Yocto Project Summit 2021.11

Hands on class
Linux debugging on Yocto Project based systems

Embedded Labworks

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$ WHOAMI

- Embedded software developer for more than 25 years.
- Consultant and trainer at Embedded Labworks.
  https://e-labworks.com/en
- Open source contributor (Buildroot, Yocto Project, Linux, etc).
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AGENDA

1. Introduction to debugging on YP based systems & Hands on 1
2. Core dump analysis & Hands on 2
3. Remote debugging with GDB & Hands on 3
4. Kernel oops analysis & Hands on 4
5. Memory leak & Hands on 5

You can find the layer created for the exercises on GitHub.
https://github.com/sergioprado/meta-yps2021-debugging

THIS CLASS IS NOT ABOUT...

- ✗ How Yocto Project/OpenEmbedded works.
- ✗ Debugging BitBake metadata (recipes, classes, etc).
- ✗ Debugging build problems.

This talk will cover tips and tricks on debugging kernel and userspace applications on Linux systems generated with OpenEmbedded and the Yocto Project.

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Linux debugging

Introduction to debugging on YP based systems

DEBUGGING TOOLS AND TECHNIQUES

- **Logging and memory dump analysis**: dmesg, kernel oops/panic, addr2line, core dump, etc.
- **Interactive debugging**: GDB, KGDB.
- **Tracing and profiling**: ftrace, systemtap, perf, LTT-NG, gprof, strace, ltrace, etc.
- **Debugging frameworks**: kmemleak, valgrind, mtrace, etc.

APPROACHES TO DEBUGGING

- There are a few approaches to debugging an embedded Linux device:
  - Directly on the target (may not be possible, depending on available resources).
  - Remote debugging via some connection to the target (network, serial port, etc).
  - Post-mortem analysis (here we collect debug information in the target but do the analysis in the host).

WHAT WE (MIGHT) NEED TO DEBUG

- **Source code** of the binary (and libraries) to be debugged.
- Binary (and libraries) compiled with **debugging symbols**.
- Binary (and libraries) compiled with **optimizations disabled**.
- Binary (and libraries) compiled with **security flags disabled**.
- Many host and target **tools**!

SOURCE CODE

- The source code of the binary (and libraries) is not shipped in the final image, but may be needed by a debugging tool like GDB.
- The source code can be included in the image with the `-src` package.
- Including all source packages:

```
IMAGE_FEATURES:append = " src-pkgs"
```

- Including the source package of a specific application:

```
IMAGE_INSTALL:append = " busybox-src"
```

DEBUGGING SYMBOLS (1)

- Debug symbols are special entries in the symbol table of an object file that make it possible for tools like GDB and `addr2line` to gain access to information from the source code of the binary (and ultimately convert addresses into file names and line numbers).

- On Yocto, debugging symbols are removed by default from binaries and split into a separate package (`-dbg`).

- Including all debug packages:

```
IMAGE_FEATURES:append = " dbg-pkgs"
```

- Including the debug package of a specific application:

```
IMAGE_INSTALL:append = " busybox-dbg"
```

DEBUGGING SYMBOLS (2)

- Another option is to just disable stripping when packaging (this is usually not necessary):

  ```
  INHIBIT_PACKAGE_STRIP:pn-busybox = "1"
  ```

- Using `debuginfod` is yet another option:

  https://docs.yoctoproject.org/dev-manual/common-tasks.html#using-the-debuginfod-server-method

  https://www.youtube.com/watch?v=S3QLr113mx8

- If you are doing remote debugging, symbol resolution will be done in the host, and probably you don't need to care about installing debugging packages in the target.

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OPTIMIZATION (1)

- When building an application, the compiler may generate an optimized binary that does not match the source code, impacting the debug experience.
- The variable `SELECTED_OPTIMIZATION` specifies the optimization flags passed to the C compiler when building for the target.
- `SELECTED_OPTIMIZATION` takes by default the value of `FULL_OPTIMIZATION`:

```
FULL_OPTIMIZATION = "-O2 -pipe ${DEBUG_FLAGS}"
```

- If `DEBUG_BUILD="1"`, then the variable `SELECTED_OPTIMIZATION` will take the value of `DEBUG_OPTIMIZATION`:

```
DEBUG_OPTIMIZATION = "-Og ${DEBUG_FLAGS} -pipe"
```

- This may vary depending on the distro you are building (e.g. `poky-tiny` sets `-Os` to enable size optimization).

OPTIMIZATION (2)

- Compiling all applications without optimization:

```
DEBUG_BUILD = "1"
```

- Compiling a specific application without optimization:

```
DEBUG_BUILD:pn-busybox = "1"
```

- Be aware that disabling optimizations may influence the system's behavior (it may even hide bugs!), so do it only when necessary.

SECURITY FLAGS

- If your distro is building applications with security flags enabled, the debugging experience might be impacted.

- This is true for Poky-based distros (currently it includes `security_flags.inc`), which enables security-related compiler flags by default.

```
require conf/distro/include/security_flags.inc
```

- In particular, if PIE (Position Independent Executable) is enabled, we are not able to easily resolve symbols, and you might want to disable it for a specific application during a debugging session:

```
SECURITY_CFLAGS:pn-busybox = "${SECURITY_NOPIE_CFLAGS}"
```

TARGET DEBUGGING TOOLS (1)

- To debug an application directly on the target, you will probably need to add a few extra tools to the image.

- Adding GDB to the rootfs for native debugging:

```
IMAGE_INSTALL:append = " gdb"
```

- Adding GDB server to the rootfs for remote debugging:

```
IMAGE_INSTALL:append = " gdbserver"
```

- The same can be achieved by adding `tools-debug` to `IMAGE_FEATURES` (it will add `gdb`, `gdbserver`, `mtrace` and `strace`):

```
IMAGE_FEATURES:append = " tools-debug"
```

TARGET DEBUGGING TOOLS (2)

- Adding Valgrind to the rootfs for memory analysis (the dbg package might also be needed for symbol resolution):
- `IMAGE_INSTALL:append = " valgrind valgrind-dbg"`

- Adding profiling tools (perf, blktrace, powertop, systemtap, lttng, valgrind, etc):

```
IMAGE_FEATURES:append = " tools-profile"
```

- Enable Eclipse debugging (gdbserver, tcf-agent, openssh-sftp-server):

```
IMAGE_FEATURES:append = " eclipse-debug"
```

- For easy connection to the target, `debug-tweaks` is useful:

```
EXTRA_IMAGE_FEATURES = "debug-tweaks"
```

HOST DEBUGGING TOOLS (1)

- In the host machine, for remote debugging or post-mortem analysis, you will need:
  - **Sysroot** (including the source code and binaries with debugging symbols).
  - **Debugging tools** (GDB, addr2line, etc).
- One can generate a stripped-down version of the filesystem for debugging with the following configuration:

```
IMAGE_GEN_DEBUGFS = "1"
IMAGE_FSTYPES_DEBUGFS = "tar.bz2"
```

HOST DEBUGGING TOOLS (2)

- Then a minimal toolchain with only the tools can be generated with:

```
$ bitbake meta-toolchain
```

- Another approach is to generate a complete SDK that will contain the sysroot with debugging symbols and all required tools:

```
$ bitbake -c populate_sdk <your-image>
```

HANDS ON 1: ENVIRONMENT (1)

- Connect to the build server:

```
$ ssh <username>@<hostname>
```

- Go to the poky directory and inspect its content (don't inspect `meta-yps2021-debugging` yet, since there are some patches in this layer that were created to inject bugs in the OS for the exercises):

```
$ cd yp-summit-nov-21/poky/
$ ls
```

- Initialize the build environment:

```
$ source ./oe-init-build-env build-debug
```

- Inspect the `local.conf` file (some packages are already enabled and prebuilt to prevent long build times during the class):

```
$ cat conf/local.conf
```

HANDS ON 1: ENVIRONMENT (2)

- The image `core-image-base` is already built, so you don't need to build it again.
- Run the image with QEMU - there are a few bugs in the image, but the boot should work just fine ;-)

```
$ runqemu nographic qemuarm64
```

- Login with the `root` user (no password) and play around with the OS. When you are done, exit QEMU by typing `CTRL-a` + `x`.
- Open another terminal (use a terminal multiplexer like `tmux` or create a new ssh connection) and test the SDK:

```
$ cd ~/yp-summit-nov-21/poky/sdk-debug
$ source ./environment-setup-cortexa57-poky-linux
$ echo $CC
```

Linux debugging

Core dump analysis

CORE DUMP

- Core dump is a file that contains a snapshot of the memory of a process.
- The core dump is generated when a process receives some signals, including `SIGQUIT`, `SIGILL`, `SIGABRT`, `SIGFPE` and `SIGSEGV`.
- One of the most common situations of a core dump generation is when an application abruptly terminates its execution due to a crash (invalid memory access, division by zero, etc).
- The core dump can be used in a debugger to inspect the state of the process at the time it was terminated.

CORE DUMP REQUIREMENTS

- There are a few requirements for the core dump file to be generated, including:
  - The process needs permission to create the core dump file.
  - It's mandatory to have enough space on the file system.
  - The core file size limit setting (RLIMIT_CORE) for the process needs to be properly configured.

- The process's RLIMIT_CORE setting is usually zero, which prevents the core dump file from being generated. To change this setting, we can use the ulimit command:

```
# ulimit -c unlimited
```

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CORE DUMP GENERATION

- By default, the name of the core dump file is `core`, generated in the working directory of the application.
- The name of the core dump file can be changed in `/proc/sys/kernel/core_pattern`.
- More information is available on the `core` man page:

```
$ man 5 core
```

CORE DUMP ANALYSIS ON YOCTO (1)

- Let's say an application called `myapp` is crashing:

```
# myapp
Segmentation fault
```

- The first step is to recompile the application without the security flags:

```
# add to local.conf
SECURITY_CFLAGS:pn-myapp = "${SECURITY_NOPIE_CFLAGS}"
```

- Now you can generate the core dump file and transfer it to your host machine:

```
# ulimit -c unlimited

# myapp
Segmentation fault (core dumped)

# ls -l core
-rw------- 1 root root 438272 Nov  5 18:14 core
```

CORE DUMP ANALYSIS ON YOCTO (2)

- Next, setup the SDK environment and go to the sysroot directory:

```
$ source <SDK_DIR>/environment-setup-cortexa57-poky-linux
$ cd <SDK_DIR>/sysroots/cortexa57-poky-linux/
```

- To do the core dump analysis with GDB, you will need the **source code** of the application and the binary with **debugging symbols**.

- To make it easier for GDB to find the sources, you can set the application's source code directory in its configuration file:

```
$ echo "dir usr/src/debug/myapp/1.0-r0/myapp-1.0/src" >> ~/.gdbinit
```

- To search for the binary with debugging symbols, you can simply use `find`:

```
$ find . -name myapp 2>/dev/null | grep "\.debug"
./usr/sbin/.debug/myapp
```

CORE DUMP ANALYSIS ON YOCTO (3)

- Now you can run GDB to analyse the core dump file:

```
$ aarch64-poky-linux-gdb ./usr/sbin/.debug/myapp -c ~/core
...
Core was generated by `myapp'.
Program terminated with signal SIGSEGV, Segmentation fault.
#0 0x0000000000401950 in main (void) at ../../myapp-1.0/src/main.c:15
15            *ptr = 10;
(gdb)
```

- You can also use `-tui` for a more graphical view of the source code:

```
$ aarch64-poky-linux-gdb -tui ./usr/sbin/.debug/myapp -c ~/core
```

HANDS ON 2: CORE DUMP ANALYSIS

- Run the command below in the target device (QEMU). The execution will fail with a `Segmentation Fault` error.

  ```
  # fping -c 5 192.168.0.1
  ```

- Generate a core dump file and transfer it to the host machine.
- In the host machine, use GDB to find the line of code in the source code of the `fping` application that is causing the issue.
- Obs.: You don't have to fix the issue, just find the root cause.

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Linux debugging

Remote debugging with GDB

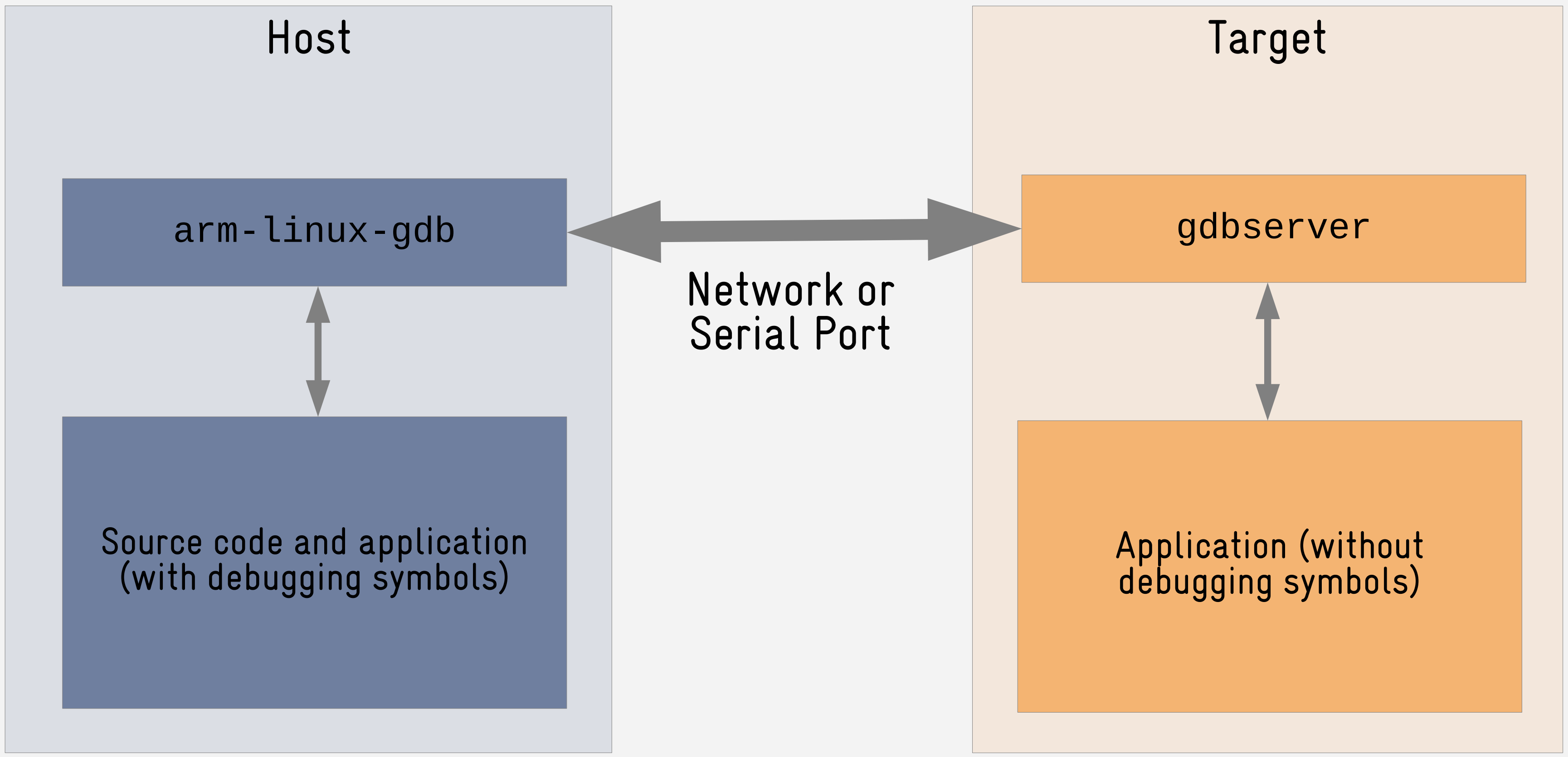
REMOTE DEBUGGING WITH GDB (1)

- GDB (GNU Project debugger) is the main choice for an interactive debugging tool on Linux.

  http://www.gnu.org/software/gdb/

- We can debug an application with GDB directly on the target (local debugging) or in the host machine (remote debugging).
  - Local debugging requires the binary with debug symbols, the source code and development tools (GDB) available on the target.
  - Remote debugging implies a client-server architecture, having a GDB server running on the target, and everything else (binary with debug symbols, source code, GDB client) in the host machine.

REMOTE DEBUGGING WITH GDB (2)


Host
arm-linux-gdb
Source code and application (with debugging symbols)
Network or Serial Port
Target
gdbserver
Application (without debugging symbols)

REMOTE DEBUGGING ON YOCTO (1)

- Let's say you want to debug an application called `myapp`.
- The first step is to recompile the application with optimization and the security flags disabled:

```
# add to local.conf
SECURITY_CFLAGS:pn-myapp = "${SECURITY_NOPIE_CFLAGS}"
DEBUG_BUILD:pn-myapp = "1"
```

- Now you can run GDB server on the target:

```
# gdbserver :3000 /usr/sbin/myapp
```

REMOTE DEBUGGING ON YOCTO (2)

- Next, setup the SDK environment and go to the sysroot directory:

```
$ source <SDK_DIR>/environment-setup-cortexa57-poky-linux
$ cd <SDK_DIR>/sysroots/cortexa57-poky-linux/
```

- To start remote debugging with GDB, you will need the **source code** of the application and the binary with **debugging symbols**.

- To make it easier for GDB to find the sources, you can set the application's source code directory in his configuration file:

```
$ echo "dir usr/src/debug/myapp/1.0-r0/myapp-1.0/src" >> ~/.gdbinit
```

- To search for the binary with debugging symbols, you can simply use `find`:

```
$ find . -name myapp 2>/dev/null | grep "\.debug"
./usr/sbin/.debug/myapp
```

REMOTE DEBUGGING ON YOCTO (3)

- Now you can run GDB to start the remote debugging session:

```
$ aarch64-poky-linux-gdb -tui ./usr/sbin/.debug/myapp
```

- Start the debugging session by adding a breakpoint in the `main` function:

```
(gdb) b main
```

- Then connect to the device and start debugging the application:

```
(gdb) target remote 192.168.7.2:3000
(gdb) continue
(gdb) next
(gdb) ...
```

HANDS ON 3: REMOTE DEBUGGING

- Run the command below in the target device (QEMU). The execution will fail with a `Segmentation Fault` error.

```
# fping -c 5 192.168.0.1
```

- Start a remote debugging session and run the application step-by-step to find the issue.

- Obs.: You don't have to fix the issue, just find the root cause.

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Linux debugging

Kernel oops analysis

KERNEL OOPS

- Kernel oops is a way for the Linux kernel to communicate the user that a certain error has occurred.

- When the kernel detects a problem, it kills any offending process and prints an oops message in the logs, including the current system status and a stack trace.

- Different kind of errors can generate a kernel oops, including an illegal memory access or the execution of invalid instructions.

- The official Linux kernel documentation about handling oops messages is available at `Documentation/admin-guide/bug-hunting.rst`.

KERNEL OOPS

```
[   35.427342] Unable to handle kernel NULL pointer dereference at virtual address 0000000000000000
[   35.427763] Mem abort info:
[   35.427916]   ESR = 0x96000045
[   35.428093]   EC = 0x25: DABT (current EL), IL = 32 bits
[   35.428308]   SET = 0, FnV = 0
[   35.428437]   EA = 0, S1PTW = 0
[   35.428531]   FSC = 0x05: level 1 translation fault
[   35.428754] Data abort info:
[   35.428889]   ISV = 0, ISS = 0x00000045
[   35.429024]   CM = 0, WnR = 1
[   35.429230] user pgtable: 4k pages, 39-bit VAs, pgdp=00000000438e1000
[   35.429470] [0000000000000000] pgd=0000000000000000, p4d=0000000000000000, pud=0000000000000000
[   35.429922] Internal error: Oops: 96000045 [#1] PREEMPT SMP
[   35.430262] Modules linked in:
[   35.430591] CPU: 1 PID: 341 Comm: ps Not tainted 5.14.9-yocto-standard #1
[   35.430941] Hardware name: linux,dummy-virt (DT)
[   35.431386] pstate: 80000005 (Nzcv daif -PAN -UAO -TCO BTYPE=--)
[   35.431614] pc : uptime_proc_show+0xfc/0x130
[   35.431806] lr : uptime_proc_show+0xa4/0x130
[   35.431972] sp : ffffffc0110ebc10
[   35.432086] x29: ffffffc0110ebc10 x28: 0000000000000001 x27: 0000000000400cc0
[   35.432404] x26: 000000007ffff000 x25: ffffff8003953038 x24: ffffffc010d588b8
[   35.432629] x23: ffffff8003953000 x22: 0000000000000004 x21: ffffffc010d58bc8
[   35.432876] x20: ffffffc010c51908 x19: 000000053af57000 x18: 0000000000000000
[   35.433117] x17: 0000000000000000 x16: 0000000000000000 x15: 0000000000000000
[   35.433375] x14: 0000000000000000 x13: 0000000000000000 x12: 0000000000000000
[   35.433616] x11: 0000000000000000 x10: 0000000000000000 x9 : 000000003b9aca00
[   35.433889] x8 : 0000000000000000 x7 : d6bf94d5e57a42bd x6 : 0000000012c921f5
[   35.434134] x5 : 000000001ba81400 x4 : 0000000000000016 x3 : 000000001664eed0
[   35.434378] x2 : 0000000000000023 x1 : ffffffc010b0c440 x0 : ffffff8003953000
[   35.434735] Call trace:
[   35.434830]  uptime_proc_show+0xfc/0x130
[   35.434949]  seq_read_iter+0x1b4/0x4b0
[   35.435096]  proc_reg_read_iter+0x98/0xe0
[   35.435318]  new_sync_read+0xd4/0x150
...
```

KERNEL OOPS ANALYSIS ON YOCTO (1)

- Kernel space debugging is not that different from userspace debugging, but may require specific kernel configuration options enabled and additional tools.

- In particular, changing the kernel configuration to enable debug options might be required.

- For kernel debugging, you will probably need to (re)compile the kernel with debugging symbols (`CONFIG_DEBUG_INFO`).

KERNEL OOPS ANALYSIS ON YOCTO (2)

- Enabling debug symbols can be done by creating a specific defconfig for your kernel or a kernel config fragment (in case you are leveraging `kernel-yocto.bbclass`):

```
$ bitbake virtual/kernel -c kernel_configme -f
$ bitbake virtual/kernel -c menuconfig
$ bitbake virtual/kernel -c diffconfig
```

- After the build, the kernel ELF image with debugging symbols (`vmlinux`) will be in the build directory (`B`). Then you can use it for debugging and symbol resolution.

KERNEL OOPS ANALYSIS ON YOCTO (3)

- Now you can open a new terminal and set up the development environment:

```
$ . <SDK_INSTALL_DIR>/environment-setup-cortexa57-poky-linux
```

- Then find the kernel build directory and move to it:

```
$ bitbake virtual/kernel -e | grep ^B=
$ cd <KERNEL_BUILD_DIR>
```

KERNEL OOPS ANALYSIS ON YOCTO (4)

- To make it easier for GDB to find the kernel sources, you can set the source code directory on its configuration file:

```
$ bitbake virtual/kernel -e | grep ^S=
$ echo "set substitute-path /usr/src/kernel <KERNEL_SOURCE_DIR>" >> ~/.gdbinit
```

- Now you can run GDB to find the line of code causing the oops message:

```
$ aarch64-poky-linux-gdb -tui vmlinux
...
(gdb) list *(uptime_proc_show+0xfc)
```

HANDS-ON 4: KERNEL OOPS ANALYSIS

- Try to list `/proc/uptime` and the kernel will emit an oops message:

```
$ cat /proc/uptime
```

- In the host machine, use GDB to find the line of code in the kernel sources that is causing the issue.
- Obs.: You don't have to fix the issue, just find the root cause.

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Linux debugging

Memory leak

VALGRIND

- Valgrind is an instrumentation framework for building dynamic analysis tools.

  http://valgrind.org/

- Valgrind tools can automatically detect threading and memory management related bugs.

- Valgrind emulates the application binary on a synthetic CPU, and for this reason, it significantly impacts application runtimes.

VALGRIND TOOLS

- `memcheck`: detects memory management issues (memory leaks, invalid memory access, uninitialized memory, etc).
- `helgrind`: identifies synchronization problems in multithreaded applications (race conditions, deadlocks, etc).
- `cachegrind`: profile cache usage in applications.
- `massif`: profile heap usage in applications.

MEMORY LEAK ANALYSIS ON YOCTO (1)

- Let's say you want to debug an application called `memleak` that is leaking memory.
- To debug it with Valgring, and in order for Valgrind to resolve symbols in the target device, it is necessary to install in the image the application's **debug** and **source** packages (also, disabling security flags is recommended):

```
IMAGE_INSTALL:append = " memleak memleak-dbg memleak-src valgrind valgrind-dbg"
SECURITY_CFLAGS:pn-memleak = "${SECURITY_NOPIE_CFLAGS}"
SECURITY_CFLAGS_pn-valgrind = "${SECURITY_NOPIE_CFLAGS}"
```

- Then you can just run the application with Valgrind on the target device.

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MEMORY LEAK ANALYSIS ON YOCTO (2)

```
$ valgrind --tool=memcheck --leak-check=full ./memleak
==8331== Memcheck, a memory error detector
==8331== Copyright (C) 2002-2013, and GNU GPL'd, by Julian Seward et al.
==8331== Using Valgrind-3.10.1 and LibVEX; rerun with -h for copyright info
==8331== Command: ./memleak
==8331==
==8331==
==8331== HEAP SUMMARY:
==8331==     in use at exit: 30 bytes in 1 blocks
==8331==   total heap usage: 1 allocs, 0 frees, 30 bytes allocated
==8331==
==8331== 30 bytes in 1 blocks are definitely lost in loss record 1 of 1
==8331==    at 0x4C2AB80: malloc (in /usr/lib/valgrind/vgpreload_memcheck-amd64-linux.so)
==8331==    by 0x4006C9: txData (main.c:18)
==8331==    by 0x4007AE: main (main.c:38)
==8331==
==8331== LEAK SUMMARY:
==8331==    definitely lost: 30 bytes in 1 blocks
==8331==    indirectly lost: 0 bytes in 0 blocks
==8331==      possibly lost: 0 bytes in 0 blocks
==8331==    still reachable: 0 bytes in 0 blocks
==8331==         suppressed: 0 bytes in 0 blocks
==8331==
==8331== For counts of detected and suppressed errors, rerun with: -v
==8331== ERROR SUMMARY: 1 errors from 1 contexts (suppressed: 0 from 0)
```

HANDS-ON 5: MEMORY LEAK ANALYSIS (1)

- For this exercise, you will need two connections to QEMU (the console and one additional connection via SSH).

- First, start QEMU with more memory so Valgrind can run properly.

```
$ runqemu nographic qemux86 qemuparams="-m 512"
```

- Then create another connection to QEMU via SSH:

```
$ ssh root@192.168.7.2
```

HANDS-ON 5: MEMORY LEAK ANALYSIS (2)

- In the SSH connection, run the following command to monitor memory usage:

```
# while true; do clear; free; sleep 1; done
```

- In the QEMU console, run `fping`:

```
# fping -l 192.168.7.1
```

- Check the memory usage in the output of the SSH connection, and you will see that some memory is leaking during `fping` execution.

- Use Valgrind to find the line of code that is causing the leak.

Thanks!

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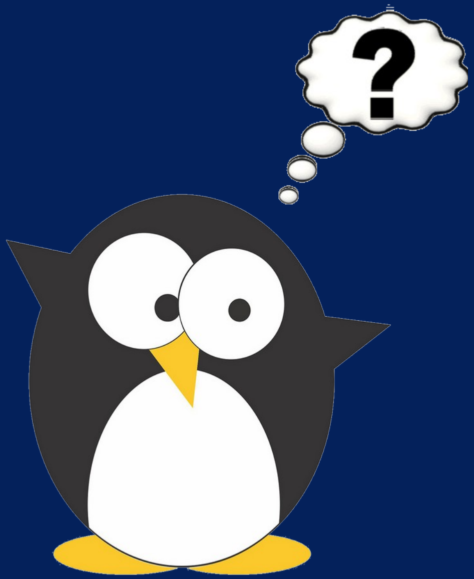

By Sergio Prado. São Paulo, September 2021