Coding Examples

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Lecture 09

B3B36PRG – Programming in C

Overview of the Lecture

- Part 1 – Undefined behaviour and inspecting implementation

- Part 2 – Debugging

- Part 3 – Examples

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!

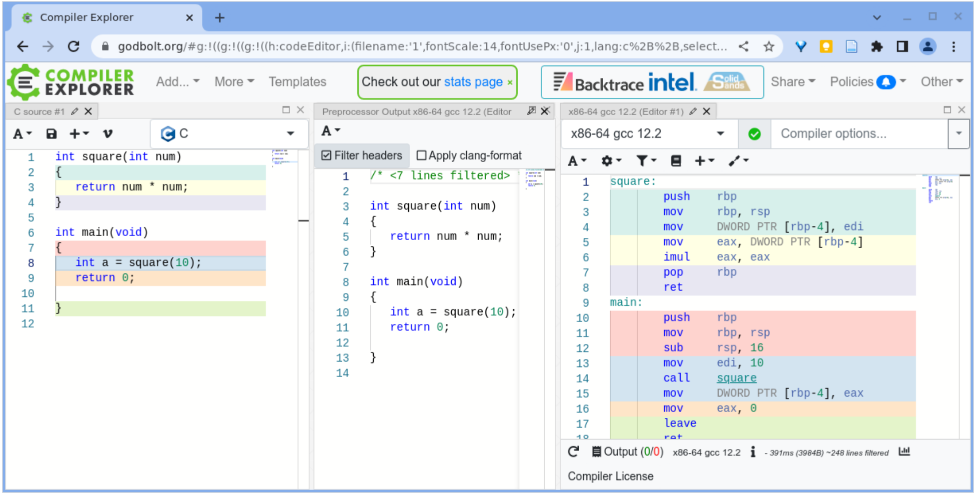
Example of Undefined Behaviour

- 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`.
  - ```c
    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.
  - ```c
    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`.

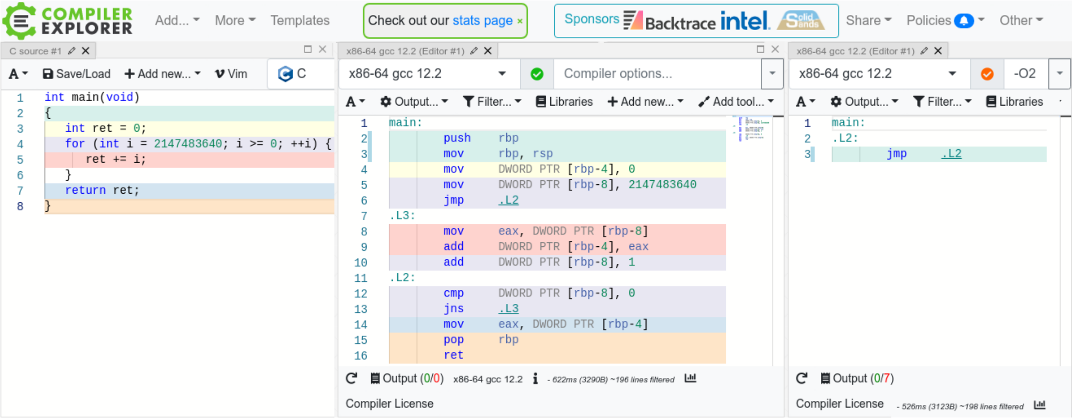
Compiler Explorer



https://godbolt.org/z/K9r1eWqcd

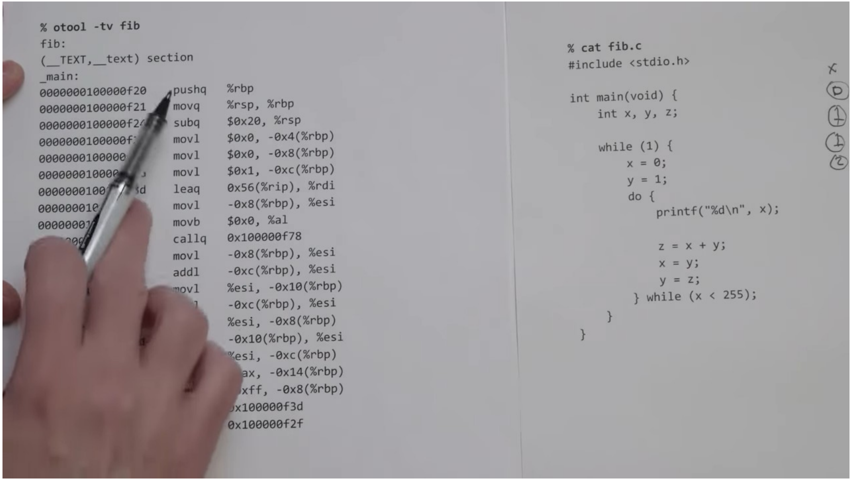
Compiler Explorer – Analysis of the Optimized Code

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



https://godbolt.org/z/G3GEz4vbv

Comparing C to Machine Code



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

Part II

Part 2 – Debugging

Debugging the Code

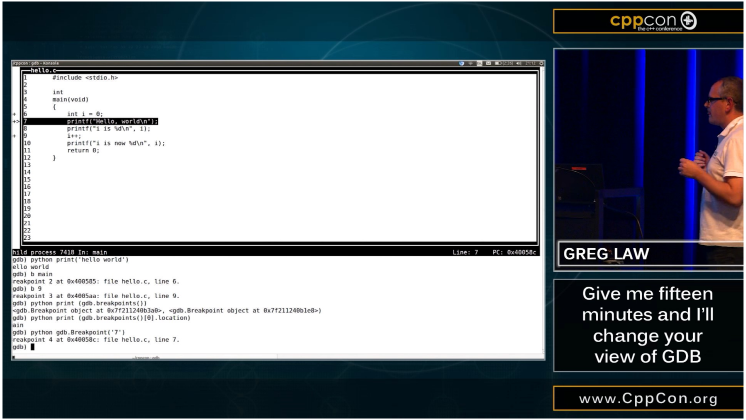
- Principally there are two ways of debugging: **stepping** (program animation) and **logging**.
- **Stepping** is interactive debugging that might be suitable for relatively small, less complex codes, and non real-time applications.
  - In stepping, we use **breakpoints**, **watches** to stop the program 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.



- *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()`.

Example of `malloc` failure

```c
#include <stdio.h>
#include <stdlib.h>
int main(void)
{
   const size_t size = 20 * 1024 * 1024; // 20 MB
   size_t *a = malloc(size * sizeof *a);  // 20 MB * sizeof(long)
   if (!a) {
      fprintf(stderr, "ERROR: malloc failed!\n");
      return -1;
   }
   for (size_t i = 0; i < size; ++i) {
      a[i] = i;
   }
   fprintf(stderr, "INFO: array of %lu size_t values initialized.\n", size);
   free(a);
   return 0;
}
```

```
$ clang mem_fail.c -o mem_fail
$ bash
$ ulimit -d 10 -m 10 -v 1000000  -w 0
$ ./mem_fail
INFO: array of 20971520 size_t values
     initialized.
$ exit
exit
$ bash
$ ulimit -d 10 -m 10 -v 10000  -w 0
$ ./mem_fail
ERROR: malloc failed!
```

lec09/mem_fail.c

- See `ulimit -help` and set the memory limits.
- Run it in separate shell to recover from too restrictive settings.

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

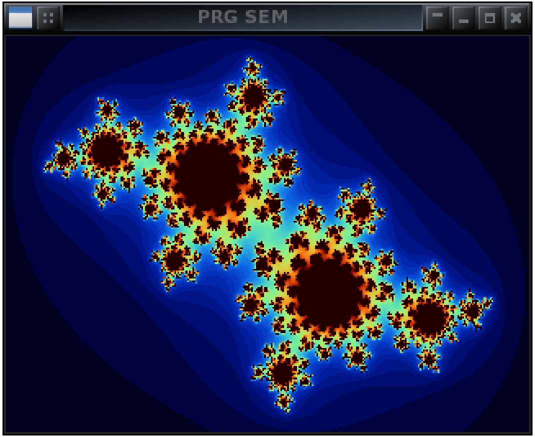
  lec09/pipes/prg_lec09_main.c, lec09/pipes/prg-lec09-module.c
- **module** opens pipe `/tmp/prg-lec09.pipe` for reading.
- **main** opens pipe `/tmp/prg-lec09.pipe` for writting.
- The applications communicate using simple character orienter protocol.
  - `'s'` – stop.
  - `'e'` – enable (start).
  - `'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.*

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.
- Semetral project.