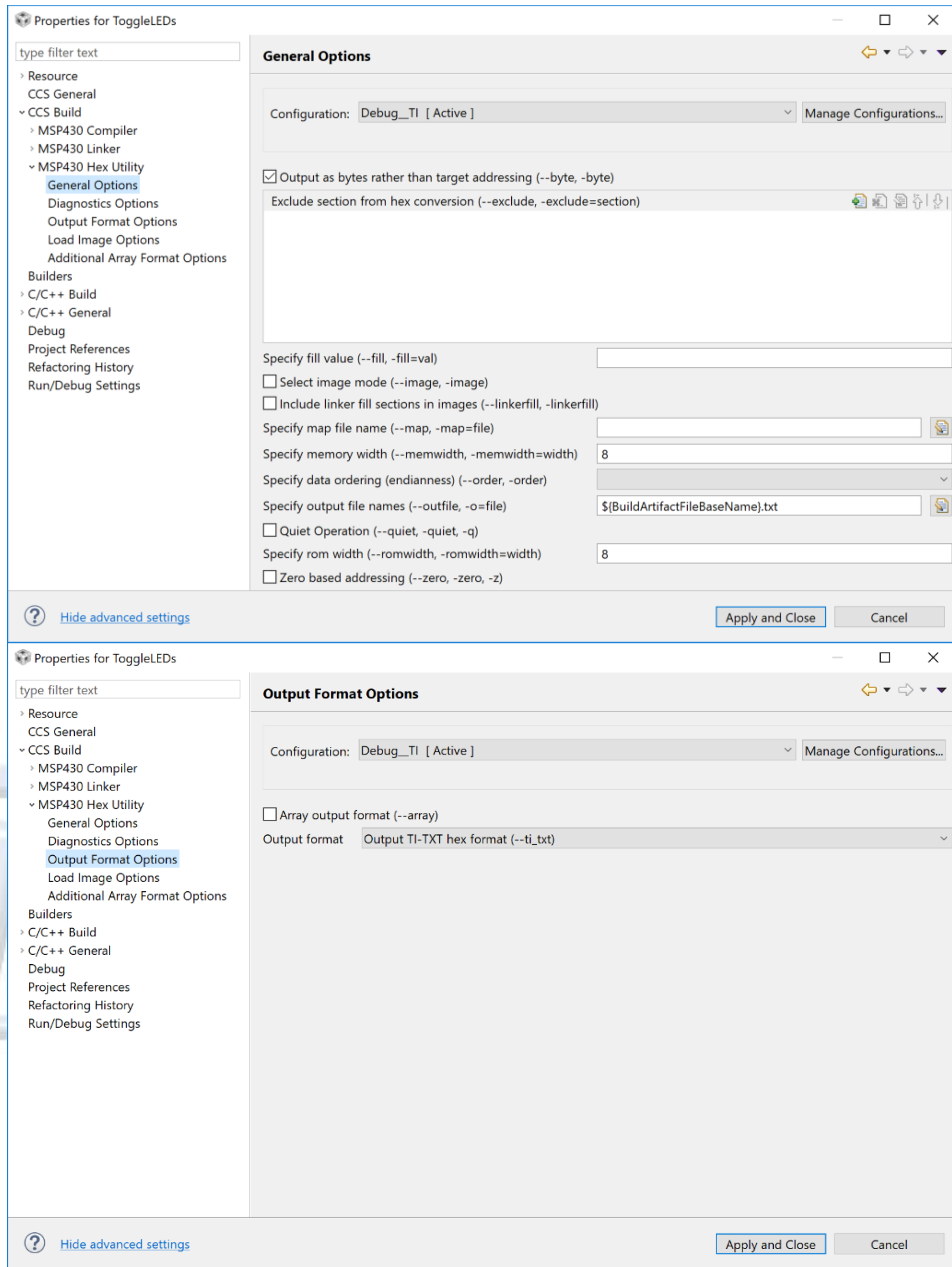


Figure 18. ToggleLEDs Project Properties for Generating HEX files

```
1   @3100
2   B2 40 80 5A 20 01 F2 D0 06 00 2A 00 C2 43 29 00
3   F2 E0 06 00 29 00 0F 43 3F 90 50 C3 F9 2F 1F 53
4   3F 90 50 C3 F5 2F FB 3F 31 40 00 31 B0 12 42 31
5   0C 43 B0 12 00 31 1C 43 B0 12 3C 31 03 43 FF 3F
6   03 43 1C 43 30 41 32 D0 10 00 FD 3F 03 43
7   @ffbe
8   FF FF
9   @ffde
10  46 31 46 31 46 31 46 31 46 31 46 31 46 31 46 31
```

```
11      46 31 46 31 46 31 46 31 46 31 46 31 46 31 46 31
12      28 31
13      q
```

Figure 19. ToggleLEDs.txt: Executable in HEX

```
Command Prompt
C:\Users\milenka\workspace_cpe325\ToggleLEDs\Debug__TI>MSP430Flasher.exe  -n MSP430FG4618 -w ToggleLEDs.txt -v -z [Vcc]
* -----/|-------------------------------------------------------------------- *
*     / |__                                                                   *
*    /_   /   MSP Flasher v1.3.18                                             *
*      | /                                                                    *
* -----|/-------------------------------------------------------------------- *
*
* Evaluating triggers...done
* Checking for available FET debuggers:
* Found USB FET @ COM7 <- Selected
* Initializing interface @ COM7...done
* Checking firmware compatibility:
* FET firmware is up to date.
* Reading FW version...done
* Setting VCC to 3000 mV...done
* Accessing device...done
* Reading device information...done
* Loading file into device...done
* Verifying memory (ToggleLEDs.txt)...done
*
* ----------------------------------------------------------------------------
* Arguments   : -n MSP430FG4618 -w ToggleLEDs.txt -v -z [Vcc]
* ----------------------------------------------------------------------------
* Driver      : loaded
* Dll Version : 31300001
* FwVersion   : 31200000
* Interface   : TIUSB
* HwVersion   : U 3.0
* JTAG Mode   : AUTO
* Device      : MSP430FG4618
* EEM         : Level 3, ClockCntrl 2
* Erase Mode  : ERASE_ALL
* Prog.File   : ToggleLEDs.txt
* Verified    : TRUE
* BSL Unlock  : FALSE
* InfoA Access: FALSE
* VCC ON      : 3000 mV
* ----------------------------------------------------------------------------
* Starting target code execution...done
* Disconnecting from device...done
*
* ----------------------------------------------------------------------------
* Driver      : closed (No error)
* ----------------------------------------------------------------------------
```

Figure 20. Running MSP430Flasher to Download Code to the Platform

MSP430Flasher utility supports many useful functions, but we are especially interested in an option of retrieving the machine code from the actual platform and storing it into an output file in either HEX or text format. Figure 21 shows the process of extracting the code from the platform. The file RetrivedHEX.txt contains the hexadecimal content of the entire Flash memory starting from the address 0x3100. This file is relatively big as it includes the content of the entire Flash memory. The memory locations that contain 0xFF are actually erased locations that do not contain any useful information and thus can be removed from the file. The resulting file without erased Flash locations is named RetrievedHEX_Stripped.txt.

The next step is to run a disassembler that takes a HEX file as an input and produces assembly code that can be inspected and reverse engineered. For this purpose we use naken_util disassembler developed by Michael Kohn and Joe Davisson as follows:

```
naken_util -msp430 -disasm RetrievedHEX_Stripped.txt > ReverseMe.txt
```

Figure 22 shows the resulting assembly code created by naken_util. The next step is to analyze the code line-by-line as shown in Figure 23. We can easily recognize that this code corresponds to ToggleLEDs program. Note: This implementation differs from the one we analyzed above becuase this one is created using TI Compiler instead of MSP430 GCC.

```
Command Prompt
C:\Users\milenka\workspace_cpe325\ToggleLEDs\Debug__TI>MSP430Flasher.exe -r [RetrievedHEX.txt, MAIN]
* -----/|-------------------------------------------------------------------- *
*     / |__                                                                   *
*    /_   /   MSP Flasher v1.3.18                                             *
*      | /                                                                    *
* -----|/-------------------------------------------------------------------- *
*
* Evaluating triggers...done
* Checking for available FET debuggers:
* Found USB FET @ COM7 <- Selected
* Initializing interface @ COM7...done
* Checking firmware compatibility:
* FET firmware is up to date.
* Reading FW version...done
* Setting VCC to 3000 mV...done
* Accessing device...done
* Reading device information...done
* Dumping memory from MAIN into RetrievedHEX.txt...done
*
* ----------------------------------------------------------------------------
* Arguments   : -r [RetrievedHEX.txt, MAIN]
* ----------------------------------------------------------------------------
* Driver      : loaded
* Dll Version : 31300001
* FwVersion   : 31200000
* Interface   : TIUSB
* HwVersion   : U 3.0
* JTAG Mode   : AUTO
* Device      : MSP430FG4618
* EEM         : Level 3, ClockCntrl 2
* Read File   : RetrievedHEX.txt (memory segment = MAIN)
* VCC OFF
* ----------------------------------------------------------------------------
* Powering down...done
* Disconnecting from device...done
*
* ----------------------------------------------------------------------------
* Driver      : closed (No error)
* ----------------------------------------------------------------------------
*/

C:\Users\milenka\workspace_cpe325\ToggleLEDs\Debug__TI>
```

Figure 21. Running MSP430Flasher to Retrieve Code from the Platform

```
1   naken_util - by Michael Kohn
2                   Joe Davisson
3       Web: http://www.mikekohn.net/
4     Email: mike@mikekohn.net
5
6   Version: April 23, 2018
7
8   Loaded ti_txt RetrievedHEX_Stripped.txt from 0x3100 to 0x314f
9   Type help for a list of commands.
10
11  Addr    Opcode Instruction                              Cycles
12  ------- ------ ----------------------------------       ------
13  0x3100: 0x40b2 mov.w #0x5a80, &0x0120                   5
14  0x3102: 0x5a80
15  0x3104: 0x0120
16  0x3106: 0xd0f2 bis.b #0x06, &0x002a                     5
17  0x3108: 0x0006
18  0x310a: 0x002a
19  0x310c: 0x43c2 mov.b #0, &0x0029                        4
20  0x310e: 0x0029
21  0x3110: 0xe0f2 xor.b #0x06, &0x0029                     5
22  0x3112: 0x0006
23  0x3114: 0x0029
24  0x3116: 0x430f mov.w #0, r15                            1
25  0x3118: 0x903f cmp.w #0xc350, r15                       2
26  0x311a: 0xc350
27  0x311c: 0x2ff9 jhs 0x3110  (offset: -14)                2
28  0x311e: 0x531f add.w #1, r15                            1
29  0x3120: 0x903f cmp.w #0xc350, r15                       2
30  0x3122: 0xc350
31  0x3124: 0x2ff5 jhs 0x3110  (offset: -22)                2
32  0x3126: 0x3ffb jmp 0x311e  (offset: -10)                2
```

```
33   0x3128: 0x4031 mov.w #0x3100, SP                     2
34   0x312a: 0x3100
35   0x312c: 0x12b0 call #0x3142                          5
36   0x312e: 0x3142
37   0x3130: 0x430c mov.w #0, r12                         1
38   0x3132: 0x12b0 call #0x3100                          5
39   0x3134: 0x3100
40   0x3136: 0x431c mov.w #1, r12                         1
41   0x3138: 0x12b0 call #0x313c                          5
42   0x313a: 0x313c
43   0x313c: 0x4303 nop   --  mov.w #0, CG                1
44   0x313e: 0x3fff jmp 0x313e  (offset: -2)              2
45   0x3140: 0x4303 nop   --  mov.w #0, CG                1
46   0x3142: 0x431c mov.w #1, r12                         1
47   0x3144: 0x4130 ret   --  mov.w @SP+, PC              3
48   0x3146: 0xd032 bis.w #0x0010, SR                     2
49   0x3148: 0x0010
50   0x314a: 0x3ffd jmp 0x3146  (offset: -6)              2
51   0x314c: 0x4303 nop   --  mov.w #0, CG                1
52   0x314e: 0xffff and.b @r15+, 0(r15)                   5
53   0x3150: 0x0000
```

Figure 22. Disassembled Code in ReverseMe.asm.txt Created Using naken_util

```
1    Addr    Opcode Instruction                           Cycles
2    ------- ------ ----------------------------------    ------
3    0x3100: 0x40b2 mov.w #0x5a80, &0x0120                5   // 0x0120 – WDTCTL; STOP WDT
4    0x3102: 0x5a80
5    0x3104: 0x0120
6    0x3106: 0xd0f2 bis.b #0x06, &0x002a                  5   // P2DIR to output
7    0x3108: 0x0006
8    0x310a: 0x002a
9    0x310c: 0x43c2 mov.b #0, &0x0029                     4   // P2OUT is cleared
10   0x310e: 0x0029
11   0x3110: 0xe0f2 xor.b #0x06, &0x0029                  5   // xor P2OUT with 0x06
12   0x3112: 0x0006
13   0x3114: 0x0029
14   0x3116: 0x430f mov.w #0, r15                         1   // clear r15
15   0x3118: 0x903f cmp.w #0xc350, r15                    2     // compare r15 to 50,000
16   0x311a: 0xc350
17   0x311c: 0x2ff9 jhs 0x3110  (offset: -14)             2   // jump if carry to 0x3110
18   0x311e: 0x531f add.w #1, r15                         1   // add #1 to r15
19   0x3120: 0x903f cmp.w #0xc350, r15                    2     // compare r15 to 50,000
20   0x3122: 0xc350
21   0x3124: 0x2ff5 jhs 0x3110  (offset: -22)             2     // jump if carry to 0x3110
22   (xoring)
23   0x3126: 0x3ffb jmp 0x311e  (offset: -10)             2   // jmp to 0x311e (incrementing)
24
```

Figure 23. Reverse Engineering of the Code in Disassembled Code Using naken_util

6 To Learn More

1. Texas Instruments, MSP430 GCC User's Guide: http://www.ti.com/lit/ug/slau646c/slau646c.pdf

2. MSP430 Flasher: http://www.ti.com/tool/MSP430-FLASHER
(should be installed on your workstation and its exe directory, e.g. c:\ti\MSP430Flasher_1.3.18, should be in the PATH system environment variable)
3. Mike Kohn's Naken_asm: https://www.mikekohn.net/micro/naken_asm.php
(should be installed on your workstation and its exe directory, e.g., c:\ti\naken_asm, should be in the PATH system environment variable)