Debugging Custom Hardware with Linux

Tools to Make Your Hardware Engineers Love You

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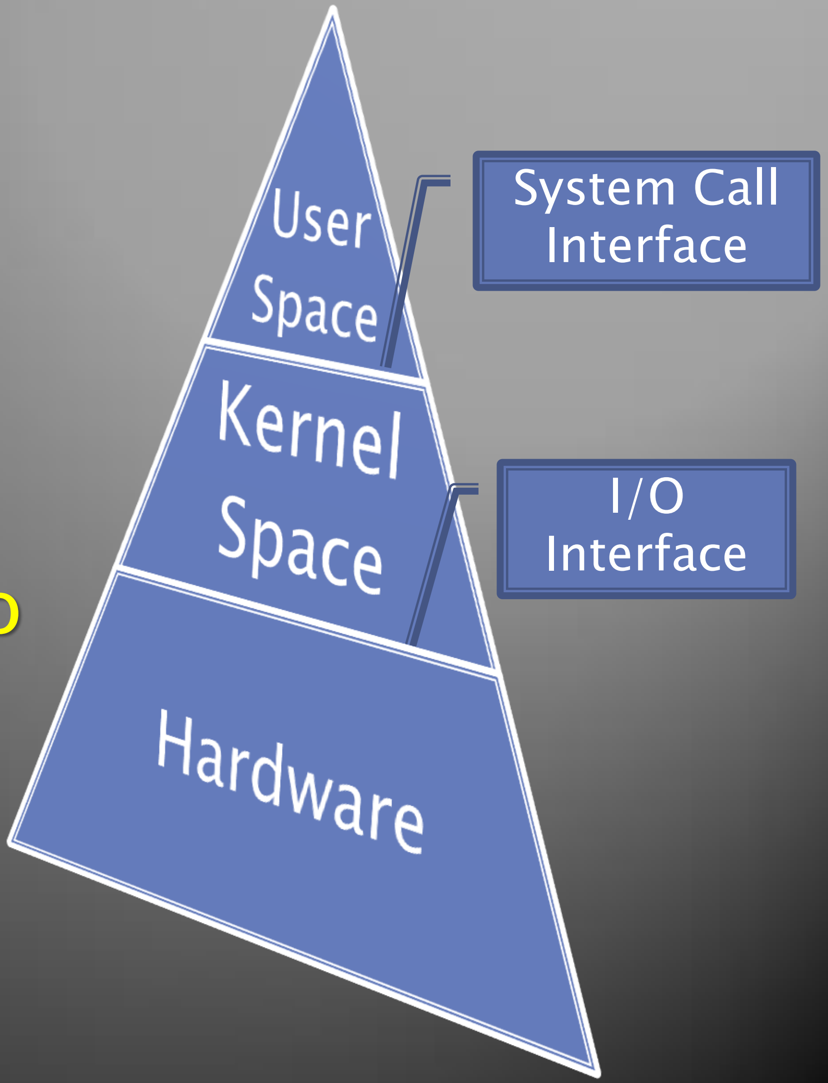
Agenda

- The Hardware Problem
- Simple Observation/Querying Tools
  - Virtual Files in /proc, /sys and debugfs
  - devmem
  - strace
  - And many others…
- Advanced Debug, Trace & Throughput Tools
  - GDB
  - Eclipse
  - LTTng
  - FIO
- General Tips and Tricks
- Interactive Debug Session

The Hardware Problem

- Kernel & User-Space development built upon foundation of hardware.

- Know what could go wrong.
- Know what tools exist to help you discover what went wrong.



Step 1: Gather Statistics
Read Virtual Text Files

- Observe! (cat/tail/more/less)
  - procfs
  - sysfs
  - debugfs

Procfs Virtual Filesystem – /proc

- /proc/interrupts, /proc/irq – System interrupt information
- /proc/iomem – Memory map
- /proc/modules – Info on kernel modules, similar to 'lsmod'
- /proc/sys/kernel/tainted – Kernel tainted info
- /proc/meminfo – Information about memory usage, both physical and swap
- /proc/cmdline – Kernel command line
- /proc/cpuinfo – Information about the processor
- /proc/filesystems – Filesystem information supported by the kernel

- /proc/<pid>/cmdline – Command line arguments passed to the <pid> process
- /proc/<pid>/mem – Memory held by the process
- /proc/<pid>/maps – Memory maps to executables and library files
- /proc/<pid>/status – Status of the process
- /proc/<pid>/environ – Environment variables
- /proc/<pid>/fd – Contains the file descriptors which is linked to the appropriate files
- /proc/<pid>/limits – Contains the information about the specific limits to the process
- /proc/<pid>/mounts – Mount related information

- More info in kernel source/Documentation/filesystems/proc.tx:
  - http://www.tldp.org/LDP/Linux-Filesystem-Hierarchy/html/proc.html

Sysfs Virtual Filesystem – /sys

- /sys/module
- /sys/module/<name>/parameters
- /sys/bus/platform/devices
- /sys/bus/platform/drivers/<name>/bind
- /sys/bus/platform/drivers/<name>/unbind

- Useful for hardware debug once kernel module created.
- Can create your own virtual files for reading and writing. Observe and also modify.

- More Info: https://www.kernel.org/doc/Documentation/filesystems/sysfs.txt

Debugfs Virtual Filesystem – /sys/kernel/debug

- Enable with:
  - Kernel Hacking
    - CONFIG_DEBUG_FS =y
  - ftrace
    - CONFIG_FUNCTION_TRACER=y
    - CONFIG_FUNCTION_GRAPH_TRACER=y
    - CONFIG_STACK_TRACER=y
    - CONFIG_DYNAMIC_FTRACE=y

- /sys/kernel/debug/tracing
- /sys/kernel/debug/tracing/events/*/enable
- /sys/kernel/debug/tracing/events/*/filter
- /sys/kernel/debug/tracing/set_event

More info:

https://www.kernel.org/doc/Documentation/filesystems/debugfs.txt

Step 2: Utilize Existing Command Line Tools

devmem

- Simple user space application
- Uses mmap() to map physical address of peripheral to virtual address
- Allows/Useful for:
  - Peeks & pokes memory locations
  - Early debug when HW is available, but driver not available
  - Debug issues to modify and monitor
- Limitations:
  - Only Read/Write one memory location

```
$ devmem
BusyBox v1.19.4 (2013-10-02 00:06:48 PDT) multi-call binary.
Usage: devmem ADDRESS [WIDTH [VALUE]]
Read/write from physical address
         ADDRESS Address to act upon
         WIDTH Width (8/16/...)
         VALUE Data to be written
```

Automating devmem

- Dump Addresses 0xFFFF_000 to 0xFFFF_00FC

```
for i in `seq 4294901760 4 4294902015`;
do
  devmem $i 32;
done
```

- Fill Addresses 0xFFFF_000 to 0xFFFF_00FC

```
for i in `seq 4294901760 4 4294902015`;
do
  j=`dd if=/dev/urandom bs=4 count=1 | hexdump -e '"0x%04x"'`
  devmem $i 32 $j;
done
```

/dev/mem & dd

- Command line:
  - dd if=/dev/mem

- Allows:
  - Dump or write blocks of data
- Limitations:
  - After kernel 2.6 /dev/mem access is limited for security

/dev/mem Alternatives

- Crash – installs unrestrited /dev/crash
  - http://people.redhat.com/anderson/
- fmem – installs unrestricted /dev/fmem
  - http://hysteria.cz/niekt0/fmem
- pmem – installs unrestricted /dev/pmem
  - http://www.rekall-forensic.com/
- LiME – Linux Memory Extractor
  - https://github.com/504ensicslabs/lime
- KDB – mdp command (kernel config options below)
  - CONFIG_FRAME_POINTER=y
  - CONFIG_KGDB=y
  - CONFIG_KGDB_SERIAL_CONSOLE=y
  - CONFIG_KGDB_KDB=y
  - CONFIG_KDB_KEYBOARD=y
  - Kdb command to dump physical memory

Other Debug Command Line Tools

- strace – display system calls used by any executable
- readelf – display information about the contents of ELF format files
- ldd – prints shared library dependencies
- LD_DEBUG environment variable
- nm – prints symbol table
- dmesg – print or control the kernel ring buffer
- lsof – list open files by directory, by pid or by socket
- iostat – monitor io devices such as disks

```
$ pmap 5732
5732: -bash
00393000  104K r-x-- /lib/ld-2.5.so
003b1000 1272K r-x-- /lib/libc-2.5.so
00520000    8K r-x-- /lib/libdl-2.5.so
0053f000   12K r-x-- /lib/libtermcap.so.2.0.8
0084d000   76K r-x-- /lib/libnsl-2.5.so
00c57000   32K r-x-- /lib/libnss_nis-2.5.so
00c8d000   36K r-x-- /lib/libnss_files-2.5.so
b7d6c000 2048K r---- /usr/lib/locale/locale-archive
```

- Memory
  - free – physical and swap memory info
  - vmstat – virtual memory statistics
  - pmap – displays process memory map
- Processes
  - top
  - ps

```
$ lsof /var
COMMAND PID USER FD TYPE DEVICE SIZE/OFF NODE NAME
syslogd 350 root 5w VREG 222,5 0 440818 /var/adm/messages
syslogd 350 root 6w VREG 222,5 339098 6248 /var/log/syslog
cron 353 root cwd VDIR 222,5 512 254550 /var -- atjobs
```

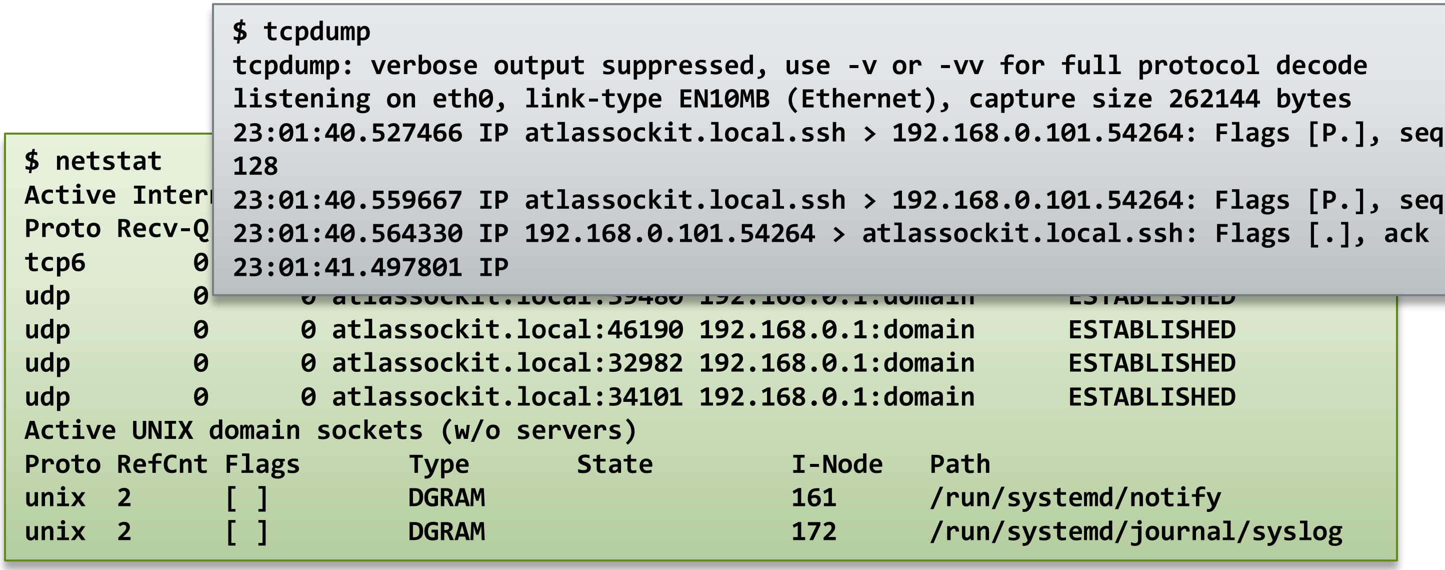
strace

- Displays system calls used by any executable
  - strace –e <syscall> : filter particular system calls
- WARNING: Overhead associated with each system call – Slower Performance.

```
$ strace ls
execve("/bin/ls", ["ls"], [/* 21 vars */]) = 0
brk(0) = 0x8c31000
access("/etc/ld.so.nohwcap", F_OK) = -1 ENOENT (No such file or directory)
mmap2(NULL, 8192, PROT_READ, MAP_PRIVATE|MAP_ANONYMOUS, -1, 0) = 0xb78c7000
access("/etc/ld.so.preload", R_OK) = -1 ENOENT (No such file or directory)
open("/etc/ld.so.cache", O_RDONLY) = 3
fstat64(3, {st_mode=S_IFREG|0644, st_size=65354, ...}) = 0
```

Ethernet, PCIe, USB

- If hardware to debug is not memory mapped but connected to a different interface:
- Ethernet
  - netstat
  - tcpdump
  - iftop
  - route
  - ss
  - vnstat
  - ntop



```
$ tcpdump
tcpdump: verbose output suppressed, use -v or -vv for full protocol decode
listening on eth0, link-type EN10MB (Ethernet), capture size 262144 bytes
23:01:40.527466 IP atlassockit.local.ssh > 192.168.0.101.54264: Flags [P.], seq
128
23:01:40.559667 IP atlassockit.local.ssh > 192.168.0.101.54264: Flags [P.], seq
23:01:40.564330 IP 192.168.0.101.54264 > atlassockit.local.ssh: Flags [.], ack
23:01:41.497801 IP
```

```
$ netstat
Active Inter
Proto Recv-Q
tcp6       0
udp        0      0 atlassockit.local:39480 192.168.0.1:domain      ESTABLISHED
udp        0      0 atlassockit.local:46190 192.168.0.1:domain      ESTABLISHED
udp        0      0 atlassockit.local:32982 192.168.0.1:domain      ESTABLISHED
udp        0      0 atlassockit.local:34101 192.168.0.1:domain      ESTABLISHED
Active UNIX domain sockets (w/o servers)
Proto RefCnt Flags       Type       State         I-Node   Path
unix  2      [ ]         DGRAM                    161      /run/systemd/notify
unix  2      [ ]         DGRAM                    172      /run/systemd/journal/syslog
```

- PCIe
  - lspci -vvv -- show/enumerate devices, device cfg with -x
  - PCI Utilities & IDs: http://mj.ucw.cz/pciutils.html
- USB
  - lsusb -v
  - usbmon

Step 3: Using Advanced Debuggers, Tracers, Performance Monitors

GNU Debugger – GDB

- Allows you to see what is going on `inside' another program while it executes -- or what another program was doing at the moment it crashed.

- Commands
  - break <location> -- set breakpoint
  - continue -- continue with program execution
  - del -- delete breakpoint, tracepoint
  - bt -- back trace
  - step # -- single step the program, can step # times
  - next -- step-over subroutine calls
  - list -- can list source code by line # or by function name
  - disas <function> -- show disassembly for function
  - catch <event> -- GDB stops program when event occurs
  - watch <expr> -- GDB stops program when expr changes

- More Info: https://www.gnu.org/software/gdb/

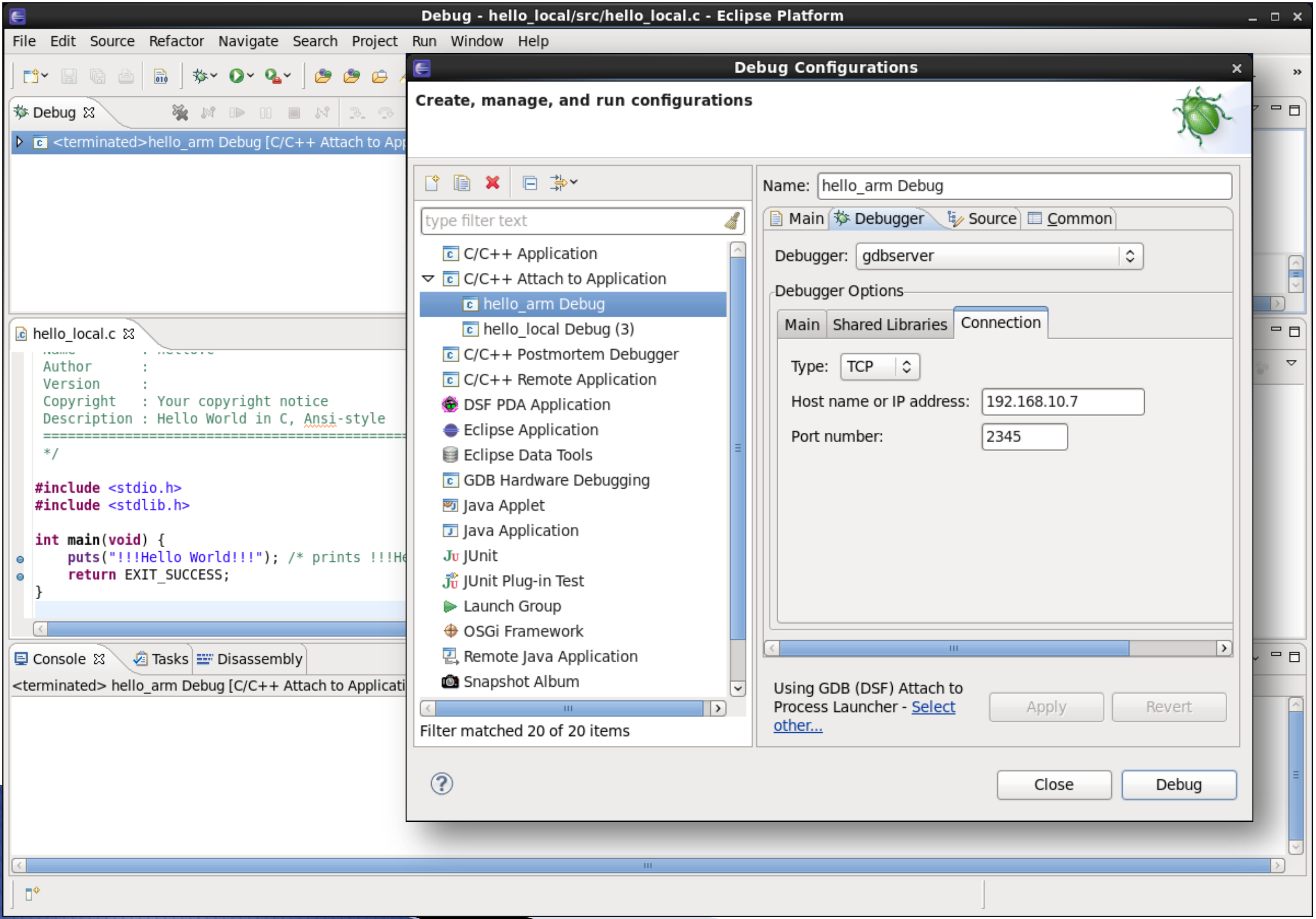
Eclipse IDE

- Debug Features
  - IDE GUI with Source debug
  - Program launching
  - Launches debuggers, including GBD local or remote (other plug-ins available)
  - Define and control breakpoints
  - Inspect memory, peripherals, CPU registers
  - Tracing and Profiling Support
  - Supports a multitude of languages including C/C++, Java, PHP, etc.
  - Plug-in Development Environments (Extensible)

- Running Eclipse with GDB
  - Create a project & select (cross-)compiler
  - Optional: Configure paths to build tools (cross-compiler, assembler, linker, etc.)
  - Create a Debug Configuration of type C/C++
  - Specify cross GDB path in Debugger/Main tab (must be configured for host and target systems)
  - Configure target IP and gdbserver port in Debugger/Connection tab
  - Run gdbserver on target and launch application to debug
  - Make sure source code and compiled elf files, kernel modules, shared libraries, etc. are on host/remote system to debug. Useful for symbols.
  - Click Debug button in Eclipse Debug Configurations window

More Info: https://eclipse.org/

Eclipse GUI



Debug - hello_local/src/hello_local.c - Eclipse Platform

Debug Configurations

Create, manage, and run configurations

<terminated>hello_arm Debug [C/C++ Attach to App

```
 Author      :
 Version     :
 Copyright   : Your copyright notice
 Description : Hello World in C, Ansi-style
 ==========================================
 */

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

int main(void) {
    puts("!!!Hello World!!!"); /* prints !!!He
    return EXIT_SUCCESS;
}
```

<terminated> hello_arm Debug [C/C++ Attach to Applicati

Name: hello_arm Debug

Debugger: gdbserver

Type: TCP

Host name or IP address: 192.168.10.7

Port number: 2345

Using GDB (DSF) Attach to Process Launcher - Select other...

Filter matched 20 of 20 items

Tracing tools – LTTng

- Open Source Tracing Framework
- Kernel space & User space
  - Kernel modules, User space Library and tools
- Command line tools
  - lttng
  - Babeltrace

- More Info: http://lttng.org/

```
$ lttng create
$ lttng enable-event --userspace hello_world:my_first_tracepoint
$ lttng start
$ lttng stop
$ lttng view
```

```
[18:10:27.684304496] (+?.?????????) hostname hello_world:my_first_tracepoint: { cpu_id = 0 }, { my_string_field = "hi there!", my_integ
[18:10:27.684338440] (+0.000033944) hostname hello_world:my_first_tracepoint: { cpu_id = 0 }, { my_string_field = "./hello", my_intege
[18:10:27.684340692] (+0.000002252) hostname hello_world:my_first_tracepoint: { cpu_id = 0 }, { my_string_field = "world", my_integer
[18:10:27.684342616] (+0.000001924) hostname hello_world:my_first_tracepoint: { cpu_id = 0 }, { my_string_field = "and", my_integer_f
[18:10:27.684343518] (+0.000000902) hostname hello_world:my_first_tracepoint: { cpu_id = 0 }, { my_string_field = "beyond", my_integ
[18:10:27.684357978] (+0.000014460) hostname hello_world:my_first_tracepoint: { cpu_id = 0 }, { my_string_field = "x^2", my_integer_f
```

Tracer Alternatives

- ftrace – Linux Kernel internal tracer
  - https://www.kernel.org/doc/Documentation/trace/ftrace.txt
  - https://www.kernel.org/doc/Documentation/trace/events.txt
- perf – Linux profiling with performance counters
  - https://perf.wiki.kernel.org/index.php/Main_Page
- SystemTap https://sourceware.org/systemtap/
- Ktap – Script-based dynamic tracing
  - http://www.ktap.org/
- Dtrace4linux
  - http://crtags.blogspot.com/
- Sysdig
  - http://www.sysdig.org/

Flexible I/O Tester – FIO

- Used for stress testing hardware
- Discover Performance Information
  - bandwidth limits
  - latencies
- I/O engines used:
  - Sync
  - Mmmap
  - Libaio
  - Posixaio
  - & more
- Works with block devices and virtual files

FIO – Sample Output

```
 ./fio --ioengine=libaio --gtod_reduce=1 --name=test --filename=/dev/nvme0n1 --bs=128K --
iodepth=4 --size=1G --readwrite=write --direct=1test: (g=0): rw=write, bs=128K-128K/128K-
128K/128K-128K, ioengine=libaio, iodepth=4


fio-2.2.8-25-g2236
Starting 1 process
Jobs: 1 (f=1)
test: (groupid=0, jobs=1): err= 0: pid=2799: Thu Feb 18 05:56:29 2016
  write: io=1024.0MB, bw=699984KB/s, iops=5468, runt=  1498msec
  cpu          : usr=18.97%, sys=25.78%, ctx=8267, majf=0, minf=31
  IO depths    : 1=0.1%, 2=0.1%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, >=64=0.0%
     submit    : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
     complete  : 0=0.0%, 4=100.0%, 8=0.0%, 16=0.0%, 32=0.0%, 64=0.0%, >=64=0.0%
     issued    : total=r=0/w=8192/d=0, short=r=0/w=0/d=0, drop=r=0/w=0/d=0
     latency   : target=0, window=0, percentile=100.00%, depth=4

Run status group 0 (all jobs):
  WRITE: io=1024.0MB, aggrb=699983KB/s, minb=699983KB/s, maxb=699983KB/s, mint=1498msec,
maxt=1498msec

Disk stats (read/write):
  nvme0n1: ios=84/7538, merge=0/0, ticks=3/4851, in_queue=4854, util=92.65%
```

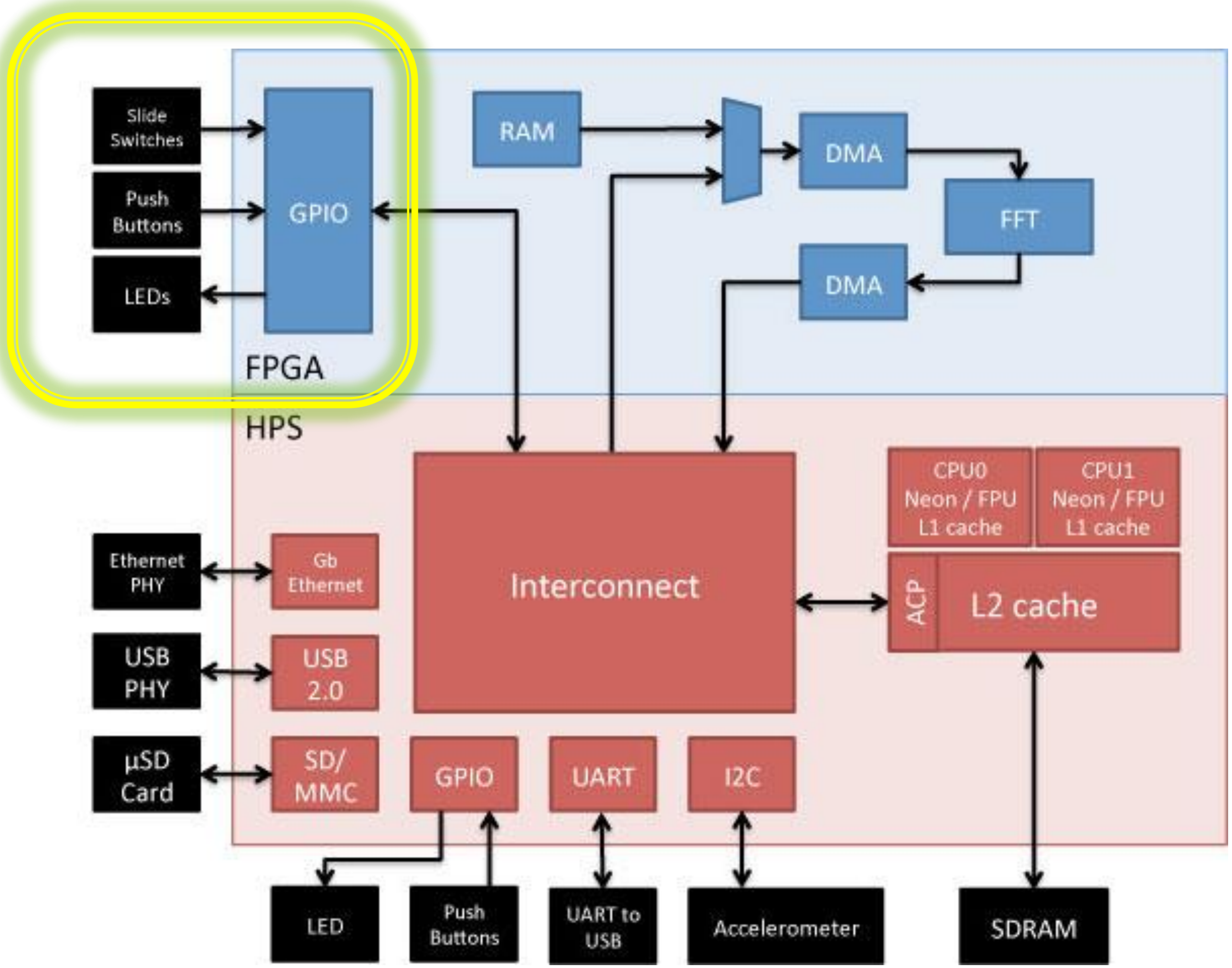
Other Useful Debug Tools

- On Chip Debugger via JTAG
  - http://openocd.org/
- rr – replay debug sessions
  - http://rr-project.org/
- Valgrind – Mem, Cache, Thread debugging
  - http://valgrind.org/

General Tips and Tricks

- Use dd to read/write blocks
- Use /dev/urandom to generate random data
- Use hexdump to format data
- Use tail –f | less (press ‘F’)
  - To follow log files in real time
- Use watch
- Automate, Automate, Automate!
  - Don’t forget shell automation!

Interactive Debug Session



- More info: https://rocketboards.org/

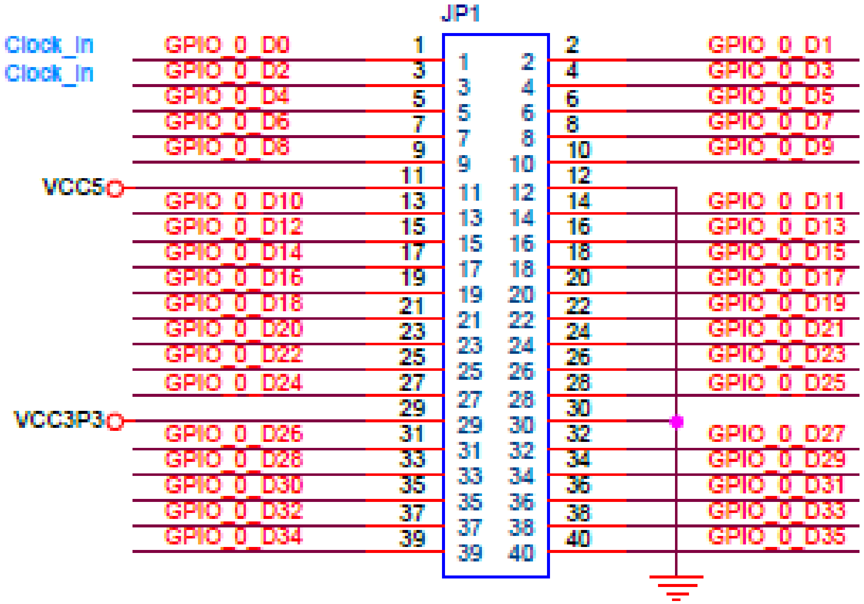
Demo 1: Procfs & Interrupts

- **Can monitor interrupts or GPIO status**

- watch -n 0 cat /proc/interrupts
- watch -n 0 cat /sys/kernel/debug/gpio

- **Alternatively:**
  - Can Read directly from HW
  - devmem 0xff204000

GPIO 0 Header



Demo 2: GDB in User Space

- devmem 0xff200000 32 0
  - zero out driving GPIOs
  - Alternatively, monitor GPIOs:
    - GPIO 0: devmem 0xff200000
    - GPIO 1: devmem 0xff200010 = 0xFDFFF7FF
- cd ~/gpio
- gdb example1
  - run GDB on small user space app
- (gdb) run
- (gdb) p pin
- CTRL-C to stop gdb
- quit

Demo 3: Debugfs & ftrace

- echo ff205000.gpio > /sys/bus/platform/drivers/altera_gpio/unbind
- cd ~/button_led
- insmod mod/uio.ko
- insmod mod/my_uio_pdrv_genirq.ko
- gdb app/example1
- (gdb) run
- (gdb) p/t count
- (gdb) quit
- grep irq /sys/kernel/debug/tracing/available_events
- echo 'irq:irq_handler_entry' >> /sys/kernel/debug/tracing/set_event
- echo 'irq:irq_handler_exit' >> /sys/kernel/debug/tracing/set_event
- ./app/example1 &
- (push buttons on board)
- grep “irq=48” /sys/kernel/debug/tracing/trace

- **(Optional:)** echo 1 > events/module/module_(load|free)/enable

Conclusions

- Observe virtual file systems
  - /proc && /sys && /sys/kernel/debug
- Monitor log files
- Utilize devmem to access register and memory in hardware early in debug
- Utilize strace and other command line tools!
- GDB & Eclipse can offer direct debugging with breakpoints and variable monitoring
- Utilize available tracer tools, if needed
- Utilize performance monitoring tools, if needed

References

- Top 25 Best Linux Performance Monitoring and Debugging Tools
  - http://www.thegeekstuff.com/2011/12/linux-performance-monitoring-tools/
- 5 User Space Debugging Tools in Linux
  - http://linoxide.com/linux-how-to/user-space-debugging-tools-linux/
  - http://www.thegeekstuff.com/2010/11/50-linux-commands/
- /proc
  - http://www.thegeekstuff.com/2010/11/linux-proc-file-system/
- Choosig Linux Tracers – Brendan Gregg
  - http://www.brendangregg.com/blog/2015-07-08/choosing-a-linux-tracer.html
- USB Debuggin Techniques
  - http://elinux.org/images/1/17/USB_Debugging_and_Profiling_Techniques.pdf
- GDB
  - https://www.gnu.org/software/gdb/
- LTTng – Open Source Trace Framework
  - http://lttng.org/
  - http://lttng.org/blog/2015/03/18/full-stack-latencies/
- openOCD – On-Chip Debugger
  - http://openocd.org/
- Eclipse
  - https://eclipse.org/

THANK YOU!

- Final slides on: http://rocketboards.org