Linux (user space) Debugging

Topics

- How can we find memory problems?
- Cross debugging using GDB and VS Code
- Debugging after a crash with a core file

Tracing Memory:
Valgrind, ASan & mtrace

C's “Safety”

- C does no memory checking on any of:
  - buffer overflows
  - dangling pointers
  - unfreed memory
  - bad pointers
- Need to use extra tools to instrument your program.
  - Instrumentation:
    ..

Valgrind

- Valgrind: a suit of debugging & profiling tools
  - Runs your application in a virtual CPU, doing translations for each instruction.
  - Adds a *significant* performance penalty: 20 – 30 times slower.
- Detects memory errors:
  - .. (not calling free())
  - .. (use after free)
  - Read/write outside of allocated block
  - ..
- (Does not detect stack memory errors)

Valgrind Install

- Install Valgrind on Target (requires internet access)

```
(byai)$ sudo apt update
(byai)$ sudo apt install valgrind
```

  See debugging guide for details.

- Cross-compile your application with -g option.
- Run Valgrind:

```
(byai)$ valgrind ./mybadapp
(byai)$ valgrind --leak-check=full \
    --show-reachable=yes ./mybadapp
```

Valgrind Demo

```
(byai)$ valgrind --leak-check=full --show-reachable=yes ./memleaker

.. normal program output...

==1503== HEAP SUMMARY:
==1503==     in use at exit: 57,344 bytes in 56 blocks
==1503==   total heap usage: 57 allocs, 1 frees, 58,368 bytes allocated
==1503==
==1503== 57,344 bytes in 56 blocks are definitely lost in loss record 1 of 1
==1503==    at 0x48348EC: malloc (vg_replace_malloc.c:263)
==1503==    by 0x104E7: intToString (memleaker.c:16)
==1503==    by 0x1052B: showConvert (memleaker.c:24)
==1503==    by 0x10573: main (memleaker.c:36)
==1503==
==1503== LEAK SUMMARY:
==1503==    definitely lost: 57,344 bytes in 56 blocks
==1503==    indirectly lost: 0 bytes in 0 blocks
==1503==      possibly lost: 0 bytes in 0 blocks
==1503==    still reachable: 0 bytes in 0 blocks
==1503==         suppressed: 0 bytes in 0 blocks
```

ABCD Memory Problems

- What is wrong with this code?

```
void foo(void)
{
    int x;
    int y = 10;
    int* ptr = &x;
    if (y == ' ') {
        *ptr = 20;
    }
    printf("X is: %d\n", x);
}
```

a) Bad pointer.

b) y is an int but compared to a char.

c) x may be undefined.

d) printf() uses incorrect type.

Valgrind Sample

Demo this one.

(byai)$ valgrind ./memabuser

- funWithVariables(): uninitialized memory
- funWithHeap(): overflow, double free
- funWithStack(): Misses error!
- funWithPointers(): Misses error!

**(byai)$ valgrind --leak-check=full **
--show-reachable=yes ./memleaker2

- Output part:

```
==1561== 1 bytes in 1 blocks are definitely lost in loss record 1 of 11
==1561==    at 0x48348EC: malloc (vg_replace_malloc.c:263)
==1561==    by 0x10753: main (memleaker2.c:48)
```

ABCD: Memory Problems

- With a partner, decide what is wrong with the code?
  - Memory leak
  - Use after free
  - Buffer overflow
  - Non-null terminated string
  - Null pointer
  - Double free
  - Poor error handling

```
void bar(void)
{
    char *pMessage =
        malloc(13 * sizeof(*pMessage));
    sprintf(pMessage, "Another test!");
    *(pMessage-1) = '\0';
    printf("%s\n", pMessage);

    int *pInt = malloc(42 * sizeof(*pInt));
    int garbage = pInt[0];
    pInt[0] = 1;
    free(pInt);
    pInt[2] = garbage;
    free(pInt);
}
```

a) Yes

b) No

c) Not sure

```
$ valgrind --leak-check=full --show-reachable=yes ./memabuser 2
==2906== Invalid write of size 1
==2906==    at 0x492D324: __vsprintf_internal (iovsprintf.c:98)
==2906==    by 0x491221B: sprintf (sprintf.c:30)
==2906==    by 0x10894F: funWithHeap (memabuser.c:25)
==2906==  Address 0x4a6f48d is 0 bytes after a block of size 13 alloc'd
==2906==
==2906== Invalid write of size 1
==2906==    at 0x10895C: funWithHeap (memabuser.c:26)
==2906==  Address 0x4a6f47f is 1 bytes before a block of size 13 alloc'd
==2906==
==2906== Invalid read of size 1
==2906==    at 0x488B2D4: __GI_strlen (vg_replace_strmem.c:495)
==2906==    by 0x4916723: __vfprintf_internal (vfprintf-process-arg.c:397)
==2906==    by 0x490CD43: printf (printf.c:33)
==2906==    by 0x10896F: funWithHeap (memabuser.c:27)
==2906==  Address 0x4a6f48d is 0 bytes after a block of size 13 alloc'd
==2906==
'Another test!'
==2906== Invalid write of size 4
==2906==    at 0x1089A8: funWithHeap (memabuser.c:34)
==2906==  Address 0x4a6f4d8 is 8 bytes inside a block of size 168 free'd
==2906==
==2906== Invalid free() / delete / delete[] / realloc()
==2906==    at 0x4887B40: free (vg_replace_malloc.c:872)
==2906==    by 0x1089B3: funWithHeap (memabuser.c:35)
==2906==  Address 0x4a6f4d0 is 0 bytes inside a block of size 168 free'd
==2906==
==2906== HEAP SUMMARY:
==2906==     in use at exit: 13 bytes in 1 blocks
==2906==   total heap usage: 3 allocs, 3 frees, 1,205 bytes allocated
==2906==
==2906== 13 bytes in 1 blocks are definitely lost in loss record 1 of 1
==2906==
```

Valgrind (cont)

- A well-behaved program should
  ..
  - i.e., should have nothing “still reachable”
- Threads
  - If you forget to call pthread_join() on a thread it leaves some memory un-freed.
  - Should join on all spawned threads or else get:

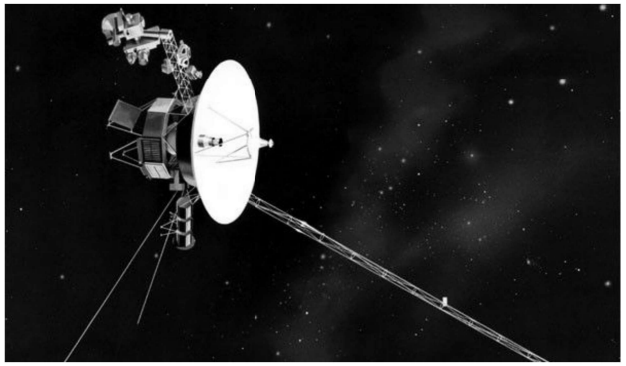
```
136 bytes in 1 blocks are possibly lost in loss record 1 of 1
 at 0x4832C44: calloc (vg_replace_malloc.c:566)
 by 0x40122CB: _dl_allocate_tls (dl-tls.c:297)
 by 0x4855C73: pthread_create@@GLIBC_2.4 (allocatestack.c:585)
 by 0x108D7:   main (demo_thread.c:36)
```

- Can find *some* stack/globals problems with:
  `(byai)$` **`valgrind --tool=exp-sgcheck ./mybadapp`**
  - Does not catch all errors.

Argument for Freeing All Memory

- When your program ends, OS frees all memory;
  Why bother ensuring you free the last of your memory?
  - ..
  - If running a remote system, may want to disable some feature for a time
- Requirements for this class

  Program must end with:
  - 0 blocks definitely lost
  - 0 blocks indirectly lost
  - 0 blocks possibly lost
  - 0 blocks still reachable



Valgrind Errors to Ignore

- Valgrind may find errors which originate in code libraries; you may usually ignore these.

```
==832== 8 bytes in 1 blocks are still reachable in loss record 1 of 8
==832==    at 0x4840AA8: calloc (vg_replace_malloc.c:623)
==832==    by 0x489573B: snd_config_update_r
          (in /usr/lib/arm-linux-gnueabihf/libasound.so.2.0.0)
```

- Turn off -pg flag to remove some warnings.
- If getting errors with __udivmoddi4:

```
==852== Use of uninitialised value of size 4
==852==    at 0x12BB2: __udivmoddi4 (in ./myGoodApp)
```

  copy code to target and build on target with its gcc.

Timing Bugs

- “Heisenbug”
  - ..

- Valgrind significantly changes the runtime performance of your application
  - May cause false timing related bugs related to performance or driving real-time hardware
  - Your code must be threadsafe:
    even if the timing changes significantly, your code must perform the correct computations and steps

Address Sanitizer (ASan)

- GCC and Clang support Address Sanitizer:
  - ..

- Similar to valgrind except
  - It's fast!
    Only x2 slowdown vs x20
  - It checks more types of errors
  - It requires compile-time change
    (cannot be run on precompiled binary)

ASan catches:

- Use after free
- Heap buffer overflow
- Stack buffer overflow
- Global buffer overflow
- Use after return
- Use after scope
- Initialization order bugs
- Memory leaks

ASan use

- Enable at compile time in CMakeLists.txt:

```
# Enable address sanitizer
# (Comment this out to make your code faster)
add_compile_options(-fsanitize=address)
add_link_options(-fsanitize=address)
```

- Bad Code

```
void foo() {
  int data[3];
  for (int i = 0; i <= 3; i++) {
    data[i] = 10;
    printf("Val: %d\n", data[i]);
  }
}
```

ASan Error Report

```
=================================================================
==99631==ERROR: AddressSanitizer: stack-buffer-overflow on address 0x7ffd9117bd4c at pc 0x55ba3bcaf310 bp 0x7f
WRITE of size 4 at 0x7ffd9117bd4c thread T0
    #0 0x55ba3bcaf30f in foo /home/brian/all-my-code/CMPT433-Code/04-Building/cmake_starter/app/src/main.c:12
    #1 0x55ba3bcaf42e in main /home/brian/all-my-code/CMPT433-Code/04-Building/cmake_starter/app/src/main.c:54
    #2 0x7f572f75ed09 in __libc_start_main ../csu/libc-start.c:308
    #3 0x55ba3bcaf139 in _start (/home/brian/all-my-code/CMPT433-Code/04-Building/cmake_starter/build/app/hell

Address 0x7ffd9117bd4c is located in stack of thread T0 at offset 44 in frame
    #0 0x55ba3bcaf25f in foo /home/brian/all-my-code/CMPT433-Code/04-Building/cmake_starter/app/src/main.c:9

  This frame has 1 object(s):
    [32, 44) 'data' (line 10) <== Memory access at offset 44 overflows this variable
HINT: this may be a false positive if your program uses some custom stack unwind mechanism, swapcontext or vfo
      (longjmp and C++ exceptions *are* supported)
SUMMARY: AddressSanitizer: stack-buffer-overflow /home/brian/all-my-code/CMPT433-Code/04-Building/cmake_starte
Shadow bytes around the buggy address:
  0x100032227750: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x100032227760: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x100032227770: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x100032227780: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x100032227790: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
=>0x1000322277a0: 00 00 00 00 f1 f1 f1 f1 00[04]f3 f3 00 00 00 00
  0x1000322277b0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x1000322277c0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x1000322277d0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x1000322277e0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
  0x1000322277f0: 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
Shadow byte legend (one shadow byte represents 8 application bytes):
  Addressable:           00
  Partially addressable: 01 02 03 04 05 06 07
  Heap left redzone:       fa
```

mtrace

- If Valgrind's overhead is too high, can use mtrace:
  - ..
- Usage:
  - In C code:

```
#include <mcheck.h>
void main() {
    mtrace();     // Call to start trace; can be anywhere
                  // Rest of your code...
}
```

  - On target, set environment variables for trace
  - Run the program (writes log file)
  - Analyze results (on host or target)

mtrace example

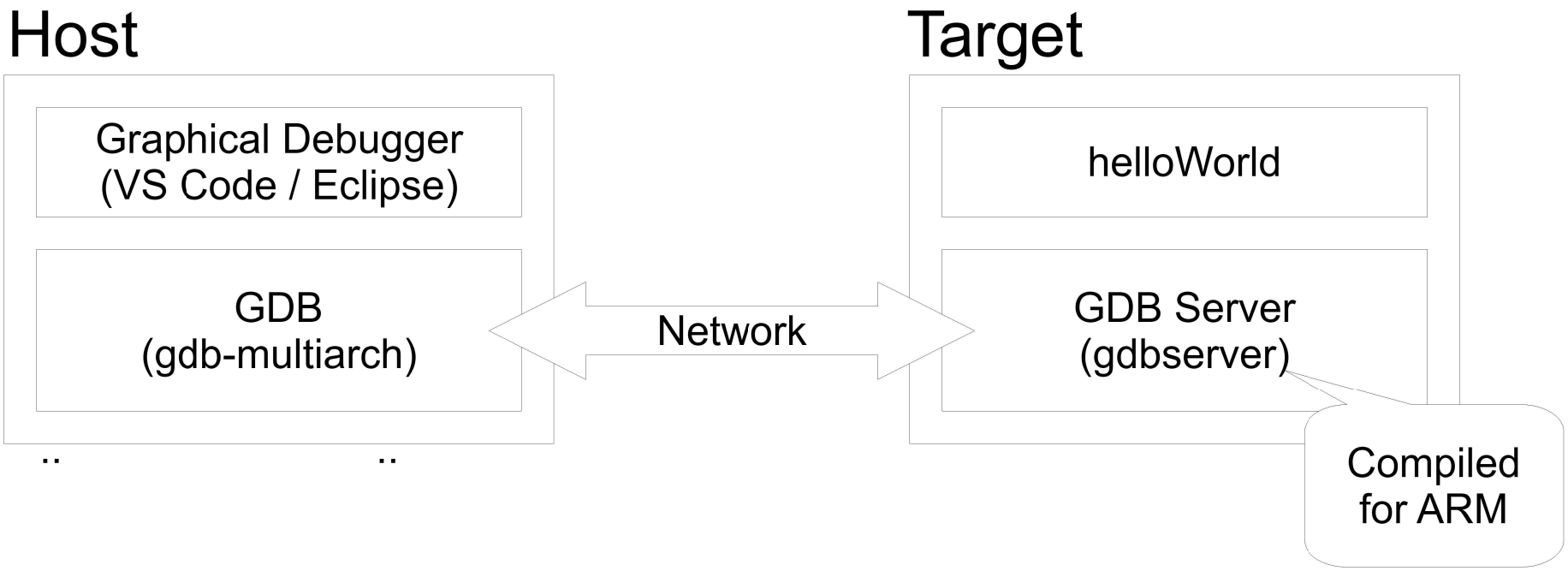
```
(byai)$ export MALLOC_TRACE=/tmp/mallocTrace.txt
(byai)$ export LD_PRELOAD=/usr/lib/aarch64-linux-gnu/libc_malloc_debug.so

(byai)$ ./memleaker
... program's normal operation....

(byai)$ mtrace ./memleaker ../mallocTrace.txt
Memory not freed:
-----------------
           Address     Size     Caller
0x0000aaaaf959f8b0     0x64  at memleaker.c:38
0x0000aaaaf959f920    0x400  at memleaker.c:16
0x0000aaaaf959fd30    0x400  at memleaker.c:16
...
```

GDB

GDB & Debug Symbols

- GDB: GNU debugger
  - Able to read structure of an executable and interactively step through it.
  - ..
    “Symbols” includes:
    - Symbol names: function, variables, parameters
    - Symbol types: return, variable, parameter types
    - File & line numbers for each instruction.
- Build app with debug symbols:
  - GCC: Use -g option:
    aarch64-linux-gnu-gcc -g -std=c99 foo.c -o foo

The Big Picture



- On Target
  `(byai)$` **`gdbserver localhost:2001 helloWorld`**
- On Host
  `(host)$` **`gdb-multiarch -q helloWorld`**

GDB Commands:

- Connect: `target remote 192.168.7.2:2001`
- View Source:..
- Breakpoints:..
  `break main, break test.c:7`
- Stepping: `run, continue`
  `step (into), next (over)`
  ..
  `print <expr>`
- Functions: `info args, info local,`
  ..
- Quit: `quit`

VS Code Debugging

- See the Debugging guide for step-by-step on how to setup VS Code (and Eclipse) for cross-debugging.

Debugging *after* a crash: Core Dumps

Core Dump

- When a process hits a runtime error,
  Linux can store the complete process state to a core file
  - Enable core file generation:

```
(byai)$ ulimit -c unlimited
(byai)$ ulimit -a          # Display's limit
```

  - User can generate core file and send it to developers for later debugging.

Debugging with Core

- Run program on target to generate core file:
  `(byai)$ ./segfaulter`
  - When program crashes, it creates a core file in current directory.

- Copy to NFS (if not there already)

- On host, open core in cross-debugger:
  `(host)$` **`cd ~/cmpt433/public/`**
  `(host)$` **`gdb-multiarch ./segfaulter core`**

May need to run in /tmp if core file is 0 bytes. chhmod a+r on core if cannot read on host.

Stripping Symbols

- Debug symbols help you debug a program.
- However, they:
  - Make the binary bigger
  - Give away information about your program.
- Can remove the debug symbols after compile:

```
(host)$ cp myApp myApp2
(host)$ aarch64-linux-gnu-strip myApp2
```

  - Copy myApp2 to target (it's smaller)!
  - When debugging core files generated by a stripped myApp2 on target, can use un-stripped myApp with symbols on host.

ABCD: Crash Debugging

- Which of the following tools would ***not*** be useful at debugging a program crash (suspected bad pointer)?

  a) valgrind

  b) core file

  c) mtrace

  d) ASan (address sanitizer)

Summary

- Tracing memory:
  - Valgrind for a deep check on memory use
  - mtrace for an efficient check on dynamic allocation
- GDB:
  - target runs gdbserver
  - host runs gdb-multiarch
- GDB Commands:
  - target remote, list, info b, b main, continue, bt, step, next, info args, up, down, quit
- Can debug in text or via an IDE
- Debug after a crash with a core file
- Strip a binary to remove symbols