# Efficient JTAG-based Linux kernel debugging

## Embedded Linux Conference Europe - 2011

# Rationale

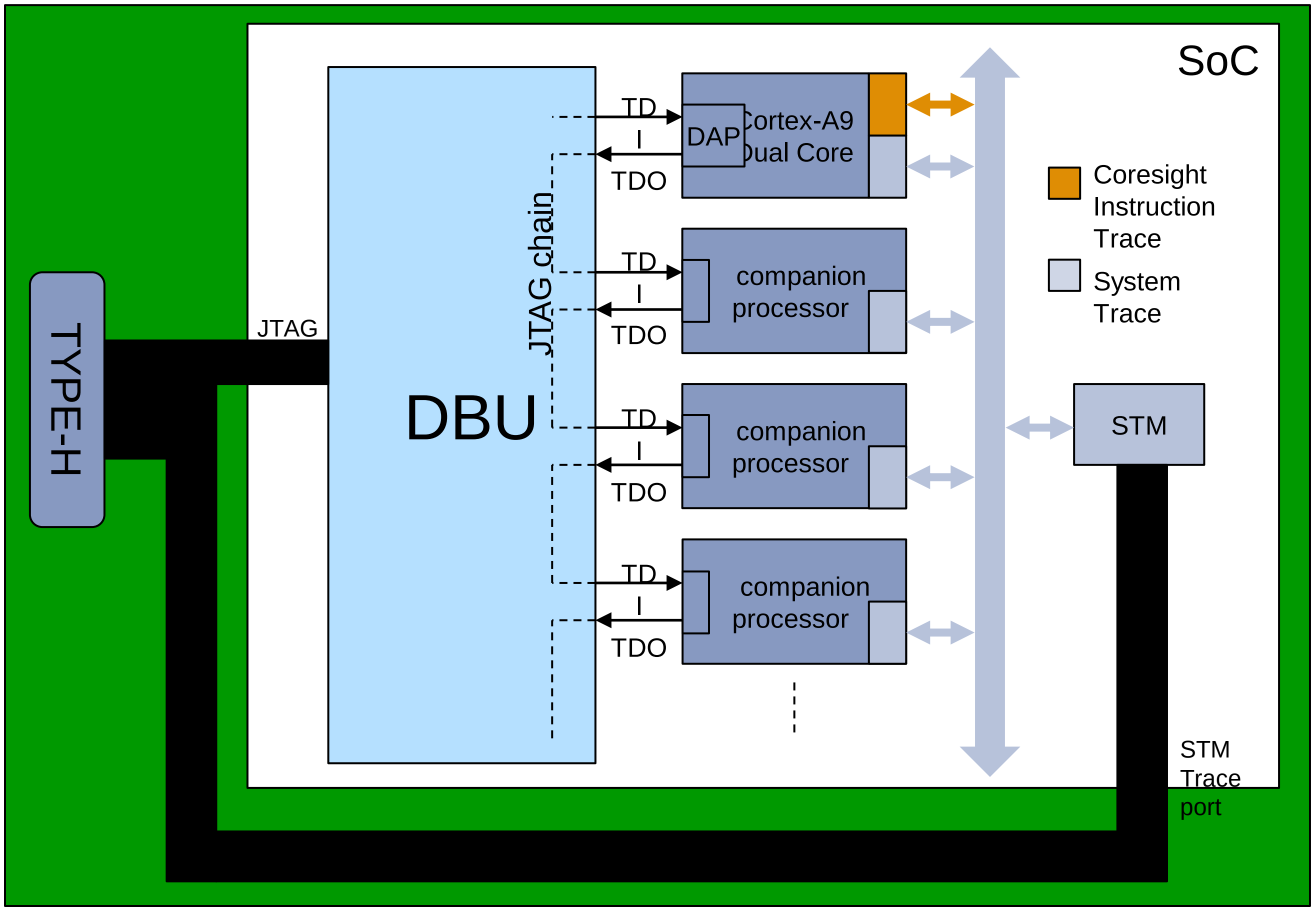
- **Embedded Linux in Devices: sustained growth for many years** and more recently increasing success of System Middleware for Devices based on Linux, especially Google Android.

- **The number of MPSoC running embedded Linux is increasing** and accordingly the software architecture is adapting, getting scalable and parallel. Now taken into account by chip vendors: cross triggering and system-wide tracing support IPs.

- **STMicroelectronics Internal requirements and historical facts** The software for multimedia appliances (set-top-boxes) is part of the reference design we provide. We needed to port a scalable Multimedia Streaming and Processing Framework from an RTOS to Linux by the time when mastering wake-up latency would mean doing kernel streaming (or using a RT co-kernel…)

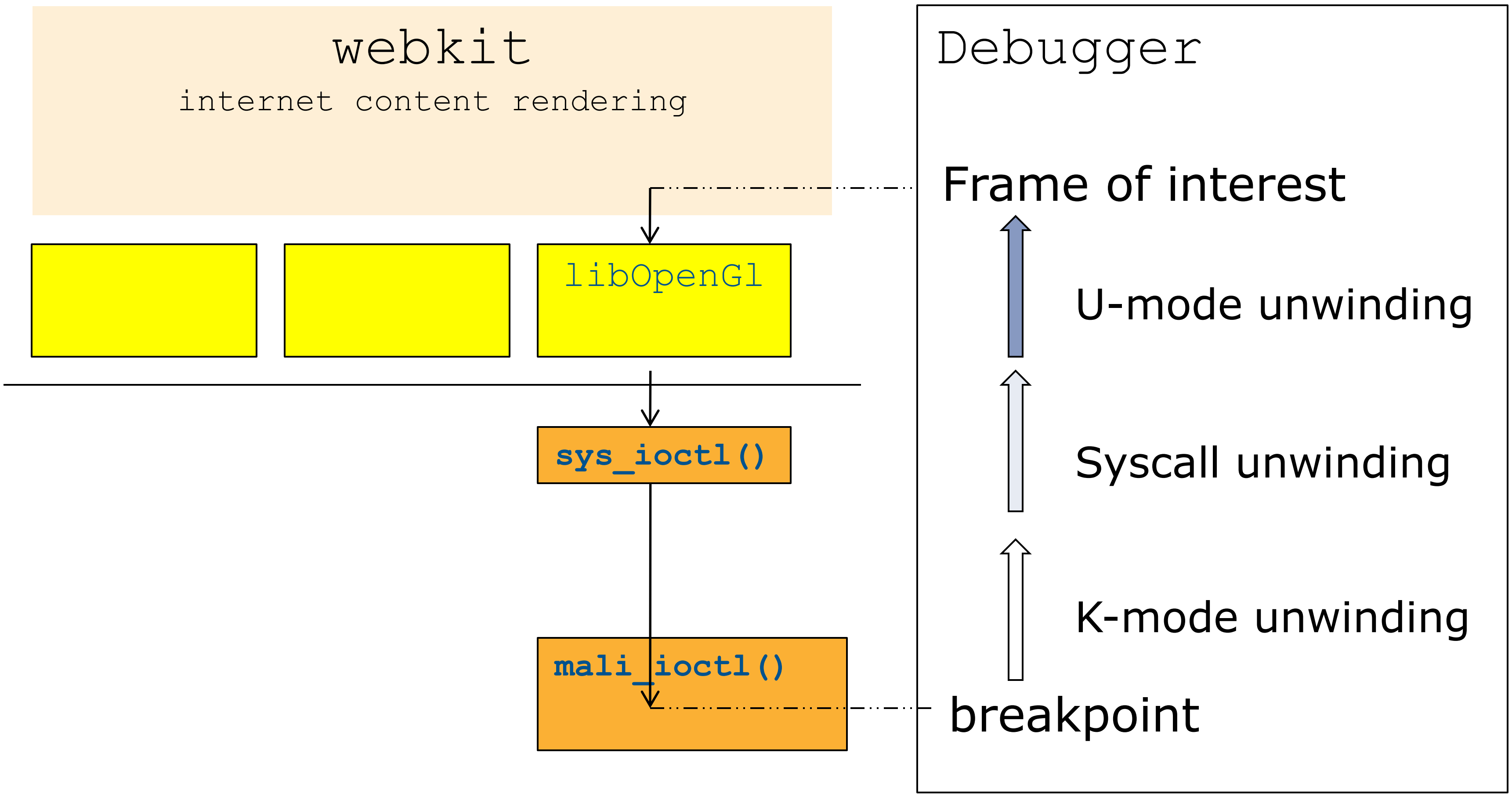
# Multi-core debugging and tracing

*Chip vendors have taken into account the need for MP-specific debug and tracing infrastructure.*



# Simple real word use case

- Set-top-box with internet browser: debug an erratic situation in a driver rooted in userland.



# Simple real word use case

```
(gdb) b sys_open
Breakpoint 4 at 0x8006dd40: file fs/open.c, line 1060.
(gdb) c
Continuing.

[Switching to ls]

Breakpoint 4, sys_open (filename=0x2956bc9c "/etc/ld.so.cache", flags=0, mode=1) at fs/open.c:1060
1060       ret = do_sys_open(AT_FDCWD, filename, flags, mode);
(gdb) bt
#0  sys_open (filename=0x2956bc9c "/etc/ld.so.cache", flags=0, mode=1) at fs/open.c:1060
#1  0x80008920 in syscall_call ()
#2  0x29568244 in open ()
…
#11 0x2955bb78 in _dl_start_final (arg=0x7b82fd80) at rtld.c:328     usermode unwinding
#12 _dl_start (arg=0x7b82fd80) at rtld.c:554
#13 0x295588cc in _start ()
```

# Kernel debuggers for devices

**KGDB**

- Requires sufficient support for RS-232 or Ethernet
- Won't remain in production / flashed kernels
- Requires kernel co-operation, less usable for serious crashes

**JTAG, the bold way**

- Find a JTAG probe that has compatibility with gdb-remote protocol
- Debug vmlinux as a baremachine "hello word" application
- Some of good tips and tricks on the web:

*www.elinux.org/DebuggingTheLinuxKernelUsingGdb*

- SMP: if you are lucky, the JTAG probe "gdbserver" exposes one thread per core in gdb.

# Kernel debuggers for devices, fancier

## Commercial Solutions

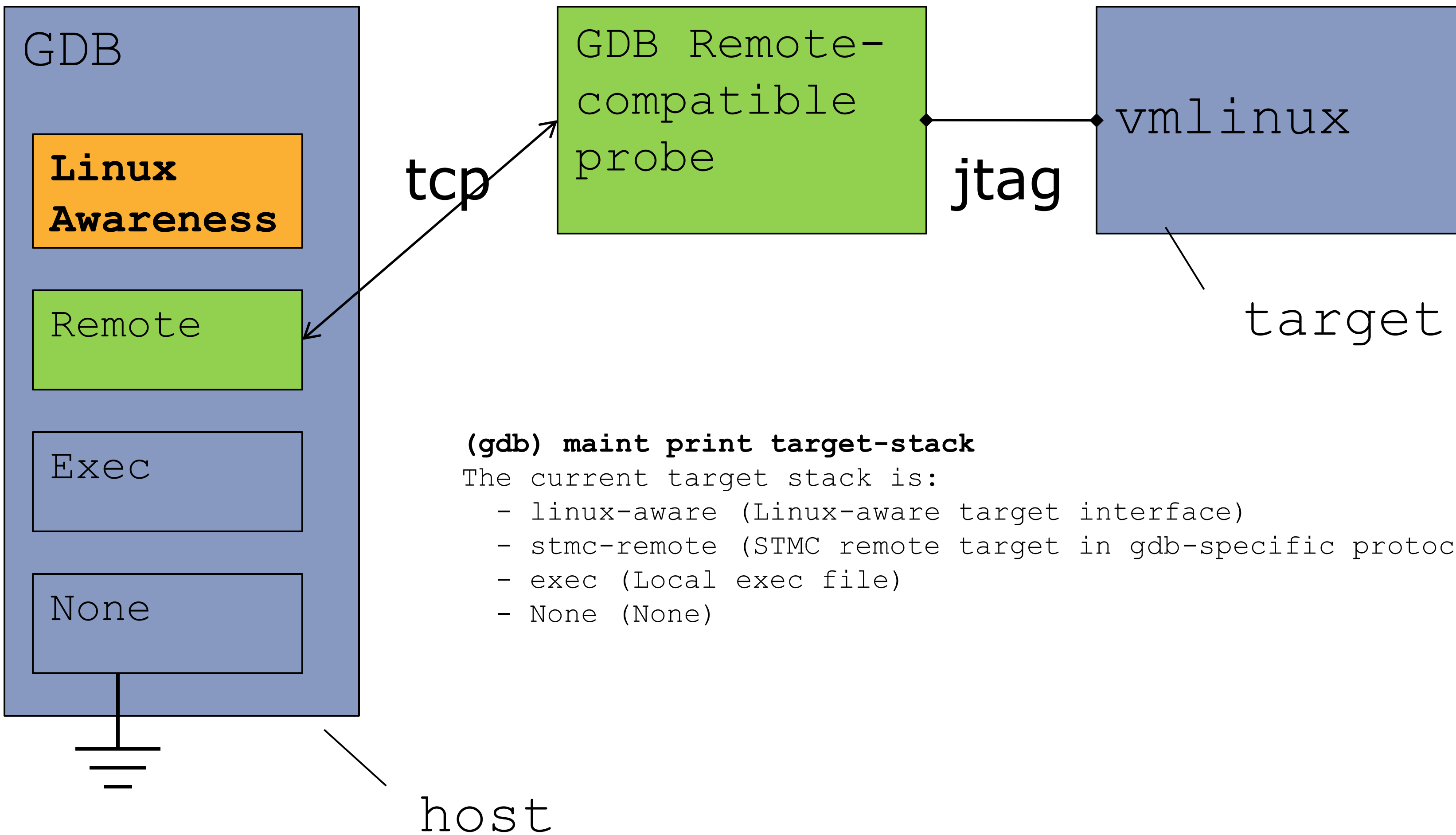
- Must be very well defined in terms of supported targets, software versions  and debugging hardware because support and service can be part of the package.

## JTAG, the presented way: implement <u>Linux Awareness</u>

- Find a JTAG probe compatible with **gdb remote protocol**
- Handle kernel modules the same way as shared libraries, with init/release hooking.
- Deal with memory translation and MMU settings, as the kernel will not do it for us
- Expose Linux tasks as selectable threads in gdb
  - *Allow stepping any of the scheduled task (one per core)*
  - *Allow backtracing*
  - *Allow breakpointing*

# Linux Awareness Components Layout

*L/A is a self contained extension, compliant with GDB target model!*




```
(gdb) maint print target-stack
The current target stack is:
  - linux-aware (Linux-aware target interface)
  - stmc-remote (STMC remote target in gdb-specific protocol)
  - exec (Local exec file)
  - None (None)
```

# Mapping Linux tasks to gdb threads

## Purpose

- Map anything that has a `task_struct` to a thread for gdb
- Be able to select this thread through usual gdb commands and
  - get the backtrace
  - list the sources matching a frame, resolve the symbols
  - set breakpoints, `stepi/nexti, step/next, finish, return...`

## Howto

- *Enumeration* walk the kernel linked lists of `task_struct`
- *Housekeeping* track process creation and deletion
- Distinguish scheduled ones (stepping allowed) from non-scheduled ones (stepping not allowed)

# Mapping Linux tasks to gdb threads

## Minimal data needed for Linux process housekeeping:

- `task_struct.`**`comm`** executable command string
- `task_struct.`**`pid`** Process ID.
- `task_struct.`**`tgid`** Thread Group ID
- `task_struct.`**`mm`** tells whether it is an anonymous context or not
- `task_struct.`**`active_mm`** tells the actual page dir. used in this context

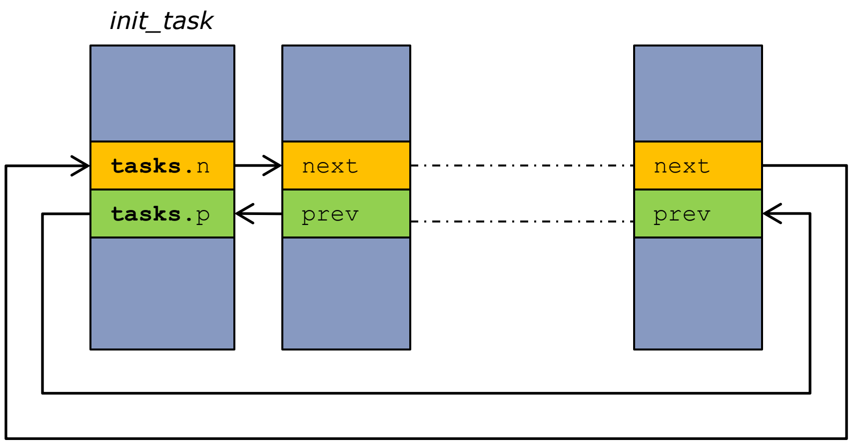
## Constraint: accessing a remote target through JTAG

- GDB internal APIs and good practices encourage dynamic typing: types (size, endianness) are provided by the target "object"
- *But accessing a remote hardware: better read a few big chunks of data than many individual structure fields !*

# Mapping Linux tasks to gdb threads

## Populating the process list

- Flat exploration: like *for_each_process in sched.h*



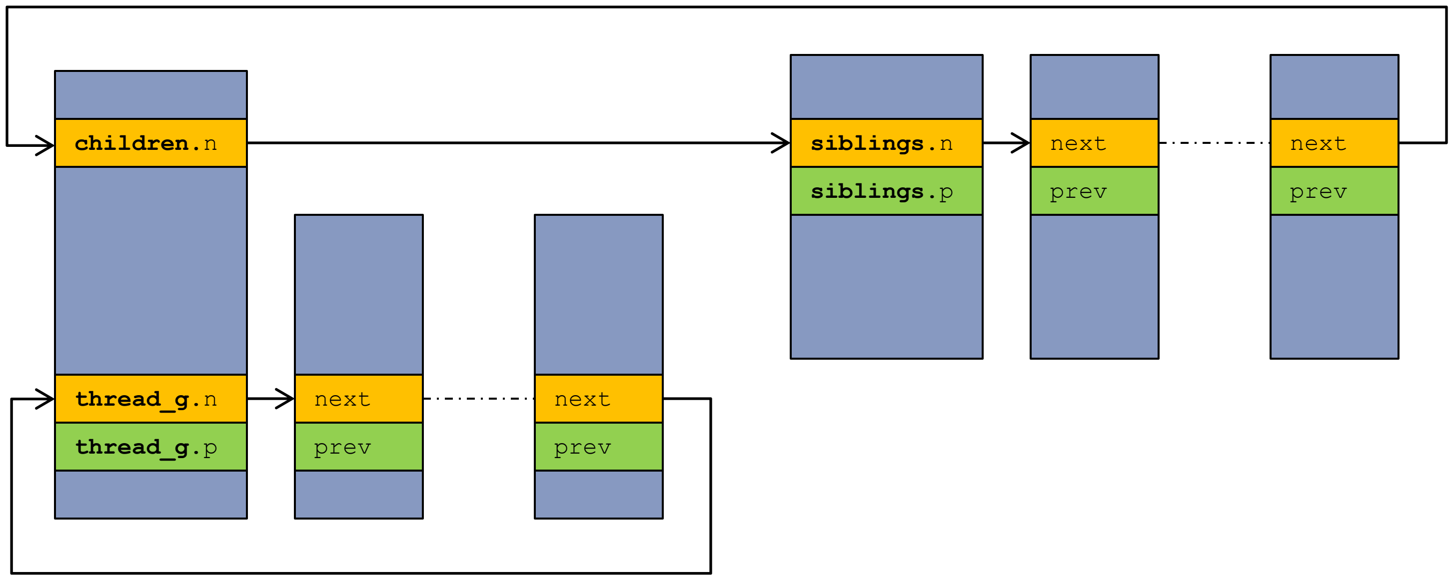

- Works, but discovery of tasks done in creation order, while we want to regroup the threads of a process...

- other “swappers” (SMP case) not reachable this way

# Mapping Linux tasks to gdb threads

## Populating the process list

- Alternate exploration:




- Other “swappers”: added by default, one per h/w thread reported by underlying remote target. Reachable through the runqueues “idle” field.

# Mapping Linux tasks: housekeeping

## Find out when to rebuild the Linux task list

- done when the Linux-Awareness target processes an inferior event: happens very often (stepping) and must be optimized!
- breakpointing do_fork / do_exit is too intrusive.
- pid.c

```
struct pid_namespace init_pid_ns = {
		.kref = {
			.refcount	= ATOMIC_INIT(2),
		},
		.pidmap = {
			[ 0 ... PIDMAP_ENTRIES-1] = { ATOMIC_INIT(BITS_PER_PAGE), NULL }
		},
		.last_pid = 0,
		.level = 0,
		.child_reaper = &init_task,
};
```

- exit.c

```
__get_cpu_var(process_counts--)
```

```
$>nm vmlinux | grep process_count
c0021280 T per_cpu__process_counts
```

# Mapping Linux tasks

## Accessing the per-cpu variables in GDB

- Fairly simple, as of today we only need:
  - `__per_cpu_offset` offset of each CPU's per_cpu page
  - `process_count`
  - `per_cpu__runqueues` (or occasionally `runqueues`)
    - `rq->idle`
    - `rq->curr` currently scheduled task

## Finding the currently scheduled task

- "`current = sp & ~(THREAD_SIZE-1)`": this won't work when putting the target in debug mode while the core is running a usermode code page.
- We need to check `rq->curr`.

# Kernel Module Debugging

## Main features

- Allow init/exit debugging without specific kernel code.
- Resolve path to modules.dep and pull symbols automatically.
- Reuse the solib infrastructure in gdb

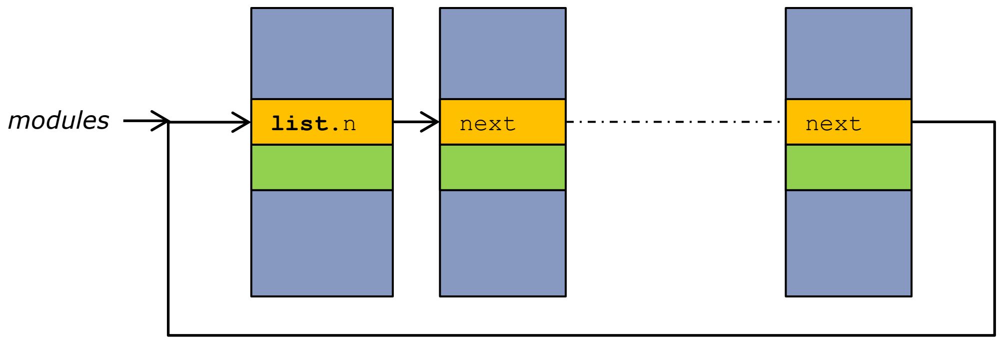
## GDB solib callbacks

- *soops_bfd_open*
- *soops_relocate_section_addresses* resolving and "linking" sections
- *soops_open_symbol_file_object*
- *soops_special_symbol_handling* related to manual symbol-loading
- *soops_current_sos* modules enumeration
- *soops_in_dynsym_resolve_code* hide the TLB-miss handler when stepping through a VM code page

# Kernel Module Debugging

## Building the modules list

- Usual kernel list starting with symbol "`modules`"




- For each module we read a block of RAM to gather the name…
- and info needed to properly handle the section layout

.init .module_init .module_core .init_size .core_size .init_text_size .init_text_size .core_text_size .core_text_size

***Hoping they won't change offset too much in struct module!***

# Kernel Module Debugging

## Virtual memory handling

- Architecture specific part (arm/memory.txt)!

```
PAGE_OFFSET         high_memory-1        Kernel direct-mapped RAM region.
                                         This maps the platforms RAM, and typically
                                         maps all platform RAM in a 1:1 relationship.

TASK_SIZE           PAGE_OFFSET-1        Kernel module space
                                         Kernel modules inserted via insmod are
                                         placed here using dynamic mappings.
```

- Accessing modules code pages requires memory translation.

For pages between TASK_SIZE and PAGE_OFFSET_1 we set

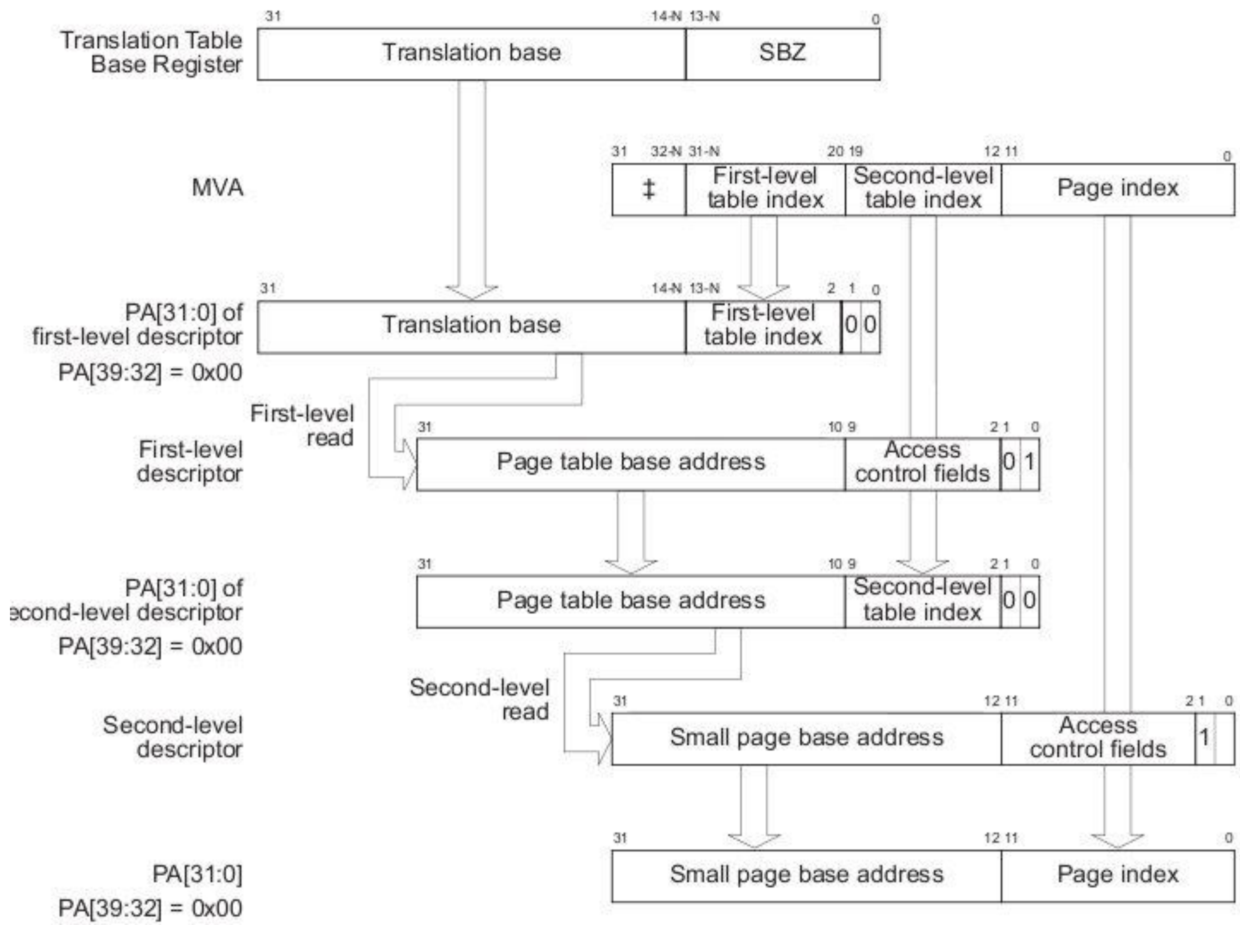
```
pdg = swapper_pg_dir + 8* (addr >> PGDIR_SHIFT)
```

Cope with physical memory offset: `pdg += phys_offset`

We read phys_offset from: `meminfo.bank[0].start`

# Kernel Module Debugging

From *ARMv7 Arch. Ref. manual*: small page translation flow



# Kernel Module Debugging

## MMU switching

- GDB remote server must supply architecture specific support
- This is currently the only arch specific constraint on gdbserver
- Very simple interface for ARM, but can be tricky on gbdserver side.

**Remote specific command example (ST-Microconnect):**

```
st cp15 c1 0 c0 0              read System Control Register
st cp15 c2 0 c0 0              read Translation Table Base Register 0
st cp15 c2 0 c0 0 0x%x         write TTRB0
st cp15 c13 0 c0 1             read Context ID register (ASID)
st cp15 c13 0 c0 1 0x%x        write ASID
```

**Example with Qemu:**

```
Qqemu.st.mrc.c2_base0;%x
Qqemu.st.mrc.c13_context;%x
```

# Kernel Module Debugging

## Hooking the init and release steps of a module's life

- Init sections are freed after module loading completed
- In order to debug in *module_init* section: hooking required

sys_load_module

↓

load_module

↓

**module_finalize(*hdr, *sechdr, *mod)**

- Hit breakpoint here
- read "*mod" = ptr to the module
- retrieve module info,
- resolve symbols
- solib_add
- set a breakpoint in **init** routine

- Detect module unload with breakpoint in `module_arch_cleanup`

- Setting a pending breakpoint triggers these hooks,
- Disabled by default to avoid heavy debug-mode activity when loading series of modules

# Userland support

## Debugging userland with the Linux Kernel Debugger

- not so simple, not so sensible, but some comfort can be granted to the user, like:
- translate VM addresses: `task_struct.active_mm.pgd` `task_struct.active_mm.id`
- pull process symbols, switch “main” and symbol space when stepping, backtracing usermode

⇒ Setting a breakpoint in kernel mode, then unwinding and stepping up to usermode is not so hard to achieve.

# Android support

## About Google's NDK

- Fine for attaching to a running Linux process
- Used not to work for regular cross-debugging (fixed?)

⇒ We had to provide users with means to debug the early init of a newly spawned Dalvik VM

## New gdb commands

- wait_exe_uid — execute canned commands when hitting `do_fork` for an executable with the given UID
- wait_android_vm — execute canned commands when hitting `do_fork` for an executable with UID in the range matching Android VMs (AID_APP)

# Project Status and Maturity

## Project Maturity

- Historically based on GDB branch for ST40(sh4)/ST200 cross debuggers, many ST-internal contributors accountable for credit: Mark Phillips, Miguel Santana, Chris Smith, Frederic Riss, ...
- Widely deployed internally through Eclipse integration (STWorkbench)
- Ongoing development for ARM MPSoC targets

## Possible improvements

- Leverage contribution of GDB as of 7.x: many contributions in the fields of scheduling control and multiple address and symbol space management.

# About contribution and prospective

## Feedback

- We will consider the possibility to contribute this work upon positive feedback from the community.

## Prospective work

- Could be a basis to develop “Debuggers for Linux Cluster On Chip” ongoing PhD in this field (*kevin pouget at st dot com*)

## Benefits of contribution

- in mainstream GDB: encourage better core/device abstraction
- in mainstream Kernel:  encourage keeping access to data used for debug agnostic to kernel version and CONFIG_XXX and “JTAG friendly”
- In JTAG probe software:  support GDB-remote, present a hardware thread for each core

# A word of conclusion

**Suggestions for JTAG probe software implementers**

- act like a remote gdbserver, handle sw/hw breakpoints
- Standardize “remote” commands for architecture specific coprocessor settings (typically cp15 operations on ARM)
- Expose one hardware thread per core
- Expose the implementation choices for SMP (whether all-block or not) thanks to remote target (gdb target abstraction).

**Linux Kernel**

so far we cope with most versions and CONFIG variants,

but would be nice if :

- Used offsets and kernel symbols not moving too often
- Fields needed for Linux-awareness kept contiguous to optimize transfers and limit intrusiveness.

# Thank you !

# Demo ...

# and questions

☺