Coding Examples

Jan Faigl

Department of Computer Science
Faculty of Electrical Engineering
Czech Technical University in Prague

Lecture 09

PRG(A) – Programming in C

Overview of the Lecture

- Part 1 – Undefined behaviour and inspecting implementation
  - Program Compilation
  - Undefined Behaviour
  - Comparing C to Machine Code
- Part 2 – Debugging
  - Debugging
- Part 3 – Examples
  - Named pipes
  - Multi-thread Appplication – HW 9
  - Multi-thread Appplications – PRG Semestral Project

Part I

Part 1 – Undefined behaviour and inspecting implementation

Arguments of the `main()` Function

- During the program execution, the OS passes to the program the number of arguments (`argc`) and the arguments (`argv`).

  In the case we are using OS.
  - The first argument is the name of the program.

```c
int main(int argc, char *argv[])
{
   int v;
   v = 10;
   v = v + 1;
   return argc;
}
```

lec09/var.c

- The program is terminated by the `return` in the `main()` function.
- The returned value is passed back to the OS and it can be further use, e.g., to control the program execution.

Reminder

Example of Compilation and Program Execution

- Building the program by the clang compiler – it automatically joins the compilation and linking of the program to the file a.out.

  clang var.c

- The output file can be specified, e.g., program file var.

  clang var.c -o var

- Then, the program can be executed as follows.

  ./var

- The compilation and execution can be joined to a single command.

  clang var.c -o var; ./var

- The execution can be conditioned to successful compilation.

  clang var.c -o var && ./var

Programs return value — 0 means OK.

Logical operator && depends on the command interpret, e.g., sh, bash, zsh.

Reminder

Example – Program Execution under Shell

- The return value of the program is stored in the variable $?.

sh, bash, zsh

- Example of the program execution with different number of arguments.

```
./var

./var; echo $?
1

./var 1 2 3; echo $?
4

./var a; echo $?
2
```

Reminder

Example – Processing the Source Code by Preprocessor

- Using the -E flag, we can perform only the preprocessor step.

  gcc -E var.c

Alternatively clang -E var.c

```
# 1 "var.c"
# 1 "<built-in>"
# 1 "<command-line>"
# 1 "var.c"
int main(int argc, char **argv) {
   int v;
   v = 10;
   v = v + 1;
   return argc;
}
```

lec09/var.c

Reminder

Example – Compilation of the Source Code to Assembler

- Using the -S flag, the source code can be compiled to Assembler.

  clang -S var.c -o var.s

```
  .file "var.c"
  .text
  .globl  main
  .align  16, 0x90
  .type main,@function
main:
      # @main
  .cfi_startproc
# BB#0:
  pushq %rbp
.Ltmp2:
  .cfi_def_cfa_offset 16
.Ltmp3:
  .cfi_offset %rbp, -16
  movq  %rsp, %rbp
.Ltmp4:
  .cfi_def_cfa_register %rbp
  movl  $0, -4(%rbp)
  movl  %edi, -8(%rbp)
  movq  %rsi, -16(%rbp)
  movl  $10, -20(%rbp)
  movl  -20(%rbp), %edi
  addl  $1, %edi
  movl  %edi, -20(%rbp)
  movl  -8(%rbp), %eax
  popq  %rbp
  ret
.Ltmp5:
  .size main, .Ltmp5-main
  .cfi_endproc


  .ident  "FreeBSD clang version 3.4.1 (
    tags/RELEASE_34/dot1-final 208032)
    20140512"
  .section  ".note.GNU-stack","",
    @progbits
```

Undefined Behaviour

- There are some statements that can cause **undefined behavior** according to the C standard.
  - `c = (b = a + 2) - (b - 1);`
  - `j = i * i++;`
- The program may behaves differently according to the used compiler, but may also not compile or may not run; or it may even crash and behave erratically or produce meaningless results.
- It may also happened if variables are used without initialization.
- Avoid statements that may produce undefined behavior!

Example of Undefined Behaviour

- C standard does not define the behaviour for the overflow of the integer value (`signed`)
  - E.g., for the complement representation, the expression can be `127 + 1` of the `char` equal to `-128` (see `lec09/demo-loop_byte.c`).
  - Representation of integer values may depend on the architecture and can be different, e.g., when binary or inverse code is used.
- Implementation of the defined behaviour can be computationally expensive, and thus the behaviour is not defined by the standard.
- Behaviour is not defined and depends on the compiler, e.g. `clang` and `gcc` without/with the optimization `-O2`.

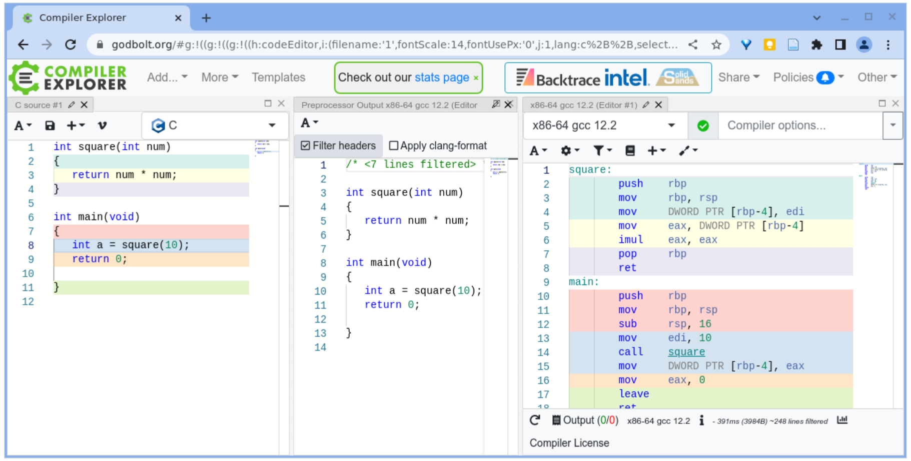
  -
    ```
    for (int i = 2147483640; i >= 0; ++i) {
       printf("%i %x\n", i, i);
    }
    ```
    `lec09/int_overflow-1.c`

    Without the optimization, the program prints 8 lines, for `-O2`, the program compiled by `clang` prints 9 lines and `gcc` produces infinite loop.

  -
    ```
    for (int i = 2147483640; i >= 0; i += 4) {
       printf("%i %x\n", i, i);
    }
    ```
    `lec09/int_overflow-2.c`

    Program compiled by `gcc` and `-O2` crashed. *Take a look to the asm code using the compiler parameter `-S`.*

Compiler Explorer


Compiler Explorer
godbolt.org/#g:!((g:!((g:!((h:codeEditor,i:(filename:'1',fontScale:14,fontUsePx:'0',j:1,lang:c%2B%2B,select...
COMPILER EXPLORER
Add... More Templates
Check out our stats page
Backtrace intel Solid Sands
Share Policies Other
C source #1
C
Preprocessor Output x86-64 gcc 12.2 (Editor
☑ Filter headers
□ Apply clang-format
x86-64 gcc 12.2 (Editor #1)
x86-64 gcc 12.2
Compiler options...
Output (0/0) x86-64 gcc 12.2 - 391ms (3984B) ~248 lines filtered
Compiler License

```
int square(int num)
{
   return num * num;
}

int main(void)
{
   int a = square(10);
   return 0;

}
```

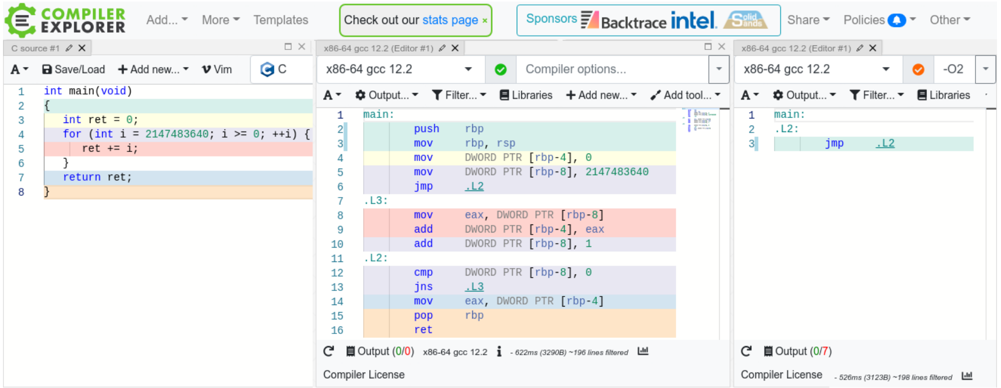
```
/* <7 lines filtered>

int square(int num)
{
   return num * num;
}

int main(void)
{
   int a = square(10);
   return 0;

}
```

```
square:
        push    rbp
        mov     rbp, rsp
        mov     DWORD PTR [rbp-4], edi
        mov     eax, DWORD PTR [rbp-4]
        imul    eax, eax
        pop     rbp
        ret
main:
        push    rbp
        mov     rbp, rsp
        sub     rsp, 16
        mov     edi, 10
        call    square
        mov     DWORD PTR [rbp-4], eax
        mov     eax, 0
        leave
        ret
```

https://godbolt.org/z/K9r1eWqcd

Compiler Explorer – Analysis of the Optimized Code

- Effect of the code optimization `-O2` on the resulting code that contains undefined behavior (integer overflow).


COMPILER EXPLORER
Add... More Templates
Check out our stats page
Sponsors Backtrace intel Solid Sands
Share Policies Other
C source #1
Save/Load Add new... Vim C
x86-64 gcc 12.2 (Editor #1)
x86-64 gcc 12.2
Compiler options...
Output... Filter... Libraries Add new... Add tool...
Output (0/0) x86-64 gcc 12.2 - 622ms (3290B) ~196 lines filtered
Compiler License
x86-64 gcc 12.2 (Editor #1)
x86-64 gcc 12.2
-O2
Output... Filter... Libraries
Output (0/7)
Compiler License - 526ms (3123B) ~198 lines filtered

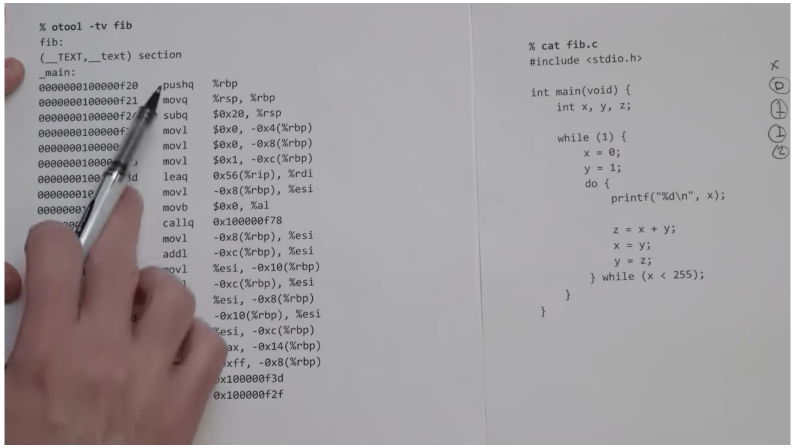
```
int main(void)
{
   int ret = 0;
   for (int i = 2147483640; i >= 0; ++i) {
      ret += i;
   }
   return ret;
}
```

```
main:
        push    rbp
        mov     rbp, rsp
        mov     DWORD PTR [rbp-4], 0
        mov     DWORD PTR [rbp-8], 2147483640
        jmp     .L2
.L3:
        mov     eax, DWORD PTR [rbp-8]
        add     DWORD PTR [rbp-4], eax
        add     DWORD PTR [rbp-8], 1
.L2:
        cmp     DWORD PTR [rbp-8], 0
        jns     .L3
        mov     eax, DWORD PTR [rbp-4]
        pop     rbp
        ret
```

```
main:
.L2:
        jmp     .L2
```

https://godbolt.org/z/G3GEz4vbv

Comparing C to Machine Code



```
% otool -tv fib
fib:
(__TEXT,__text) section
_main:
0000000100000f20    pushq   %rbp
0000000100000f21    movq    %rsp, %rbp
0000000100000f2     subq    $0x20, %rsp
0000000100000f      movl    $0x0, -0x4(%rbp)
0000000100000       movl    $0x0, -0x8(%rbp)
000000010000        movl    $0x1, -0xc(%rbp)
0000000100    3d    leaq    0x56(%rip), %rdi
000000010           movl    -0x8(%rbp), %esi
00000001            movb    $0x0, %al
                    callq   0x100000f78
                    movl    -0x8(%rbp), %esi
                    addl    -0xc(%rbp), %esi
                    movl    %esi, -0x10(%rbp)
                            -0xc(%rbp), %esi
                            %esi, -0x8(%rbp)
                            -0x10(%rbp), %esi
                            %esi, -0xc(%rbp)
                            ax, -0x14(%rbp)
                            xff, -0x8(%rbp)
                            x100000f3d
                            0x100000f2f
```

```
% cat fib.c
#include <stdio.h>

int main(void) {
    int x, y, z;

    while (1) {
        x = 0;
        y = 1;
        do {
            printf("%d\n", x);

            z = x + y;
            x = y;
            y = z;
        } while (x < 255);
    }
}
```

https://www.youtube.com/watch?v=yOyaJXpAYZQ

Part II

Part 2 – Debugging

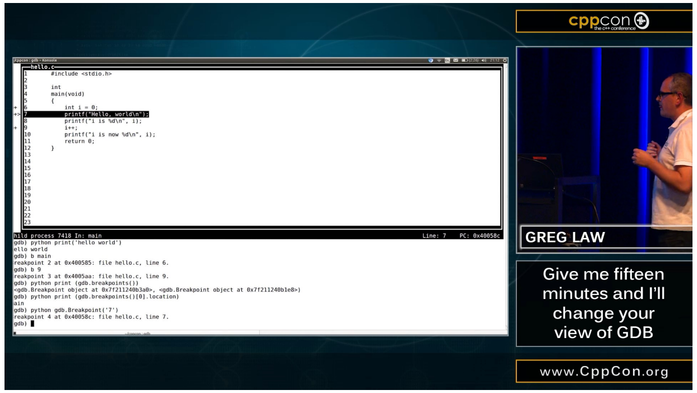
Debugging the Code

- Principally there are two ways of debugging: **stepping** (program animation) and **logging**.
- **Stepping** is interactive debugging that might be suitable for relatively small, less complex codes, and non real-time applications.
  - In stepping, we use **breakpoints**, **watches** to stop the program execution at certain conditions and then inspect variables and stepping next instructions.
  - In C, most of the visual interfaces uses **gdb**.
  - It might be suitable to compile the program with **debugging information**, e.g., using `-g` flag.

    `clang -g main.c -o main`
- **Logging** can range from simple print messages to `stderr` to sophisticated **loggers**, such as `log4c`.
- We can further enjoy tools such as **valgrind** for dynamic analysis, specifically for bugs in memory access. *For more than 20 years, see* `https://valgrind.org/`.

Debugging using gdb (or VS Code)

- Interactive example of debugging or watch the available examples and tutorials.



```
hello.c
1       #include <stdio.h>
2
3       int
4       main(void)
5       {
6           int i = 0;
7           printf("Hello, world\n");
8           printf("i is %d\n", i);
9           i++;
10          printf("i is now %d\n", i);
11          return 0;
12      }
13
14
15
16
17
18
19
20
21
22
23
hild process 7418 In: main                                          Line: 7    PC: 0x40058c
gdb) python print('hello world')
ello world
gdb) b main
reakpoint 2 at 0x400585: file hello.c, line 6.
gdb) b 9
reakpoint 3 at 0x4005aa: file hello.c, line 9.
gdb) python print (gdb.breakpoints())
<gdb.Breakpoint object at 0x7f211240b3a0>, <gdb.Breakpoint object at 0x7f211240b1e8>)
gdb) python print (gdb.breakpoints()[0].location)
ain
gdb) python gdb.Breakpoint('7')
reakpoint 4 at 0x40058c: file hello.c, line 7.
gdb)
```

- *CppCon 2015: Greg Law " Give me 15 minutes & I'll change your view of GDB."*

https://www.youtube.com/watch?v=PorfLSr3DDI

Example of using valgrind

```c
#include <stdio.h>
#include <stdlib.h>

int main(void)
{
   int *a = malloc(2 * sizeof *a);

   for (int i = 0; i < 3; ++i) {
      a[i] = i;
   }
   for (int i = 0; i < 3; ++i) {
      printf("%d\n", a[i]);
   }
   //free(a);
   return 0;
}
```

```
$ clang -g mem_val.c -o mem_val
$ valgrind ./mem_val
....
==87826== Invalid write of size 4
==87826==    at 0x201999: main (mem_val.c:9)
==87826==  Address 0x5400048 is 0 bytes after
     a block of size 8 alloc'd
==87826==    at 0x4853B74: malloc (in /usr/
     local/libexec/valgrind/vgpreload_memcheck-
     amd64-freebsd.so)
==87826==    by 0x201978: main (mem_val.c:6)
==87826==
....
0
```

lec09/mem_val.c

- Try to compile the program with and w/o `-g`.
- See the **valgrind** output with and w/o calling `free()`.

Part III

Part 3 – Examples

Communication using Named Pipes

- Implement two applications **main** and **module** that communicates through named **pipes**. lec09/pipes/create_pipes.sh

  lec09/pipes/prg_lec09_main.c, lec09/pipes/prg-lec09-module.c
- **module** opens pipe `/tmp/prg-lec09.pipe` for reading.
- **main** opens pipe `/tmp/prg-lec09.pipe` for writting.
- The applications communicate using simple character orienter protocol.
  - `'s'` – stop.
  - `'e'` – enable (start).
  - `'b'` – bye.
  - `'1'`–`'5'` – set sleep period to 50 ms, 100 ms, 200 ms, 500 ms, 1000 ms.
- The pipe can be opened using functions from the `prg_io_nonblock` library.

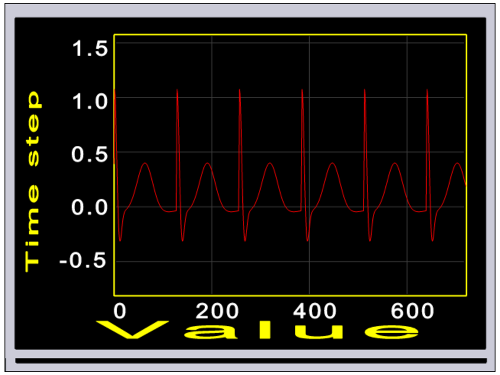
  lec09/pipes/prg_io_nonblock.h, lec09/pipes/prg_io_nonblock.c
- Examine the provide code and test it. *The example is without threads.*

Used in HW 9 (PRGA) and semestral project.

Remote Control of Signal Generator and Plot Visualization – HW 9

- Implement multi-thread application with separate threads for sources of asynchronous events.
  - User input from `stdin` (**keyboard**).
  - Pipe reading from the signal generator.
- Use simple OpenGL-based visualization `otk`.
- Implement the main program logic in the main (`boss`) thread using `event queue`.
  - The main thread reads from the queue.
  - The secondary threads (keyboard and pipe) write to the queue.
- The main thread manages output resources (**visualization**, **write to pipe**).

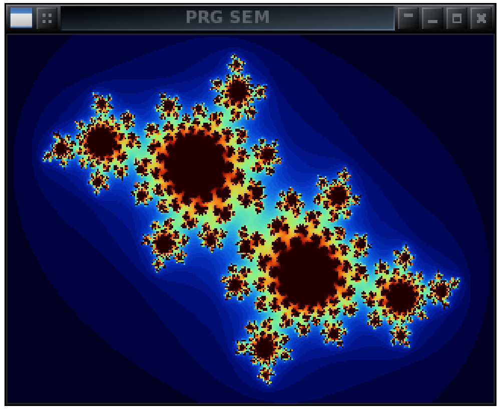
  Eventually also `stdout` or even `stderr`, which is, however, not required.
- Use the example of multi-thread application from Lecture 8.



https://cw.fel.cvut.cz/wiki/courses/bab36prga/hw/hw9

https://cw.fel.cvut.cz/wiki/courses/bab36prga/hw/hw9hints

Remote Control of Computational Application (Module) – Semetral Project



- Implement multi-thread application with separate threads for sources of asynchronous events.
  - User input from `stdin` (**keyboard**).
  - Pipe reading from the computational module.
- Use simple visualization using `sdl`.
- Implement the main program logic in the main (boss) thread using `event queue`.
  - The main thread reads from the queue.
  - The secondary threads (keyboard and pipe) write to the queue.
- The main thread manages output resources (**visualization**, **write to pipe**).

  Eventually also `stdout` or even `stderr`, which is, however, not required.
- Use the example of multi-thread application from Lecture 8.

https://cw.fel.cvut.cz/wiki/courses/b3b36prg/semestral-project/start

Summary of the Lecture

Topics Discussed

- Program compilation.
- Undefined behaviour.
- Comments on debugging.
- Named pipes.
- PRGA's HW 9 and PRG's semetral project.

- Next: ANSI C, C99, C11 – differences and extensions