Linux kernel and driver development training

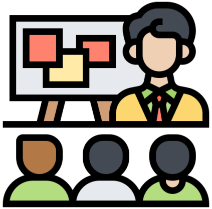
Latest update: February 24, 2023.

Document updates and training details:
https://bootlin.com/training/kernel

Corrections, suggestions, contributions and translations are welcome!
Send them to feedback@bootlin.com

Linux kernel and driver development training

- These slides are the training materials for Bootlin's *Linux kernel and driver development* training course.
- If you are interested in following this course with an experienced Bootlin trainer, we offer:
  - **Public online sessions**, opened to individual registration. Dates announced on our site, registration directly online.
  - **Dedicated online sessions**, organized for a team of engineers from the same company at a date/time chosen by our customer.
  - **Dedicated on-site sessions**, organized for a team of engineers from the same company, we send a Bootlin trainer on-site to deliver the training.
- Details and registrations: `https://bootlin.com/training/kernel`
- Contact: `training@bootlin.com`



Icon by Eucalyp, Flaticon

About Bootlin

Bootlin introduction

- Engineering company
  - In business since 2004
  - Before 2018: *Free Electrons*
- Team based in France and Italy
- Serving **customers worldwide**
- **Highly focused and recognized expertise**
  - Embedded Linux
  - Linux kernel
  - Embedded Linux build systems
- **Strong open-source** contributor
- Activities
  - **Engineering** services
  - **Training** courses
- https://bootlin.com

Bootlin engineering services

Bootloader / firmware development

U-Boot, Barebox, OP-TEE, TF-A, .../

Linux kernel porting and driver development

Linux BSP development, maintenance and upgrade

Embedded Linux build systems

Yocto, OpenEmbedded, Buildroot, ...

Embedded Linux integration

Boot time, real-time, security, multimedia, networking

Open-source upstreaming

Get code integrated in upstream Linux, U-Boot, Yocto, Buildroot, ...

Bootlin training courses

Embedded Linux system development On-site: 4 or 5 days Online: 7 * 4 hours	Linux kernel driver development On-site: 5 days Online: 7 * 4 hours	Yocto Project system development On-site: 3 days Online: 4 * 4 hours	Buildroot system development On-site: 3 days Online: 5 * 4 hours
Understanding the Linux graphics stack On-site: 2 days Online: 4 * 4 hours	Embedded Linux boot time optimization On-site: 3 days Online: 4 * 4 hours	Real-Time Linux with PREEMPT_RT On-site: 2 days Online: 3 * 4 hours	Linux debugging, tracing, profiling and performance analysis On-site: 3 days Online: 4 * 4 hours

Bootlin, an open-source contributor

- Strong contributor to the **Linux** kernel
  - In the top 30 of companies contributing to Linux worldwide
  - Contributions in most areas related to hardware support
  - Several engineers maintainers of subsystems/platforms
  - 8000 patches contributed
  - https://bootlin.com/community/contributions/kernel-contributions/
- Contributor to **Yocto Project**
  - Maintainer of the official documentation
  - Core participant to the QA effort
- Contributor to **Buildroot**
  - Co-maintainer
  - 5000 patches contributed
- Significant contributions to U-Boot, OP-TEE, Barebox, etc.
- Fully **open-source training materials**

Bootlin on-line resources

- Website with a technical blog:
  https://bootlin.com
- Engineering services:
  https://bootlin.com/engineering
- Training services:
  https://bootlin.com/training
- Twitter:
  https://twitter.com/bootlincom
- LinkedIn:
  https://www.linkedin.com/company/bootlin
- Elixir - browse Linux kernel sources on-line:
  https://elixir.bootlin.com

Icon by Freepik, Flaticon

Generic course information

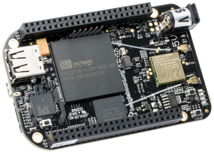
bootlin

embedded Linux and kernel engineering

Supported hardware

BeagleBone Black or BeagleBone Black Wireless, from BeagleBoard.org

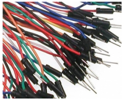
- Texas Instruments AM335x (ARM Cortex-A8 CPU)
- SoC with 3D acceleration, additional processors (PRUs) and lots of peripherals.
- 512 MB of RAM
- 4 GB of on-board eMMC storage
- USB host and USB device, microSD, micro HDMI
- WiFi and Bluetooth (wireless version), otherwise Ethernet
- 2 x 46 pins headers, with access to many expansion buses (I2C, SPI, UART and more)
- A huge number of expansion boards, called *capes*. See https://elinux.org/Beagleboard:BeagleBone_Capes.



Shopping list: hardware for this course

- BeagleBone Black or BeagleBone Black Wireless - Multiple distributors:
  See https://beagleboard.org/Products/.
- USB Serial Cable - 3.3 V - Female ends (for serial console) [1]
- Nintendo Nunchuk with UEXT connector [2]
- Breadboard jumper wires - Male ends (to connect the Nunchuk) [3]
- USB Serial Cable - 3.3 V - Male ends (for serial labs, two if possible):
  Olimex: https://frama.link/BEGcpgo7
- Note that both USB serial cables are the same.
  Only the gender of their connector changes.



[1] https://www.olimex.com/Products/Components/Cables/USB-Serial-Cable/USB-SERIAL-F/
[2] https://www.olimex.com/Products/Modules/Sensors/MOD-WII/MOD-Wii-UEXT-NUNCHUCK/
[3] https://www.olimex.com/Products/Breadboarding/JUMPER-WIRES/JW-110x10/

Training quiz and certificate

- You have been given a quiz to test your knowledge on the topics covered by the course. That's not too late to take it if you haven't done it yet!
- At the end of the course, we will submit this quiz to you again. That time, you will see the correct answers.
- It allows Bootlin to assess your progress thanks to the course. That's also a kind of challenge, to look for clues throughout the lectures and labs / demos, as all the answers are in the course!
- Another reason is that we only give training certificates to people who achieve at least a 50% score in the final quiz **and** who attended all the sessions.

Participate!

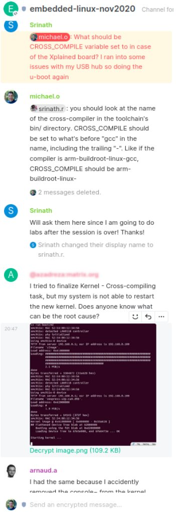
During the lectures...

- Don't hesitate to ask questions. Other people in the audience may have similar questions too.
- Don't hesitate to share your experience too, for example to compare Linux with other operating systems you know.
- Your point of view is most valuable, because it can be similar to your colleagues' and different from the trainer's.
- In on-line sessions
  - Please always keep your camera on!
  - Also make sure your name is properly filled.
  - You can also use the "Raise your hand" button when you wish to ask a question but don't want to interrupt.
- All this helps the trainer to engage with participants, see when something needs clarifying and make the session more interactive, enjoyable and useful for everyone.

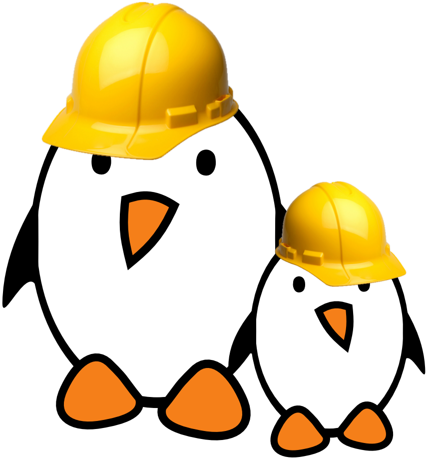
Collaborate!

As in the Free Software and Open Source community, collaboration between participants is valuable in this training session:

- Use the dedicated Matrix channel for this session to add questions.
- If your session offers practical labs, you can also report issues, share screenshots and command output there.
- Don't hesitate to share your own answers and to help others especially when the trainer is unavailable.
- The Matrix channel is also a good place to ask questions outside of training hours, and after the course is over.



Practical lab - Training Setup



Prepare your lab environment

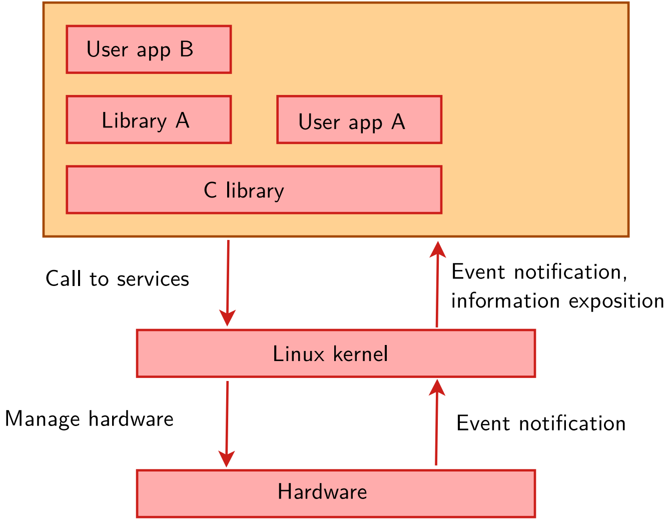
- Download and extract the lab archive

Linux Kernel Introduction

embedded Linux and kernel engineering

Linux kernel features

Linux kernel in the system



Linux kernel main roles

- **Manage all the hardware resources**: CPU, memory, I/O.
- Provide a **set of portable, architecture and hardware independent APIs** to allow user space applications and libraries to use the hardware resources.
- **Handle concurrent accesses and usage** of hardware resources from different applications.
    - Example: a single network interface is used by multiple user space applications through various network connections. The kernel is responsible for “multiplexing” the hardware resource.

System calls

- The main interface between the kernel and user space is the set of system calls
- About 400 system calls that provide the main kernel services
  - File and device operations, networking operations, inter-process communication, process management, memory mapping, timers, threads, synchronization primitives, etc.
- This system call interface is wrapped by the C library, and user space applications usually never make a system call directly but rather use the corresponding C library function

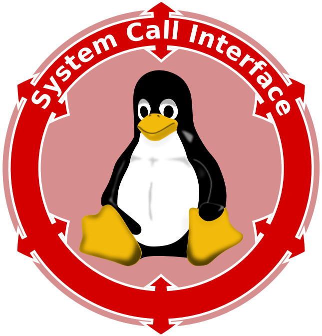
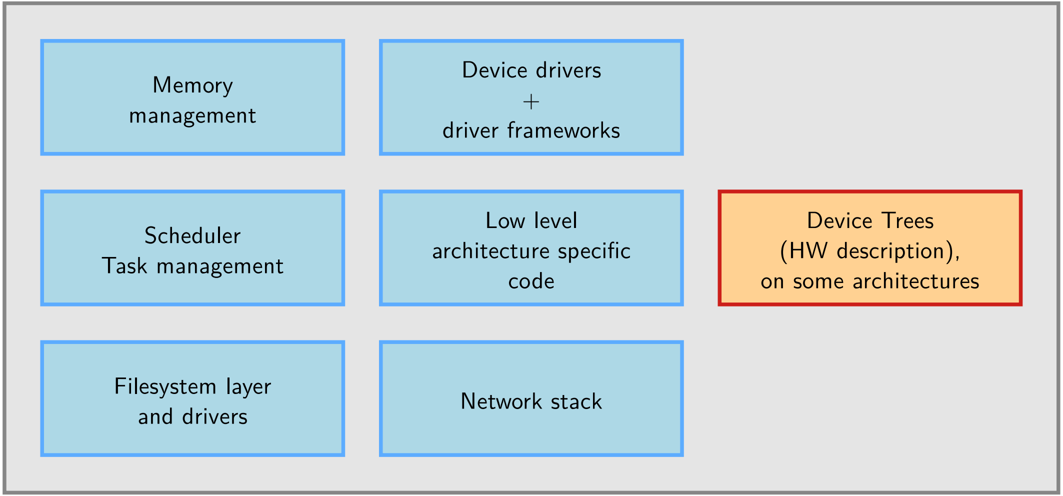


Image credits (Wikipedia): https://bit.ly/2U2rdGB

Pseudo filesystems

- Linux makes system and kernel information available in user space through **pseudo filesystems**, sometimes also called **virtual filesystems**
- Pseudo filesystems allow applications to see directories and files that do not exist on any real storage: they are created and updated on the fly by the kernel
- The two most important pseudo filesystems are
  - `proc`, usually mounted on `/proc`:
    Operating system related information (processes, memory management parameters...)
  - `sysfs`, usually mounted on `/sys`:
    Representation of the system as a tree of devices connected by buses. Information gathered by the kernel frameworks managing these devices.

Linux Kernel



Linux kernel sources

Location of official kernel sources

- The mainline versions of the Linux kernel, as released by Torvalds
  - These versions follow the development model of the kernel
  - They may not contain the latest developments from a specific area yet
  - A good pick for products development phase
  - `https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux.git`
- The stable versions of the Linux kernel, as maintained by a maintainers group
  - These versions do not bring new features compared to Linus' tree
  - Only bug fixes and security fixes are pulled there
  - Each version is stabilized during the development period of the next mainline kernel
  - Certain versions can be maintained for much longer, 2+ years
  - A good pick for products commercialization phase
  - `https://git.kernel.org/pub/scm/linux/kernel/git/stable/linux.git`

Location of non-official kernel sources

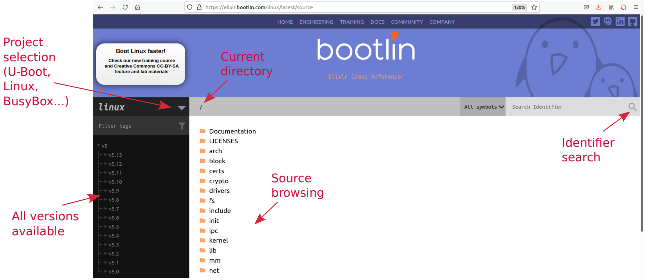
- Many chip vendors supply their own kernel sources
  - Focusing on hardware support first
  - Can have a very important delta with mainline Linux
  - Sometimes they break support for other platforms/devices without caring
  - Useful in early phases only when mainline hasn't caught up yet (many vendors invest in the mainline kernel at the same time)
  - Suitable for PoC, not suitable for products on the long term as usually no updates are provided to these kernels
  - Getting stuck with a deprecated system with broken software that cannot be updated has a real cost in the end
- Many kernel sub-communities maintain their own kernel, with usually newer but fewer stable features, only for cutting-edge development
  - Architecture communities (ARM, MIPS, PowerPC, etc)
  - Device drivers communities (I2C, SPI, USB, PCI, network, etc)
  - Other communities (real-time, etc)
  - Not suitable to be used in products

Getting Linux sources

- The kernel sources are available from https://kernel.org/pub/linux/kernel as **full tarballs** (complete kernel sources) and **patches** (differences between two kernel versions).
- But today the entire open source community has settled in favor of Git
  - Fast, efficient with huge code bases, reliable, open source
  - Incidentally written by Torvalds

Going through Linux sources

- Development tools:
  - Any text editor will work
  - Vim and Emacs support ctags and cscope and therefore can help with symbol lookup and auto-completion.
  - It's also possible to use more elaborate IDEs to develop kernel code, like Visual Studio Code.
- Powerful web browsing: Elixir
  - Generic source indexing tool and code browser for C and C++.
  - Very easy to find symbols declaration/implementation/usage
  - Try out https://elixir.bootlin.com!



Linux kernel size

- Linux v5.18 sources:
  - 75,878 files (`git ls-files | wc -l`)
  - 33,242,942 lines (`git ls-files | xargs cat | wc -l`)
  - 1,154,591,060 bytes (`git ls-files | xargs cat | wc -c`)
- But a compressed Linux kernel just sizes a few megabytes.
- So, why are these sources so big?
  Because they include thousands of device drivers, many network protocols, support many architectures and filesystems...
- The Linux core (scheduler, memory management...) is pretty small!

Linux kernel sources structure

As of kernel version v5.18 (in percentage of total number of lines).

Source code:

- `drivers/`: 61.1%
- `arch/`: 11.6%
- `fs/`: 4.4%
- `sound/`: 4.1%
- `tools/`: 3.9%
- `net/`: 3.7%
- `include/`: 3.5%
- `kernel/`: 1.3%
- `lib/`: 0.7%
- `usr/`: 0.6%
- `mm/`: 0.5%
- `scripts/`: 0.4%
- `security/`: 0.3%
- `crypto/`: 0.3%
- `block/`: 0.2%
- `samples/`: 0.1%
- `ipc/`: 0.0%
- `virt/`: 0.0%
- `init/`: 0.0%
- `certs/`: 0.0%

Doc and bindings:

- `Documentation/`: 3.4%

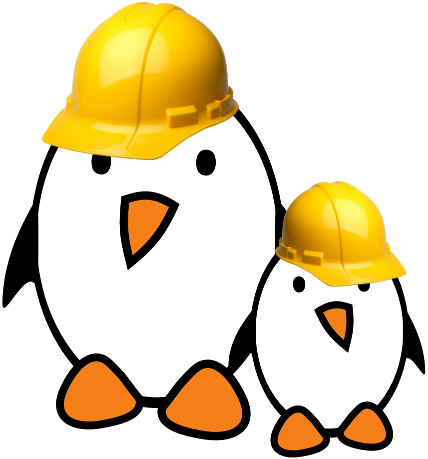
Build system files:

- `Kbuild`
- `Kconfig`
- `Makefile`

Other files:

- `COPYING`
- `CREDITS`
- `MAINTAINERS`
- `README`

Practical lab - Downloading kernel source code



- Clone the mainline Linux source tree with git

Linux kernel source code

Programming language

- Implemented in C like all UNIX systems
- A little Assembly is used too:
  - CPU and machine initialization, exceptions
  - Critical library routines.
- No C++ used, see http://vger.kernel.org/lkml/#s15-3
- All the code compiled with gcc
  - Many gcc specific extensions used in the kernel code, any ANSI C compiler will not compile the kernel
  - See https://gcc.gnu.org/onlinedocs/gcc-10.2.0/gcc/C-Extensions.html
- Ongoing work to compile the kernel with the LLVM C compiler (Clang) too: https://clangbuiltlinux.github.io/
- There are also plans to create new code in Rust too: https://lwn.net/Articles/829858/

No C library

- The kernel has to be standalone and can't use user space code.
- Architectural reason: user space is implemented on top of kernel services, not the opposite.
- Technical reason: the kernel is on its own during the boot up phase, before it has accessed a root filesystem.
- Hence, kernel code has to supply its own library implementations (string utilities, cryptography, uncompression...)
- So, you can't use standard C library functions in kernel code (`printf()`, `memset()`, `malloc()`,...).
- Fortunately, the kernel provides similar C functions for your convenience, like `printk()`, `memset()`, `kmalloc()`, ...

Portability

- The Linux kernel code is designed to be portable
- All code outside `arch/` should be portable
- To this aim, the kernel provides macros and functions to abstract the architecture specific details
  - Endianness
  - I/O memory access
  - Memory barriers to provide ordering guarantees if needed
  - DMA API to flush and invalidate caches if needed
- Never use floating point numbers in kernel code. Your code may need to run on a low-end processor without a floating point unit.

Linux kernel to user API/ABI stability

Linux kernel to userspace API is stable

- Source code for userspace applications will not have to be updated when compiling for a more recent kernel
  - System calls, `/proc` and `/sys` content cannot be removed or changed. Only new entries can be added.

Linux kernel to userspace ABI is stable

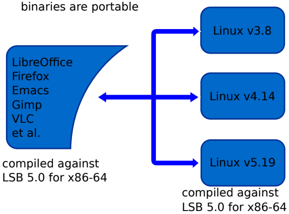
- Binaries are portable and can be executed on a more recent kernel
  - The way memory is accessed, the size of the variables in memory, how structures are organized, the calling convention, etc, are all stable over time.

Linux kernel to user API

☑ API stability **is** guaranteed, source code is portable!

Linux kernel to user ABI

☑ compatible ABI **can be** guaranteed, binaries are portable



Modified Image from Wikipedia: https://bit.ly/2U2rdGB

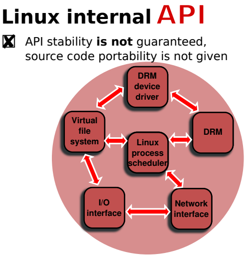
Linux internal API/ABI instability

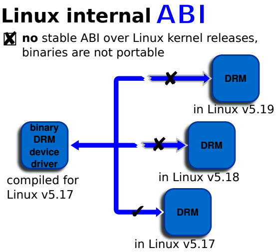
Linux internal API is not stable

- The source code of a driver is not portable across versions
  - In-tree drivers are updated by the developer proposing the API change: works great for mainline code
  - An out-of-tree driver compiled for a given version may no longer compile or work on a more recent one
  - See process/stable-api-nonsense for reasons why

Linux internal ABI is not stable

- A binary module compiled for a given kernel version cannot be used with another version
  - The module loading utilities will perform this check prior to the insertion





Modified Image from Wikipedia: https://bit.ly/2U2rdGB

Kernel memory constraints

- No memory protection
- The kernel doesn't try to recover from attemps to access illegal memory locations. It just dumps *oops* messages on the system console.
- Fixed size stack (8 or 4 KB). Unlike in user space, no mechanism was implemented to make it grow. Don't use recursion!
- Swapping is not implemented for kernel memory either (except *tmpfs* which lives completely in the page cache and on swap)

Linux kernel licensing constraints

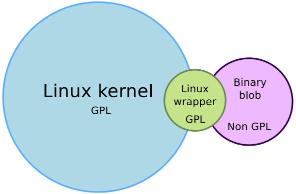
- The Linux kernel is licensed under the GNU General Public License version 2
  - This license gives you the right to use, study, modify and share the software freely
- However, when the software is redistributed, either modified or unmodified, the GPL requires that you redistribute the software under the same license, with the source code
  - If modifications are made to the Linux kernel (for example to adapt it to your hardware), it is a derivative work of the kernel, and therefore must be released under GPLv2.
- The GPL license has been successfully enforced in courts: `https://en.wikipedia.org/wiki/Gpl-violations.org#Notable_victories`
- However, you're only required to do so
  - At the time the device starts to be distributed
  - To your customers, not to the entire world

Proprietary code and the kernel

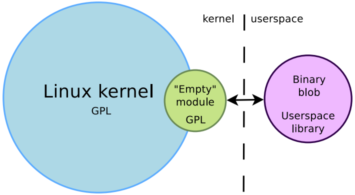
- It is illegal to distribute a binary kernel that includes statically compiled proprietary drivers
- The kernel modules are a gray area: unclear if they are legal or not
  - The general opinion of the kernel community is that proprietary modules are bad: process/kernel-driver-statement
  - From a legal point of view, each driver is probably a different case:
    - Are they derived works of the kernel?
    - Are they designed to be used with another operating system?
- Is it really useful to keep drivers secret anyway?

Abusing the kernel licensing constraints

- There are some examples of proprietary drivers
  - Nvidia uses a wrapper between their drivers and the kernel
  - They claim the drivers could be used with a different OS with another wrapper
  - Unclear whether it makes it legal or not



- The current trend is to hide the logic in the firmware or in userspace. The GPL kernel driver is almost empty and either:
  - Blindly writes an incoming flow of bytes in the hardware
  - Exposes a huge MMIO region to userspace through `mmap`



Advantages of GPL drivers

- You don't have to write your driver from scratch. You can reuse code from similar free software drivers.
- Your drivers can be freely and easily shipped by others (for example by Linux distributions or embedded Linux build systems).
- Legal certainty, you are sure that a GPL driver is fine from a legal point of view.

Advantages of mainlining your kernel drivers

- The community, reviewers and maintainers will review your code before accepting it, offering you the opportunity to enhance it and understand better the internal APIs.
- Once accepted, you will get cost-free bug and security fixes, support for new features, and general improvements.
- Your work will automatically follow the API changes.
- Accessing your code will be much easier for users.
- Your code will remain valid no matter the kernel version.

This will for sure reduce your maintenance and support work

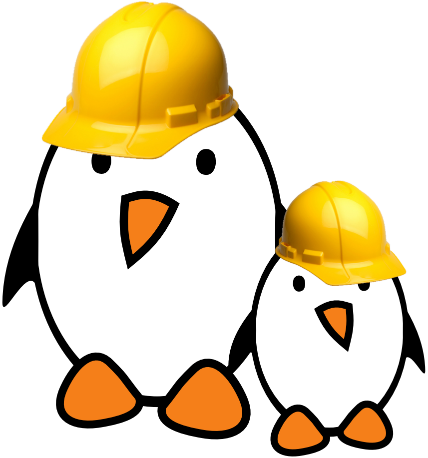
User space device drivers 1/2

- The kernel provides certain mechanisms to access hardware directly from userspace:
  - USB devices with *libusb*, `https://libusb.info/`
  - SPI devices with *spidev*, `spi/spidev`
  - I2C devices with *i2cdev*, `i2c/dev-interface`
  - Memory-mapped devices with *UIO*, including interrupt handling, `driver-api/uio-howto`
- These solutions can only be used if:
  - There is no need to leverage an existing kernel subsystem such as the networking stack or filesystems.
  - There is no need for the kernel to act as a "multiplexer" for the device: only one application accesses the device.
- Certain classes of devices like printers and scanners do not have any kernel support, they have always been handled in user space for historical reasons.
- Otherwise this is *not* how the system should be architectured. Kernel drivers should always be preferred!

User space device drivers 2/2

- Advantages
  - No need for kernel coding skills.
  - Drivers can be written in any language, even Perl!
  - Drivers can be kept proprietary.
  - Driver code can be killed and debugged. Cannot crash the kernel.
  - Can use floating-point computation.
  - Potentially higher performance, especially for memory-mapped devices, thanks to the avoidance of system calls.
- Drawbacks
  - The kernel has no longer access to the device.
  - None of the standard applications will be able to use it.
  - Cannot use any hardware abstraction or software helpers from the kernel
  - Need to adapt applications when changing the hardware.
  - Less straightforward to handle interrupts: increased latency.

Practical lab - Kernel Source Code - Exploring



- Explore kernel sources manually
- Use automated tools to explore the source code

Linux Kernel Usage

Kernel configuration

Kernel configuration

- The kernel contains thousands of device drivers, filesystem drivers, network protocols and other configurable items
- Thousands of options are available, that are used to selectively compile parts of the kernel source code
- The kernel configuration is the process of defining the set of options with which you want your kernel to be compiled
- The set of options depends
  - On the target architecture and on your hardware (for device drivers, etc.)
  - On the capabilities you would like to give to your kernel (network capabilities, filesystems, real-time, etc.). Such generic options are available in all architectures.

Kernel configuration and build system

- The kernel configuration and build system is based on multiple Makefiles
- One only interacts with the main `Makefile`, present at the **top directory** of the kernel source tree
- Interaction takes place
  - using the `make` tool, which parses the Makefile
  - through various **targets**, defining which action should be done (configuration, compilation, installation, etc.).
  - Run `make help` to see all available targets.
- Example
  - `cd linux/`
  - `make <target>`

Specifying the target architecture

First, specify the architecture for the kernel to build

- Set `ARCH` to the name of a directory under `arch/`:
  `ARCH=arm` or `ARCH=arm64` or `ARCH=riscv`, etc
- By default, the kernel build system assumes that the kernel is configured and built for the host architecture (`x86` in our case, native kernel compiling)
- The kernel build system will use this setting to:
  - Use the configuration options for the target architecture.
  - Compile the kernel with source code and headers for the target architecture.

Choosing a compiler

The compiler invoked by the kernel Makefile is `$(CROSS_COMPILE)gcc`

- Specifying the compiler is already needed at configuration time, as some kernel configuration options depend on the capabilities of the compiler.
- When compiling natively
  - Leave `CROSS_COMPILE` undefined and the kernel will be natively compiled for the host architecture using `gcc`.
- When using a cross-compiler
  - Specify the prefix of your cross-compiler executable, for example for `arm-linux-gnueabi-gcc`:
    `CROSS_COMPILE=arm-linux-gnueabi-`

Set `LLVM` to `1` to compile your kernel with Clang.
See our LLVM tools for the Linux kernel presentation.

Specifying ARCH and CROSS_COMPILE

There are actually two ways of defining `ARCH` and `CROSS_COMPILE`:

- Pass `ARCH` and `CROSS_COMPILE` on the `make` command line:
  `make ARCH=arm CROSS_COMPILE=arm-linux- ...`
  Drawback: it is easy to forget to pass these variables when you run any `make` command, causing your build and configuration to be screwed up.
- Define `ARCH` and `CROSS_COMPILE` as environment variables:
  ```
  export ARCH=arm
  export CROSS_COMPILE=arm-linux-
  ```
  Drawback: it only works inside the current shell or terminal. You could put these settings in a file that you source every time you start working on the project, see also the https://direnv.net/ project.

Initial configuration

Difficult to find which kernel configuration will work with your hardware and root filesystem. Start with one that works!

- Desktop or server case:
  - Advisable to start with the configuration of your running kernel:
    `cp /boot/config-`uname -r` .config`
- Embedded platform case:
  - Default configurations stored in-tree as minimal configuration files (only listing settings that are different with the defaults) in `arch/<arch>/configs/`
  - `make help` will list the available configurations for your platform
  - To load a default configuration file, just run `make foo_defconfig` (will erase your current `.config`!)
    - On ARM 32-bit, there is usually one default configuration per CPU family
    - On ARM 64-bit, there is only one big default configuration to customize

Create your own default configuration

- Use a tool such as `make menuconfig` to make changes to the configuration
- Saving your changes will overwrite your `.config` (not tracked by Git)
- When happy with it, create your own default configuration file:
  - Create a minimal configuration (non-default settings) file:
    `make savedefconfig`
  - Save this default configuration in the right directory:
    `mv defconfig arch/<arch>/configs/myown_defconfig`
- This way, you can share a reference configuration inside the kernel sources and other developers can now get the same `.config` as you by running
  `make myown_defconfig`

Built-in or module?

- The **kernel image** is a **single file**, resulting from the linking of all object files that correspond to features enabled in the configuration
  - This is the file that gets loaded in memory by the bootloader
  - All built-in features are therefore available as soon as the kernel starts, at a time where no filesystem exists
- Some features (device drivers, filesystems, etc.) can however be compiled as **modules**
  - These are *plugins* that can be loaded/unloaded dynamically to add/remove features to the kernel
  - Each **module is stored as a separate file in the filesystem**, and therefore access to a filesystem is mandatory to use modules
  - This is not possible in the early boot procedure of the kernel, because no filesystem is available

Kernel option types

There are different types of options, defined in `Kconfig` files:

- `bool` options, they are either
  - *true* (to include the feature in the kernel) or
  - *false* (to exclude the feature from the kernel)
- `tristate` options, they are either
  - *true* (to include the feature in the kernel image) or
  - *module* (to include the feature as a kernel module) or
  - *false* (to exclude the feature)
- `int` options, to specify integer values
- `hex` options, to specify hexadecimal values
  Example: `CONFIG_PAGE_OFFSET=0xC0000000`
- `string` options, to specify string values
  Example: `CONFIG_LOCALVERSION=-no-network`
  Useful to distinguish between two kernels built from different options

Kernel option dependencies

Enabling a network driver requires the network stack to be enabled, therefore configuration symbols have two ways to express dependencies:

- depends on dependency:

  ```
  config B
      depends on A
  ```

  - B is not visible until A is enabled
  - Works well for dependency chains

- select dependency:

  ```
  config A
      select B
  ```

  - When A is enabled, B is enabled too (and cannot be disabled manually)
  - Should preferably not select symbols with depends on dependencies
  - Used to declare hardware features or select libraries

```
config SPI_ATH79
        tristate "Atheros AR71XX/AR724X/AR913X SPI controller driver"
        depends on ATH79 || COMPILE_TEST
        select SPI_BITBANG
        help
          This enables support for the SPI controller present on the
          Atheros AR71XX/AR724X/AR913X SoCs.
```

Kernel configuration details

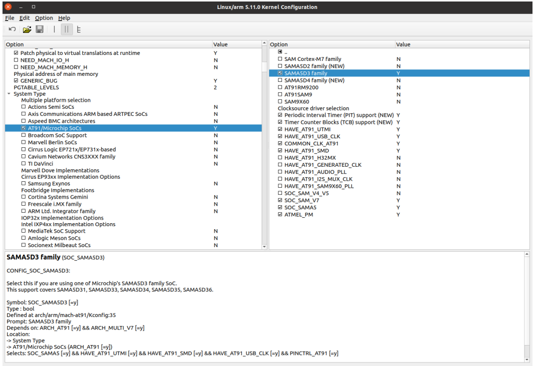
- The configuration is stored in the `.config` file at the root of kernel sources
  - Simple text file, `CONFIG_PARAM=value`
  - Options are grouped by sections and are prefixed with `CONFIG_`
  - Included by the top-level kernel Makefile
  - Typically not edited by hand because of the dependencies

```
#
# CD-ROM/DVD Filesystems
#
CONFIG_ISO9660_FS=m
CONFIG_JOLIET=y
CONFIG_ZISOFS=y
CONFIG_UDF_FS=y
# end of CD-ROM/DVD Filesystems

#
# DOS/FAT/EXFAT/NT Filesystems
#
CONFIG_FAT_FS=y
CONFIG_MSDOS_FS=y
# CONFIG_VFAT_FS is not set
CONFIG_FAT_DEFAULT_CODEPAGE=437
# CONFIG_EXFAT_FS is not set
```

xconfig

`make xconfig`

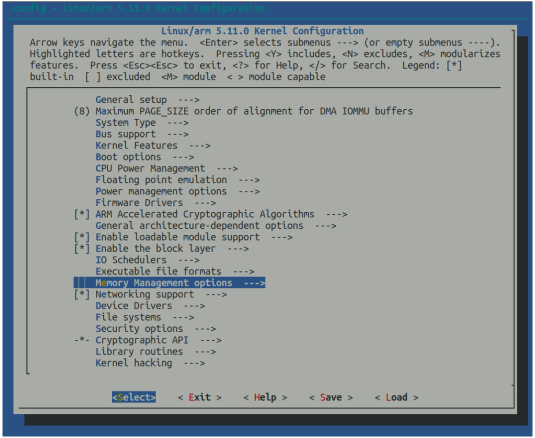
- The most common graphical interface to configure the kernel.
- File browser: easy to load configuration files
- Search interface to look for parameters (`[Ctrl] + [f]`)
- Required Debian/Ubuntu packages: `qt5-default` (`qtbase5-dev` on Ubuntu 22.04)



menuconfig

`make menuconfig`

- Useful when no graphics are available. Very efficient interface.
- Same interface found in other tools: BusyBox, Buildroot...
- Convenient number shortcuts to jump directly to search results.
- Required Debian/Ubuntu packages: `libncurses-dev`



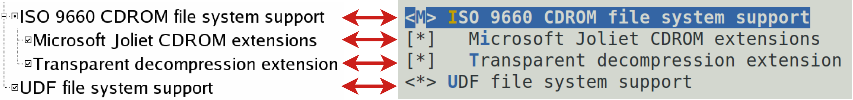
Kernel configuration options

You can switch from one tool to another, they all load/save the same `.config` file, and show the same set of options

Compiled as a module:
`CONFIG_ISO9660_FS=m`

Additional driver options:
`CONFIG_JOLIET=y`
`CONFIG_ZISOFS=y`

Statically built:
`CONFIG_UDF_FS=y`



Values in resulting .config file

Parameter values as displayed by xconfig

Parameter values as displayed by menuconfig

make oldconfig

`make oldconfig`

- Useful to upgrade a `.config` file from an earlier kernel release
- Asks for values for new parameters.
- ... unlike `make menuconfig` and `make xconfig` which silently set default values for new parameters.

If you edit a `.config` file by hand, it's useful to run `make oldconfig` afterwards, to set values to new parameters that could have appeared because of dependency changes.

Undoing configuration changes

A frequent problem:

- After changing several kernel configuration settings, your kernel no longer works.
- If you don't remember all the changes you made, you can get back to your previous configuration:

  ```
  $ cp .config.old .config
  ```
- All the configuration tools keep this `.config.old` backup copy.

Compiling and installing the kernel

Kernel compilation

`make`

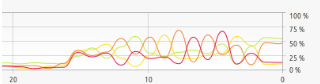
- Only works from the top kernel source directory
- Should not be performed as a priviledged user
- Run several **j**obs in parallel. Our advice: `ncpus * 2` to fully load the CPU and I/Os at all times.
  Example: `make -j 8`
- To **re**compile faster (7x according to some benchmarks), use the `ccache` compiler cache:
  `export CROSS_COMPILE="ccache arm-linux-"`

Benefits of parallel compile jobs (make -j<n>)

Tests on Linux 5.11 on arm

`make allnoconfig` configuration

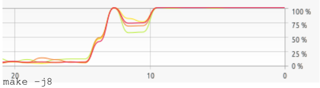
`gnome-system-monitor` showing the load on 4 threads / 2 CPUs



`make`

Command: make

Total time: 129 s



`make -j8`

Command: make -j8

Total time: 67 s

Kernel compilation results

- `arch/<arch>/boot/Image`, uncompressed kernel image that can be booted
- `arch/<arch>/boot/*Image*`, compressed kernel images that can also be booted
  - `bzImage` for x86, `zImage` for ARM, `Image.gz` for RISC-V, `vmlinux.bin.gz` for ARC, etc.
- `arch/<arch>/boot/dts/*.dtb`, compiled Device Tree Blobs
- All kernel modules, spread over the kernel source tree, as `.ko` (*Kernel Object*) files.
- `vmlinux`, a raw uncompressed kernel image in the ELF format, useful for debugging purposes but generally not used for booting purposes

Kernel installation: native case

- `sudo make install`
  - Does the installation for the host system by default
- Installs
  - `/boot/vmlinuz-<version>`
    Compressed kernel image. Same as the one in `arch/<arch>/boot`
  - `/boot/System.map-<version>`
    Stores kernel symbol addresses for debugging purposes (obsolete: such information is usually stored in the kernel itself)
  - `/boot/config-<version>`
    Kernel configuration for this version
- In GNU/Linux distributions, typically re-runs the bootloader configuration utility to make the new kernel available at the next boot.

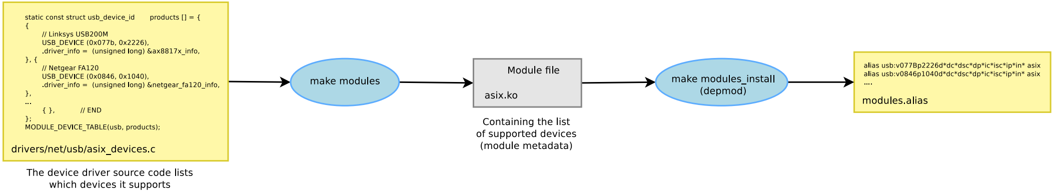
Kernel installation: embedded case

- `make install` is rarely used in embedded development, as the kernel image is a single file, easy to handle.
- Another reason is that there is no standard way to deploy and use the kernel image.
- Therefore making the kernel image available to the target is usually manual or done through scripts in build systems.
- It is however possible to customize the `make install` behavior in `arch/<arch>/boot/install.sh`

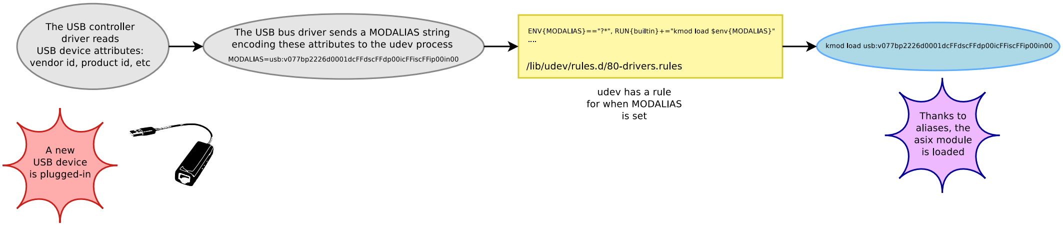
Module installation: native case

- `sudo make modules_install`
  - Does the installation for the host system by default, so needs to be run as root
- Installs all modules in `/lib/modules/<version>/`
  - `kernel/`
    Module `.ko` (Kernel Object) files, in the same directory structure as in the sources.
  - `modules.alias`, `modules.alias.bin`
    Aliases for module loading utilities , see next slide
  - `modules.dep`, `modules.dep.bin`
    Module dependencies. Kernel modules can depend on other modules, based on the symbols (functions and data structures) they use.
  - `modules.symbols`, `modules.symbols.bin`
    Tells which module a given symbol belongs to (related to module dependencies).
  - `modules.builtin`
    List of modules that are builtin the kernel.

Kernel compiling



System operation



Module installation: embedded case

- In embedded development, you can't directly use `make modules_install` as it would install target modules in `/lib/modules` on the host!
- The `INSTALL_MOD_PATH` variable is needed to generate the module related files and install the modules in the target root filesystem instead of your host root filesystem (no need to be root):
  `make INSTALL_MOD_PATH=<dir>/ modules_install`

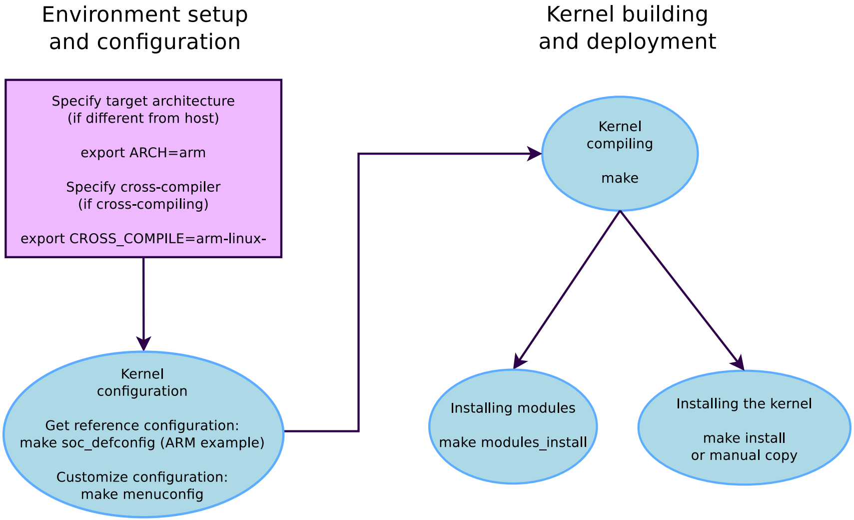
Kernel cleanup targets

- From `make help`:

```
Cleaning targets:
  clean           - Remove most generated files but keep the config and
                    enough build support to build external modules
  mrproper        - Remove all generated files + config + various backup files
  distclean       - mrproper + remove editor backup and patch files
```

- If you are in a git tree, remove all files not tracked (and ignored) by git:
  `git clean -fdx`

Kernel building overview



Booting the kernel

Hardware description

- Many embedded architectures have a lot of non-discoverable hardware (serial, Ethernet, I2C, Nand flash, USB controllers...)
- This hardware needs to be described and passed to the Linux kernel.
- Using C code directly within the kernel is legacy, nowadays the bootloader/firmware is expected to provide this description when starting the kernel:
  - On x86: using ACPI tables
  - On most embedded devices: using an OpenFirmware Device Tree (DT)
- This way, a kernel supporting different SoCs knows which SoC and device initialization hooks to run on the current board.

Booting with U-Boot

- On ARM32, U-Boot can boot `zImage`, on ARM64 or RISC-V, it boots the `Image` file
- In addition to the kernel image, U-Boot should also pass a DTB to the kernel.
- The typical boot process is therefore:
  1. Load `zImage` at address X in memory
  2. Load `<board>.dtb` at address Y in memory
  3. Start the kernel with `bootz X - Y`
     The `-` in the middle indicates no *initramfs*

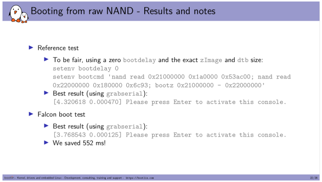
Kernel command line

- In addition to the compile time configuration, the kernel behavior can be adjusted with no recompilation using the **kernel command line**
- The kernel command line is a string that defines various arguments to the kernel
  - It is very important for system configuration
  - `root=` for the root filesystem (covered later)
  - `console=` for the destination of kernel messages
  - Example: `console=ttyS0 root=/dev/mmcblk0p2 rootwait`
  - Many more exist. The most important ones are documented in `admin-guide/kernel-parameters` in kernel documentation.

Passing the kernel command line

- U-Boot carries the Linux kernel command line string in its `bootargs` environment variable
- Right before starting the kernel, it will store the contents of `bootargs` in the `chosen` section of the Device Tree
- The kernel will behave differently depending on its configuration:
  - If `CONFIG_CMDLINE_FROM_BOOTLOADER` is set:
    The kernel will use only the string from the bootloader
  - If `CONFIG_CMDLINE_FORCE` is set:
    The kernel will only use the string received at configuration time in `CONFIG_CMDLINE`
  - If `CONFIG_CMDLINE_EXTEND` is set:
    The kernel will concatenate both strings

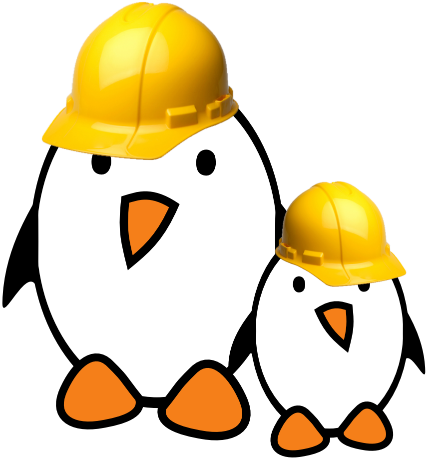
See the "Understanding U-Boot Falcon Mode" presentation from Michael Opdenacker, for details about how U-Boot boots Linux.



Slides: https://bootlin.com/pub/conferences/2021/lee/
Video: https://www.youtube.com/watch?v=LFe3x2QMhSo

Kernel log

- The kernel keeps its messages in a circular buffer in memory
  - The size is configurable using `CONFIG_LOG_BUF_SHIFT`
- When a module is loaded, related information is available in the kernel log.
- Kernel log messages are available through the `dmesg` command (**d**iagnostic **mes**sa**g**e)
- Kernel log messages are also displayed on the console pointed by the `console=` kernel command line argument
  - Console messages can be filtered by level using the `loglevel` parameter:
    - `loglevel=` allows to filter messages displayed on the console based on priority
    - `ignore_loglevel` (same as `loglevel=8`) will lead to all messages being printed
    - `quiet` (same as `loglevel=0`) prevents any message to be displayed on the console
  - Example: `console=ttyS0 root=/dev/mmcblk0p2 loglevel=5`
- It is possible to write to the kernel log from user space:
  `echo "<n>Debug info" > /dev/kmsg`



1st lab: board and bootloader setup:

- Prepare the board and access its serial port
- Configure its bootloader to use TFTP

2nd lab: kernel compiling and booting:

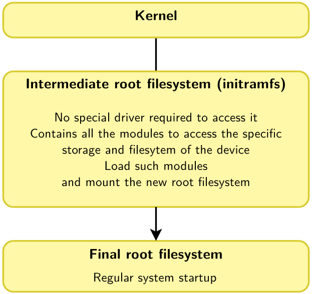
- Set up a cross-compiling environment
- Cross-compile a kernel for an ARM target platform
- Boot this kernel from a directory on your workstation, accessed by the board through NFS

Using kernel modules

Advantages of modules

- Modules make it easy to develop drivers without rebooting: load, test, unload, rebuild, load...
- Useful to keep the kernel image size to the minimum (essential in GNU/Linux distributions for PCs).
- Also useful to reduce boot time: you don't spend time initializing devices and kernel features that you only need later.
- Caution: once loaded, have full control and privileges in the system. No particular protection. That's why only the `root` user can load and unload modules.
- To increase security, possibility to allow only signed modules, or to disable module support entirely.

Using kernel modules to support many different devices and setups



The modules in the initramfs are updated every time a kernel upgrade is available.

Module utilities: extracting information

`<module_name>`: name of the module file without the trailing `.ko`

- `modinfo <module_name>` (for modules in `/lib/modules`)
  `modinfo <module_path>.ko`
  Gets information about a module without loading it: parameters, license, description and dependencies.

Module utilities: loading

- `sudo insmod <module_path>.ko`
  Tries to load the given module. The full path to the module object file must be given.
- `sudo modprobe <top_module_name>`
  Most common usage of `modprobe`: tries to load all the dependencies of the given top module, and then this module. Lots of other options are available. `modprobe` automatically looks in `/lib/modules/<version>/` for the object file corresponding to the given module name.
- `lsmod`
  Displays the list of loaded modules
  Compare its output with the contents of `/proc/modules`!

Understanding module loading issues

- When loading a module fails, `insmod` often doesn't give you enough details!
- Details are often available in the kernel log.
- Example:

```
$ sudo insmod ./intr_monitor.ko
insmod: error inserting './intr_monitor.ko': -1 Device or resource busy
$ dmesg
[17549774.552000] Failed to register handler for irq channel 2
```

Module utilities: removals

- `sudo rmmod <module_name>`
  Tries to remove the given module.
  Will only be allowed if the module is no longer in use (for example, no more processes opening a device file)
- `sudo modprobe -r <top_module_name>`
  Tries to remove the given top module and all its no longer needed dependencies

Passing parameters to modules

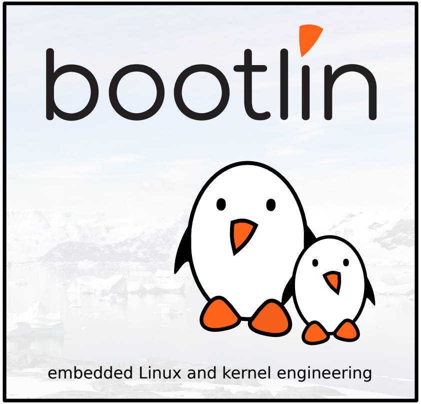
- Find available parameters:
  `modinfo usb-storage`
- Through `insmod`:
  `sudo insmod ./usb-storage.ko delay_use=0`
- Through `modprobe`:
  Set parameters in `/etc/modprobe.conf` or in any file in `/etc/modprobe.d/`:
  `options usb-storage delay_use=0`
- Through the kernel command line, when the module is built statically into the kernel:
  `usb-storage.delay_use=0`
  - `usb-storage` is the *module name*
  - `delay_use` is the *module parameter name*. It specifies a delay before accessing a USB storage device (useful for rotating devices).
  - `0` is the *module parameter value*

Check module parameter values

How to find/edit the current values for the parameters of a loaded module?

- Check `/sys/module/<name>/parameters`.
- There is one file per parameter, containing the parameter value.
- Also possible to change parameter values if these files have write permissions (depends on the module code).
- Example:
  `echo 0 > /sys/module/usb_storage/parameters/delay_use`

Developing kernel modules



Hello module 1/2

```c
// SPDX-License-Identifier: GPL-2.0
/* hello.c */
#include <linux/init.h>
#include <linux/module.h>
#include <linux/kernel.h>

static int __init hello_init(void)
{
  pr_alert("Good morrow to this fair assembly.\n");
  return 0;
}

static void __exit hello_exit(void)
{
  pr_alert("Alas, poor world, what treasure hast thou lost!\n");
}

module_init(hello_init);
module_exit(hello_exit);
MODULE_LICENSE("GPL");
MODULE_DESCRIPTION("Greeting module");
MODULE_AUTHOR("William Shakespeare");
```

Hello module 2/2

- Code marked as `__init`:
  - Removed after initialization (static kernel or module.)
  - See how init memory is reclaimed when the kernel finishes booting:

```
[    2.689854] VFS: Mounted root (nfs filesystem) on device 0:15.
[    2.698796] devtmpfs: mounted
[    2.704277] Freeing unused kernel memory: 1024K
[    2.710136] Run /sbin/init as init process
```

- Code marked as `__exit`:
  - Discarded when module compiled statically into the kernel, or when module unloading support is not enabled.
- Code of this example module available on https://frama.link/Q3CNXnom

Hello module explanations

- Headers specific to the Linux kernel: `linux/xxx.h`
  - No access to the usual C library, we're doing kernel programming
- An initialization function
  - Called when the module is loaded, returns an error code (`0` on success, negative value on failure)
  - Declared by the `module_init()` macro: the name of the function doesn't matter, even though `<modulename>_init()` is a convention.
- A cleanup function
  - Called when the module is unloaded
  - Declared by the `module_exit()` macro.
- Metadata information declared using `MODULE_LICENSE()`, `MODULE_DESCRIPTION()` and `MODULE_AUTHOR()`

Symbols exported to modules 1/2

- From a kernel module, only a limited number of kernel functions can be called
- Functions and variables have to be explicitly exported by the kernel to be visible to a kernel module
- Two macros are used in the kernel to export functions and variables:
  - `EXPORT_SYMBOL(symbolname)`, which exports a function or variable to all modules
  - `EXPORT_SYMBOL_GPL(symbolname)`, which exports a function or variable only to GPL modules
  - Linux 5.3: contains the same number of symbols with `EXPORT_SYMBOL()` and symbols with `EXPORT_SYMBOL_GPL()`
- A normal driver should not need any non-exported function.

Symbols exported to modules 2/2

Kernel

void func1() {...}

void func2() {...}
EXPORT_SYMBOL(func2);

void func3() {...}
EXPORT_SYMBOL_GPL(func3);

func1();	OK
func2();	OK
func3();	OK
func4();	NOK

GPL Module A

void func4() {...}
EXPORT_SYMBOL_GPL(func4);

func1();	NOK
func2();	OK
func3();	OK
func4();	OK

Non-GPL Module B

func1();	NOK
func2();	OK
func3();	NOK
func4();	NOK

GPL Module C

func1();	NOK
func2();	OK
func3();	OK
func4();	OK

Module license

- Several usages
  - Used to restrict the kernel functions that the module can use if it isn't a GPL licensed module
    - Difference between `EXPORT_SYMBOL()` and `EXPORT_SYMBOL_GPL()`
  - Used by kernel developers to identify issues coming from proprietary drivers, which they can't do anything about ("Tainted" kernel notice in kernel crashes and oopses).
  - See `admin-guide/tainted-kernels` for details about `tainted` flag values.
  - Useful for users to check that their system is 100% free (for the kernel, check `/proc/sys/kernel/tainted`; run `vrms` to check installed packages)
- Values
  - GPL compatible (see `include/linux/license.h`: `GPL`, `GPL v2`, `GPL and additional rights`, `Dual MIT/GPL`, `Dual BSD/GPL`, `Dual MPL/GPL`)
  - `Proprietary`

Compiling a module

Two solutions

- *Out of tree*, when the code is outside of the kernel source tree, in a different directory
  - Not integrated into the kernel configuration/compilation process
  - Needs to be built separately
  - The driver cannot be built statically, only as a module
- Inside the kernel tree
  - Well integrated into the kernel configuration/compilation process
  - The driver can be built statically or as a module

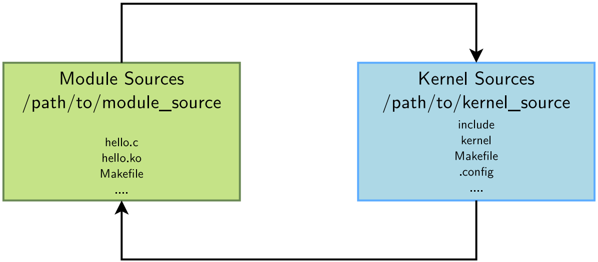
Compiling an out-of-tree module 1/2

- The below `Makefile` should be reusable for any single-file out-of-tree Linux module
- The source file is `hello.c`
- Just run `make` to build the `hello.ko` file

```
ifneq ($(KERNELRELEASE),)
obj-m := hello.o
else
KDIR := /path/to/kernel/sources

all:
<tab>$(MAKE) -C $(KDIR) M=$$PWD
endif
```

- `KDIR`: kernel source or headers directory (see next slides)

Compiling an out-of-tree module 2/2



- The module `Makefile` is interpreted with `KERNELRELEASE` undefined, so it calls the kernel `Makefile`, passing the module directory in the `M` variable
- The kernel `Makefile` knows how to compile a module, and thanks to the `M` variable, knows where the `Makefile` for our module is. This module `Makefile` is then interpreted with `KERNELRELEASE` defined, so the kernel sees the `obj-m` definition.

Modules and kernel version

- To be compiled, a kernel module needs access to *kernel headers*, containing the definitions of functions, types and constants.
- Two solutions
  - Full kernel sources (configured + `make modules_prepare`)
  - Only kernel headers (`linux-headers-*` packages in Debian/Ubuntu distributions, or directory created by `make headers_install`).
- The sources or headers must be configured (`.config` file)
  - Many macros or functions depend on the configuration
- You also need the kernel `Makefile`, the `scripts/` directory, and a few others.
- A kernel module compiled against version X of kernel headers will not load in kernel version Y
  - `modprobe` / `insmod` will say `Invalid module format`

New driver in kernel sources 1/2

- To add a new driver to the kernel sources:
  - Add your new source file to the appropriate source directory. Example: `drivers/usb/serial/navman.c`
  - Single file drivers in the common case, even if the file is several thousand lines of code big. Only really big drivers are split in several files or have their own directory.
  - Describe the configuration interface for your new driver by adding the following lines to the `Kconfig` file in this directory:

```
config USB_SERIAL_NAVMAN
        tristate "USB Navman GPS device"
        depends on USB_SERIAL
        help
          To compile this driver as a module, choose M
          here: the module will be called navman.
```

New driver in kernel sources 2/2

- Add a line in the `Makefile` file based on the `Kconfig` setting:
  `obj-$(CONFIG_USB_SERIAL_NAVMAN) += navman.o`
- It tells the kernel build system to build `navman.c` when the `USB_SERIAL_NAVMAN` option is enabled. It works both if compiled statically or as a module.
  - Run `make xconfig` and see your new options!
  - Run `make` and your new files are compiled!
  - See `kbuild/` for details and more elaborate examples like drivers with several source files, or drivers in their own subdirectory, etc.

Hello module with parameters 1/2

```
// SPDX-License-Identifier: GPL-2.0
/* hello_param.c */
#include <linux/init.h>
#include <linux/module.h>

MODULE_LICENSE("GPL");

static char *whom = "world";
module_param(whom, charp, 0644);
MODULE_PARM_DESC(whom, "Recipient of the hello message");

static int howmany = 1;
module_param(howmany, int, 0644);
MODULE_PARM_DESC(howmany, "Number of greetings");
```

Hello module with parameters 2/2

```c
static int __init hello_init(void)
{
    int i;

    for (i = 0; i < howmany; i++)
        pr_alert("(%d) Hello, %s\n", i, whom);
    return 0;
}

static void __exit hello_exit(void)
{
    pr_alert("Goodbye, cruel %s\n", whom);
}

module_init(hello_init);
module_exit(hello_exit);
```

Thanks to Jonathan Corbet for the examples

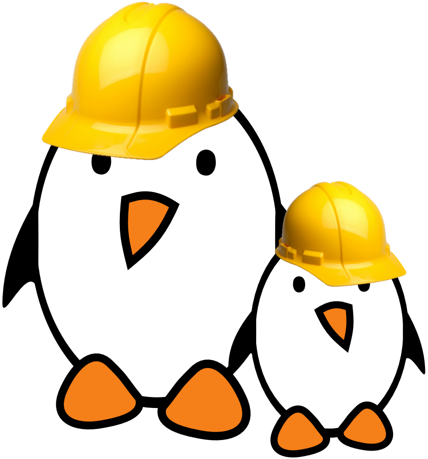
Source code available on: https://github.com/bootlin/training-materials/blob/master/code/hello-param/hello_param.c

Declaring a module parameter

```
module_param(
    name, /* name of an already defined variable */
    type, /* standard types (different from C types) are:
           * byte, short, ushort, int, uint, long, ulong
           * charp: a character pointer
           * bool: a bool, values 0/1, y/n, Y/N.
           * invbool: the above, only sense-reversed (N = true). */
    perm  /* for /sys/module/<module_name>/parameters/<param>,
           *  0: no such module parameter value file */
);

/* Example: drivers/block/loop.c */
static int max_loop;
module_param(max_loop, int, 0444);
MODULE_PARM_DESC(max_loop, "Maximum number of loop devices");
```

Modules parameter arrays are also possible with `module_param_array()`.

Practical lab - Writing modules



- Create, compile and load your first module
- Add module parameters
- Access kernel internals from your module

Accessing hardware devices

Corrections, suggestions, contributions and translations are welcome!

Describing non-discoverable hardware

Non-discoverable buses

- On embedded systems, devices are often not connected through a bus allowing enumeration, hotplugging, and providing unique identifiers for devices.
- For example, the devices on I2C buses or SPI buses, or the devices directly part of the system-on-chip.
- However, we still want all of these devices to be part of the device model.
- Such devices, instead of being dynamically detected, must be statically described.

Describing non-discoverable hardware

1. Directly in the **OS/bootloader code**

- Using compiled data structures, typically in C
- How it was done on most embedded platforms in Linux, U-Boot.
- Considered not maintainable/sustainable on ARM32, which motivated the move to another solution.

Describing non-discoverable hardware

2. Using **ACPI** tables

- On *x86* systems, but also on a subset of ARM64 platforms
- Tables provided by the firmware

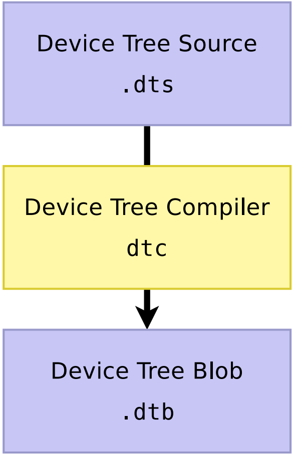
Describing non-discoverable hardware

3. Using a **Device Tree**

- Originates from **OpenFirmware**, defined by Sun, used on SPARC and PowerPC
  - That's why many Linux/U-Boot functions related to DT have a `of_` prefix
- Now used by most embedded-oriented CPU architectures that run Linux: ARC, ARM64, RISC-V, ARM32, PowerPC, Xtensa, MIPS, etc.
- Writing/tweaking a DT is necessary when porting Linux to a new board, or when connecting additional peripherals

Device Tree: from source to blob

- A tree data structure describing the hardware is written by a developer in a **Device Tree Source** file, `.dts`
- Processed by the **Device Tree Compiler**, `dtc`
- Produces a more efficient representation: **Device Tree Blob**, `.dtb`
- Additional C preprocessor pass
- `.dtb` $\rightarrow$ accurately describes the hardware platform in an **OS-agnostic** way.
- `.dtb` $\approx$ few dozens of kilobytes
- DTB also called **FDT**, *Flattened Device Tree*, once loaded into memory.
  - `fdt` command in U-Boot
  - `fdt_` APIs



dtc example

```
$ cat foo.dts
/dts-v1/;

/ {
        welcome = <0xBADCAFE>;
        bootlin {
                webinar = "great";
                demo = <1>, <2>, <3>;
        };
};
```

dtc example

```
$ cat foo.dts
/dts-v1/;

/ {
        welcome = <0xBADCAFE>;
        bootlin {
                webinar = "great";
                demo = <1>, <2>, <3>;
        };
};
```

```
$ dtc -I dts -O dtb -o foo.dtb foo.dts
$ ls -l foo.dt*
-rw-r--r-- 1 thomas thomas 169 ... foo.dtb
-rw-r--r-- 1 thomas thomas 102 ... foo.dts
```

dtc example

```
$ cat foo.dts
/dts-v1/;

/ {
        welcome = <0xBADCAFE>;
        bootlin {
                webinar = "great";
                demo = <1>, <2>, <3>;
        };
};
```

```
$ dtc -I dts -O dtb -o foo.dtb foo.dts
$ ls -l foo.dt*
-rw-r--r-- 1 thomas thomas 169 ... foo.dtb
-rw-r--r-- 1 thomas thomas 102 ... foo.dts
```

```
$ dtc -I dtb -O dts foo.dtb
/dts-v1/;

/ {
        welcome = <0xbadcafe>;

        bootlin {
                webinar = "great";
                demo = <0x01 0x02 0x03>;
        };
};
```

Where are Device Tree Sources located ?

- Even though they are OS-agnostic, **no central and OS-neutral** place to host Device Tree sources and share them between projects
  - Often discussed, never done
- In practice, the Linux kernel sources can be considered as the **canonical location** for Device Tree Source files
  - `arch/<ARCH>/boot/dts`
  - $\approx$ 4500 Device Tree Source files (`.dts` and `.dtsi`) in Linux as of 6.0.
- Duplicated/synced in various projects
  - U-Boot, Barebox, TF-A

Device Tree base syntax

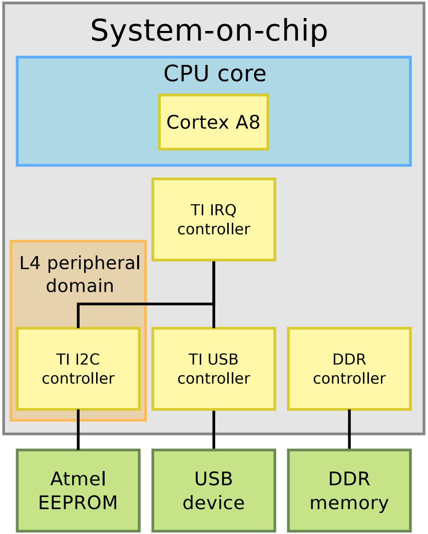
- Tree of **nodes**
- Nodes with **properties**
- Node ≈ a device or IP block
- Properties ≈ device characteristics
- Notion of **cells** in property values
- Notion of **phandle** to point to other nodes
- `dtc` only does syntax checking, no semantic validation

```
/ {
    node@0 {
        a-string-property = "A string";
        a-string-list-property = "first string", "second string";
        a-byte-data-property = [0x01 0x23 0x34 0x56];

        child-node@0 {
            first-child-property;
            second-child-property = <1>;
            a-reference-to-something = <&node1>;
        };

        child-node@1 {
        };
    };

    node1: node@1 {
        an-empty-property;
        a-cell-property = <1 2 3 4>;

        child-node@0 {
        };
    };
};
```

Node name
Unit address
Property name
Property value
Properties of node@0
Bytestring
A phandle (reference to another node)
Label
Four cells (32 bits values)

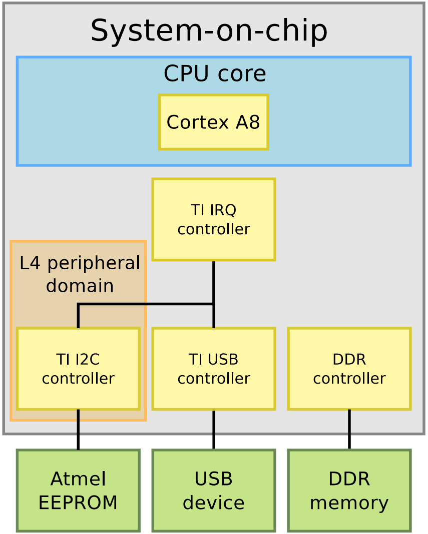
DT overall structure: simplified example

```
/ {
  #address-cells = <1>;
  #size-cells = <1>;
  model = "TI AM335x BeagleBone Black";
  compatible = "ti,am335x-bone-black", "ti,am335x-bone", "ti,am33xx";

  cpus { ... };
  memory@80000000 { ... };
  chosen { ... };
  ocp {
    intc: interrupt-controller@48200000 { ... };
    usb0: usb@47401300 { ... };
    l4_per: interconnect@44c00000 {
      i2c0: i2c@40012000 { ... };
    };
  };
};
```



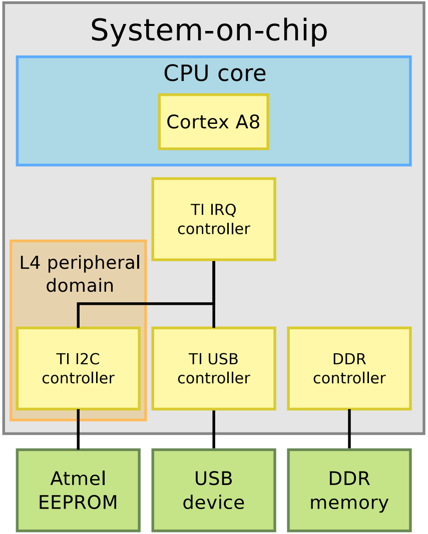
DT overall structure: simplified example

```
/ {
  cpus {
    #address-cells = <1>;
    #size-cells = <0>;
    cpu0: cpu@0 {
      compatible = "arm,cortex-a8";
      enable-method = "ti,am3352";
      device_type = "cpu";
      reg = <0>;
    };
  };

  memory@0x80000000 {
    device_type = "memory";
    reg = <0x80000000 0x10000000>; /* 256 MB */
  };

  chosen {
    bootargs = "";
    stdout-path = &uart0;
  };

  ocp { ... };
};
```



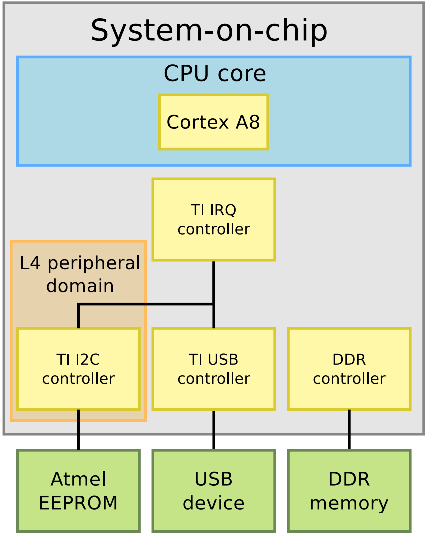
DT overall structure: simplified example

```
/ {
  cpus { ... };
  memory@0x80000000 { ... };
  chosen { ... };

  ocp {
    compatible = "simple-pm-bus";
    clocks = <&l3_clkctrl AM3_L3_L3_MAIN_CLKCTRL 0>;
    clock-names = "fck";
    #address-cells = <1>;
    #size-cells = <1>;

    intc: interrupt-controller@48200000 { ... };
    usb0: usb@47401300 { ... };

    l4_per: interconnect@44c00000 {
      compatible = "ti,am33xx-l4-wkup", "simple-pm-bus";
      reg = <0x44c00000 0x800>, <0x44c00800 0x800>,
            <0x44c01000 0x400>, <0x44c01400 0x400>;
      reg-names = "ap", "la", "ia0", "ia1";
      #address-cells = <1>;
      #size-cells = <1>;

      i2c0: i2c@40012000 { ... };
    };
  };
};
```



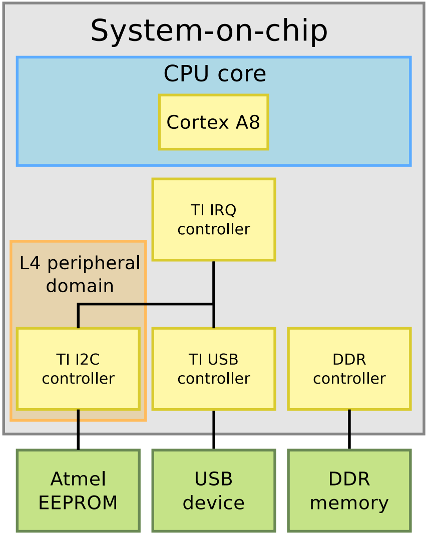
DT overall structure: simplified example

```
/ {
  cpus { ... };
  memory@0x80000000 { ... };
  chosen { ... };
  ocp {

    intc: interrupt-controller@48200000 {
      compatible = "ti,am33xx-intc";
      interrupt-controller;
      #interrupt-cells = <1>;
      reg = <0x48200000 0x1000>;
    };

    usb0: usb@47401300 {
      compatible = "ti,musb-am33xx";
      reg = <0x1400 0x400>, <0x1000 0x200>;
      reg-names = "mc", "control";
      interrupts = <18>;
      dr_mode = "otg";
      dmas = <&cppi41dma  0 0 &cppi41dma  1 0 ...>;
      status = "okay";
    };

    l4_per: interconnect@44c00000 {
      i2c0: i2c@40012000 { ... };
    };
  };
};
```



DT overall structure: simplified example

```
/ {
  cpus { ... };
  memory@0x80000000 { ... };
  chosen { ... };
  ocp {
    intc: interrupt-controller@48200000 { ... };
    usb0: usb@47401300 { ... };
    l4_per: interconnect@44c00000 {

      i2c0: i2c@40012000 {
        compatible = "ti,omap4-i2c";
        #address-cells = <1>;
        #size-cells = <0>;
        reg = <0x0 0x1000>;
        interrupts = <70>;
        status = "okay";
        pinctrl-names = "default";
        pinctrl-0 = <&i2c0_pins>;
        clock-frequency = <400000>;

        baseboard_eeprom: baseboard_eeprom@50 {
          compatible = "atmel,24c256";
          reg = <0x50>;
        };
      };
    };
  };
};
```



Device Tree inheritance

- Device Tree files are not monolithic, they can be split in several files, including each other.
- `.dtsi` files are included files, while `.dts` files are *final* Device Trees
  - Only `.dts` files are accepted as input to `dtc`
- Typically, `.dtsi` will contain
  - definitions of SoC-level information
  - definitions common to several boards
- The `.dts` file contains the board-level information
- The inclusion works by **overlaying** the tree of the including file over the tree of the included file.
- Allows an including file to **override** values specified by an included file
- Uses the C pre-processor `#include` directive

Device Tree inheritance example

Definition of the AM33xx SoC family

```
&l4_wkup {
    target-module@b000 {
        i2c0: i2c@0 {
            compatible = "ti,omap4-i2c";
            reg = <0x0 0x1000>;
            interrupts = <70>;
            status = "disabled";
        };
    };
};
```

am33xx-l4.dtsi

+

Definition of the Bone Black board

```
#include "am33xx-l4.dtsi"

&i2c0 {
    pinctrl-names = "default";
    pinctrl-0 = <&i2c0_pins>;
    status = "okay";

    baseboard_eeprom: eeprom@50 {
        compatible = "atmel,24c256";
        reg = <0x50>;
    };
};
```

am335x-boneblack.dts

Note 1

The actual Device Trees for this platform are more complicated. This example is highly simplified.

=

Compiled DTB

```
&l4_wkup {
    target-module@b000 {
        i2c0: i2c@0 {
            compatible = "ti,omap4-i2c";
            reg = <0x0 0x1000>;
            interrupts = <70>;
            pinctrl-names = "default";
            pinctrl-0 = <&i2c0_pins>;
            status = "okay";

            baseboard_eeprom: eeprom@50 {
                compatible = "atmel,24c256";
                reg = <0x50>;
            };
        };
    };
};
```

am335x-boneblack.dtb

Note 2

The real DTB is in binary format. Here we show the text equivalent of the DTB contents.

Inheritance and labels

Doing:

soc.dtsi

```
/ {
  ocp {
    uart0: serial@0 {
      compatible = "ti,am3352-uart", "ti,omap3-uart";
      reg = <0x0 0x1000>;
      status = "disabled";
    };
  };
};
```

board.dts

```
#include "soc.dtsi"

/ {
  ocp {
    serial@0 {
      status = "okay";
    };
  };
};
```

Inheritance and labels

Doing:

soc.dtsi

```
/ {
  ocp {
    uart0: serial@0 {
      compatible = "ti,am3352-uart", "ti,omap3-uart";
      reg = <0x0 0x1000>;
      status = "disabled";
    };
  };
};
```

board.dts

```
#include "soc.dtsi"

/ {
  ocp {
    serial@0 {
      status = "okay";
    };
  };
};
```

Is exactly equivalent to:

soc.dtsi

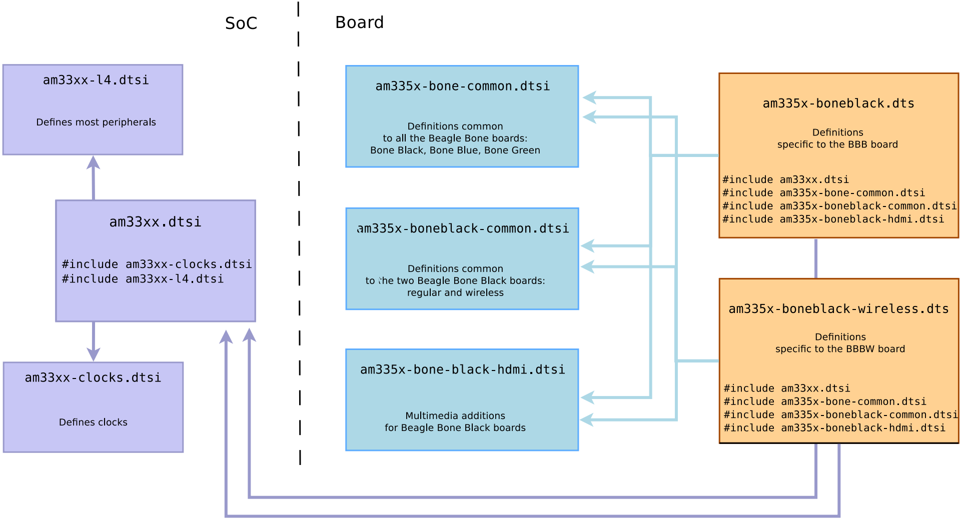
```
/ {
  ocp {
    uart0: serial@0 {
      compatible = "ti,am3352-uart", "ti,omap3-uart";
      reg = <0x0 0x1000>;
      status = "okay";
    };
  };
};
```

board.dts

```
#include "soc.dtsi"

&uart0 {
  status = "okay";
};
```

→ this solution is now often preferred

DT inheritance in Bone Black support

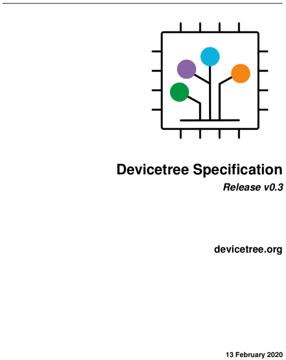


Device Tree design principles

- **Describe hardware** (how the hardware is), not configuration (how I choose to use the hardware)
- **OS-agnostic**
  - For a given piece of HW, Device Tree should be the same for U-Boot, FreeBSD or Linux
  - There should be no need to change the Device Tree when updating the OS
- Describe **integration of hardware components**, not the internals of hardware components
  - The details of how a specific device/IP block is working is handled by code in device drivers
  - The Device Tree describes how the device/IP block is connected/integrated with the rest of the system: IRQ lines, DMA channels, clocks, reset lines, etc.
- Like all beautiful design principles, these principles are sometimes violated.

Device Tree specifications

- How to write the correct nodes/properties to describe a given hardware platform ?
- **DeviceTree Specifications** → base Device Tree syntax + number of standard properties.
  - https://www.devicetree.org/specifications/
  - Not sufficient to describe the wide variety of hardware.
- **Device Tree Bindings** → documents that each specify how a piece of HW should be described
  - Documentation/devicetree/bindings/ in Linux kernel sources
  - Reviewed by DT bindings maintainer team
  - Legacy: human readable documents
  - New norm: YAML-written specifications


Devicetree Specification

Release v0.3

devicetree.org

13 February 2020

Device Tree binding: legacy style

Documentation/devicetree/bindings/i2c/i2c-omap.txt

```
I2C for OMAP platforms

-Required properties :
- compatible : Must be
       "ti,omap2420-i2c" for OMAP2420 SoCs
       "ti,omap2430-i2c" for OMAP2430 SoCs
       "ti,omap3-i2c" for OMAP3 SoCs
       "ti,omap4-i2c" for OMAP4+ SoCs
       "ti,am654-i2c", "ti,omap4-i2c" for AM654 SoCs
       "ti,j721e-i2c", "ti,omap4-i2c" for J721E SoCs
       "ti,am64-i2c", "ti,omap4-i2c" for AM64 SoCs
- ti,hwmods : Must be "i2c<n>", n being the instance number (1-based)
- #address-cells = <1>;
- #size-cells = <0>;

Recommended properties :
- clock-frequency : Desired I2C bus clock frequency in Hz. Otherwise
  the default 100 kHz frequency will be used.

Optional properties:
- Child nodes conforming to i2c bus binding

Note: Current implementation will fetch base address, irq and dma
from omap hwmod data base during device registration.
Future plan is to migrate hwmod data base contents into device tree
blob so that, all the required data will be used from device tree dts
file.
```

```
Examples :

i2c1: i2c@0 {
    compatible = "ti,omap3-i2c";
    #address-cells = <1>;
    #size-cells = <0>;
    ti,hwmods = "i2c1";
    clock-frequency = <400000>;
};
```

Device Tree binding: YAML style

Documentation/devicetree/bindings/i2c/ti,omap4-i2c.yaml

```yaml
# SPDX-License-Identifier: (GPL-2.0-only OR BSD-2-Clause)
%YAML 1.2
---
$id: http://devicetree.org/schemas/i2c/ti,omap4-i2c.yaml#
$schema: http://devicetree.org/meta-schemas/core.yaml#

title: I2C controllers on TI's OMAP and K3 SoCs

maintainers:
  - Vignesh Raghavendra <vigneshr@ti.com>

properties:
  compatible:
    oneOf:
      - enum:
          - ti,omap2420-i2c
          - ti,omap2430-i2c
          - ti,omap3-i2c
          - ti,omap4-i2c
      - items:
          - enum:
              - ti,am4372-i2c
              - ti,am64-i2c
              - ti,am654-i2c
              - ti,j721e-i2c
          - const: ti,omap4-i2c

  reg:
    maxItems: 1
```

```yaml
  interrupts:
    maxItems: 1

  clocks:
    maxItems: 1

  clock-names:
    const: fck

  clock-frequency: true

  power-domains: true

  "#address-cells":
    const: 1

  "#size-cells":
    const: 0

  ti,hwmods:
    description:
      Must be "i2c<n>", n being [...]
    $ref: /schemas/types.yaml#/definitions/string
    deprecated: true

required:
  - compatible
  - reg
  - interrupts
```

```yaml
additionalProperties: false

if:
  properties:
    compatible:
      enum:
        - ti,omap2420-i2c
        - ti,omap2430-i2c
        - ti,omap3-i2c
        - ti,omap4-i2c
then:
  properties:
    ti,hwmods:
      items:
        - pattern: "^i2c([1-9])$"
else:
  properties:
    ti,hwmods: false

examples:
  - |
    #include <dt-bindings/interrupt-controller/irq.h>
    #include <dt-bindings/interrupt-controller/arm-gic.h>

    main_i2c0: i2c@2000000 {
        compatible = "ti,j721e-i2c", "ti,omap4-i2c";
        reg = <0x2000000 0x100>;
        interrupts = <GIC_SPI 200 IRQ_TYPE_LEVEL_HIGH>;
    };
```

Validating Device Tree in Linux

- `dtc` only does syntactic validation
- YAML bindings allow to do semantic validation
- Linux kernel `make` rules:
  - `make dt_binding_check`
    verify that YAML bindings are valid
  - `make dtbs_check`
    validate DTs currently enabled against YAML bindings
  - `make DT_SCHEMA_FILES=Documentation/devicetree/bindings/trivial-devices.yaml dtbs_check`
    validate DTs against a specific YAML binding

The properties

Device tree properties can be:

- Fully generic
  - Their meaning is usually described in one place: the core DT schema available at https://github.com/devicetree-org/dt-schema.
  - `compatible`, `reg`, `\#address-cells`, etc
- Subsystem specific and cover generic consumer bindings
  - Their meaning is either described in the `dt-schema` Github or under Documentation/device-tree/bindings.
  - `clocks`, `interrupts`, `regulators`, etc
- Subsystem specific
  - All devices of a certain class may use them, often starting with the class name
  - `spi-cpha`, `i2c-scl-internal-delay-ns`, `nand-ecc-engine`, `mac-address`, etc
- Vendor/device specific
  - To describe uncommon or very specific properties
  - Always described in the device's binding file and prefixed with `<vendor>,`
  - `ti,hwmods`, `xlnx,num-channels`, `nxp,tx-output-mode`, etc
- Some of them are deprecated, watch out the bindings!

The compatible property

- Is a list of strings
  - From the most specific to the least specific
- Describes the specific **binding** to which the node complies.
- It uniquely identifies the **programming model** of the device.
- Practically speaking, it is used by the operating system to find the **appropriate driver** for this device.
- When describing real hardware, the typical form is `vendor,model`
- Examples:
  - `compatible = "arm,armv7-timer";`
  - `compatible = "st,stm32mp1-dwmac", "snps,dwmac-4.20a";`
  - `compatible = "regulator-fixed";`
  - `compatible = "gpio-keys";`
- Special value: `simple-bus` → bus where all sub-nodes are memory-mapped devices

compatible property and Linux kernel drivers

- Top-level DT nodes with a `compatible` property and nodes that are sub-nodes of `simple-bus` will cause Linux to identify those devices as **platform devices**
  - Instantiated automatically at boot time
- Sub-nodes of I2C controllers → *I2C devices*
- Sub-nodes of SPI controllers → *SPI devices*
- Each Linux driver has a table of compatible strings it supports
  - `struct of_device_id[]`
- When a DT node compatible string matches a given driver, the device is *bound* to that driver.

```
/ {
  timer {                          Platform device
    compatible = "...";
  };
  soc {
    compatible = "simple-bus";
    uart@1000 {                    Platform device
      compatible = "...";
    };
    i2c@2000 {                     Platform device
      compatible = "...";
      eeprom@65 {                  I2C device
        compatible = "...";
      };
    };
  };
};
```

Matching with drivers in Linux: platform driver

drivers/i2c/busses/i2c-omap.c

```
static const struct of_device_id omap_i2c_of_match[] = {
        {
                .compatible = "ti,omap4-i2c",
                .data = &omap4_pdata,
        },
        {
                .compatible = "ti,omap3-i2c",
                .data = &omap3_pdata,
        },
        [...]
        { },
};
MODULE_DEVICE_TABLE(of, omap_i2c_of_match);

[...]

static struct platform_driver omap_i2c_driver = {
        .probe          = omap_i2c_probe,
        .remove         = omap_i2c_remove,
        .driver         = {
                .name   = "omap_i2c",
                .pm     = &omap_i2c_pm_ops,
                .of_match_table = of_match_ptr(omap_i2c_of_match),
        },
};
```

Matching with drivers in Linux: I2C driver

sound/soc/codecs/cs42l51.c

```
const struct of_device_id cs42l51_of_match[] = {
        { .compatible = "cirrus,cs42l51", },
        { }
};
MODULE_DEVICE_TABLE(of, cs42l51_of_match);
```

sound/soc/codecs/cs42l51-i2c.c

```
static struct i2c_driver cs42l51_i2c_driver = {
        .driver = {
                .name = "cs42l51",
                .of_match_table = cs42l51_of_match,
                .pm = &cs42l51_pm_ops,
        },
        .probe = cs42l51_i2c_probe,
        .remove = cs42l51_i2c_remove,
        .id_table = cs42l51_i2c_id,
};
```

reg property

- Most important property after `compatible`
- **Memory-mapped** devices: base physical address and size of the memory-mapped registers. Can have several entries for multiple register areas.

```
sai4: sai@50027000 {
    reg = <0x50027000 0x4>, <0x500273f0 0x10>;
};
```

reg property

- Most important property after `compatible`
- **Memory-mapped** devices: base physical address and size of the memory-mapped registers. Can have several entries for multiple register areas.
- **I2C** devices: address of the device on the I2C bus.

```
&i2c1 {
    hdmi-transmitter@39 {
        reg = <0x39>;
    };
    cs42l51: cs42l51@4a {
        reg = <0x4a>;
    };
};
```

reg property

- Most important property after `compatible`
- **Memory-mapped** devices: base physical address and size of the memory-mapped registers. Can have several entries for multiple register areas.
- **I2C** devices: address of the device on the I2C bus.
- **SPI** devices: chip select number

```
&qspi {
        flash0: mx66l51235l@0 {
                reg = <0>;
        };
        flash1: mx66l51235l@1 {
                reg = <1>;
        };
};
```

reg property

- Most important property after `compatible`
- **Memory-mapped** devices: base physical address and size of the memory-mapped registers. Can have several entries for multiple register areas.
- **I2C** devices: address of the device on the I2C bus.
- **SPI** devices: chip select number
- The unit address must be the address of the first `reg` entry.

```
sai4: sai@50027000 {
    reg = <0x50027000 0x4>, <0x500273f0 0x10>;
};
```

Status property

- The `status` property indicates if the device is really in use or not
  - `okay` or `ok` → the device is really in use
  - any other value, by convention `disabled` → the device is not in use
- In Linux, controls if a device is instantiated
- In `.dtsi` files describing SoCs: all devices that interface to the outside world have `status = disabled`
- Enabled on a per-device basis in the board `.dts`

Resources: interrupts, clocks, DMA, reset lines, ...

- Common pattern for resources shared by multiple hardware blocks
  - Interrupt lines
  - Clock controllers
  - DMA controllers
  - Reset controllers
  - ...
- A Device Tree node describing the *controller* as a device
- References from other nodes that use resources provided by this *controller*

```
intc: interrupt-controller@a0021000 {
   compatible = "arm,cortex-a7-gic";
   #interrupt-cells = <3>;
   interrupt-controller;
   reg = <0xa0021000 0x1000>, <0xa0022000 0x2000>;
};

rcc: rcc@50000000 {
   compatible = "st,stm32mp1-rcc", "syscon";
   reg = <0x50000000 0x1000>;
   #clock-cells = <1>;
   #reset-cells = <1>;
};

dmamux1: dma-router@48002000 {
   compatible = "st,stm32h7-dmamux";
   reg = <0x48002000 0x1c>;
   #dma-cells = <3>;
   clocks = <&rcc DMAMUX>;
   resets = <&rcc DMAMUX_R>;
};

spi3: spi@4000c000 {
   interrupts = <GIC_SPI 51 IRQ_TYPE_LEVEL_HIGH>;
   clocks = <&rcc SPI3_K>;
   resets = <&rcc SPI3_R>;
   dmas = <&dmamux1 61 0x400 0x05>,  <&dmamux1 62 0x400 0x05>;
};
```

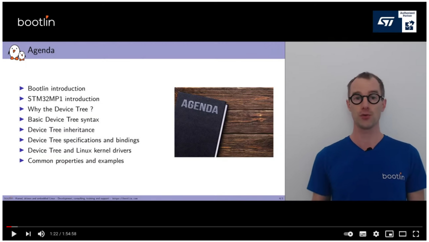
Generic suffixes

- `xxx-gpios`
  - When drivers need access to GPIOs
  - May be subsystem-specific or vendor-specific
  - Examples: `enable-gpios`, `ts`, `txrx-gpios`
- `xxx-names`
  - Sometimes naming items is relevant
  - Allows drivers to perform lookups by name rather than ID
  - The order of definition of each item still matters
  - Examples: `gpio-names`, `clock-names`, `reset-names`

```
uart0@4000c000 {
    dmas = <&edma 26 0>, <&edma 27 0>;
    dma-names = "tx", "rx";
    ...
};
```

References

- Device Tree 101 webinar, Thomas Petazzoni (2021):
  Slides: https://bootlin.com/blog/device-tree-101-webinar-slides-and-videos/
  Video: https://youtu.be/a9CZ1Uk3OYQ
- Kernel documentation
  - driver-api/driver-model/
  - devicetree/
  - filesystems/sysfs
- https://devicetree.org
- The kernel source code
  - Full of examples of other drivers!



Discoverable hardware: USB and PCI

Discoverable hardware

- Some busses have built-in hardware discoverability mechanisms
- Most common busses: USB and PCI
- Hardware devices can be enumerated, and their characteristics retrieved with just a driver or the bus controller
- Useful Linux commands
  - `lsusb`, lists all USB devices detected
  - `lspci`, lists all PCI devices detected
  - A detected device does not mean it has a kernel driver associated to it!
- Association with kernel drivers done based on product ID/vendor ID, or some other characteristics of the device: device class, device sub-class, etc.

Useful general-purpose kernel APIs

Memory/string utilities

- In include/linux/string.h
  - Memory-related: memset(), memcpy(), memmove(), memscan(), memcmp(), memchr()
  - String-related: strcpy(), strcat(), strcmp(), strchr(), strrchr(), strlen() and variants
  - Allocate and copy a string: kstrdup(), kstrndup()
  - Allocate and copy a memory area: kmemdup()
- In include/linux/kernel.h
  - String to int conversion: simple_strtoul(), simple_strtol(), simple_strtoull(), simple_strtoll()
  - Other string functions: sprintf(), sscanf()

Linked lists

- Convenient linked-list facility in `include/linux/list.h`
  - Used in thousands of places in the kernel
- Add a `struct list_head` member to the structure whose instances will be part of the linked list. It is usually named `node` when each instance needs to only be part of a single list.
- Define the list with the `LIST_HEAD()` macro for a global list, or define a `struct list_head` element and initialize it with `INIT_LIST_HEAD()` for lists embedded in a structure.
- Then use the `list_*()` API to manipulate the list
  - Add elements: `list_add()`, `list_add_tail()`
  - Remove, move or replace elements: `list_del()`, `list_move()`, `list_move_tail()`, `list_replace()`
  - Test the list: `list_empty()`
  - Iterate over the list: `list_for_each_*()` family of macros

From `include/soc/at91/atmel_tcb.h`

```
/*
 * Definition of a list element, with a
 * struct list_head member
 */
struct atmel_tc
{
    /* some members */
    struct list_head node;
};
```

Linked lists examples 2/2

From drivers/misc/atmel_tclib.c

```
/* Define the global list */
static LIST_HEAD(tc_list);

static int __init tc_probe(struct platform_device *pdev) {
    struct atmel_tc *tc;
    tc = kzalloc(sizeof(struct atmel_tc), GFP_KERNEL);
    /* Add an element to the list */
    list_add_tail(&tc->node, &tc_list);
}

struct atmel_tc *atmel_tc_alloc(unsigned block, const char *name)
{
    struct atmel_tc *tc;
    /* Iterate over the list elements */
    list_for_each_entry(tc, &tc_list, node) {
        /* Do something with tc */
    }
    [...]
}
```

Linux device and driver model

Corrections, suggestions, contributions and translations are welcome!

embedded Linux and kernel engineering

Introduction

The need for a device model?

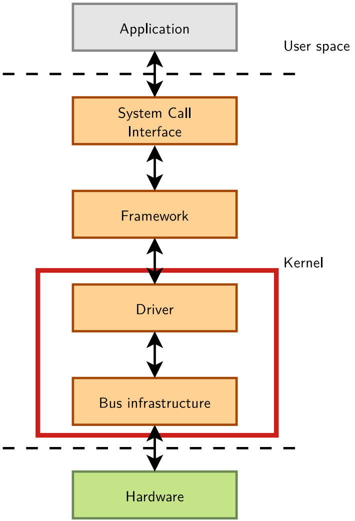
- The Linux kernel runs on a wide range of architectures and hardware platforms, and therefore needs to **maximize the reusability** of code between platforms.
- For example, we want the same *USB device driver* to be usable on a x86 PC, or an ARM platform, even though the USB controllers used on these platforms are different.
- This requires a clean organization of the code, with the *device drivers* separated from the *controller drivers*, the hardware description separated from the drivers themselves, etc.
- This is what the Linux kernel **Device Model** allows, in addition to other advantages covered in this section.

Kernel and Device Drivers

In Linux, a driver is always interfacing with:

- a **framework** that allows the driver to expose the hardware features in a generic way.
- a **bus infrastructure**, part of the device model, to detect/communicate with the hardware.

This section focuses on the *bus infrastructure*, while *kernel frameworks* are covered later in this training.



Device Model data structures

- The *device model* is organized around three main data structures:
  - The `struct bus_type` structure, which represents one type of bus (USB, PCI, I2C, etc.)
  - The `struct device_driver` structure, which represents one driver capable of handling certain devices on a certain bus.
  - The `struct device` structure, which represents one device connected to a bus
- The kernel uses inheritance to create more specialized versions of `struct device_driver` and `struct device` for each bus subsystem.
- In order to explore the device model, we will
  - First look at a popular bus that offers dynamic enumeration, the *USB bus*
  - Continue by studying how buses that do not offer dynamic enumeration are handled.

Bus Drivers

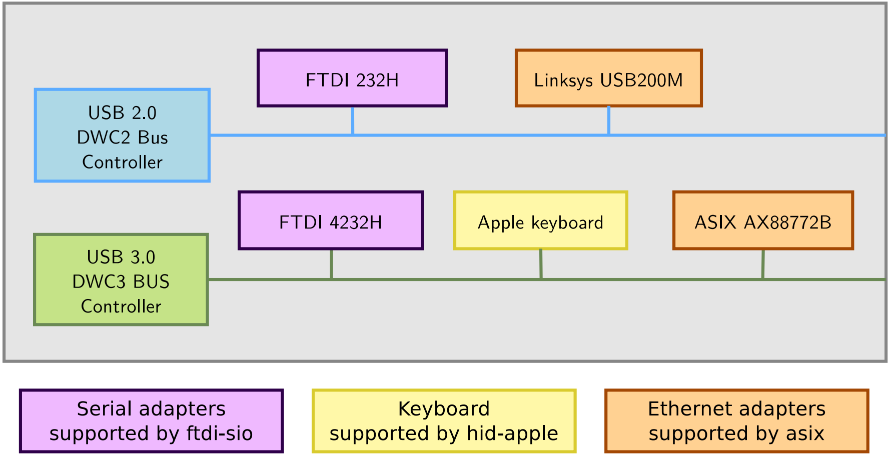
- The first component of the device model is the bus driver
  - One bus driver for each type of bus: USB, PCI, SPI, MMC, I2C, etc.
- It is responsible for
  - Registering the bus type (`struct bus_type`)
  - Allowing the registration of adapter drivers (USB controllers, I2C adapters, etc.), able to detect the connected devices (if possible), and providing a communication mechanism with the devices
  - Allowing the registration of device drivers (USB devices, I2C devices, PCI devices, etc.), managing the devices
  - Matching the device drivers against the devices detected by the adapter drivers.
  - Provides an API to implement both adapter drivers and device drivers
  - Defining driver and device specific structures, mainly `struct usb_driver` and `struct usb_interface`

sysfs

- The bus, device, drivers, etc. structures are internal to the kernel
- The `sysfs` virtual filesystem offers a mechanism to export such information to user space
- Used for example by `udev` to provide automatic module loading, firmware loading, mounting of external media, etc.
- `sysfs` is usually mounted in `/sys`
  - `/sys/bus/` contains the list of buses
  - `/sys/devices/` contains the list of devices
  - `/sys/class` enumerates devices by the framework they are registered to (`net`, `input`, `block`...), whatever bus they are connected to. Very useful!

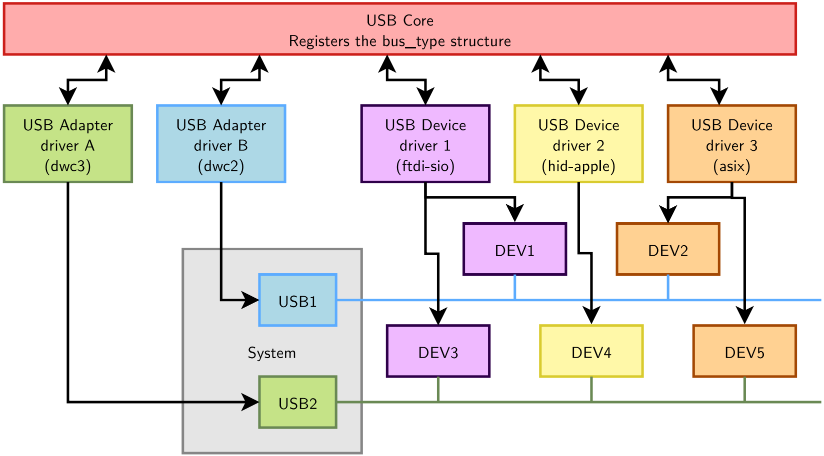
Example of the USB bus

Example: USB Bus 1/3



Hardware view of the bus

Example: USB Bus 2/3



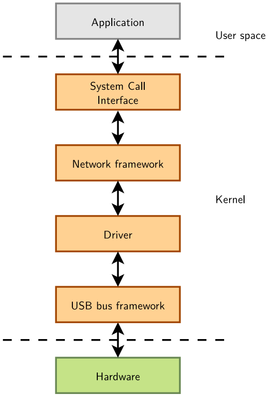
Device model view of the bus

Example: USB Bus 3/3

- Core infrastructure (bus driver)
  - drivers/usb/core/
  - struct bus_type is defined in drivers/usb/core/driver.c and registered in drivers/usb/core/usb.c
- Adapter drivers
  - drivers/usb/host/
  - For EHCI, UHCI, OHCI, XHCI, and their implementations on various systems (Microchip, IXP, Xilinx, OMAP, Samsung, PXA, etc.)
- Device drivers
  - Everywhere in the kernel tree, classified by their type (Example: drivers/net/usb/)

Example of Device Driver

- To illustrate how drivers are implemented to work with the device model, we will study the source code of a driver for a USB network card
  - It is USB device, so it has to be a USB device driver
  - It exposes a network device, so it has to be a network driver
  - Most drivers rely on a bus infrastructure (here, USB) and register themselves in a framework (here, network)
- We will only look at the device driver side, and not the adapter driver side
- The driver we will look at is `drivers/net/usb/rtl8150.c`



Device Identifiers

- Defines the set of devices that this driver can manage, so that the USB core knows for which devices this driver should be used
- The MODULE_DEVICE_TABLE() macro allows depmod (run by make modules_install) to extract the relationship between device identifiers and drivers, so that drivers can be loaded automatically by udev. See /lib/modules/$(uname -r)/modules.{alias,usbmap}

```
static struct usb_device_id rtl8150_table[] = {
    { USB_DEVICE(VENDOR_ID_REALTEK, PRODUCT_ID_RTL8150) },
    { USB_DEVICE(VENDOR_ID_MELCO, PRODUCT_ID_LUAKTX) },
    { USB_DEVICE(VENDOR_ID_MICRONET, PRODUCT_ID_SP128AR) },
    { USB_DEVICE(VENDOR_ID_LONGSHINE, PRODUCT_ID_LCS8138TX) },
    [...]
    {}
};
MODULE_DEVICE_TABLE(usb, rtl8150_table);
```

Instantiation of usb_driver

- `struct usb_driver` is a structure defined by the USB core. Each USB device driver must instantiate it, and register itself to the USB core using this structure
- This structure inherits from `struct device_driver`, which is defined by the device model.

```
static struct usb_driver rtl8150_driver = {
    .name = "rtl8150",
    .probe = rtl8150_probe,
    .disconnect = rtl8150_disconnect,
    .id_table = rtl8150_table,
    .suspend = rtl8150_suspend,
    .resume = rtl8150_resume
};
```

Driver registration and unregistration

- When the driver is loaded / unloaded, it must register / unregister itself to / from the USB core
- Done using `usb_register()` and `usb_deregister()`, provided by the USB core.

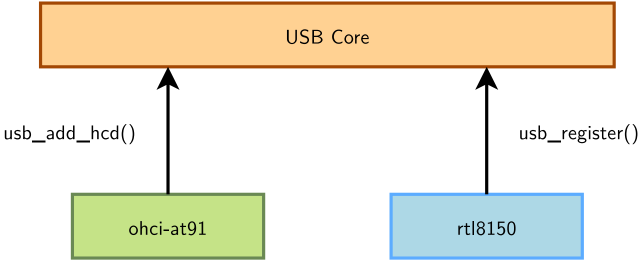
```
static int __init usb_rtl8150_init(void)
{
    return usb_register(&rtl8150_driver);
}

static void __exit usb_rtl8150_exit(void)
{
    usb_deregister(&rtl8150_driver);
}

module_init(usb_rtl8150_init);
module_exit(usb_rtl8150_exit);
```

- All this code is actually replaced by a call to the `module_usb_driver()` macro:

```
module_usb_driver(rtl8150_driver);
```

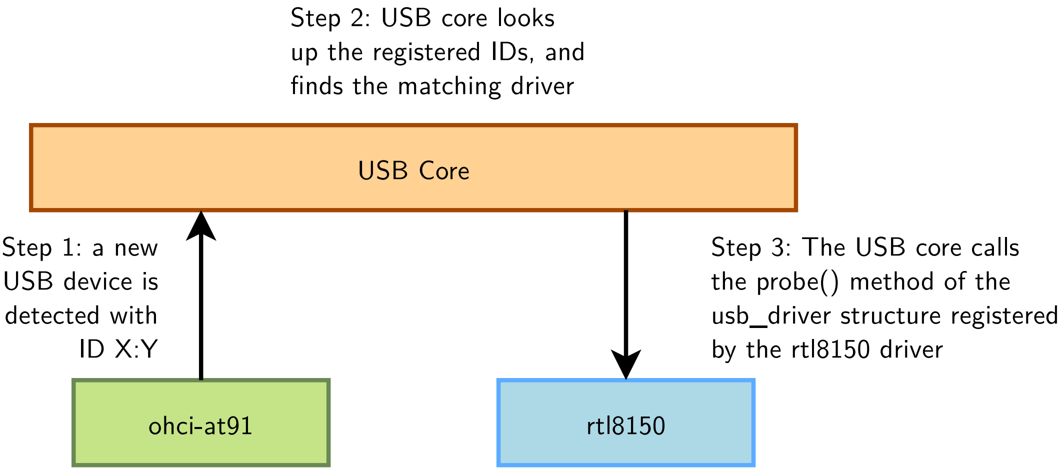
At Initialization

- The USB adapter driver that corresponds to the USB controller of the system registers itself to the USB core
- The `rtl8150` USB device driver registers itself to the USB core



- The USB core now knows the association between the vendor/product IDs of `rtl8150` and the `struct usb_driver` structure of this driver

When a device is detected



Probe Method

- Invoked **for each device** bound to a driver
- The `probe()` method receives as argument a structure describing the device, usually specialized by the bus infrastructure (`struct pci_dev`, `struct usb_interface`, etc.)
- This function is responsible for
  - Initializing the device, mapping I/O memory, registering the interrupt handlers. The bus infrastructure provides methods to get the addresses, interrupt numbers and other device-specific information.
  - Registering the device to the proper kernel framework, for example the network infrastructure.

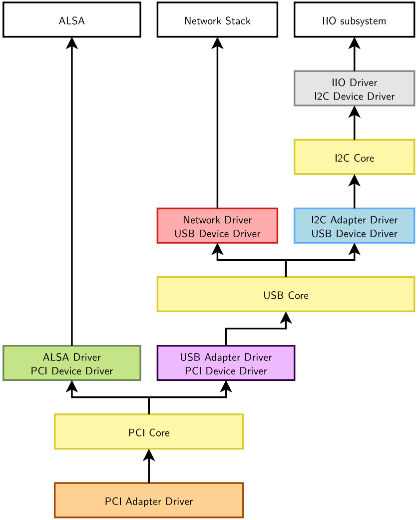
Example: probe() and disconnect() methods

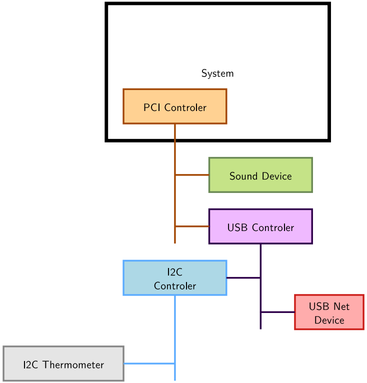
```c
static int rtl8150_probe(struct usb_interface *intf,
    const struct usb_device_id *id)
{
    rtl8150_t *dev;
    struct net_device *netdev;

    netdev = alloc_etherdev(sizeof(rtl8150_t));
    [...]
    dev = netdev_priv(netdev);
    tasklet_init(&dev->tl, rx_fixup, (unsigned long)dev);
    spin_lock_init(&dev->rx_pool_lock);
    [...]
    netdev->netdev_ops = &rtl8150_netdev_ops;
    alloc_all_urbs(dev);
    [...]
    usb_set_intfdata(intf, dev);
    SET_NETDEV_DEV(netdev, &intf->dev);
    register_netdev(netdev);

    return 0;
}
```

```c
static void rtl8150_disconnect(struct usb_interface *intf)
{
        rtl8150_t *dev = usb_get_intfdata(intf);

        usb_set_intfdata(intf, NULL);
        if (dev) {
                set_bit(RTL8150_UNPLUG, &dev->flags);
                tasklet_kill(&dev->tl);
                unregister_netdev(dev->netdev);
                unlink_all_urbs(dev);
                free_all_urbs(dev);
                free_skb_pool(dev);
                if (dev->rx_skb)
                        dev_kfree_skb(dev->rx_skb);
                kfree(dev->intr_buff);
                free_netdev(dev->netdev);
        }
}
```

Source: drivers/net/usb/rtl8150.c

The Model is Recursive





Platform drivers

Platform devices

- Amongst the non-discoverable devices, a huge family are the devices that are directly part of a system-on-chip: UART controllers, Ethernet controllers, SPI or I2C controllers, graphic or audio devices, etc.
- In the Linux kernel, a special bus, called the **platform bus** has been created to handle such devices.
- It supports **platform drivers** that handle **platform devices**.
- It works like any other bus (USB, PCI), except that devices are enumerated statically instead of being discovered dynamically.

Implementation of a Platform Driver (1)

The driver implements a `struct platform_driver` structure (example taken from `drivers/tty/serial/imx.c`, simplified)

```
static struct platform_driver serial_imx_driver = {
        .probe          = serial_imx_probe,
        .remove         = serial_imx_remove,
        .id_table       = imx_uart_devtype,
        .driver         = {
                .name   = "imx-uart",
                .of_match_table = imx_uart_dt_ids,
                .pm     = &imx_serial_port_pm_ops,
        },
};
```

Implementation of a Platform Driver (2)

... and registers its driver to the platform driver infrastructure

```
static int __init imx_serial_init(void) {
    return platform_driver_register(&serial_imx_driver);
}

static void __exit imx_serial_cleanup(void) {
    platform_driver_unregister(&serial_imx_driver);
}

module_init(imx_serial_init);
module_exit(imx_serial_cleanup);
```

Most drivers actually use the `module_platform_driver()` macro when they do nothing special in `init()` and `exit()` functions:

```
module_platform_driver(serial_imx_driver);
```

Platform device instantiation

- As platform devices cannot be detected dynamically, they are defined statically
  - Legacy way: by direct instantiation of `struct platform_device` structures, as done on a few old ARM platforms. The device was part of a list, and the list of devices was added to the system during board initialization.
  - Current way: By parsing an "external" description, like a *device tree* on most embedded platforms today, from which `struct platform_device` structures are created.

Using additional hardware resources

- Regular DT descriptions contain many information, including phandles (pointers) towards additional hardware blocks or hardware details which cannot be discovered.
  - Some of them are available through a generic array of resourses, like addresses for the I/O registers and IRQ lines:
    - Such information can be represented using `struct resource`, and an array of `struct resource` is associated to each `struct platform_device`.
  - Common information/dependencies are parsed by the relevant subsystems, like clocks, GPIOs, or DMA channels:
    - Each subsystem is responsible of instantiating its components, and offering an API to retrieve these objects and use them from device drivers.
  - Specific information might be directly be retrieved by device drivers, through (expensive) direct DT lookups (old drivers use `struct platform_data`).
- All these methods allow the same driver to be used with multiple devices functioning similarly, but with different addresses, IRQs, etc.

Using Resources

- The platform driver has access to the resources:

```
res = platform_get_resource(pdev, IORESOURCE_MEM, 0);
base = ioremap(res->start, PAGE_SIZE);
sport->rxirq = platform_get_irq(pdev, 0);
```

- As well as the various common dependencies through individual APIs:
  - `clk_get()`
  - `gpio_request()`
  - `dma_request_channel()`

Driver data

- In addition to the per-device resources and information, drivers may require driver-specific information to behave slighlty differently when different flavors of an IP block are driven by the same driver.
- A `void * data` pointer can be used to store per-compatible specificities:

```
static const struct of_device_id marvell_nfc_of_ids[] = {
        {
                .compatible = "marvell,armada-8k-nand-controller",
                .data = &marvell_armada_8k_nfc_caps,
        },
};
```

- Which can be retrieved in the probe with:

```
        /* Get NAND controller capabilities */
        if (pdev->id_entry) /* legacy way */
                nfc->caps = (void *)pdev->id_entry->driver_data;
        else /* current way */
                nfc->caps = of_device_get_match_data(&pdev->dev);
```

Introduction to the I2C subsystem

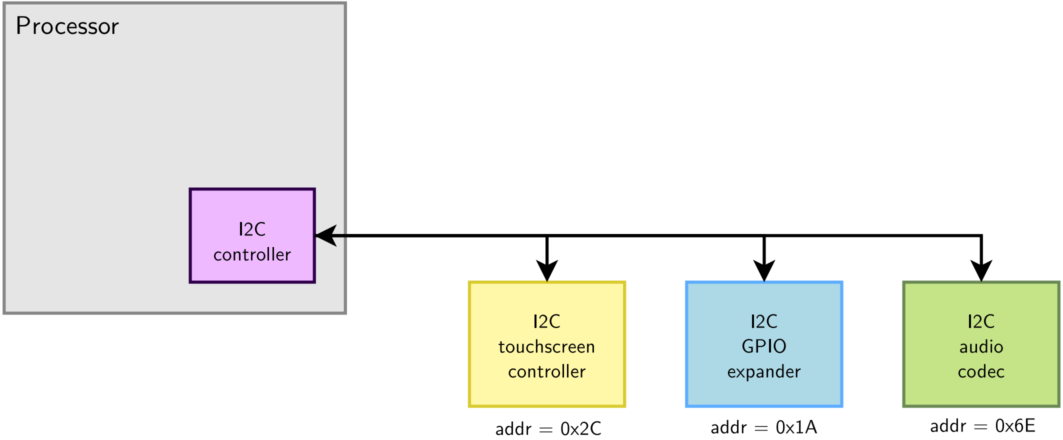
bootlin

embedded Linux and kernel engineering

What is I2C?

- A very commonly used low-speed bus to connect on-board and external devices to the processor.
- Uses only two wires: SDA for the data, SCL for the clock.
- It is a master/slave bus: only the master can initiate transactions, and slaves can only reply to transactions initiated by masters.
- In a Linux system, the I2C controller embedded in the processor is typically the master, controlling the bus.
- Each slave device is identified by an I2C address (you can't have 2 devices with the same address on the same bus). Each transaction initiated by the master contains this address, which allows the relevant slave to recognize that it should reply to this particular transaction.

An I2C bus example



The I2C bus driver

- Like all bus subsystems, the I2C bus driver is responsible for:
  - Providing an API to implement I2C controller drivers
  - Providing an API to implement I2C device drivers, in kernel space
  - Providing an API to implement I2C device drivers, in user space
- The core of the I2C bus driver is located in `drivers/i2c/`.
- The I2C controller drivers are located in `drivers/i2c/busses/`.
- The I2C device drivers are located throughout `drivers/`, depending on the framework used to expose the devices (e.g. `drivers/input/` for input devices).

Registering an I2C device driver

- Like all bus subsystems, the I2C subsystem defines a `struct i2c_driver` that inherits from `struct device_driver`, and which must be instantiated and registered by each I2C device driver.
  - As usual, this structure points to the `->probe()` and `->remove()` functions.
  - It also contains an `id_table`, used for non-DT based probing of I2C devices.
  - A `->probe_new()` function can replace `->probe()` when no `id_table` is provided.
- The `i2c_add_driver()` and `i2c_del_driver()` functions are used to register/unregister the driver.
- If the driver doesn't do anything else in its `init()`/`exit()` functions, it is advised to use the `module_i2c_driver()` macro instead.

Registering an I2C device driver: example

```
static const struct i2c_device_id adxl345_i2c_id[] = {
        { "adxl345", ADXL345 },
        { "adxl375", ADXL375 },
        { }
};

MODULE_DEVICE_TABLE(i2c, adxl345_i2c_id);

static const struct of_device_id adxl345_of_match[] = {
        { .compatible = "adi,adxl345" },
        { .compatible = "adi,adxl375" },
        { },
};

MODULE_DEVICE_TABLE(of, adxl345_of_match);

static struct i2c_driver adxl345_i2c_driver = {
        .driver = {
                .name   = "adxl345_i2c",
                .of_match_table = adxl345_of_match,
        },
        .probe          = adxl345_i2c_probe,
        .remove         = adxl345_i2c_remove,
        .id_table       = adxl345_i2c_id,
};

module_i2c_driver(adxl345_i2c_driver);
```

From `drivers/iio/accel/adxl345_i2c.c`

Registering an I2C device: non-DT

- On non-DT platforms, the `struct i2c_board_info` structure allows to describe how an I2C device is connected to a board.
- Such structures are normally defined with the `I2C_BOARD_INFO()` helper macro.
  - Takes as argument the device name and the slave address of the device on the bus.
- An array of such structures is registered on a per-bus basis using `i2c_register_board_info()`, when the platform is initialized.

Registering an I2C device, non-DT example

```
static struct i2c_board_info __initdata em7210_i2c_devices[] = {
        {
                I2C_BOARD_INFO("rs5c372a", 0x32),
        },
};

...

static void __init em7210_init_machine(void)
{
        register_iop32x_gpio();
        platform_device_register(&em7210_serial_device);
        platform_device_register(&iop3xx_i2c0_device);
        platform_device_register(&iop3xx_i2c1_device);
        platform_device_register(&em7210_flash_device);
        platform_device_register(&iop3xx_dma_0_channel);
        platform_device_register(&iop3xx_dma_1_channel);

        i2c_register_board_info(0, em7210_i2c_devices,
                ARRAY_SIZE(em7210_i2c_devices));
}
```

From arch/arm/mach-iop32x/em7210.c

Registering an I2C device, in the DT

- In the Device Tree, the I2C controller device is typically defined in the `.dtsi` file that describes the processor.
  - Normally defined with `status = "disabled"`.
- At the board/platform level:
  - the I2C controller device is enabled (`status = "okay"`)
  - the I2C bus frequency is defined, using the `clock-frequency` property.
  - the I2C devices on the bus are described as children of the I2C controller node, where the `reg` property gives the I2C slave address on the bus.
- See the binding for the corresponding driver for a specification of the expected DT properties. Example: `Documentation/devicetree/bindings/i2c/i2c-omap.txt`

Registering an I2C device, DT example (1/2)

Definition of the I2C controller

```
i2c0: i2c@01c2ac00 {
        compatible = "allwinner,sun7i-a20-i2c",
                     "allwinner,sun4i-a10-i2c";
        reg = <0x01c2ac00 0x400>;
        interrupts = <GIC_SPI 7 IRQ_TYPE_LEVEL_HIGH>;
        clocks = <&apb1_gates 0>;
        status = "disabled";
        #address-cells = <1>;
        #size-cells = <0>;
};
```

From arch/arm/boot/dts/sun7i-a20.dtsi

`#address-cells`: number of 32-bit values needed to encode the address fields
`#size-cells`: number of 32-bit values needed to encode the size fields
See details in https://elinux.org/Device_Tree_Usage

Registering an I2C device, DT example (2/2)

Definition of the I2C device

```
&i2c0 {
	pinctrl-names = "default";
	pinctrl-0 = <&i2c0_pins_a>;
	status = "okay";

	axp209: pmic@34 {
		compatible = "x-powers,axp209";
		reg = <0x34>;
		interrupt-parent = <&nmi_intc>;
		interrupts = <0 IRQ_TYPE_LEVEL_LOW>;

		interrupt-controller;
		#interrupt-cells = <1>;
	};
};
```

From arch/arm/boot/dts/sun7i-a20-olinuxino-micro.dts

probe_new() / probe() and remove()

- The ->probe_new() function is responsible for initializing the device and registering it in the appropriate kernel framework. It receives as argument:
  - A struct i2c_client pointer, which represents the I2C device itself. This structure inherits from struct device.
- Alternatively, the ->probe() function receives as arguments:
  - A similar struct i2c_client pointer.
  - A struct i2c_device_id pointer, which points to the I2C device ID entry that matched the device that is being probed.
- The ->remove() function is responsible for unregistering the device from the kernel framework and shut it down. It receives as argument:
  - The same struct i2c_client pointer that was passed as argument to ->probe_new() or ->probe()

Probe example

```
static int da311_probe(struct i2c_client *client,
                       const struct i2c_device_id *id)
{
        struct iio_dev *indio_dev;          // framework structure
        da311_data *data;                   // per device structure
        ...
        // Allocate framework structure with per device struct inside
        indio_dev = devm_iio_device_alloc(&client->dev, sizeof(*data));
        data = iio_priv(indio_dev);
        data->client = client;
        i2c_set_clientdata(client, indio_dev);
        // Prepare device and initialize indio_dev
        ...
        // Register device to framework
        ret = iio_device_register(indio_dev);
        ...
        return ret;
}
```

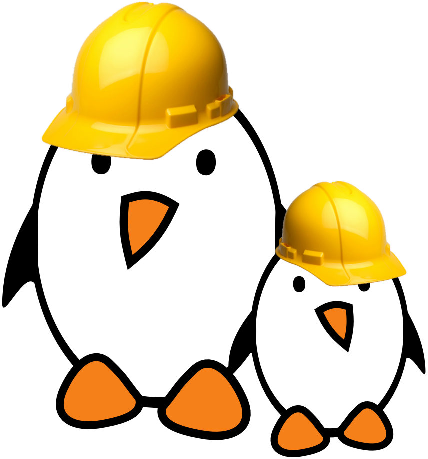
From drivers/iio/accel/da311.c

Remove example

```
static int da311_remove(struct i2c_client *client)
{
        struct iio_dev *indio_dev = i2c_get_clientdata(client);
        // Unregister device from framework
        iio_device_unregister(indio_dev);
        return da311_enable(client, false);
}
```

From drivers/iio/accel/da311.c

Practical lab - Linux device model for an I2C driver



- Modify the Device Tree to instantiate an I2C device.
- Implement a driver that registers as an I2C driver.
- Make sure that the probe/remove functions are called when there is a device/driver match.
- Explore the *sysfs* entries related to your driver and device.

Communicating with the I2C device: raw API

The most **basic API** to communicate with the I2C device provides functions to either send or receive data:

- `int i2c_master_send(const struct i2c_client *client, const char *buf, int count);`
  Sends the contents of `buf` to the client.
- `int i2c_master_recv(const struct i2c_client *client, char *buf, int count);`
  Receives `count` bytes from the client, and store them into `buf`.

Both functions return a negative error number in case of failure, otherwise the number of transmitted bytes.

Communicating with the I2C device: message transfer

The message transfer API allows to describe **transfers** that consists of several **messages**, with each message being a transaction in one direction:

- `int i2c_transfer(struct i2c_adapter *adap, struct i2c_msg *msgs, int num);`
- The `struct i2c_adapter` pointer can be found by using `client->adapter`
- The `struct i2c_msg` structure defines the length, location, and direction of the message.

I2C: message transfer example

```
static int st1232_ts_read_data(struct st1232_ts_data *ts)
{
        ...
        struct i2c_client *client = ts->client;
        struct i2c_msg msg[2];
        int error;
        ...
        u8 start_reg = ts->chip_info->start_reg;
        u8 *buf = ts->read_buf;

        /* read touchscreen data */
        msg[0].addr = client->addr;
        msg[0].flags = 0;
        msg[0].len = 1;
        msg[0].buf = &start_reg;

        msg[1].addr = ts->client->addr;
        msg[1].flags = I2C_M_RD;
        msg[1].len = ts->read_buf_len;
        msg[1].buf = buf;

        error = i2c_transfer(client->adapter, msg, 2);
        ...
}
```

From `drivers/input/touchscreen/st1232.c`

SMBus calls

- SMBus is a subset of the I2C protocol.
- It defines a standard set of transactions, such as reading/writing from a register-like interface.
- Linux provides SMBus functions that should preferably be used instead of the raw API with devices supporting SMBus.
- Such a driver will be usable with both SMBus and I2C adapters
  - SMBus adapters cannot send raw I2C commands
  - I2C adapters will receive an SMBus-like command crafted by the core
- Example: the `i2c_smbus_read_byte_data()` function allows to read one byte of data from a device "register".
  - It does the following operations:
    `S Addr Wr [A] Comm [A] Sr Addr Rd [A] [Data] NA P`
  - Which means it first writes a one byte data command (*Comm*, which is the "register" address), and then reads back one byte of data (*[Data]*).
- See `i2c/smbus-protocol` for details.

List of SMBus functions

- Read/write one byte
  - `s32 i2c_smbus_read_byte(const struct i2c_client *client);`
  - `s32 i2c_smbus_write_byte(const struct i2c_client *client, u8 value);`
- Write a command byte, and read or write one byte
  - `s32 i2c_smbus_read_byte_data(const struct i2c_client *client, u8 command);`
  - `s32 i2c_smbus_write_byte_data(const struct i2c_client *client, u8 command, u8 value);`
- Write a command byte, and read or write one word
  - `s32 i2c_smbus_read_word_data(const struct i2c_client *client, u8 command);`
  - `s32 i2c_smbus_write_word_data(const struct i2c_client *client, u8 command, u16 value);`
- Write a command byte, and read or write a block of data (max 32 bytes)
  - `s32 i2c_smbus_read_block_data(const struct i2c_client *client, u8 command, u8 *values);`
  - `s32 i2c_smbus_write_block_data(const struct i2c_client *client, u8 command, u8 length, const u8 *values);`
- Write a command byte, and read or write a block of data (no limit)
  - `s32 i2c_smbus_read_i2c_block_data(const struct i2c_client *client, u8 command, u8 length, u8 *values);`
  - `s32 i2c_smbus_write_i2c_block_data(const struct i2c_client *client, u8 command, u8 length, const u8 *values);`

I2C functionality

- Not all I2C controllers support all functionalities.
- The I2C controller drivers therefore tell the I2C core which functionalities they support.
- An I2C device driver must check that the functionalities they need are provided by the I2C controller in use on the system.
- The `i2c_check_functionality()` function allows to make such a check.
- Examples of functionalities: `I2C_FUNC_I2C` to be able to use the raw I2C functions, `I2C_FUNC_SMBUS_BYTE_DATA` to be able to use SMBus commands to write a command and read/write one byte of data.
- See `include/uapi/linux/i2c.h` for the full list of existing functionalities.

References

- https://en.wikipedia.org/wiki/I2C, general presentation of the I2C protocol
- i2c/, details about Linux support for I2C
  - i2c/writing-clients
    How to write I2C kernel device drivers
  - i2c/dev-interface
    How to write I2C user-space device drivers
  - i2c/instantiating-devices
    How to instantiate devices
  - i2c/smbus-protocol
    Details on the SMBus functions
  - i2c/functionality
    How the functionality mechanism works
- See also Luca Ceresoli's introduction to I2C (slides, video).

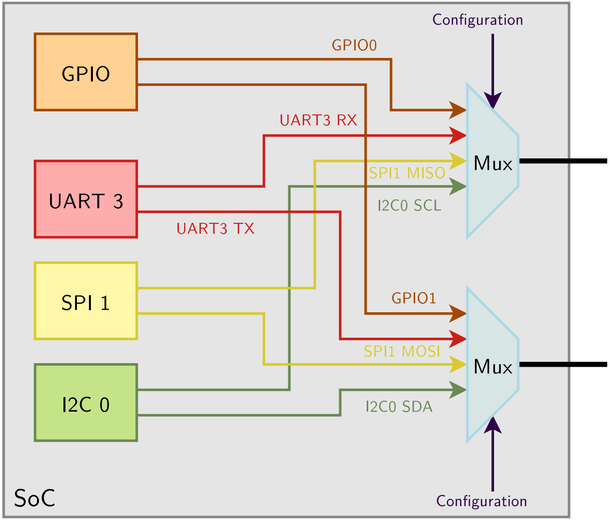
Introduction to pin muxing

embedded Linux and kernel engineering

What is pin muxing?

- Modern SoCs (System on Chip) include more and more hardware blocks, many of which need to interface with the outside world using *pins*.
- However, the physical size of the chips remains small, and therefore the number of available pins is limited.
- For this reason, not all of the internal hardware block features can be exposed on the pins simultaneously.
- The pins are **multiplexed**: they expose either the functionality of hardware block A **or** the functionality of hardware block B.
- This *multiplexing* is usually software configurable.

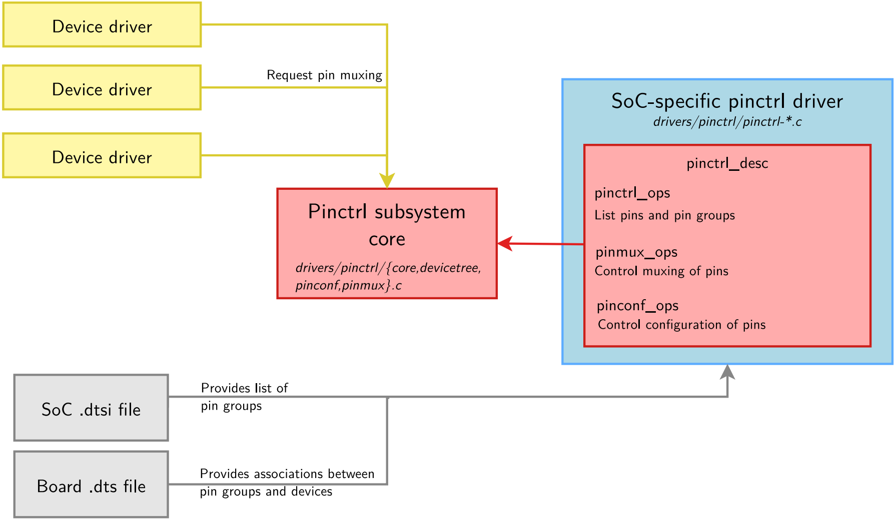
Pin muxing diagram



Pin muxing in the Linux kernel

- Since Linux 3.2, a `pinctrl` subsystem has been added.
- This subsystem, located in `drivers/pinctrl/` provides a generic subsystem to handle pin muxing. It offers:
  - A pin muxing driver interface, to implement the system-on-chip specific drivers that configure the muxing.
  - A pin muxing consumer interface, for device drivers.
- Most *pinctrl* drivers provide a Device Tree binding, and the pin muxing must be described in the Device Tree.
  - The exact Device Tree binding depends on each driver. Each binding is defined in `Documentation/devicetree/bindings/pinctrl`.

pinctrl subsystem diagram



Device Tree properties for consumer devices

The devices that require certains pins to be muxed will use the `pinctrl-<x>` and `pinctrl-names` Device Tree properties.

- The `pinctrl-0`, `pinctrl-1`, `pinctrl-<x>` properties link to a pin configuration for a given state of the device.
- The `pinctrl-names` property associates a name to each state. The name `default` is special, and is automatically selected by a device driver, without having to make an explicit *pinctrl* function call.
- See `Documentation/devicetree/bindings/pinctrl/pinctrl-bindings.txt` for details.

Device Tree properties for consumer devices - Examples

```
i2c0: i2c@11000 {
        ...
        pinctrl-0 = <&pmx_twsi0>;
        pinctrl-names = "default";
        ...
};
```

Most common case
(arch/arm/boot/dts/kirkwood.dtsi)

```
i2c0: i2c@f8014000 {
        ...
        pinctrl-names = "default", "gpio";
        pinctrl-0 = <&pinctrl_i2c0>;
        pinctrl-1 = <&pinctrl_i2c0_gpio>;
        ...
};
```

Case with multiple pin states
(arch/arm/boot/dts/sama5d4.dtsi)

Defining pinctrl configurations

- The different *pinctrl configurations* must be defined as child nodes of the main *pinctrl device* (which controls the muxing of pins).
- The configurations may be defined at:
  - the SoC level (`.dtsi` file), for pin configurations that are often shared between multiple boards
  - at the board level (`.dts` file) for configurations that are board specific.
- The `pinctrl-<x>` property of the consumer device points to the pin configuration it needs through a DT *phandle*.
- The description of the configurations is specific to each *pinctrl driver*. See `Documentation/devicetree/bindings/pinctrl` for the pinctrl bindings.

Example on OMAP/AM33xx

- On OMAP/AM33xx, the `pinctrl-single` driver is used. It is common between multiple SoCs and simply allows to configure pins by writing a value to a register.
  - In each pin configuration, a `pinctrl-single,pins` value gives a list of *(register, value)* pairs needed to configure the pins.
- To know the correct values, one must use the SoC and board datasheets.

```
/* Excerpt from am335x-boneblue.dts */

&am33xx_pinmux {
    ...
    i2c2_pins: pinmux_i2c2_pins {
        pinctrl-single,pins = <
            AM33XX_IOPAD(0x978, PIN_INPUT_PULLUP | MUX_MODE3)
            /* (D18) uart1_ctsn.I2C2_SDA */
            AM33XX_IOPAD(0x97c, PIN_INPUT_PULLUP | MUX_MODE3)
            /* (D17) uart1_rtsn.I2C2_SCL */
        >;
    };
};

&i2c2 {
    pinctrl-names = "default";
    pinctrl-0 = <&i2c2_pins>;

    status = "okay";
    clock-frequency = <400000>;
    ...

    pressure@76 {
        compatible = "bosch,bmp280";
        reg = <0x76>;
    };
};
```

Example on the Allwinner A20 SoC

SoC level

UART0 pin mux config

```
/ {
   ...
   soc {
       ...
       pio: pinctrl@01c20800 {
       compatible = "allwinner,sun7i-a20-pinctrl";
       reg = <0x01c20800 0x400>;
       ...

       uart0_pb_pins: uart0-pb-pins {
         pins = "PB22", "PB23";
         function = "uart0";
       };
       ...
     };
   };
};
```

arch/arm/boot/dts/sun7i-a20.dtsi

Board level

Declare LED device and associate pin mux config

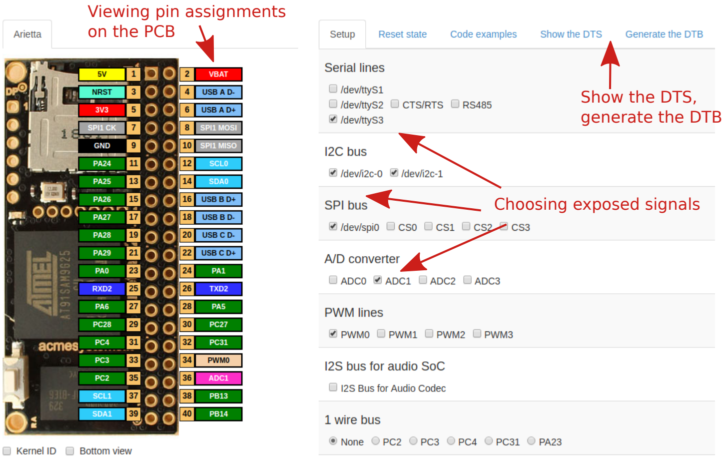
LED pin mux config

Enable UART0 and associate pin mux config

```
/ {
  ...
        leds {
                compatible = "gpio-leds";
                pinctrl-names = "default";
                pinctrl-0 = <&led_pins_olinuxino>;

                led {
                        label = "a20-olinuxino-micro:green:usr";
                        gpios = <&pio 7 2 GPIO_ACTIVE_HIGH>;
                        default-state = "on";
                };
        };
  ...
};


&pio {
        ....

        led_pins_olinuxino: led_pins@0 {
                pins = "PH2";
                function = "gpio_out";
                drive-strength = <20>;
        };

  ...
};

&uart0 {
        pinctrl-names = "default";
        pinctrl-0 = <&uart0_pb_pins>;
        status = "okay";
};
```

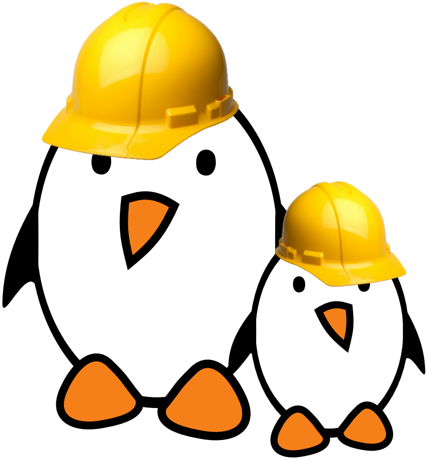
arch/arm/boot/dts/sun7i-a20-olinuxino-micro.dts

Illustration: live pin muxing configuration



Try ACME Systems' on-line pin-out generator: http://linux.tanzilli.com/

Practical lab - Communicate with the Nunchuk



- Configure the pinmuxing for the I2C bus used to communicate with the Nunchuk
- Validate that the I2C communication works with user space tools.
- Extend the I2C driver started in the previous lab to communicate with the Nunchuk.

Kernel frameworks for device drivers

Corrections, suggestions, contributions and translations are welcome!

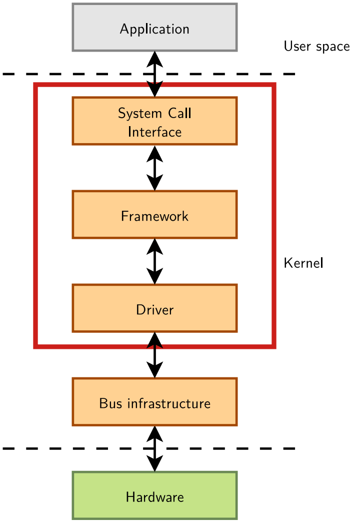
embedded Linux and kernel engineering

Kernel and Device Drivers

In Linux, a driver is always interfacing with:

- a **framework** that allows the driver to expose the hardware features to user space applications.
- a **bus infrastructure**, part of the device model, to detect/communicate with the hardware.

This section focuses on the *kernel frameworks*, while the *bus infrastructure* was covered earlier in this training.



User space vision of devices

Types of devices

Under Linux, there are essentially three types of devices:

- **Network devices**. They are represented as network interfaces, visible in user space using `ip a`
- **Block devices**. They are used to provide user space applications access to raw storage devices (hard disks, USB keys). They are visible to the applications as *device files* in `/dev`.
- **Character devices**. They are used to provide user space applications access to all other types of devices (input, sound, graphics, serial, etc.). They are also visible to the applications as *device files* in `/dev`.

$\rightarrow$ Most devices are *character devices*, so we will study these in more details.

Major and minor numbers

- Within the kernel, all block and character devices are identified using a *major* and a *minor* number.
- The *major number* typically indicates the family of the device.
- The *minor number* allows drivers to distinguish the various devices they manage.
- Most major and minor numbers are statically allocated, and identical across all Linux systems.
- They are defined in `admin-guide/devices`.

Devices: everything is a file

- A very important UNIX design decision was to represent most *system objects* as files
- It allows applications to manipulate all *system objects* with the normal file API (`open`, `read`, `write`, `close`, etc.)
- So, devices had to be represented as files to the applications
- This is done through a special artifact called a **device file**
- It is a special type of file, that associates a file name visible to user space applications to the triplet *(type, major, minor)* that the kernel understands
- All *device files* are by convention stored in the `/dev` directory

Device files examples

Example of device files in a Linux system

```
$ ls -l /dev/ttyS0 /dev/tty1 /dev/sda /dev/sda1 /dev/sda2 /dev/sdc1 /dev/zero
brw-rw---- 1 root disk    8,  0 2011-05-27 08:56 /dev/sda
brw-rw---- 1 root disk    8,  1 2011-05-27 08:56 /dev/sda1
brw-rw---- 1 root disk    8,  2 2011-05-27 08:56 /dev/sda2
brw-rw---- 1 root disk    8, 32 2011-05-27 08:56 /dev/sdc
crw------- 1 root root    4,  1 2011-05-27 08:57 /dev/tty1
crw-rw---- 1 root dialout 4, 64 2011-05-27 08:56 /dev/ttyS0
crw-rw-rw- 1 root root    1,  5 2011-05-27 08:56 /dev/zero
```

Example C code that uses the usual file API to write data to a serial port

```c
int fd;
fd = open("/dev/ttyS0", O_RDWR);
write(fd, "Hello", 5);
close(fd);
```

Creating device files

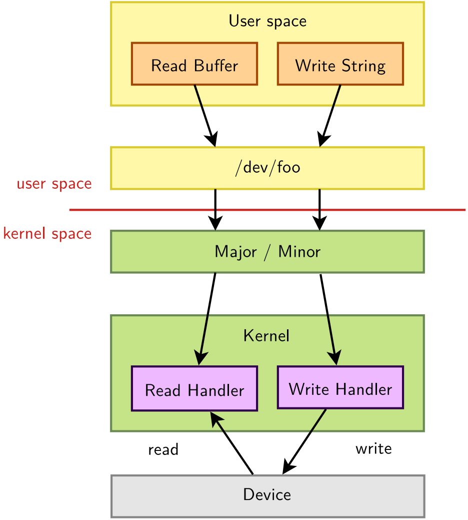
- Before Linux 2.6.32, on basic Linux systems, the device files had to be created manually using the `mknod` command
  - `mknod /dev/<device> [c|b] major minor`
  - Needed root privileges
  - Coherency between device files and devices handled by the kernel was left to the system developer
- The `devtmpfs` virtual filesystem can be mounted on `/dev` and contains all the devices registered to kernel frameworks. The `CONFIG_DEVTMPFS_MOUNT` kernel configuration option makes the kernel mount it automatically at boot time, except when booting on an initramfs.

Character drivers

A character driver in the kernel

- From the point of view of an application, a *character device* is essentially a **file**.
- The driver of a character device must therefore implement **operations** that let applications think the device is a file: `open`, `close`, `read`, `write`, etc.
- In order to achieve this, a character driver must implement the operations described in the `struct file_operations` structure and register them.
- The Linux filesystem layer will ensure that the driver's operations are called when a user space application makes the corresponding system call.

From user space to the kernel: character devices



File operations

Here are the most important operations for a character driver, from the definition of `struct file_operations`:

```
struct file_operations {
    struct module *owner;
    ssize_t (*read) (struct file *, char __user *,
        size_t, loff_t *);
    ssize_t (*write) (struct file *, const char __user *,
        size_t, loff_t *);
    long (*unlocked_ioctl) (struct file *, unsigned int,
        unsigned long);
    int (*mmap) (struct file *, struct vm_area_struct *);
    int (*open) (struct inode *, struct file *);
    int (*release) (struct inode *, struct file *);
    ...
};
```

Many more operations exist. All of them are optional.

open() and release()

- `int foo_open(struct inode *i, struct file *f)`
  - Called when user space opens the device file.
  - **Only implement this function when you do something special with the device at `open()` time.**
  - `struct inode` is a structure that uniquely represents a file in the filesystem (be it a regular file, a directory, a symbolic link, a character or block device)
  - `struct file` is a structure created every time a file is opened. Several file structures can point to the same `inode` structure.
    - Contains information like the current position, the opening mode, etc.
    - Has a `void *private_data` pointer that one can freely use.
    - A pointer to the `file` structure is passed to all other operations
- `int foo_release(struct inode *i, struct file *f)`
  - Called when user space closes the file.
  - **Only implement this function when you do something special with the device at `close()` time.**

read() and write()

- `ssize_t foo_read(struct file *f, char __user *buf, size_t sz, loff_t *off)`
  - Called when user space uses the `read()` system call on the device.
  - Must read data from the device, write at most `sz` bytes to the user space buffer `buf`, and update the current position in the file `off`. `f` is a pointer to the same file structure that was passed in the `open()` operation
  - Must return the number of bytes read.
    `0` is usually interpreted by userspace as the end of the file.
  - On UNIX, `read()` operations typically block when there isn't enough data to read from the device
- `ssize_t foo_write(struct file *f, const char __user *buf, size_t sz, loff_t *off)`
  - Called when user space uses the `write()` system call on the device
  - The opposite of `read`, must read at most `sz` bytes from `buf`, write it to the device, update `off` and return the number of bytes written.

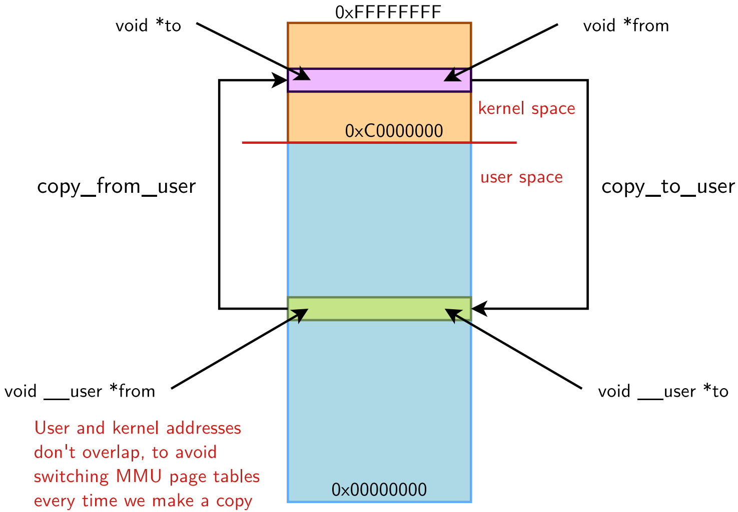
Exchanging data with user space 1/3

- Kernel code isn't allowed to directly access user space memory, using `memcpy()` or direct pointer dereferencing
  - Doing so does not work on some architectures
  - If the address passed by the application was invalid, the application would segfault.
  - **Never** trust user space. A malicious application could pass a kernel address which you could overwrite with device data (`read` case), or which you could dump to the device (`write` case).
- To keep the kernel code portable, secure, and have proper error handling, your driver must use special kernel functions to exchange data with user space.

Exchanging data with user space 2/3

- A single value
  - `get_user(v, p);`
    - The kernel variable `v` gets the value pointed by the user space pointer `p`
  - `put_user(v, p);`
    - The value pointed by the user space pointer `p` is set to the contents of the kernel variable `v`.
- A buffer
  - `unsigned long copy_to_user(void __user *to, const void *from, unsigned long n);`
  - `unsigned long copy_from_user(void *to, const void __user *from, unsigned long n);`
- The return value must be checked. Zero on success, non-zero on failure. If non-zero, the convention is to return `-EFAULT`.

Exchanging data with user space 3/3



User and kernel addresses don't overlap, to avoid switching MMU page tables every time we make a copy

Zero copy access to user memory

- Having to copy data to or from an intermediate kernel buffer can become expensive when the amount of data to transfer is large (video).
- *Zero copy* options are possible:
  - `mmap()` system call to allow user space to directly access memory mapped I/O space. See our `mmap()` chapter.
  - `get_user_pages()` and related functions to get a mapping to user pages without having to copy them.

unlocked_ioctl()

- `long unlocked_ioctl(struct file *f, unsigned int cmd, unsigned long arg)`
  - Associated to the `ioctl()` system call.
  - Called unlocked because it didn't hold the Big Kernel Lock (gone now).
  - Allows to extend the driver capabilities beyond the limited read/write API.
  - For example: changing the speed of a serial port, setting video output format, querying a device serial number... Used extensively in the V4L2 (video) and ALSA (sound) driver frameworks.
  - `cmd` is a number identifying the operation to perform.
    See `driver-api/ioctl` for the recommended way of choosing `cmd` numbers.
  - `arg` is the optional argument passed as third argument of the `ioctl()` system call. Can be an integer, an address, etc.
  - The semantic of `cmd` and `arg` is driver-specific.

ioctl() example: kernel side

```
#include <linux/phantom.h>

static long phantom_ioctl(struct file *file, unsigned int cmd,
    unsigned long arg)
{
    struct phm_reg r;
    void __user *argp = (void __user *)arg;

    switch (cmd) {
    case PHN_SET_REG:
        if (copy_from_user(&r, argp, sizeof(r)))
            return -EFAULT;
        /* Do something */
        break;
    ...
    case PHN_GET_REG:
        if (copy_to_user(argp, &r, sizeof(r)))
            return -EFAULT;
        /* Do something */
        break;
    ...
    default:
        return -ENOTTY;
    }

    return 0;
}
```

Selected excerpt from `drivers/misc/phantom.c`

Ioctl() Example: Application Side

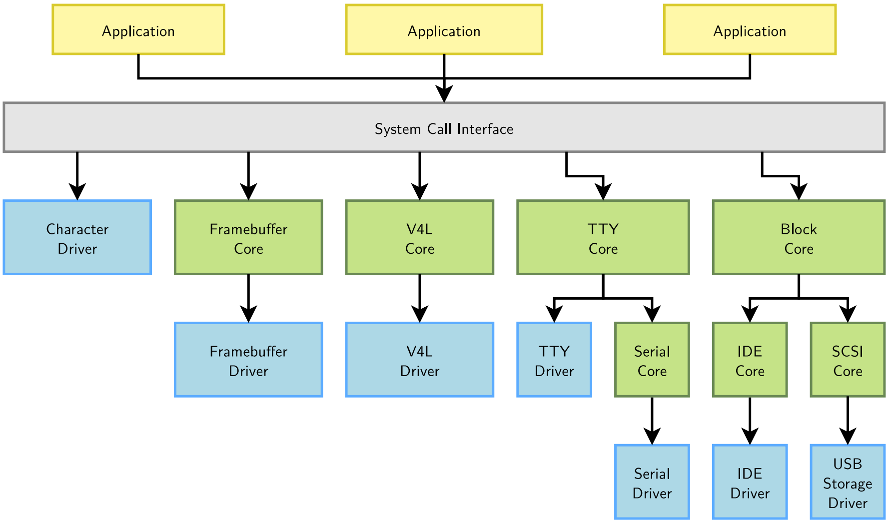
```c
#include <linux/phantom.h>

int main(void)
{
    int fd, ret;
    struct phm_reg reg;

    fd = open("/dev/phantom");
    assert(fd > 0);

    reg.field1 = 42;
    reg.field2 = 67;

    ret = ioctl(fd, PHN_SET_REG, &reg);
    assert(ret == 0);

    return 0;
}
```

The concept of kernel frameworks

Beyond character drivers: kernel frameworks

- Many device drivers are not implemented directly as character drivers
- They are implemented under a *framework*, specific to a given device type (framebuffer, V4L, serial, etc.)
  - The framework allows to factorize the common parts of drivers for the same type of devices
  - From user space, they are still seen as character devices by the applications
  - The framework allows to provide a coherent user space interface (`ioctl`, etc.) for every type of device, regardless of the driver

Example: Some Kernel Frameworks



Example: Framebuffer Framework

- Kernel option `CONFIG_FB`
  - `menuconfig FB`
    - `tristate "Support for frame buffer devices"`
- Implemented in C files in `drivers/video/fbdev/core/`
- Defines the user/kernel API
  - `include/uapi/linux/fb.h` (constants and structures)
- Defines the set of operations a framebuffer driver must implement and helper functions for the drivers
  - `struct fb_ops`
  - `include/linux/fb.h`

Framebuffer driver operations

Here are the operations a framebuffer driver can or must implement, and define them in a `struct fb_ops` structure (excerpt from `drivers/video/fbdev/skeletonfb.c`)

```
static struct fb_ops xxxfb_ops = {
    .owner = THIS_MODULE,
    .fb_open = xxxfb_open,
    .fb_read = xxxfb_read,
    .fb_write = xxxfb_write,
    .fb_release = xxxfb_release,
    .fb_check_var = xxxfb_check_var,
    .fb_set_par = xxxfb_set_par,
    .fb_setcolreg = xxxfb_setcolreg,
    .fb_blank = xxxfb_blank,
    .fb_pan_display = xxxfb_pan_display,
    .fb_fillrect = xxxfb_fillrect,              /* Needed !!! */
    .fb_copyarea = xxxfb_copyarea,              /* Needed !!! */
    .fb_imageblit = xxxfb_imageblit,            /* Needed !!! */
    .fb_cursor = xxxfb_cursor,                  /* Optional !!! */
    .fb_rotate = xxxfb_rotate,
    .fb_sync = xxxfb_sync,
    .fb_ioctl = xxxfb_ioctl,
    .fb_mmap = xxxfb_mmap,
};
```

Framebuffer driver code

- In the probe() function, registration of the framebuffer device and operations

```
static int xxxfb_probe (struct pci_dev *dev, const struct pci_device_id *ent)
{
    struct fb_info *info;
    [...]
    info = framebuffer_alloc(sizeof(struct xxx_par), device);
    [...]
    info->fbops = &xxxfb_ops;
    [...]
    if (register_framebuffer(info) < 0)
        return -EINVAL;
    [...]
}
```

- register_framebuffer() will create a new character device in *devtmpfs* that can be used by user space applications with the generic framebuffer API.

Device-managed allocations

Device managed allocations

- The probe() function is typically responsible for allocating a significant number of resources: memory, mapping I/O registers, registering interrupt handlers, etc.
- These resource allocations have to be properly freed:
  - In the probe() function, in case of failure
  - In the remove() function
- This required a lot of failure handling code that was rarely tested
- To solve this problem, *device managed* allocations have been introduced.
- The idea is to associate resource allocation with the struct device, and automatically release those resources
  - When the device disappears
  - When the device is unbound from the driver
- Functions prefixed by devm_
- See driver-api/driver-model/devres for details

Device managed allocations: memory allocation example

- Normally done with `kmalloc(size_t, gfp_t)`, released with `kfree(void *)`
- Device managed with `devm_kmalloc(struct device *, size_t, gfp_t)`

Without devm functions

```
int foo_probe(struct platform_device *pdev)
{
        struct foo_t *foo = kmalloc(sizeof(struct foo_t),
                                    GFP_KERNEL);
        /* Register to framework, store
         * reference to framework structure in foo */
        ...
        if (failure) {
                kfree(foo);
                return -EBUSY;
        }
        platform_set_drvdata(pdev, foo);
        return 0;
}

void foo_remove(struct platform_device *pdev)
{
        struct foo_t *foo = platform_get_drvdata(pdev);
        /* Retrieve framework structure from foo
           and unregister it */
        ...
        kfree(foo);
}
```

With devm functions

```
int foo_probe(struct platform_device *pdev)
{
        struct foo_t *foo = devm_kmalloc(&pdev->dev,
                                   sizeof(struct foo_t),
                                   GFP_KERNEL);
        /* Register to framework, store
         * reference to framework structure in foo */
        ...
        if (failure)
                return -EBUSY;
        platform_set_drvdata(pdev, foo);
        return 0;
}

void foo_remove(struct platform_device *pdev)
{
        struct foo_t *foo = platform_get_drvdata(pdev);
        /* Retrieve framework structure from foo
           and unregister it */
        ...
        /* foo automatically freed */
}
```

Driver data structures and links

Driver-specific Data Structure

- Each *framework* defines a structure that a device driver must register to be recognized as a device in this framework
  - `struct uart_port` for serial ports, `struct net_device` for network devices, `struct fb_info` for framebuffers, etc.
- In addition to this structure, the driver usually needs to store additional information about each device
- This is typically done
  - By subclassing the appropriate framework structure
  - By storing a reference to the appropriate framework structure
  - Or by including your information in the framework structure

Driver-specific Data Structure Examples 1/2

- i.MX serial driver: `struct imx_port` is a subclass of `struct uart_port`

```
struct imx_port {
    struct uart_port port;
    struct timer_list timer;
    unsigned int old_status;
    int txirq, rxirq, rtsirq;
    unsigned int have_rtscts:1;
    [...]
};
```

- ds1305 RTC driver: `struct ds1305` has a reference to `struct rtc_device`

```
struct ds1305 {
    struct spi_device       *spi;
    struct rtc_device       *rtc;
    [...]
};
```

Driver-specific Data Structure Examples 2/2

- rtl8150 network driver: `struct rtl8150` has a reference to `struct net_device` and is allocated within that framework structure.

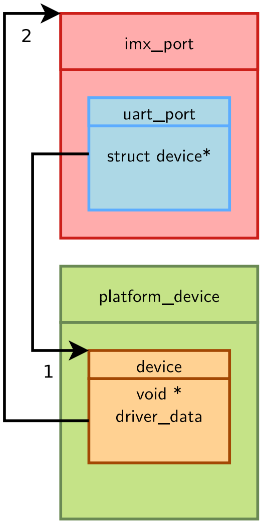
```
struct rtl8150 {
    unsigned long flags;
    struct usb_device *udev;
    struct tasklet_struct tl;
    struct net_device *netdev;
    [...]
};
```

Links between structures 1/4

- The framework structure typically contains a `struct device *` pointer that the driver must point to the corresponding `struct device`
  - It's the relationship between the logical device (for example a network interface) and the physical device (for example the USB network adapter)
- The device structure also contains a `void *` pointer that the driver can freely use.
  - It's often used to link back the device to the higher-level structure from the framework.
  - It allows, for example, from the `struct platform_device` structure, to find the structure describing the logical device

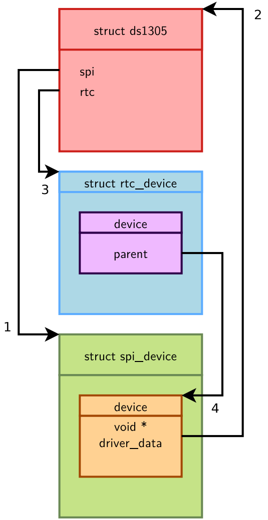
Links between structures 2/4

```
static int serial_imx_probe(struct platform_device *pdev)
{
    struct imx_port *sport; /* per device structure */
    [...]
    sport = devm_kzalloc(&pdev->dev, sizeof(*sport), GFP_KERNEL);
    [...]
    /* setup the link between uart_port and the struct
     * device inside the platform_device */
    sport->port.dev = &pdev->dev;                          // Arrow 1
    [...]
    /* setup the link between the struct device inside
     * the platform device to the imx_port structure */
    platform_set_drvdata(pdev, sport);                     // Arrow 2
    [...]
    uart_add_one_port(&imx_reg, &sport->port);
}

static int serial_imx_remove(struct platform_device *pdev)
{
    /* retrieve the imx_port from the platform_device */
    struct imx_port *sport = platform_get_drvdata(pdev);
    [...]
    uart_remove_one_port(&imx_reg, &sport->port);
    [...]
}
```



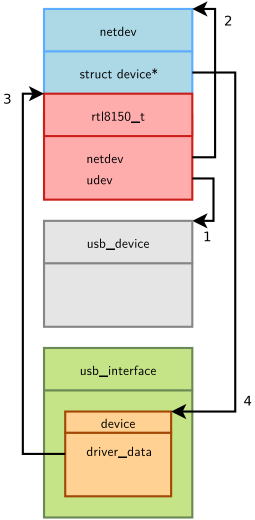
Links between structures 3/4

```
static int ds1305_probe(struct spi_device *spi)
{
    struct ds1305                   *ds1305;

    [...]

    /* set up driver data */
    ds1305 = devm_kzalloc(&spi->dev, sizeof(*ds1305), GFP_KERNEL);
    if (!ds1305)
            return -ENOMEM;
    ds1305->spi = spi;                          // Arrow 1
    spi_set_drvdata(spi, ds1305);               // Arrow 2

    [...]

    ds1305->rtc = devm_rtc_allocate_device(&spi->dev);
                                                // Arrows 3 and 4

    [...]
}

static int ds1305_remove(struct spi_device *spi)
{
    struct ds1305 *ds1305 = spi_get_drvdata(spi);

    [...]
}
```



Links between structures 4/4

```
static int rtl8150_probe(struct usb_interface *intf,
    const struct usb_device_id *id)
{
    struct usb_device *udev = interface_to_usbdev(intf);
    rtl8150_t *dev;
    struct net_device *netdev;

    netdev = alloc_etherdev(sizeof(rtl8150_t));
    dev = netdev_priv(netdev);

    [...]

    dev->udev = udev;       // Arrow 1
    dev->netdev = netdev;   // Arrow 2

    [...]

    usb_set_intfdata(intf, dev);        // Arrow 3
    SET_NETDEV_DEV(netdev, &intf->dev); // Arrow 4

    [...]
}

static void rtl8150_disconnect(struct usb_interface *intf)
{
    rtl8150_t *dev = usb_get_intfdata(intf);

    [...]
}
```

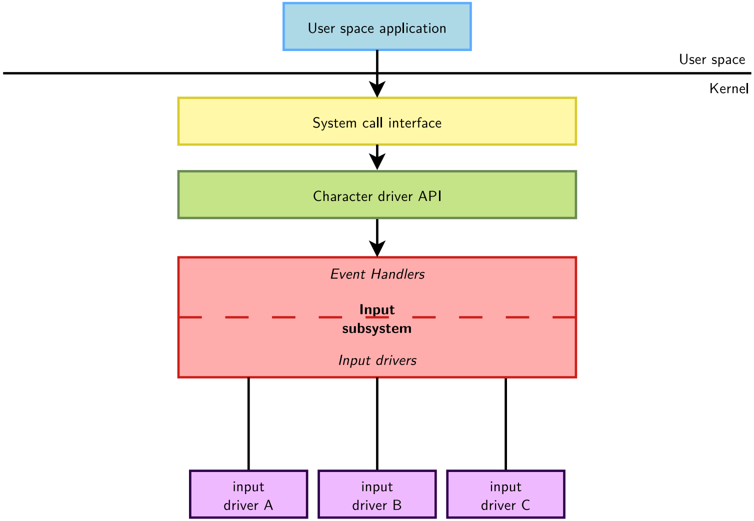


The input subsystem

What is the input subsystem?

- The input subsystem takes care of all the input events coming from the human user.
- Initially written to support the USB *HID* (Human Interface Device) devices, it quickly grew up to handle all kinds of inputs (using USB or not): keyboards, mice, joysticks, touchscreens, etc.
- The input subsystem is split in two parts:
  - **Device drivers**: they talk to the hardware (for example via USB), and provide events (keystrokes, mouse movements, touchscreen coordinates) to the input core
  - **Event handlers**: they get events from drivers and pass them where needed via various interfaces (most of the time through evdev)
- In user space it is usually used by the graphic stack such as *X.Org*, *Wayland* or *Android's InputManager*.

Input subsystem diagram



Input subsystem overview

- Kernel option `CONFIG_INPUT`
  - `menuconfig INPUT`
    - `tristate "Generic input layer (needed for keyboard, mouse, ...)"`
- Implemented in `drivers/input/`
  - `input.c`, `input-polldev.c`, `evdev.c`...
- Defines the user/kernel API
  - `include/uapi/linux/input.h`
- Defines the set of operations an input driver must implement and helper functions for the drivers
  - `struct input_dev` for the device driver part
  - `struct input_handler` for the event handler part
  - `include/linux/input.h`

Input subsystem API 1/3

An *input device* is described by a very long `struct input_dev` structure, an excerpt is:

```
struct input_dev {
    const char *name;
    [...]
    struct input_id id;
    [...]
    unsigned long evbit[BITS_TO_LONGS(EV_CNT)];
    unsigned long keybit[BITS_TO_LONGS(KEY_CNT)];
    [...]
    int (*getkeycode)(struct input_dev *dev,
                      struct input_keymap_entry *ke);
    [...]
    int (*open)(struct input_dev *dev);
    [...]
    int (*event)(struct input_dev *dev, unsigned int type,
                 unsigned int code, int value);
    [...]
};
```

Before being used, this structure must be allocated and initialized, typically with:

`struct input_dev *devm_input_allocate_device(struct device *dev);`

Input subsystem API 2/3

- Depending on the type of events that will be generated, the input bit fields `evbit` and `keybit` must be configured: For example, for a button we only generate `EV_KEY` type events, and from these only `BTN_0` events code:

```
set_bit(EV_KEY, myinput_dev.evbit);
set_bit(BTN_0, myinput_dev.keybit);
```

- `set_bit()` is an atomic operation allowing to set a particular bit to `1` (explained later).
- Once the *input device* is allocated and filled, the function to register it is:
`int input_register_device(struct input_dev *);`

Input subsystem API 3/3

The events are sent by the driver to the event handler using `input_event(struct input_dev *dev, unsigned int type, unsigned int code, int value);`

- The event types are documented in `input/event-codes`
- An event is composed by one or several input data changes (packet of input data changes) such as the button state, the relative or absolute position along an axis, etc..
- After submitting potentially multiple events, the *input* core must be notified by calling: `void input_sync(struct input_dev *dev)`:
- The input subsystem provides other wrappers such as `input_report_key()`, `input_report_abs()`, ...

Example from drivers/hid/usbhid/usbmouse.c

```
static void usb_mouse_irq(struct urb *urb)
{
        struct usb_mouse *mouse = urb->context;
        signed char *data = mouse->data;
        struct input_dev *dev = mouse->dev;
        ...

        input_report_key(dev, BTN_LEFT,   data[0] & 0x01);
        input_report_key(dev, BTN_RIGHT,  data[0] & 0x02);
        input_report_key(dev, BTN_MIDDLE, data[0] & 0x04);
        input_report_key(dev, BTN_SIDE,   data[0] & 0x08);
        input_report_key(dev, BTN_EXTRA,  data[0] & 0x10);

        input_report_rel(dev, REL_X,     data[1]);
        input_report_rel(dev, REL_Y,     data[2]);
        input_report_rel(dev, REL_WHEEL, data[3]);

        input_sync(dev);
        ...
}
```

Polling input devices

- The input subsystem provides an API to support simple input devices that *do not raise interrupts* but have to be *periodically scanned or polled* to detect changes in their state.
- Setting up polling is done using `input_setup_polling()`:
  `int input_setup_polling(struct input_dev *dev, void (*poll_fn)(struct input_dev *dev));`
- `poll_fn` is the function that will be called periodically.
- The polling interval can be set using `input_set_poll_interval()` or `input_set_min_poll_interval()` and `input_set_max_poll_interval()`

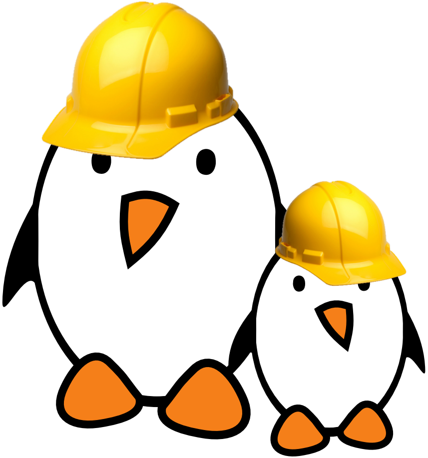
evdev user space interface

- The main user space interface to *input devices* is the **event interface**
- Each *input device* is represented as a `/dev/input/event<X>` character device
- A user space application can use blocking and non-blocking reads, but also `select()` (to get notified of events) after opening this device.
- Each read will return `struct input_event` structures of the following format:

```
struct input_event {
        struct timeval time;
        unsigned short type;
        unsigned short code;
        unsigned int value;
};
```

- A very useful application for *input device* testing is `evtest`, from https://cgit.freedesktop.org/evtest/

Practical lab - Expose the Nunchuk to user space

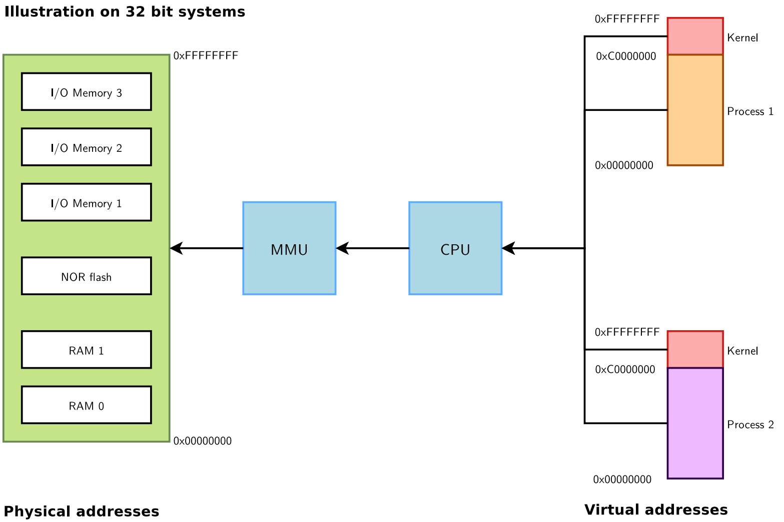


- Extend the Nunchuk driver to expose the Nunchuk features to user space applications, as an *input* device.
- Test the operation of the Nunchuk using `evtest`

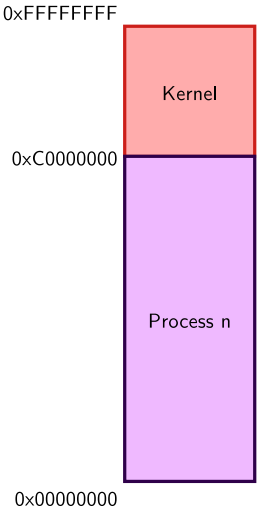
Memory Management

embedded Linux and kernel engineering

Physical and virtual memory

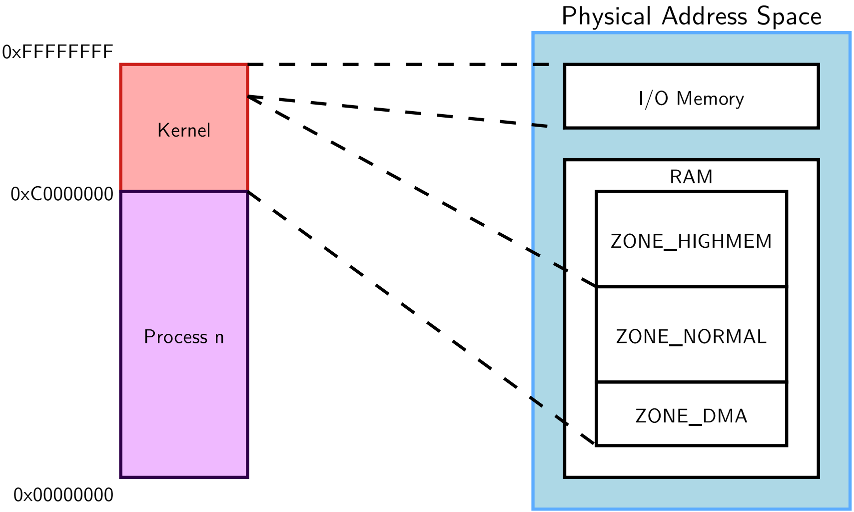


Virtual memory organization (on 32 bit)



- 1GB reserved for kernel-space
  - Contains kernel code and core data structures, identical in all address spaces
  - Most memory can be a direct mapping of physical memory at a fixed offset
- Complete 3GB exclusive mapping available for each user space process
  - Process code and data (program, stack, ...)
  - Memory-mapped files
  - Not necessarily mapped to physical memory (demand fault paging used for dynamic mapping to physical memory pages)
  - Differs from one address space to another

Physical / virtual memory mapping (on 32 bit)



Accessing more physical memory on 32 bit

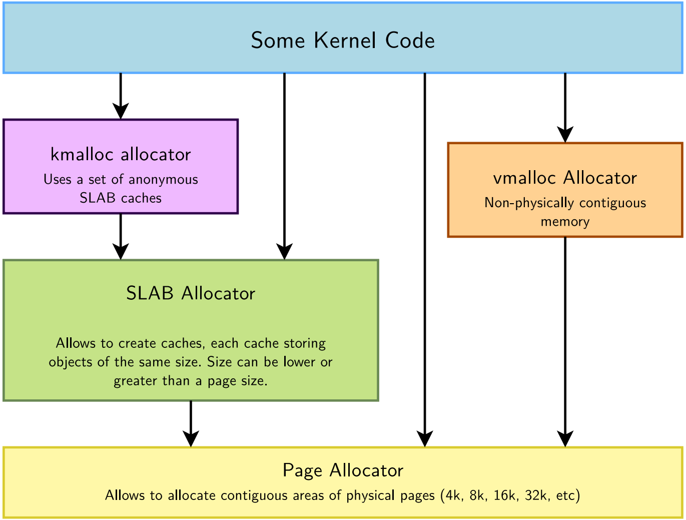
If you cannot use a 64 bit system (see `x86/x86_64/mm` for example)

- Only less than 1GB memory addressable directly through kernel virtual addresses
- If more physical memory is present on the platform, part of the memory will not be accessible by kernel space, but can be used by user space
- To allow the kernel to access more physical memory:
  - Change the 3GB/1GB memory split to 2GB/2GB or 1GB/3GB (`CONFIG_VMSPLIT_2G` or `CONFIG_VMSPLIT_1G`) ⇒ reduce total user memory available for each process
  - Activate *highmem* support if available for your architecture:
    - Allows kernel to map parts of its non-directly accessible memory
    - Mapping must be requested explicitly
    - Limited addresses ranges reserved for this usage
- See Arnd Bergmann's *4GB by 4GB split* presentation (video and slides) at Linaro Connect virtual 2020: https://frama.link/fD1HvuVP

Notes on user space memory

- New user space memory is allocated either from the already allocated process memory, or using the `mmap` system call
- Note that memory allocated may not be physically allocated:
  - Kernel uses demand fault paging to allocate the physical page (the physical page is allocated when access to the virtual address generates a page fault)
  - ... or may have been swapped out, which also induces a page fault
- User space memory allocation is allowed to over-commit memory (more than available physical memory) $\Rightarrow$ can lead to out of memory
- OOM killer kicks in and selects a process to kill to retrieve some memory. That's better than letting the system freeze.

Allocators in the kernel



Page allocator

- Appropriate for medium-size allocations
- A page is usually 4K, but can be made greater in some architectures (sh, mips: 4, 8, 16 or 64 KB, but not configurable in x86 or arm).
- Buddy allocator strategy, so only allocations of power of two number of pages are possible: 1 page, 2 pages, 4 pages, 8 pages, 16 pages, etc.
- Typical maximum size is 8192 KB, but it might depend on the kernel configuration.
- The allocated area is contiguous in the kernel virtual address space, but also maps to physically contiguous pages. It is allocated in the identity-mapped part of the kernel memory space.
  - This means that large areas may not be available or hard to retrieve due to physical memory fragmentation.
  - The *Contiguous Memory Allocator* is a solution to satisfy requests for large contiguous areas (see `https://lwn.net/Articles/486301/`).

Page allocator API: get free pages

- `unsigned long get_zeroed_page(int flags)`
  - Returns the virtual address of a free page, initialized to zero
  - `flags`: see the next pages for details.
- `unsigned long __get_free_page(int flags)`
  - Same, but doesn't initialize the contents
- `unsigned long __get_free_pages(int flags, unsigned int order)`
  - Returns the starting virtual address of an area of several contiguous pages in physical RAM, with order being `log2(number_of_pages)`.Can be computed from the size with the `get_order()` function.

Page allocator API: free pages

- `void free_page(unsigned long addr)`
  - Frees one page.
- `void free_pages(unsigned long addr, unsigned int order)`
  - Frees multiple pages. Need to use the same order as in allocation.

Page allocator flags

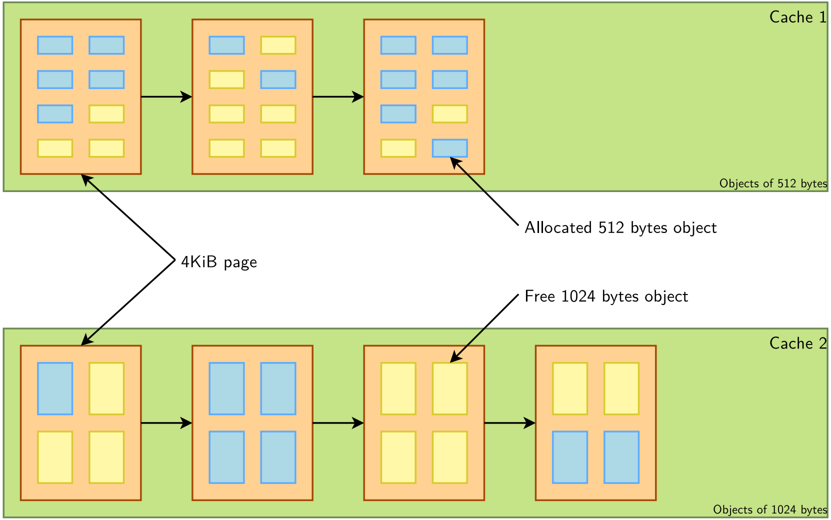
The most common ones are:

- GFP_KERNEL
  - Standard kernel memory allocation. The allocation may block in order to find enough available memory. Fine for most needs, except in interrupt handler context.
- GFP_ATOMIC
  - RAM allocated from code which is not allowed to block (interrupt handlers or critical sections). Never blocks, allows to access emergency pools, but can fail if no free memory is readily available.
- GFP_DMA
  - Allocates memory in an area of the physical memory usable for DMA transfers. See our DMA chapter.
- Others are defined in include/linux/gfp.h.
  See also the documentation in core-api/memory-allocation

SLAB allocator 1/2

- The SLAB allocator allows to create *caches*, which contain a set of objects of the same size. In English, *slab* means *tile*.
- The object size can be smaller or greater than the page size
- The SLAB allocator takes care of growing or reducing the size of the cache as needed, depending on the number of allocated objects. It uses the page allocator to allocate and free pages.
- SLAB caches are used for data structures that are present in many instances in the kernel: directory entries, file objects, network packet descriptors, process descriptors, etc.
  - See `/proc/slabinfo`
- They are rarely used for individual drivers.
- See `include/linux/slab.h` for the API

SLAB allocator 2/2



Different SLAB allocators

There are three different, but API compatible, implementations of a SLAB allocator in the Linux kernel. A particular implementation is chosen at configuration time.

- SLAB: legacy, well proven allocator.
  Linux 5.10 on arm (32 bit): used in 39 `defconfig` files
- SLOB: much simpler. More space efficient but doesn't scale well.
  Can save space in small systems (depends on `CONFIG_EXPERT`).
  Linux 5.10 on arm (32 bit): used in 7 `defconfig` files
  Results on BeagleBone Black: -5 KB compressed kernel size, +1.43 s boot time!
- SLUB: more recent and simpler than SLAB, scaling much better (in particular for huge systems) and creating less fragmentation. Now the default allocator.
  Linux 5.10 on arm (32 bit): used in 9 `defconfig` files
  Results on BeagleBone Black: +4 KB compressed kernel, + 2ms total boot time.

```
Choose SLAB allocator

    SLAB
<X> SLUB (Unqueued Allocator)
    SLOB (Simple Allocator)
```

kmalloc allocator

- The kmalloc allocator is the general purpose memory allocator in the Linux kernel
- For small sizes, it relies on generic SLAB caches, named `kmalloc-XXX` in `/proc/slabinfo`
- For larger sizes, it relies on the page allocator
- The allocated area is guaranteed to be physically contiguous
- The allocated area size is rounded up to the size of the smallest SLAB cache in which it can fit (while using the SLAB allocator directly allows to have more flexibility)
- It uses the same flags as the page allocator (`GFP_KERNEL`, `GFP_ATOMIC`, `GFP_DMA`, etc.) with the same semantics.
- Maximum sizes, on `x86` and `arm` (see `https://j.mp/YIGq6W`):
  - Per allocation: 4 MB
  - Total allocations: 128 MB
- Should be used as the primary allocator unless there is a strong reason to use another one.

kmalloc API 1/2

- `#include <linux/slab.h>`
- `void *kmalloc(size_t size, int flags);`
  - Allocate `size` bytes, and return a pointer to the area (virtual address)
  - `size`: number of bytes to allocate
  - `flags`: same flags as the page allocator
- `void kfree(const void *objp);`
  - Free an allocated area
- Example: (`drivers/infiniband/core/cache.c`)

```
struct ib_port_attr *tprops;
tprops = kmalloc(sizeof *tprops, GFP_KERNEL);
...
kfree(tprops);
```

kmalloc API 2/2

- `void *kzalloc(size_t size, gfp_t flags);`
  - Allocates a zero-initialized buffer
- `void *kcalloc(size_t n, size_t size, gfp_t flags);`
  - Allocates memory for an array of `n` elements of `size` size, and zeroes its contents.
- `void *krealloc(const void *p, size_t new_size, gfp_t flags);`
  - Changes the size of the buffer pointed by `p` to `new_size`, by reallocating a new buffer and copying the data, unless `new_size` fits within the alignment of the existing buffer.

devm_ kmalloc functions

Allocations with automatic freeing when the corresponding device or module is unprobed.

- `void *devm_kmalloc(struct device *dev, size_t size, int flags);`
- `void *devm_kzalloc(struct device *dev, size_t size, int flags);`
- `void *devm_kcalloc(struct device *dev, size_t n, size_t size, gfp_t flags);`
- `void *devm_kfree(struct device *dev, void *p);`

  Useful to immediately free an allocated buffer

For use in `probe()` functions, in which you have access to a `struct device` structure.

vmalloc allocator

- The `vmalloc()` allocator can be used to obtain memory zones that are contiguous in the virtual addressing space, but not made out of physically contiguous pages. The requested memory size is rounded up to the next page.
- The allocated area is in the kernel space part of the address space, but outside of the identically-mapped area
- Allocations of fairly large areas is possible (almost as big as total available memory, see https://j.mp/YIGq6W again), since physical memory fragmentation is not an issue, but areas cannot be used for DMA, as DMA usually requires physically contiguous buffers.
- Example use: to allocate kernel buffers to load module code.
- API in `include/linux/vmalloc.h`
  - `void *vmalloc(unsigned long size);`
    - Returns a virtual address
  - `void vfree(void *addr);`

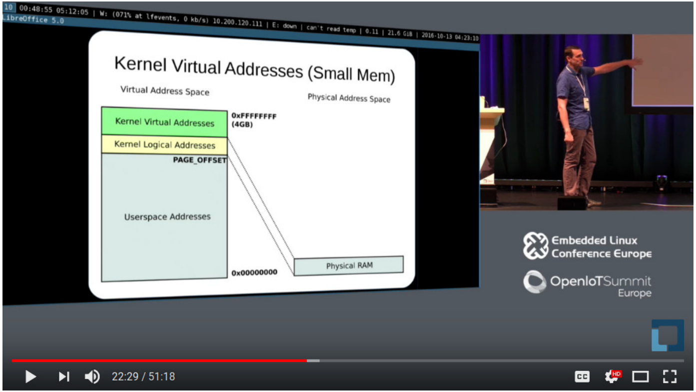
Kernel memory debugging

- KASAN (*Kernel Address Sanitizer*)
  - Dynamic memory error detector, to find use-after-free and out-of-bounds bugs.
  - Available on most architectures
  - See `dev-tools/kasan` for details.
- KFENCE (*Kernel Electric Fence*)
  - A low overhead alternative to KASAN, trading performance for precision. Meant to be used in production systems.
  - Only available on `x86`, `arm64` and `powerpc` (Linux 5.13 status)
  - See `dev-tools/kfence` for details.
- `Kmemleak`
  - Dynamic checker for memory leaks
  - This feature is available for all architectures.
  - See `dev-tools/kmemleak` for details.

KASAN and Kmemleak have a significant overhead. Only use them in development!

Kernel memory management: resources

Virtual memory and Linux, Alan Ott and Matt Porter, 2016
Great and much more complete presentation about this topic
https://bit.ly/2Af1G2i (video: https://bit.ly/2Bwwv0C)

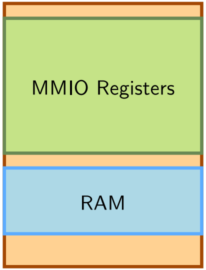


I/O Memory

Corrections, suggestions, contributions and translations are welcome!

Memory-Mapped I/O

- Same address bus to address memory and I/O device registers
- Access to the I/O device registers using regular instructions
- Most widely used I/O method across the different architectures supported by Linux



Physical Memory address space, accessed with normal load/store instructions

Requesting I/O memory

- Tells the kernel which driver is using which I/O registers
- `struct resource *request_mem_region(unsigned long start,`
  `unsigned long len, char *name);`
- `void release_mem_region(unsigned long start, unsigned long len);`
- Allows to prevent other drivers from requesting the same I/O registers, but is purely voluntary.

/proc/iomem example - ARM 32 bit (BeagleBone Black, Linux 5.11)

```
40300000-4030ffff : 40300000.sram sram@0
44e00c00-44e00cff : 44e00c00.prm prm@c00
44e00d00-44e00dff : 44e00d00.prm prm@d00
44e00e00-44e00eff : 44e00e00.prm prm@e00
44e00f00-44e00fff : 44e00f00.prm prm@f00
44e01000-44e010ff : 44e01000.prm prm@1000
44e01100-44e011ff : 44e01100.prm prm@1100
44e01200-44e012ff : 44e01200.prm prm@1200
44e07000-44e07fff : 44e07000.gpio gpio@0
44e09000-44e0901f : serial
44e0b000-44e0bfff : 44e0b000.i2c i2c@0
44e10800-44e10a37 : pinctrl-single
44e10f90-44e10fcf : 44e10f90.dma-router dma-router@f90
48024000-48024fff : 48024000.serial serial@0
48042000-480423ff : 48042000.timer timer@0
48044000-480443ff : 48044000.timer timer@0
48046000-480463ff : 48046000.timer timer@0
48048000-480483ff : 48048000.timer timer@0
4804a000-4804a3ff : 4804a000.timer timer@0
4804c000-4804cfff : 4804c000.gpio gpio@0
48060000-48060fff : 48060000.mmc mmc@0
4819c000-4819cfff : 4819c000.i2c i2c@0
481a8000-481a8fff : 481a8000.serial serial@0
481ac000-481acfff : 481ac000.gpio gpio@0
481ae000-481aefff : 481ae000.gpio gpio@0
481d8000-481d8fff : 481d8000.mmc mmc@0
49000000-4900ffff : 49000000.dma edma3_cc
4a100000-4a1007ff : 4a100000.ethernet ethernet@0
4a101200-4a1012ff : 4a100000.ethernet ethernet@0
80000000-9fdfffff : System RAM
80008000-80cfffff : Kernel code
80e00000-80f3d807 : Kernel data
```

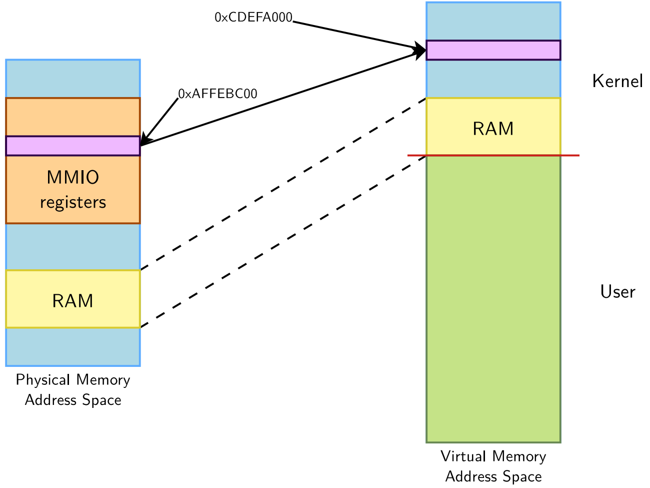
Mapping I/O memory in virtual memory

- Load/store instructions work with virtual addresses
- To access I/O memory, drivers need to have a virtual address that the processor can handle, because I/O memory is not mapped by default in virtual memory.
- The `ioremap` function satisfies this need:

```
#include <asm/io.h>

void __iomem *ioremap(phys_addr_t phys_addr, unsigned long size);
void iounmap(void __iomem *addr);
```

- Caution: check that `ioremap()` doesn't return a `NULL` address!

ioremap()




```
ioremap(0xAFFEBC00, 4096) = 0xCDEFA000
```

Managed API

Using request_mem_region() and ioremap() in device drivers is now deprecated. You should use the below "managed" functions instead, which simplify driver coding and error handling:

- devm_ioremap(), devm_iounmap()
- devm_ioremap_resource()
  - Takes care of both the request and remapping operations!
- devm_platform_ioremap_resource()
  - Takes care of platform_get_resource(), request_mem_region() and ioremap()
  - Caution: unlike the other devm_ functions, its first argument is of type struct pdev, not a pointer to struct device:
  - Example: drivers/char/hw_random/st-rng.c:

```
base = devm_platform_ioremap_resource(pdev, 0);
if (IS_ERR(base))
        return PTR_ERR(base);
```

Accessing MMIO devices

- Directly reading from or writing to addresses returned by `ioremap()` (*pointer dereferencing*) may not work on some architectures.
- To do PCI-style, little-endian accesses (byte swapping being done automatically assuming a little-endian device):

```
unsigned read[bwlq](void *addr);
void write[bwlq](unsigned val, void *addr);
```

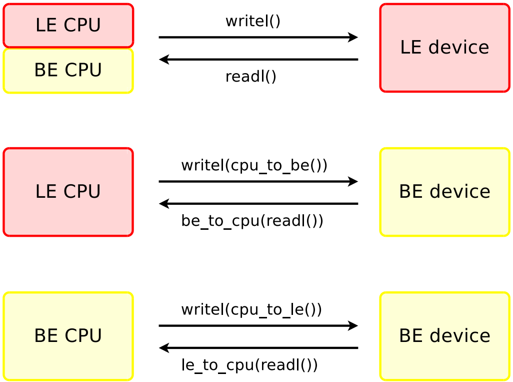
- These helpers are protected against ordering issues and will generally do the right thing for your architecture
- Caching is disabled on I/O memory

Byte endianness

- Not all devices are little-endian
- Most networking protocols are big-endian
- Manual handling of the endianness may sometimes be required

For portability purposes, drivers should handle all possibilities:

- `cpu_to_be32()`
- `cpu_to_le32()`
- `be32_to_cpu()`
- `le32_to_cpu()`



Ordering

- The compiler and/or CPU can reorder memory accesses, which might cause trouble for your devices is they expect one register to be read/written before another one.
  - Memory barriers are available to prevent this reordering
  - `write[bwlq]` starts with a write memory barrier which prior writes cannot cross
  - `read[bwlq]` ends with a read memory barrier which guarantees the ordering with regard to the subsequent reads
- Sometimes compiler/CPU reordering is not an issue, in this case the code may be optimized by dropping the memory barriers, using the relaxed helpers:

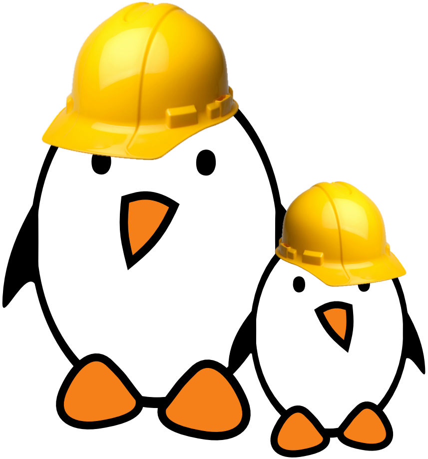
```
unsigned read[bwlq]_relaxed(void *addr);
void write[bwlq]_relaxed(unsigned val, void *addr);
```

- To do pure raw accesses, without barriers nor endianness conversion:

```
unsigned __raw_read[bwlq](void *addr);
void __raw_write[bwlq](unsigned val, void *addr);
```

/dev/mem

- Used to provide user space applications with direct access to physical addresses.
- Usage: open /dev/mem and read or write at given offset. What you read or write is the value at the corresponding physical address.
- Used by applications such as the X server to write directly to device memory.
- On x86, arm, arm64, riscv, powerpc, parisc, s390: CONFIG_STRICT_DEVMEM option to restrict /dev/mem to non-RAM addresses, for security reasons (Linux 5.12 status). CONFIG_IO_STRICT_DEVMEM goes beyond and only allows to access *idle* I/O ranges (not appearing in /proc/iomem).



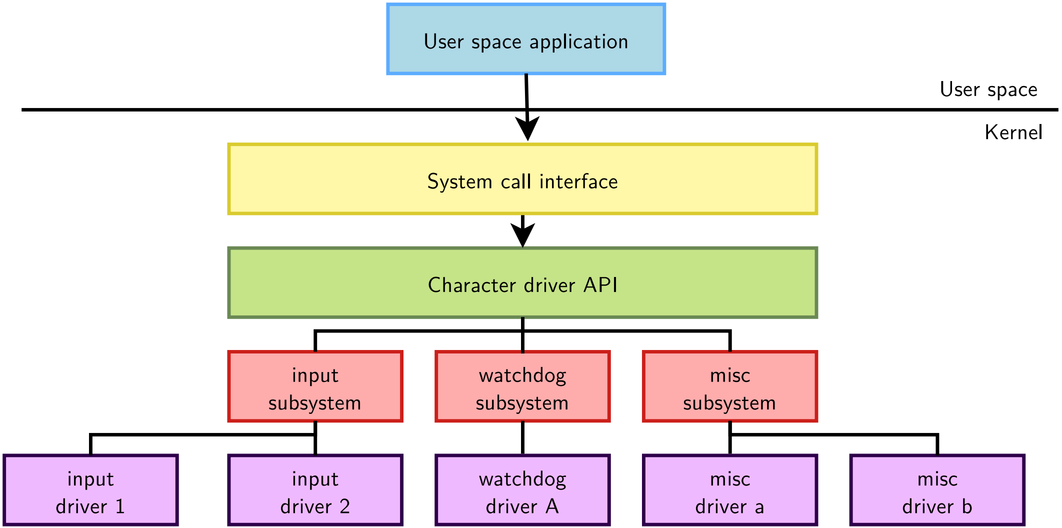
- Add UART devices to the board device tree
- Access I/O registers to control the device and send first characters to it.

The misc subsystem

Why a *misc* subsystem?

- The kernel offers a large number of **frameworks** covering a wide range of device types: input, network, video, audio, etc.
  - These frameworks allow to factorize common functionality between drivers and offer a consistent API to user space applications.
- However, there are some devices that **really do not fit in any of the existing frameworks**.
  - Highly customized devices implemented in a FPGA, or other weird devices for which implementing a complete framework is not useful.
- The drivers for such devices could be implemented directly as raw *character drivers* (with `cdev_init()` and `cdev_add()`).
- But there is a subsystem that makes this work a little bit easier: the **misc subsystem**.
  - It is really only a **thin layer** above the *character driver* API.
  - Another advantage is that devices are integrated in the Device Model (device files appearing in *devtmpfs*, which you don't have with raw character devices).

Misc subsystem diagram



Misc subsystem API (1/2)

- The misc subsystem API mainly provides two functions, to register and unregister **a single** *misc device*:
  - `int misc_register(struct miscdevice * misc);`
  - `void misc_deregister(struct miscdevice *misc);`
- A *misc device* is described by a `struct miscdevice` structure:

```
struct miscdevice  {
        int minor;
        const char *name;
        const struct file_operations *fops;
        struct list_head list;
        struct device *parent;
        struct device *this_device;
        const char *nodename;
        umode_t mode;
};
```

Misc subsystem API (2/2)

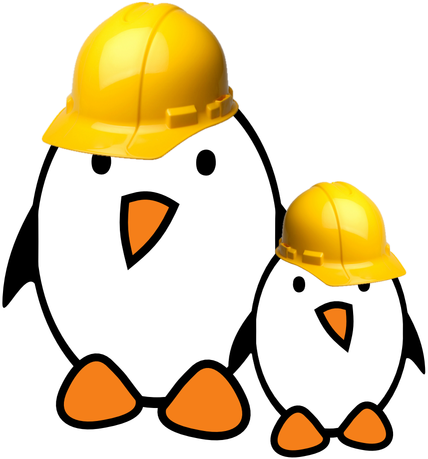
The main fields to be filled in `struct miscdevice` are:

- `minor`, the minor number for the device, or `MISC_DYNAMIC_MINOR` to get a minor number automatically assigned.
- `name`, name of the device, which will be used to create the device node if *devtmpfs* is used.
- `fops`, pointer to the same `struct file_operations` structure that is used for raw character drivers, describing which functions implement the *read*, *write*, *ioctl*, etc. operations.
- `parent`, pointer to the `struct device` of the underlying "physical" device (platform device, I2C device, etc.)

User space API for misc devices

- *misc devices* are regular character devices
- The operations they support in user space depends on the operations the kernel driver implements:
  - The `open()` and `close()` system calls to open/close the device.
  - The `read()` and `write()` system calls to read/write to/from the device.
  - The `ioctl()` system call to call some driver-specific operations.

Practical lab - Output-only serial port driver



- Extend the driver started in the previous lab by registering it into the *misc* subsystem.
- Implement serial output functionality through the *misc* subsystem.
- Test serial output using user space applications.

Processes, scheduling and interrupts

embedded Linux and kernel engineering

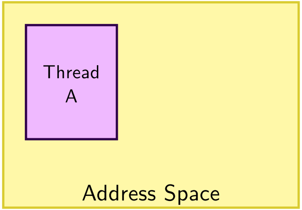
Processes and scheduling

Process, thread?

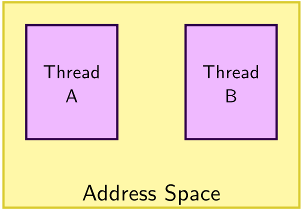
- Confusion about the terms *process*, *thread* and *task*
- In UNIX, a process is created using `fork()` and is composed of
  - An address space, which contains the program code, data, stack, shared libraries, etc.
  - A single thread, which is the only entity known by the scheduler.
- Additional threads can be created inside an existing process, using `pthread_create()`
  - They run in the same address space as the initial thread of the process
  - They start executing a function passed as argument to `pthread_create()`

Process, thread: kernel point of view

- In kernel space, each thread running in the system is represented by a structure of type `struct task_struct`
- From a scheduling point of view, it makes no difference between the initial thread of a process and all additional threads created dynamically using `pthread_create()`



Process after fork()

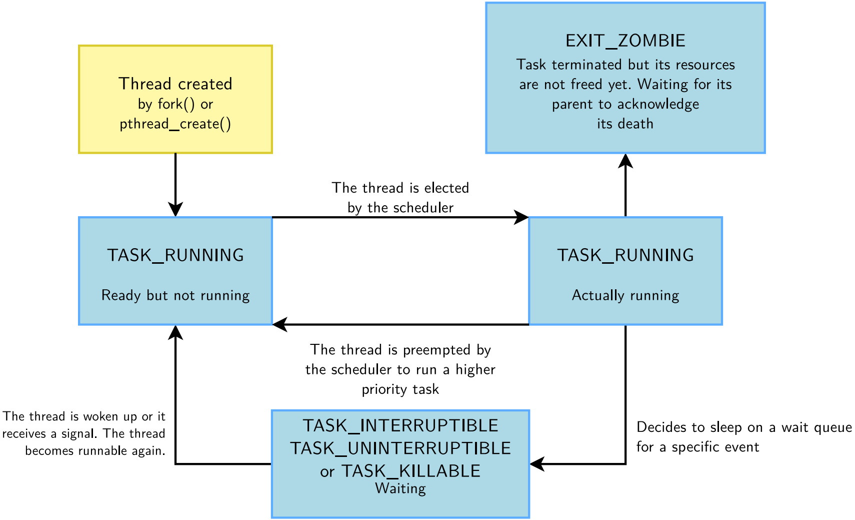


Same process after pthread_create()

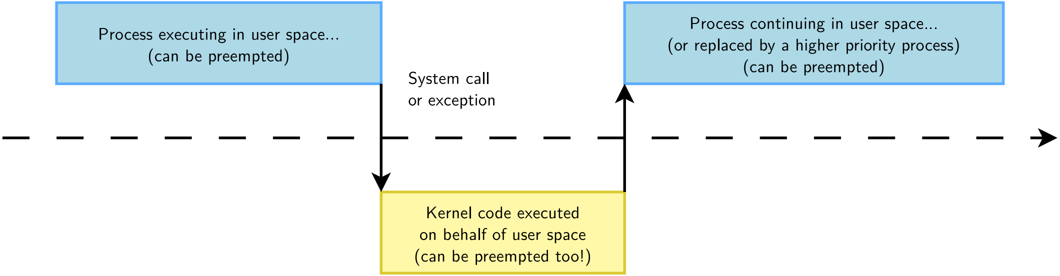
Relation between execution mode, address space and context

- When speaking about *process* and *thread*, these concepts need to be clarified:
  - *Mode* is the level of privilege allowing to perform some operations:
    - *Kernel Mode*: in this level CPU can perform any operation allowed by its architecture; any instruction, any I/O operation, any area of memory accessed.
    - *User Mode*: in this level, certain instructions are not permitted (especially those that could alter the global state of the machine), some memory areas cannot be accessed.
  - Linux splits its *address space* in *kernel space* and *user space*
    - *Kernel space* is reserved for code running in *Kernel Mode*.
    - *User space* is the place were applications execute (accessible from *Kernel Mode*).
  - *Context* represents the current state of an execution flow.
    - The *process context* can be seen as the content of the registers associated to this process: execution register, stack register...
    - The *interrupt context* replaces the *process context* when the interrupt handler is executed.

A thread life



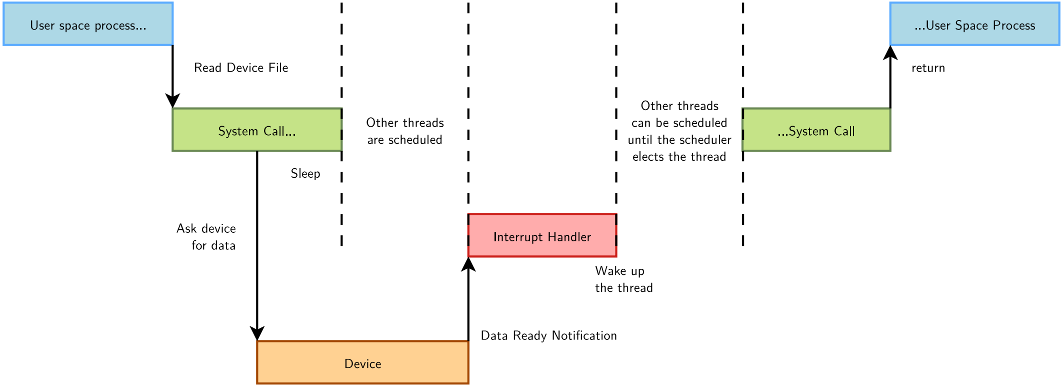
Execution of system calls



The execution of system calls takes place in the context of the thread requesting them.

Sleeping

Sleeping



Sleeping is needed when a process (user space or kernel space) is waiting for data.

How to sleep with a wait queue 1/3

- Must declare a wait queue, which will be used to store the list of threads waiting for an event
- Dynamic queue declaration:
  - Typically one queue per device managed by the driver
  - It's convenient to embed the wait queue inside a per-device data structure.
  - Example from drivers/net/ethernet/marvell/mvmdio.c:

```
struct orion_mdio_dev {
        ...
        wait_queue_head_t smi_busy_wait;
};
struct orion_mdio_dev *dev;
...
init_waitqueue_head(&dev->smi_busy_wait);
```

- Static queue declaration:
  - Using a global variable when a global resource is sufficient
  - `DECLARE_WAIT_QUEUE_HEAD(module_queue);`

How to sleep with a waitqueue 2/3

Several ways to make a kernel process sleep

- `void wait_event(queue, condition);`
  - Sleeps until the task is woken up **and** the given C expression is true. Caution: can't be interrupted (can't kill the user space process!)
- `int wait_event_killable(queue, condition);`
  - Can be interrupted, but only by a *fatal* signal (`SIGKILL`). Returns `-ERESTARTSYS` if interrupted.
- `int wait_event_interruptible(queue, condition);`
  - The most common variant
  - Can be interrupted by any signal. Returns `-ERESTARTSYS` if interrupted.

How to sleep with a waitqueue 3/3

- `int wait_event_timeout(queue, condition, timeout);`
  - Also stops sleeping when the task is woken up **or** the timeout expired (a timer is used).
  - Returns `0` if the timeout elapsed, non-zero if the condition was met.
- `int wait_event_interruptible_timeout(queue, condition, timeout);`
  - Same as above, interruptible.
  - Returns `0` if the timeout elapsed, `-ERESTARTSYS` if interrupted, positive value if the condition was met.

How to sleep with a waitqueue - Example

```
sig = wait_event_interruptible(ibmvtpm->wq,
                               !ibmvtpm->tpm_processing_cmd);
if (sig)
        return -EINTR;
```

From drivers/char/tpm/tpm_ibmvtpm.c

Waking up!

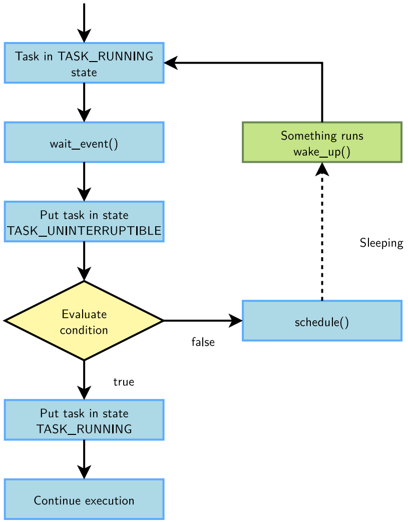
Typically done by interrupt handlers when data sleeping processes are waiting for become available.

- `wake_up(&queue);`
  - Wakes up all processes in the wait queue
- `wake_up_interruptible(&queue);`
  - Wakes up all processes waiting in an interruptible sleep on the given queue

Exclusive vs. non-exclusive

- `wait_event_interruptible()` puts a task in a non-exclusive wait.
  - All non-exclusive tasks are woken up by `wake_up()` / `wake_up_interruptible()`
- `wait_event_interruptible_exclusive()` puts a task in an exclusive wait.
  - `wake_up()` / `wake_up_interruptible()` wakes up all non-exclusive tasks and only one exclusive task
  - `wake_up_all()` / `wake_up_interruptible_all()` wakes up all non-exclusive and all exclusive tasks
- Exclusive sleeps are useful to avoid waking up multiple tasks when only one will be able to “consume” the event.
- Non-exclusive sleeps are useful when the event can “benefit” to multiple tasks.

Sleeping and waking up - Implementation



The scheduler doesn't keep evaluating the sleeping condition!

- `wait_event(queue, cond);`

  The process is put in the `TASK_UNINTERRUPTIBLE` state.

- `wake_up(&queue);`

  All processes waiting in `queue` are woken up, so they get scheduled later and have the opportunity to evaluate the condition again and go back to sleep if it is not met.

See `include/linux/wait.h` for implementation details.

How to sleep with completions 1/2

- Use `wait_for_completion()` when no particular condition must be enforced at the time of the wake-up
  - Leverages the power of wait queues
  - Simplifies its use
  - Highly efficient using low level scheduler facilities
- Preparation of the completion structure:
  - Static declaration and initialization:
    `DECLARE_COMPLETION(setup_done);`
  - Dynamic declaration:
    `init_completion(&object->setup_done);`
  - The completion object should get a meaningful name (eg. not just “done”).
- Ready to be used by signal consumers and providers as soon as the completion object is initialized
- See `include/linux/completion.h` for the full API
- Internal documentation at `scheduler/completion.rst`

How to sleep with completions 2/2

- Enter a wait state with
  `void wait_for_completion(struct completion *done)`
  - All `wait_event()` flavors are also supported, such as: `wait_for_completion_timeout()`, `wait_for_completion_interruptible\{,_timeout\}()`, `wait_for_completion_killable\{,_timeout\}()`, etc
- Wake up consumers with
  `void complete(struct completion *done)`
  - Several calls to `complete()` are valid, they will wake up the same number of threads waiting on this object (acts as a FIFO).
  - A single `complete_all()` call would wake up all present and future threads waiting on this completion object
- Reset the counter with
  `void reinit_completion(struct completion *done)`
  - Resets the number of "done" completions still pending
  - Mind not to call `init_completion()` twice, which could confuse the enqueued tasks

Waiting when there is no interrupt

- When there is no interrupt mechanism tied to a particular hardware state, it is tempting to implement a custom busy-wait loop.
  - Spoiler alert: this is highly discouraged!
- For long lasting pauses, rely on helpers which leverage the system clock
  - `wait_event()` helpers are (also) very useful outside of interruption situations
  - Release the CPU with `schedule()`
- For shorter pauses, use helpers which implement software loops
  - `msleep()`/`msleep_interruptible()` put the process in sleep for a given amount of milliseconds
  - `udelay()`/`udelay_range()` waste CPU cycles in order to save a couple of context switches for a sub-millisecond period
  - `cpu_relax()` does nothing, but may be used as a way to not being optimized out by the compiler when busy looping for very short periods

Waiting when hardware is involved

- When hardware is involved in the waiting process
  - but there is no interrupt available
  - or because a context switch would be too expensive
- Specific polling I/O accessors may be used:
  - Exhaustive list in include/iopoll.h

    ```
    int read[bwlq]_poll_timeout[_atomic](addr, val, cond,
                                          delay_us, timeout_us)
    ```

    - addr: I/O memory location
    - val: Content of the register pointed with
    - cond: Boolean condition based on val
    - delay_us: Polling delay between reads
    - timeout_us: Timeout delay after which the operation fails and returns -ETIMEDOUT
  - _atomic variant uses udelay() instead of usleep().

Interrupt Management

Registering an interrupt handler 1/2

The *managed* API is recommended:

```
int devm_request_irq(struct device *dev, unsigned int irq, irq_handler_t handler,
                     unsigned long irq_flags, const char *devname, void *dev_id);
```

- `device` for automatic freeing at device or module release time.
- `irq` is the requested IRQ channel. For platform devices, use `platform_get_irq()` to retrieve the interrupt number.
- `handler` is a pointer to the IRQ handler function
- `irq_flags` are option masks (see next slide)
- `devname` is the registered name (for `/proc/interrupts`). For platform drivers, good idea to use `pdev->name` which allows to distinguish devices managed by the same driver (example: `44e0b000.i2c`).
- `dev_id` is an opaque pointer. It can typically be used to pass a pointer to a per-device data structure. It cannot be NULL as it is used as an identifier for freeing interrupts on a shared line.

Releasing an interrupt handler

```
void devm_free_irq(struct device *dev, unsigned int irq, void *dev_id);
```

- Explicitly release an interrupt handler. Done automatically in normal situations.

Defined in `include/linux/interrupt.h`

Registering an interrupt handler 2/2

Here are the most frequent `irq_flags` bit values in drivers (can be combined):

- `IRQF_SHARED`: interrupt channel can be shared by several devices.
  - When an interrupt is received, all the interrupt handlers registered on the same interrupt line are called.
  - This requires a hardware status register telling whether an IRQ was raised or not.
- `IRQF_ONESHOT`: for use by threaded interrupts (see next slides). Keeping the interrupt line disabled until the thread function has run.

Interrupt handler constraints

- No guarantee in which address space the system will be in when the interrupt occurs: can't transfer data to and from user space.
- Interrupt handler execution is managed by the CPU, not by the scheduler. Handlers can't run actions that may sleep, because there is nothing to resume their execution. In particular, need to allocate memory with `GFP_ATOMIC`.
- Interrupt handlers are run with all interrupts disabled on the local CPU (see https://lwn.net/Articles/380931). Therefore, they have to complete their job quickly enough, to avoiding blocking interrupts for too long.

/proc/interrupts on Raspberry Pi 2 (ARM, Linux 4.19)

```
           CPU0       CPU1       CPU2       CPU3
 17:    1005317          0          0          0  ARMCTRL-level   1 Edge      3f00b880.mailbox
 18:         36          0          0          0  ARMCTRL-level   2 Edge      VCHIQ doorbell
 40:          0          0          0          0  ARMCTRL-level  48 Edge      bcm2708_fb DMA
 42:     427715          0          0          0  ARMCTRL-level  50 Edge      DMA IRQ
 56:  478426356          0          0          0  ARMCTRL-level  64 Edge      dwc_otg, dwc_otg_pcd, dwc_otg_hcd:usb1
 80:     411468          0          0          0  ARMCTRL-level  88 Edge      mmc0
 81:        502          0          0          0  ARMCTRL-level  89 Edge      uart-pl011
161:          0          0          0          0  bcm2836-timer   0 Edge      arch_timer
162:   10963772    6378711   16583353    6406625  bcm2836-timer   1 Edge      arch_timer
165:          0          0          0          0  bcm2836-pmu     9 Edge      arm-pmu
FIQ:                                              usb_fiq
IPI0:         0          0          0          0  CPU wakeup interrupts
IPI1:         0          0          0          0  Timer broadcast interrupts
IPI2:   2625198    4404191    7634127    3993714  Rescheduling interrupts
IPI3:      3140      56405      49483      59648  Function call interrupts
IPI4:         0          0          0          0  CPU stop interrupts
IPI5:   2167923     477097    5350168     412699  IRQ work interrupts
IPI6:         0          0          0          0  completion interrupts
Err:          0
```

Note: interrupt numbers shown on the left-most column are virtual numbers when the Device Tree is used. The physical interrupt numbers can be found in /sys/kernel/debug/irq/irqs/<nr> files when CONFIG_GENERIC_IRQ_DEBUGFS=y.

Interrupt handler prototype

- `irqreturn_t foo_interrupt(int irq, void *dev_id)`
  - `irq`, the IRQ number
  - `dev_id`, the per-device pointer that was passed to `devm_request_irq()`
- Return value
  - `IRQ_HANDLED`: recognized and handled interrupt
  - `IRQ_NONE`: used by the kernel to detect spurious interrupts, and disable the interrupt line if none of the interrupt handlers has handled the interrupt.
  - `IRQ_WAKE_THREAD`: handler requests to wake the handler thread (see next slides)

Typical interrupt handler's job

- Acknowledge the interrupt to the device (otherwise no more interrupts will be generated, or the interrupt will keep firing over and over again)
- Read/write data from/to the device
- Wake up any process waiting for such data, typically on a per-device wait queue:
  `wake_up_interruptible(&device_queue);`

Threaded interrupts

The kernel also supports threaded interrupts:

- The interrupt handler is executed inside a thread.
- Allows to block during the interrupt handler, which is often needed for I2C/SPI devices as the interrupt handler needs time to communicate with them.
- Allows to set a priority for the interrupt handler execution, which is useful for real-time usage of Linux

```
int devm_request_threaded_irq(struct device *dev, unsigned int irq,
                              irq_handler_t handler, irq_handler_t thread_fn,
                              unsigned long flags, const char *name,
                              void *dev);
```

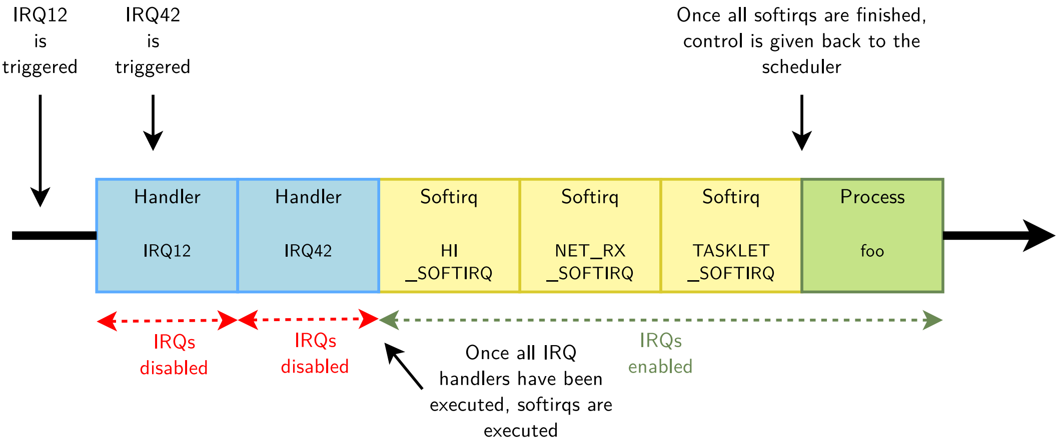
- `handler`, “hard IRQ” handler
- `thread_fn`, executed in a thread

Top half and bottom half processing

Splitting the execution of interrupt handlers in 2 parts

- Top half
  - This is the real interrupt handler, which should complete as quickly as possible since all interrupts are disabled. It takes the data out of the device and if substantial post-processing is needed, schedule a bottom half to handle it.
- Bottom half
  - Is the general Linux name for various mechanisms which allow to postpone the handling of interrupt-related work. Implemented in Linux as softirqs, tasklets or workqueues.

Top half and bottom half diagram



Softirqs

- Softirqs are a form of bottom half processing
- The softirqs handlers are executed with all interrupts enabled, and a given softirq handler can run simultaneously on multiple CPUs
- They are executed once all interrupt handlers have completed, before the kernel resumes scheduling processes, so sleeping is not allowed.
- The number of softirqs is fixed in the system, so softirqs are not directly used by drivers, but by kernel subsystems (network, etc.)
- The list of softirqs is defined in `include/linux/interrupt.h`: `HI_SOFTIRQ`, `TIMER_SOFTIRQ`, `NET_TX_SOFTIRQ`, `NET_RX_SOFTIRQ`, `BLOCK_SOFTIRQ`, `IRQ_POLL_SOFTIRQ`, `TASKLET_SOFTIRQ`, `SCHED_SOFTIRQ`, `HRTIMER_SOFTIRQ`, `RCU_SOFTIRQ`
- `HI_SOFTIRQ` and `TASKLET_SOFTIRQ` are used to execute tasklets

Example usage of softirqs - NAPI

NAPI = *New API*

- Interface in the Linux kernel used for interrupt mitigation in network drivers
- Principle: when the network traffic exceeds a given threshhold ("budget"), disable network interrupts and consume incoming packets through a polling function, instead of processing each new packet with an interrupt.
- This reduces overhead due to interrupts and yields better network throughput.
- The polling function is run by `napi_schedule()`, which uses `NET_RX_SOFTIRQ`.
- See https://en.wikipedia.org/wiki/New_API for details
- See also our commented network driver on https://frama.link/qCaWu1-U

Tasklets

- Tasklets are executed within the `HI_SOFTIRQ` and `TASKLET_SOFTIRQ` softirqs. They are executed with all interrupts enabled, but a given tasklet is guaranteed to execute on a single CPU at a time.
- Tasklets are typically created with the `tasklet_init()` function, when your driver manages multiple devices, otherwise statically with `DECLARE_TASKLET()`. A tasklet is simply implemented as a function. Tasklets can easily be used by individual device drivers, as opposed to softirqs.
- The interrupt handler can schedule tasklet execution with:
  - `tasklet_schedule()` to get it executed in `TASKLET_SOFTIRQ`
  - `tasklet_hi_schedule()` to get it executed in `HI_SOFTIRQ` (highest priority)

Tasklet example: drivers/crypto/atmel-sha.c 1/2

```
/* The tasklet function */
static void atmel_sha_done_task(unsigned long data)
{
        struct atmel_sha_dev *dd = (struct atmel_sha_dev *)data;
        [...]
}

/* Probe function: registering the tasklet */
static int atmel_sha_probe(struct platform_device *pdev)
{
        struct atmel_sha_dev *sha_dd; /* Per device structure */
        [...]
        platform_set_drvdata(pdev, sha_dd);
        [...]
        tasklet_init(&sha_dd->done_task, atmel_sha_done_task,
                     (unsigned long)sha_dd);
        [...]
        err = devm_request_irq(&pdev->dev, sha_dd->irq, atmel_sha_irq,
                               IRQF_SHARED, "atmel-sha", sha_dd);
        [...]
}
```

Tasklet example: drivers/crypto/atmel-sha.c 2/2

```
/* Remove function: removing the tasklet */
static int atmel_sha_remove(struct platform_device *pdev)
{
        static struct atmel_sha_dev *sha_dd;
        sha_dd = platform_get_drvdata(pdev);
        [...]
        tasklet_kill(&sha_dd->done_task);
        [...]
}

/* Interrupt handler: triggering execution of the tasklet */
static irqreturn_t atmel_sha_irq(int irq, void *dev_id)
{
        struct atmel_sha_dev *sha_dd = dev_id;
        [...]
        tasklet_schedule(&sha_dd->done_task);
        [...]
}
```

Workqueues

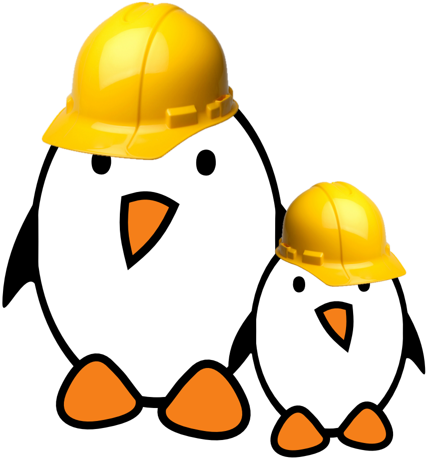
- Workqueues are a general mechanism for deferring work. It is not limited in usage to handling interrupts. It can typically be used for background work which can be scheduled.
- Workqueues may be created by subsystems or drivers with `alloc_workqueue()`. The default queue can also be used.
- Functions registered to run in workqueues, called workers, are executed in thread context which means:
  - All interrupts are enabled
  - Sleeping is allowed
- A worker is usually allocated in a per-device structure, initialized and registered with `INIT_WORK()` and typically triggered with `queue_work()` when using a dedicated queue or `schedule_work()` when using the default queue
- The complete API is in `include/linux/workqueue.h`
- Example (`drivers/crypto/atmel-i2c`):

```
INIT_WORK(&work_data->work, atmel_i2c_work_handler);
schedule_work(&work_data->work);
```

Interrupt management summary

- Device driver
  - In the `probe()` function, for each device, use `devm_request_irq()` to register an interrupt handler for the device's interrupt channel.
- Interrupt handler
  - Called when an interrupt is raised.
  - Acknowledge the interrupt
  - If needed, schedule a per-device tasklet taking care of handling data.
  - Wake up processes waiting for the data on a per-device queue
- Device driver
  - In the `remove()` function, for each device, the interrupt handler is automatically unregistered.

Practical lab - Interrupts



- Adding read capability to the character driver developed earlier.
- Register an interrupt handler for each device.
- Waiting for data to be available in the read file operation.
- Waking up the code when data are available from the devices.

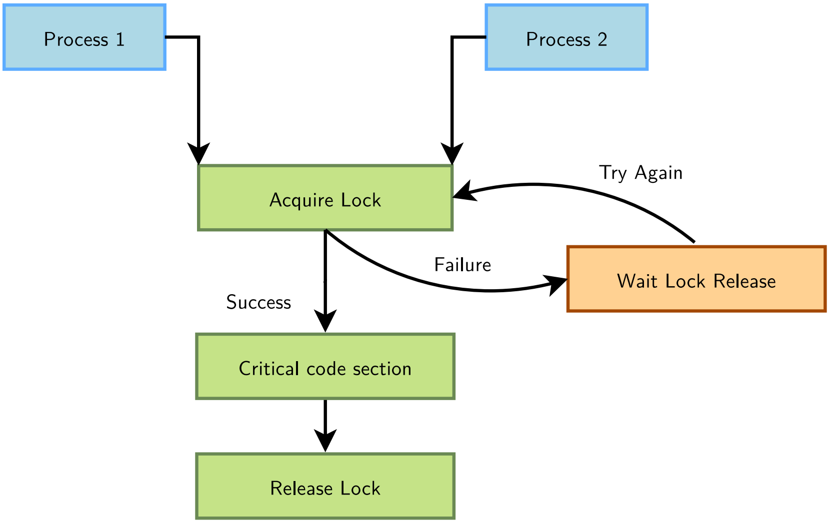
Concurrent Access to Resources: Locking

embedded Linux and kernel engineering

Sources of concurrency issues

- In terms of concurrency, the kernel has the same constraint as a multi-threaded program: its state is global and visible in all executions contexts
- Concurrency arises because of
  - *Interrupts*, which interrupts the current thread to execute an interrupt handler. They may be using shared resources (memory addresses, hardware registers...)
  - *Kernel preemption*, if enabled, causes the kernel to switch from the execution of one thread to another. They may be using shared resources.
  - *Multiprocessing*, in which case code is really executed in parallel on different processors, and they may be using shared resources as well.
- The solution is to keep as much local state as possible and for the shared resources that can't be made local (such as hardware ones), use locking.

Concurrency protection with locks



Linux mutexes

mutex = **mut***ual* **ex***clusion*

- The kernel's main locking primitive. It's a *binary lock*. Note that *counting locks* (*semaphores*) are also available, but used 30x less frequently.
- The process requesting the lock blocks when the lock is already held. Mutexes can therefore only be used in contexts where sleeping is allowed.
- Mutex definition:
  - `#include <linux/mutex.h>`
- Initializing a mutex statically (unusual case):
  - `DEFINE_MUTEX(name);`
- Or initializing a mutex dynamically (the usual case, on a per-device basis):
  - `void mutex_init(struct mutex *lock);`

Locking and unlocking mutexes 1/2

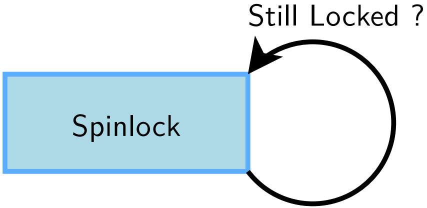
- `void mutex_lock(struct mutex *lock);`
  - Tries to lock the mutex, sleeps otherwise.
  - Caution: can't be interrupted, resulting in processes you cannot kill!
- `int mutex_lock_killable(struct mutex *lock);`
  - Same, but can be interrupted by a fatal (`SIGKILL`) signal. If interrupted, returns a non zero value and doesn't hold the lock. Test the return value!!!
- `int mutex_lock_interruptible(struct mutex *lock);`
  - Same, but can be interrupted by any signal.

Locking and unlocking mutexes 2/2

- `int mutex_trylock(struct mutex *lock);`
  - Never waits. Returns a non zero value if the mutex is not available.
- `int mutex_is_locked(struct mutex *lock);`
  - Just tells whether the mutex is locked or not.
- `void mutex_unlock(struct mutex *lock);`
  - Releases the lock. Do it as soon as you leave the critical section.

Spinlocks

- Locks to be used for code that is not allowed to sleep (interrupt handlers), or that doesn't want to sleep (critical sections). Be very careful not to call functions which can sleep!
- Originally intended for multiprocessor systems
- Spinlocks never sleep and keep spinning in a loop until the lock is available.
- The critical section protected by a spinlock is not allowed to sleep.



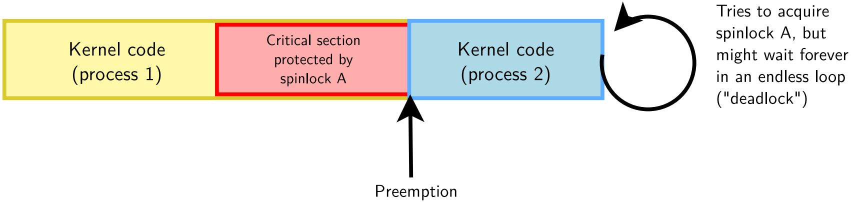
Initializing spinlocks

- Statically (unusual)
  - `DEFINE_SPINLOCK(my_lock);`
- Dynamically (the usual case, on a per-device basis)
  - `void spin_lock_init(spinlock_t *lock);`

Using spinlocks 1/3

Several variants, depending on where the spinlock is called:

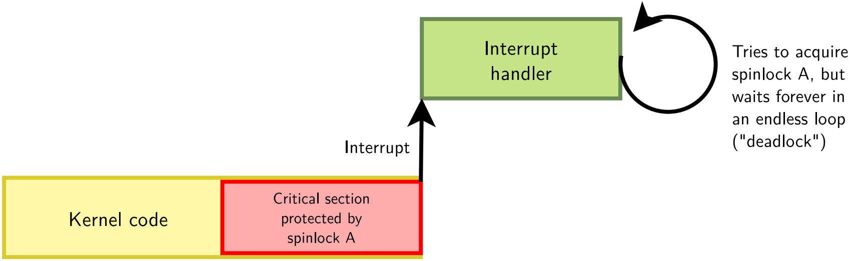
- `void spin_lock(spinlock_t *lock);`
- `void spin_unlock(spinlock_t *lock);`
    - Used for locking in process context (critical sections in which you do not want to sleep) as well as atomic sections.
    - Kernel preemption on the local CPU is disabled. We need to avoid deadlocks (and unbounded latencies) because of preemption from processes that want to get the same lock:



- Disabling kernel preemption also disables migration to avoid the same kind of issue as pictured above from happening.

Using spinlocks 2/3

- `void spin_lock_irqsave(spinlock_t *lock, unsigned long flags);`
- `void spin_unlock_irqrestore(spinlock_t *lock, unsigned long flags);`
    - Disables / restores IRQs on the local CPU.
    - Typically used when the lock can be accessed in both process and interrupt context.
    - We need to avoid deadlocks because of interrupts that want to get the same lock.



Using spinlocks 3/3

- `void spin_lock_bh(spinlock_t *lock);`
- `void spin_unlock_bh(spinlock_t *lock);`
  - Disables software interrupts, but not hardware ones.
  - Useful to protect shared data accessed in process context and in a soft interrupt (*bottom half*).
  - No need to disable hardware interrupts in this case.
- Note that reader / writer spinlocks also exist, allowing for multiple simultaneous readers.

Spinlock example

- From `drivers/tty/serial/uartlite.c`
- Spinlock structure embedded into `struct uart_port`

```
struct uart_port {
        spinlock_t lock;
        /* Other fields */
};
```

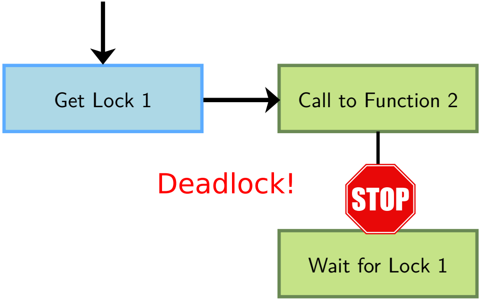
- Spinlock taken/released with protection against interrupts

```
static unsigned int ulite_tx_empty(struct uart_port *port) {
        unsigned long flags;

        spin_lock_irqsave(&port->lock, flags);
        /* Do something */
        spin_unlock_irqrestore(&port->lock, flags);
}
```

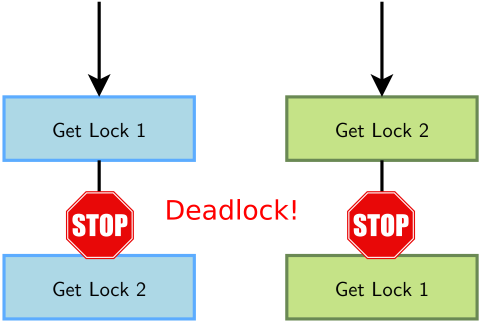
More deadlock situations

They can lock up your system. Make sure they never happen!

Rule 1: don't call a function that can try to get access to the same lock



Rule 2: if you need multiple locks, always acquire them in the same order!



Debugging locking

- Lock debugging: prove locking correctness
  - CONFIG_PROVE_LOCKING
  - Adds instrumentation to kernel locking code
  - Detect violations of locking rules during system life, such as:
    - Locks acquired in different order (keeps track of locking sequences and compares them).
    - Spinlocks acquired in interrupt handlers and also in process context when interrupts are enabled.
  - Not suitable for production systems but acceptable overhead in development.
  - See locking/lockdep-design for details
- CONFIG_DEBUG_ATOMIC_SLEEP allows to detect code that incorrectly sleeps in atomic section (while holding lock typically).
  - Warning displayed in the dmesg in case of such violation.

Concurrency issues

- Kernel Concurrency SANitizer framework
- `CONFIG_KCSAN`, introduced in Linux 5.8.
- Dynamic race detector relying on compile time instrumentation.
- Can find concurrency issues (mainly data races) in your system.
- See `dev-tools/kcsan` and `https://lwn.net/Articles/816850/` for details.

Alternatives to locking

As we have just seen, locking can have a strong negative impact on system performance. In some situations, you could do without it.

- By using lock-free algorithms like *Read Copy Update* (RCU).
  - RCU API available in the kernel
  - See https://en.wikipedia.org/wiki/Read-copy-update for a coverage of how it works.
- When relevant, use atomic operations.

RCU API

- Conditions where RCU is useful:
  - Synchronization between many readers vs. one writer
  - Focus on getting consistent data rather than getting the latest data
- Kind of enforces ownership by enforcing space/time synchronization
- RCU API (`Documentation/RCU/whatisRCU.rst`):
  - `rcu_read_lock()` and `rcu_read_unlock()`: reclaim/release read access
  - `synchronize_rcu()` or `call_rcu()`: wait for pre-existing readers
  - `rcu_assign_pointer()`: update RCU-protected pointer
  - `rcu_dereference()`: load RCU-protected pointer
- RCU mentorship session by Paul E. McKenney: https://youtu.be/K-4TI5gFsig

RCU protected reads: accessing structure members in a consistent way

Unsafe read

```
struct myconf { int a, b; } *current_conf; /* initialized */

unsafe_get(int *cur_a, int *cur_b)
{
        *cur_a = current_conf->a;
        /* What if *current_conf gets updated now? The assignement is inconsistent! */
        *cur_b = current_conf->b;
};
```

Safe read

```
struct myconf { int a, b; } *current_conf; /* initialized */

safe_get(int *cur_a, int *cur_b)
{
        struct myconf *conf;

        rcu_read_lock();
        conf = rcu_dereference(current_conf);
        *cur_a = conf->a;
        /* If *current_conf is updated, conf->a and conf->b will remain consistent! */
        *cur_b = conf->b;
        rcu_read_unlock();
};
```

RCU protected writes: updating a pointer in a consistent way

Unsafe write

```
struct myconf { int a, b; } *current_conf; /* initialized */

unsafe_set(int cur_a, int cur_b)
{
        struct myconf *newconf = kmalloc(...), *oldconf;
        newconf->a = cur_a, newconf->b = cur_b;

        oldconf = current_conf;
        current_conf = newconf;
        kfree(oldconf); /* Readers might still have a reference over the freed struct! */
};
```

Safe write

```
struct myconf { int a, b; } *current_conf; /* initialized */

safe_set(int cur_a, int cur_b)
{
        struct myconf *newconf = kmalloc(...), *oldconf;
        newconf->a = cur_a, newconf->b = cur_b;

        oldconf = rcu_dereference(current_conf);
        rcu_assign_pointer(current_conf, newconf);
        /* Readers might still have a reference over the old struct here... */
        synchronize_rcu();
        /* ...but not here! No more readers of the old struct, kfree() is safe! */
        kfree(oldconf);
};
```

Atomic variables 1/2

`#include <linux/atomic.h>`

- Useful when the shared resource is an integer value
- Even an instruction like `n++` is not guaranteed to be atomic on all processors!
- Ideal for RMW (Read-Modify-Write) operations
- Main atomic operations on `atomic_t` (signed integer, at least 24 bits):
  - Set or read the counter:
    - `void atomic_set(atomic_t *v, int i);`
    - `int atomic_read(atomic_t *v);`
  - Operations without return value:
    - `void atomic_inc(atomic_t *v);`
    - `void atomic_dec(atomic_t *v);`
    - `void atomic_add(int i, atomic_t *v);`
    - `void atomic_sub(int i, atomic_t *v);`

Atomic variables 2/2

- Similar functions testing the result:
  - `int atomic_inc_and_test(...);`
  - `int atomic_dec_and_test(...);`
  - `int atomic_sub_and_test(...);`
- Functions returning the new value:
  - `int atomic_inc_return(...);`
  - `int atomic_dec_return(...);`
  - `int atomic_add_return(...);`
  - `int atomic_sub_return(...);`

Atomic bit operations

- Supply very fast, atomic operations
- On most platforms, apply to an `unsigned long *` type.
- Apply to a `void *` type on a few others.
- Ideal for bitmaps
- Set, clear, toggle a given bit:
  - `void set_bit(int nr, unsigned long *addr);`
  - `void clear_bit(int nr, unsigned long *addr);`
  - `void change_bit(int nr, unsigned long *addr);`
- Test bit value:
  - `int test_bit(int nr, unsigned long *addr);`
- Test and modify (return the previous value):
  - `int test_and_set_bit(...);`
  - `int test_and_clear_bit(...);`
  - `int test_and_change_bit(...);`

Kernel locking: summary and references

- Use mutexes in code that is allowed to sleep
- Use spinlocks in code that is not allowed to sleep (interrupts) or for which sleeping would be too costly (critical sections)
- Use atomic operations to protect integers or addresses

See `kernel-hacking/locking` in kernel documentation for many details about kernel locking mechanisms.

Further reading: see the classical *dining philosophers problem* for a nice illustration of synchronization and concurrency issues.

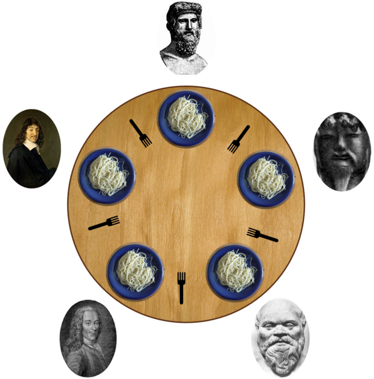
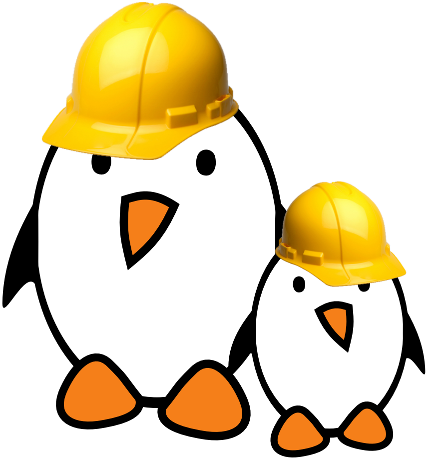


Image source: Wikipedia (https://frama.link/xg3Wnd0F)

Practical lab - Locking



- Add locking to the driver to prevent concurrent accesses to shared resources

Kernel debugging

Debugging using messages (1/3)

Three APIs are available

- The old `printk()`, no longer recommended for new debugging messages
- The `pr_*()` family of functions: `pr_emerg()`, `pr_alert()`, `pr_crit()`, `pr_err()`, `pr_warning()`, `pr_notice()`, `pr_info()`, `pr_cont()`
  and the special `pr_debug()` (see next pages)
  - Defined in `include/linux/printk.h`
  - They take a classic format string with arguments
  - Example:

    ```
    pr_info("Booting CPU %d\n", cpu);
    ```
  - Here's what you get in the kernel log:

    ```
    [  202.350064] Booting CPU 1
    ```
- `print_hex_dump_debug()`: useful to dump a buffer with `hexdump` like display

Debugging using messages (2/3)

- The `dev_*()` family of functions: `dev_emerg()`, `dev_alert()`, `dev_crit()`, `dev_err()`, `dev_warn()`, `dev_notice()`, `dev_info()` and the special `dev_dbg()` (see next page)
  - They take a pointer to `struct device` as first argument, and then a format string with arguments
  - Defined in `include/linux/dev_printk.h`
  - To be used in drivers integrated with the Linux device model
  - Example:

    ```
    dev_info(&pdev->dev, "in probe\n");
    ```

  - Here's what you get in the kernel log:

    ```
    [   25.878382] serial 48024000.serial: in probe
    [   25.884873] serial 481a8000.serial: in probe
    ```

- `*_ratelimited()` version exists which limits the amount of print if called too much based on `/proc/sys/kernel/printk_ratelimit{_burst}` values

Debugging using messages (3/3)

- The kernel defines many more format specifiers than the standard `printf()` existing ones.
  - `%p`: Display the hashed value of pointer by default.
  - `%px`: Always display the address of a pointer (use carefully on non-sensitive addresses).
  - `%pK`: Display hashed pointer value, zeros or the pointer address depending on `kptr_restrict` sysctl value.
  - `%pOF`: Device-tree node format specifier.
  - `%pr`: Resource structure format specifier.
  - `%pa`: Physical address display (work on all architectures 32/64 bits)
- `/proc/sys/kernel/kptr_restrict` should be set to `1` in order to display pointers which uses `%pK`
- See `core-api/printk-formats` for an exhaustive list of supported format specifiers

pr_debug() and dev_dbg()

- When the driver is compiled with `DEBUG` defined, all these messages are compiled and printed at the debug level. `DEBUG` can be defined by `#define DEBUG` at the beginning of the driver, or using `ccflags-$(CONFIG_DRIVER) += -DDEBUG` in the `Makefile`
- When the kernel is compiled with `CONFIG_DYNAMIC_DEBUG`, then these messages can dynamically be enabled on a per-file, per-module or per-message basis
  - Details in `admin-guide/dynamic-debug-howto`
  - Very powerful feature to only get the debug messages you're interested in.
- When neither `DEBUG` nor `CONFIG_DYNAMIC_DEBUG` are used, these messages are not compiled in.

Configuring the priority

- Each message is associated to a priority, ranging from `0` for emergency to `7` for debug, as specified in `include/linux/kern_levels.h`.
- All the messages, regardless of their priority, are stored in the kernel log ring buffer
  - Typically accessed using the `dmesg` command
- Some of the messages may appear on the console, depending on their priority and the configuration of
  - The `loglevel` kernel parameter, which defines the priority number below which messages are displayed on the console. Details in `admin-guide/kernel-parameters`. Examples: `loglevel=0`: no message, `loglevel=8`: all messages
  - The value of `/proc/sys/kernel/printk`, which allows to change at runtime the priority above which messages are displayed on the console. Details in `admin-guide/sysctl/kernel`

DebugFS

A virtual filesystem to export debugging information to user space.

- Kernel configuration: `CONFIG_DEBUG_FS`
  - `Kernel hacking -> Debug Filesystem`
- The debugging interface disappears when Debugfs is configured out.
- You can mount it as follows:
  - `sudo mount -t debugfs none /sys/kernel/debug`
- First described on https://lwn.net/Articles/115405/
- API documented in the Linux Kernel Filesystem API: `filesystems` (section *The debugfs filesystem*)

DebugFS API

- Create a sub-directory for your driver:
  - `struct dentry *debugfs_create_dir(const char *name, struct dentry *parent);`
- Expose an integer as a file in DebugFS. Example:
  - `struct dentry *debugfs_create_u8 (const char *name, mode_t mode, struct dentry *parent, u8 *value);`
    - `u8`, `u16`, `u32`, `u64` for decimal representation
    - `x8`, `x16`, `x32`, `x64` for hexadecimal representation
- Expose a binary blob as a file in DebugFS:
  - `struct dentry *debugfs_create_blob(const char *name, mode_t mode, struct dentry *parent, struct debugfs_blob_wrapper *blob);`
- Also possible to support writable DebugFS files or customize the output using the more generic `debugfs_create_file()` function.

Deprecated debugging mechanisms

Some additional debugging mechanisms, whose usage is now considered deprecated

- Adding special `ioctl()` commands for debugging purposes. DebugFS is preferred.
- Adding special entries in the `proc` filesystem. DebugFS is preferred.
- Adding special entries in the `sysfs` filesystem. DebugFS is preferred.
- Using `printk()`. The `pr_*()` and `dev_*()` functions are preferred.

Using Magic SysRq

Functionnality provided by serial drivers

- Allows to run multiple debug / rescue commands even when the kernel seems to be in deep trouble
  - On PC: press `[Alt]` + `[Prnt Scrn]` + `<character>` simultaneously (`[SysRq]` = `[Alt]` + `[Prnt Scrn]`)
  - On embedded: in the console, send a break character (Picocom: press `[Ctrl]` + `a` followed by `[Ctrl]` + `\`), then press `<character>`
- Example commands:
  - `h`: show available commands
  - `s`: sync all mounted filesystems
  - `b`: reboot the system
  - `n`: makes RT processes nice-able.
  - `w`: shows the kernel stack of all sleeping processes
  - `t`: shows the kernel stack of all running processes
  - You can even register your own!
- Detailed in admin-guide/sysrq

kgdb - A kernel debugger

- `CONFIG_KGDB` in *Kernel hacking*.
- The execution of the kernel is fully controlled by gdb from another machine, connected through a serial line.
- Can do almost everything, including inserting breakpoints in interrupt handlers.
- Feature supported for the most popular CPU architectures
- `CONFIG_GDB_SCRIPTS` allows to build GDB python scripts that are provided by the kernel.
  - See `dev-tools/gdb-kernel-debugging` for more information

Using kgdb (1/2)

- Details available in the kernel documentation: dev-tools/kgdb
- You must include a kgdb I/O driver. One of them is kgdb over serial console (kgdboc: kgdb over console, enabled by CONFIG_KGDB_SERIAL_CONSOLE)
- Configure kgdboc at boot time by passing to the kernel:
  - `kgdboc=<tty-device>,<bauds>`.
  - For example: `kgdboc=ttyS0,115200`
- Or at runtime using sysfs:
  - `echo ttyS0 > /sys/module/kgdboc/parameters/kgdboc`
  - If the console does not have polling support, this command will yield an error.

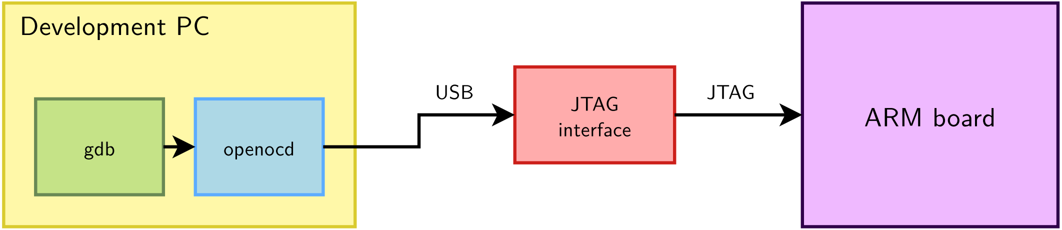
Using kgdb (2/2)

- Then also pass `kgdbwait` to the kernel: it makes `kgdb` wait for a debugger connection.
- Boot your kernel, and when the console is initialized, interrupt the kernel with a break character and then `g` in the serial console (see our *Magic SysRq* explanations).
- On your workstation, start `gdb` as follows:
  - `arm-linux-gdb ./vmlinux`
  - `(gdb) set remotebaud 115200`
  - `(gdb) target remote /dev/ttyS0`
- Once connected, you can debug a kernel the way you would debug an application program.
- On GDB side, the first threads represent the CPU context (ShadowCPU<x>), then all the other threads represents a task.

Debugging with a JTAG interface

Two types of JTAG dongles

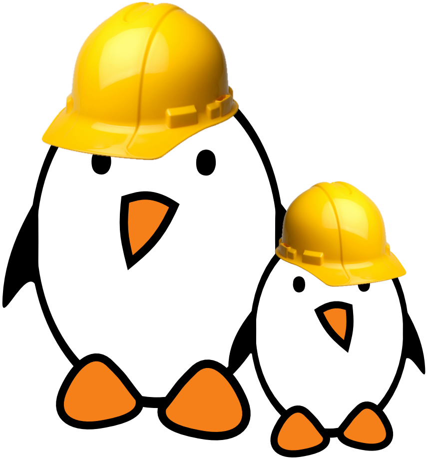
- The ones offering a gdb compatible interface, over a serial port or an Ethernet connection. gdb can directly connect to them.
- The ones not offering a gdb compatible interface are generally supported by OpenOCD (Open On Chip Debugger): http://openocd.sourceforge.net/
  - OpenOCD is the bridge between the gdb debugging language and the JTAG interface of the target CPU.
  - See the very complete documentation: http://openocd.org/documentation/
  - For each board, you'll need an OpenOCD configuration file (ask your supplier)



More kernel debugging tips

- Make sure `CONFIG_KALLSYMS_ALL` is enabled
  - Is turned on by default
  - To get oops messages with symbol names instead of raw addresses
- On ARM, if your kernel doesn't boot or hangs without any message, you can activate early debugging options (`CONFIG_DEBUG_LL` and `CONFIG_EARLYPRINTK`), and add `earlyprintk` to the kernel command line.

Practical lab - Kernel debugging



- Use the dynamic debug feature.
- Add debugfs entries
- Load a broken driver and see it crash
- Analyze the error information dumped by the kernel.
- Disassemble the code and locate the exact C instruction which caused the failure.

Porting the Linux kernel to an ARM board

bootlin
embedded Linux and kernel engineering

Porting the Linux kernel

- The Linux kernel supports a lot of different CPU architectures
- Each of them is maintained by a different group of contributors
  - See the `MAINTAINERS` file for details
- The organization of the source code and the methods to port the Linux kernel to a new board are therefore very architecture-dependent
  - For example, some architectures use the Device Tree, some do not.
- This presentation is mainly focused on the ARM (32-bit) architecture

Architecture, CPU and Machine

- In the source tree, each architecture has its own directory
  - `arch/arm/` for the ARM 32-bit architecture
  - `arch/arm64/` for the ARM 64-bit architecture
- The `arch/arm/` directory contains generic ARM code
  - `boot/`, `common/`, `configs/`, `kernel/`, `lib/`, `mm/`, `nwfpe/`, `vfp/`, `tools/` and several others.
- And many directories for different SoC families
  - `mach-*` directories: `mach-pxa/` for PXA SoCs, `mach-imx/` for Freescale iMX SoCs, etc. They essentially contain:
    - a small SoC description file
    - power management code
    - SMP code
- Some SoC families share some code, in directories named `plat-*`
- Device Tree source files are in `arch/arm/boot/dts/`

Before the Device Tree and ARM cleanup

- Until 2011, the ARM architecture wasn't using the Device Tree, and a large portion of the SoC support was located in `arch/arm/mach-<soc>`.
- Each board supported by the kernel was associated to an unique *machine ID*.
- The entire list of *machine ID* can be downloaded at https://www.arm.linux.org.uk/developer/machines/download.php and one could freely register an additional one.
- The Linux kernel was defining a *machine structure* for each board, which associates the *machine ID* with a set of information and callbacks.
- The bootloader had to pass the *machine ID* to the kernel in a specific ARM register.

This way, the kernel knew what board it was booting on, and which init callbacks it had to execute.

The Device Tree and the ARM cleanup

- As the ARM architecture gained significantly in popularity, some major refactoring was needed.
- First, the Device Tree was introduced on ARM: instead of using C code to describe SoCs and boards, a specialized language is used.
- Second, many driver infrastructures were created to replace custom code in `arch/arm/mach-<soc>`:
  - The common clock framework in `drivers/clk/`
  - The pinctrl subsystem in `drivers/pinctrl/`
  - The irqchip subsystem in `drivers/irqchip/`
  - The clocksource subsystem in `drivers/clocksource/`
- The amount of code in `mach-<soc>` has now significantly reduced.

Adding the support for a new ARM board

Provided the SoC used on your board is supported by the Linux kernel:

1. Create a *Device Tree* file in `arch/arm/boot/dts/`, generally named `<soc-name>-<board-name>.dts`, and make it include the relevant SoC `.dtsi` file.
   - Your Device Tree will describe all the SoC peripherals that are enabled, the pin muxing, as well as all the devices on the board.
2. Modify `arch/arm/boot/dts/Makefile` to make sure your Device Tree gets built as a *DTB* during the kernel build.
3. Tweak an existing configuration that matches your SoC and save it as `<board-name>_defconfig` in `arch/arm/configs/`
4. If needed, develop the missing device drivers for the devices that are on your board outside the SoC.

Understanding the SoC support

- Let's consider another ARM platform here for the kernel side of the support: the Marvell Armada 370/XP.
- For this platform, the core of the SoC support is located in `arch/arm/mach-mvebu/`
- The `board-v7.c` file (see code on the next slide) contains the "*entry point*" of the SoC definition, the `DT_MACHINE_START` .. `MACHINE_END` definition:
  - Defines the list of platform compatible strings that will match this platform, in this case `marvell,armada-370-xp`. This allows the kernel to know which `DT_MACHINE` structure to use depending on the DTB that is passed at boot time.
  - Defines various callbacks for the platform initialization, the most important one being the `.init_machine` callback, running initialization code for the associated SoC.

arch/arm/mach-mvebu/board-v7.c (Linux 5.3)

```
static void __init mvebu_dt_init(void)
{
        if (of_machine_is_compatible("marvell,armadaxp"))
                i2c_quirk();
}

static void __init armada_370_xp_dt_fixup(void)
{
#ifdef CONFIG_SMP
        smp_set_ops(smp_ops(armada_xp_smp_ops));
#endif
}

static const char * const armada_370_xp_dt_compat[] __initconst = {
        "marvell,armada-370-xp",
        NULL,
};

DT_MACHINE_START(ARMADA_370_XP_DT, "Marvell Armada 370/XP (Device Tree)")
        .l2c_aux_val    = 0,
        .l2c_aux_mask   = ~0,
        .init_machine   = mvebu_dt_init,
        .init_irq       = mvebu_init_irq,
        .restart        = mvebu_restart,
        .reserve        = mvebu_memblock_reserve,
        .dt_compat      = armada_370_xp_dt_compat,
        .dt_fixup       = armada_370_xp_dt_fixup,
MACHINE_END
```

Components of the minimal SoC support

The minimal SoC support consists of

- An SoC *entry point* file, `arch/arm/mach-mvebu/board-v7.c`
- At least one SoC `.dtsi` DT and one board `.dts` DT, in `arch/arm/boot/dts/`
- An interrupt controller driver, `drivers/irqchip/irq-armada-370-xp.c`
- A timer driver, `drivers/clocksource/timer-armada-370-xp.c`
- An earlyprintk implementation to get early messages from the console, `arch/arm/Kconfig.debug` and `arch/arm/include/debug/`
- A serial port driver in `drivers/tty/serial/`. For Armada 370/XP, the 8250 driver `drivers/tty/serial/8250/` is used.

This allows to boot a minimal system up to user space, using a root filesystem in *initramfs*.

Extending the minimal SoC support

Once the minimal SoC support is in place, the following core components should be added:

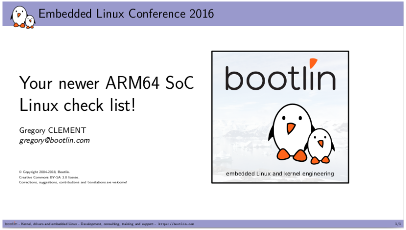
- Support for the clocks. Usually requires some clock drivers, as well as DT representations of the clocks. See `drivers/clk/mvebu/` for Armada 370/XP clock drivers.
- Support for pin muxing, through the *pinctrl* subsystem. See `drivers/pinctrl/mvebu/` for the Armada 370/XP drivers.
- Support for GPIOs, through the *GPIO* subsystem. See `drivers/gpio/gpio-mvebu.c` for the Armada 370/XP GPIO driver.
- Support for SMP, through `struct smp_operations`. See `arch/arm/mach-mvebu/platsmp.c`.

Adding controller drivers

Once the core pieces of the SoC support have been implemented, the remaining part is to add drivers for the different hardware blocks:

- Ethernet controller driver, in `drivers/net/ethernet/marvell/mvneta.c`
- SATA controller driver, in `drivers/ata/sata_mv.c`
- I2C controller driver, in `drivers/i2c/busses/i2c-mv64xxx.c`
- SPI controller driver, in `drivers/spi/spi-orion.c`
- PCIe controller driver, in `drivers/pci/controller/pci-mvebu.c`
- USB controller driver, in `drivers/usb/host/ehci-orion.c`
- etc.

- Gregory Clement, Your newer ARM64 SoC Linux support check-list!
  https://bit.ly/2r8lHnE
- Thomas Petazzoni, Your new ARM SoC Linux support check-list!
  https://bit.ly/2ivqtDD
- Our technical presentations on various kernel subsystems:
  https://bootlin.com/docs/



Power Management

PM building blocks

- Several power management *building blocks*
  - Clock framework
  - Suspend and resume
  - CPUidle
  - Runtime power management
  - Power domains
  - Frequency and voltage scaling
- Independent *building blocks* that can be improved gradually during development

Clock framework (1)

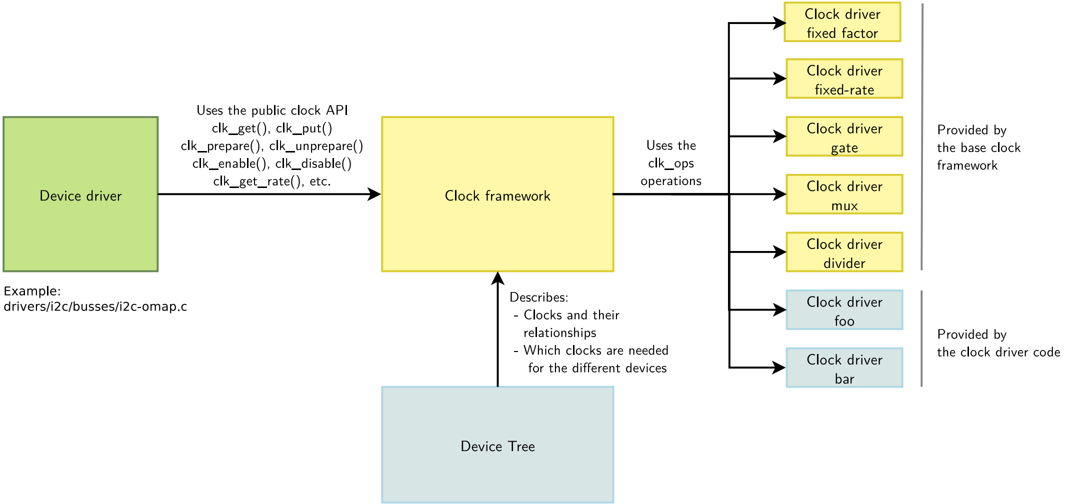
- Generic framework to manage clocks used by devices in the system
- Allows to reference count clock users and to shutdown the unused clocks to save power
- Simple API described in `include/linux/clk.h`.
  - `clk_get()` to lookup and obtain a reference to a clock producer
  - `clk_enable()` to inform the system when the clock source should be running
  - `clk_disable()` to inform the system when the clock source is no longer required.
  - `clk_put()` to free the clock source
  - `clk_get_rate()` to obtain the current clock rate (in Hz) for a clock source
  - `clk_set_rate()` to set the current clock rate (in Hz) of a clock source

Clock framework (2)

The common clock framework

- Allows to declare the available clocks and their association to devices in the Device Tree
- Provides a *debugfs* representation of the clock tree
- Is implemented in `drivers/clk/`

Diagram overview of the common clock framework



Clock framework (3)

The interface of the CCF divided into two halves:

- Common Clock Framework core
  - Common definition of `struct clk`
  - Common implementation of the `clk.h` API (defined in `drivers/clk/clk.c`)
  - `struct clk_ops`: operations invoked by the clk API implementation
  - Not supposed to be modified when adding a new driver
- Hardware-specific
  - Callbacks registered with `struct clk_ops` and the corresponding hardware-specific structures
  - Has to be written for each new hardware clock
  - Example: `drivers/clk/mvebu/clk-cpu.c`

Clock framework (4)

Hardware clock operations: device tree

- The **device tree** is the **mandatory way** to declare a clock and to get its resources, as for any other driver using DT we have to:
  - **Parse** the device tree to **setup** the clock: the resources but also the properties are retrieved.
  - Declare the **compatible** clocks and associate each to an **initialization** function using `CLK_OF_DECLARE()`
  - Example: `arch/arm/boot/dts/armada-xp.dtsi` and `drivers/clk/mvebu/armada-xp.c`

See our presentation about the Clock Framework for more details:
https://bootlin.com/pub/conferences/2013/elce/common-clock-framework-how-to-use-it/

Suspend and resume (to / from RAM)

- Infrastructure in the kernel to support suspend and resume
- System on Chip hooks
  - Define operations (at least `valid()` and `enter()`) `struct platform_suspend_ops` structure. See the documentation for this structure for details about possible operations and the way they are used.
  - Registered using the `suspend_set_ops()` function
  - See `arch/arm/mach-at91/pm.c`
- Device driver hooks
  - `pm` operations (`suspend()` and `resume()` hooks) in the `struct device_driver` as a `struct dev_pm_ops` structure in (`struct platform_driver`, `struct usb_driver`, etc.)
  - See `drivers/net/ethernet/cadence/macb_main.c`
- *Hibernate to disk* is based on suspend to RAM, copying the RAM contents (after a simulated suspend) to a swap partition.

Triggering suspend / hibernate

- `struct suspend_ops` functions are called by the `enter_state()` function. `enter_state()` also takes care of executing the suspend and resume functions for your devices.
- Read `kernel/power/suspend.c`
- The execution of this function can be triggered from user space:
  - `echo mem > /sys/power/state` (suspend to RAM)
  - `echo disk > /sys/power/state` (hibernate to disk)
- Systemd can also manage suspend and hibernate for you, and offers customizations
  - `systemctl suspend` or `systemctl hibernate`.
  - See https://www.man7.org/linux/man-pages/man8/systemd-suspend.service.8.html

Saving power in the idle loop

- The idle loop is what you run when there's nothing left to run in the system.
- `arch_cpu_idle()` implemented in all architectures in `arch/<arch>/kernel/process.c`
- Example: `arch/arm/kernel/process.c`
- The CPU can run power saving HLT instructions, enter NAP mode, and even disable the timers (tickless systems).
- See also https://en.wikipedia.org/wiki/Idle_loop

Managing idle

Adding support for multiple idle levels

- Modern CPUs have several sleep states offering different power savings with associated wake up latencies
- The *dynamic tick* feature allows to remove the periodic timer tick to save power, and to know when the next event is scheduled, for smarter sleeps.
- CPUidle infrastructure to change sleep states
  - Platform-specific driver defining sleep states and transition operations
  - Platform-independent governors
  - Available in particular for x86/ACPI and most ARM SoCs
  - See `admin-guide/pm/cpuidle` in kernel documentation.

PowerTOP

https://01.org/powertop/

- With dynamic ticks, allows to fix parts of kernel code and applications that wake up the system too often.
- PowerTOP allows to track the worst offenders
- Now available on ARM cpus implementing CPUidle
- Also gives you useful hints for reducing power.
- Try it on your x86 laptop:
  `sudo powertop`

Runtime power management

- Managing per-device idle, each device being managed by its device driver independently from others.
- According to the kernel configuration interface: *Enable functionality allowing I/O devices to be put into energy-saving (low power) states at run time (or autosuspended) after a specified period of inactivity and woken up in response to a hardware-generated wake-up event or a driver's request.*
- New hooks must be added to the drivers: `runtime_suspend()`, `runtime_resume()`, `runtime_idle()` in the `struct dev_pm_ops` structure in `struct device_driver`.
- API and details on `power/runtime_pm`
- See `drivers/net/ethernet/cadence/macb_main.c` again.

Generic PM Domains (genpd)

- Generic infrastructure to implement power domains based on Device Tree descriptions, allowing to group devices by the physical power domain they belong to. This sits at the same level as bus type for calling PM hooks.
- All the devices in the same PD get the same state at the same time.
- Specifications and examples available at `Documentation/devicetree/bindings/power/power_domain.txt`
- Driver example: `drivers/soc/rockchip/pm_domains.c` (`rockchip_pd_power_on()`, `rockchip_pd_power_off()`, `rockchip_pm_add_one_domain()`...)
- DT example: look for `rockchip,px30-power-controller` (`arch/arm64/boot/dts/rockchip/px30.dtsi`) and find PD definitions and corresponding devices.
- See Kevin Hilman's talk at Kernel Recipes 2017: `https://youtu.be/SctfvoskABM`

Frequency and voltage scaling (1)

Frequency and voltage scaling possible through the `cpufreq` kernel infrastructure.

- Generic infrastructure: `drivers/cpufreq/cpufreq.c` and `include/linux/cpufreq.h`
- Generic governors, responsible for deciding frequency and voltage transitions
  - `performance`: maximum frequency
  - `powersave`: minimum frequency
  - `ondemand`: measures CPU consumption to adjust frequency
  - `conservative`: often better than `ondemand`. Only increases frequency gradually when the CPU gets loaded.
  - `userspace`: leaves the decision to a user space daemon.
- This infrastructure can be controlled from `/sys/devices/system/cpu/cpu<n>/cpufreq/`

Frequency and voltage scaling (2)

- CPU frequency drivers are in drivers/cpufreq/. Example: drivers/cpufreq/omap-cpufreq.c
- Must implement the operations of the cpufreq_driver structure and register them using cpufreq_register_driver()
  - init() for initialization
  - exit() for cleanup
  - verify() to verify the user-chosen policy
  - setpolicy() or target() to actually perform the frequency change
- See documentation in cpu-freq/ for useful explanations

Regulator framework

- Modern embedded platforms have hardware responsible for voltage and current regulation
- The regulator framework allows to take advantage of this hardware to save power when parts of the system are unused
  - A consumer interface for device drivers (i.e. users)
  - Regulator driver interface for regulator drivers
  - Machine interface for board configuration
  - sysfs interface for user space
- See `power/regulator/` in kernel documentation.

BSP work for a new board

In case you just need to create a BSP for your board, and your CPU already has full PM support, you should just need to:

- Create clock definitions and bind your devices to them.
- Implement PM handlers (suspend, resume) in the drivers for your board specific devices.
- Implement runtime PM handlers in your drivers.
- Implement board specific power management if needed (mainly battery management)
- Implement regulator framework hooks for your board if needed.
- Attach on-board devices to PM domains if needed
- All other parts of the PM infrastructure should be already there: suspend / resume, cpuidle, cpu frequency and voltage scaling, PM domains.

Useful resources

- power/ in kernel documentation.
  - Will give you many useful details.
- Introduction to kernel power management, Kevin Hilman (Kernel Recipes 2015)
  - https://www.youtube.com/watch?v=juJJZORgVwI

The kernel development and contribution process

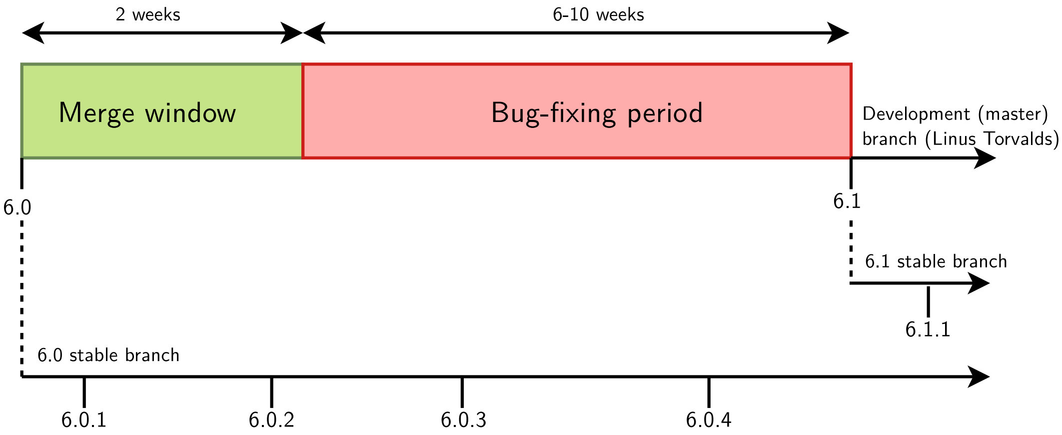
Linux versioning scheme and development process

Linux versioning scheme

- Until 2003, there was a new "stabilized" release branch of Linux every 2 or 3 years (2.0, 2.2, 2.4). Development branches took 2-3 years to be merged (too slow!).
- Since 2003, there is a new official release of Linux about every 10 weeks:
  - Versions `2.6` (Dec. 2003) to `2.6.39` (May 2011)
  - Versions `3.0` (Jul. 2011) to `3.19` (Feb. 2015)
  - Versions `4.0` (Apr. 2015) to `4.20` (Dec. 2018)
  - Versions `5.0` (Mar. 2019) to `5.19` (July 2022)
  - Version `6.0` was released in Oct. 2022.
- Features are added to the kernel in a progressive way. Since 2003, kernel developers have managed to do so without having to introduce a massively incompatible development branch.
- For each release, there are bugfix and security updates called stable releases: 6.0.1, 6.0.2, etc.

Linux development model

Using merge and bug fixing windows



Need for long term support (1)

- Issue: bug and security fixes only released for most recent kernel versions.
- Solution: the last release of each year is made an LTS *(Long Term Support)* release, and is supposed to be supported (and receive bug and security fixes) for up to 6 years.

Version	Maintainer	Released	Projected EOL
5.15	Greg Kroah-Hartman & Sasha Levin	2021-10-31	Oct, 2023
5.10	Greg Kroah-Hartman & Sasha Levin	2020-12-13	Dec, 2026
5.4	Greg Kroah-Hartman & Sasha Levin	2019-11-24	Dec, 2025
4.19	Greg Kroah-Hartman & Sasha Levin	2018-10-22	Dec, 2024
4.14	Greg Kroah-Hartman & Sasha Levin	2017-11-12	Jan, 2024
4.9	Greg Kroah-Hartman & Sasha Levin	2016-12-11	Jan, 2023

Captured on `https://kernel.org` in Oct. 2022, following the *Releases* link.

- Example at Google: starting from *Android O (2017)*, all new Android devices will have to run such an LTS kernel.

Need for long term support (2)

- You could also get long term support from a commercial embedded Linux provider.
  - Wind River Linux can be supported for up to 15 years.
  - Ubuntu Core can be supported for up to 10 years.
- *"If you are not using a supported distribution kernel, or a stable / longterm kernel, you have an insecure kernel"* - Greg KH, 2019
  Some vulnerabilities are fixed in stable without ever getting a CVE.
- The *Civil Infrastructure Platform* project is an industry / Linux Foundation effort to support much longer (at least 10 years) selected LTS versions (currently 4.4, 4.19, 5.10) on selected architectures. See `https://wiki.linuxfoundation.org/civilinfrastructureplatform/cipkernelmaintenance`.

Contributing to the Linux kernel

Getting help and reporting bugs

- If you are using a custom kernel from a hardware vendor, contact that company. The community will have less interest supporting a custom kernel.
- Otherwise, or if this doesn't work, try to reproduce the issue on the latest version of the kernel.
- Make sure you investigate the issue as much as you can: see `admin-guide/bug-bisect`
- Check for previous bugs reports. Use web search engines, accessing public mailing list archives.
- If you're the first to face the issue, it's very useful for others to report it, even if you cannot investigate it further.
- If the subsystem you report a bug on has a mailing list, use it. Otherwise, contact the official maintainer (see the `MAINTAINERS` file). Always give as many useful details as possible.

How to Become a Kernel Developer?

Recommended resources

- See process/submitting-patches for guidelines and https://kernelnewbies.org/UpstreamMerge for very helpful advice to have your changes merged upstream (by Rik van Riel).
- Watch the *Write and Submit your first Linux kernel Patch* talk by Greg. K.H: https://www.youtube.com/watch?v=LLBrBBImJt4
- How to Participate in the Linux Community (by Jonathan Corbet). A guide to the kernel development process https://j.mp/tX2Ld6

Contribute to the Linux Kernel (1)

- Clone Linus Torvalds' tree:
  - `git clone https://git.kernel.org/pub/scm/linux/kernel/git/torvalds/linux`
- Keep your tree up to date
  - `git pull`
- Look at the master branch and check whether your issue / change hasn't been solved / implemented yet. Also check the maintainer's git tree and mailing list (see the `MAINTAINERS` file).You may miss submissions that are not in mainline yet.
- If the maintainer has its own git tree, create a remote branch tracking this tree. This is much better than creating another clone (doesn't duplicate common stuff):
  - `git remote add linux-omap https://git.kernel.org/pub/scm/linux/kernel/git/tmlind/linux-omap`
  - `git fetch linux-omap`

Contribute to the Linux Kernel (2)

- Either create a new branch starting from the current commit in the master branch:
  - `git checkout -b feature`
- Or, if more appropriate, create a new branch starting from the maintainer's master branch:
  - `git checkout -b feature linux-omap/master` (remote tree / remote branch)
- In your new branch, implement your changes.
- Test your changes (must at least compile them).
- Run `git add` to add any new files to the index.

Configure git send-email

- Make sure you already have configured your name and e-mail address (should be done before the first commit).
  - `git config --global user.name 'My Name'`
  - `git config --global user.email me@mydomain.net`
- Configure your SMTP settings. Example for a Google Mail account:
  - `git config --global sendemail.smtpserver smtp.googlemail.com`
  - `git config --global sendemail.smtpserverport 587`
  - `git config --global sendemail.smtpencryption tls`
  - `git config --global sendemail.smtpuser jdoe@gmail.com`
  - `git config --global sendemail.smtppass xxx`

Contribute to the Linux Kernel (3)

- Group your changes by sets of logical changes, corresponding to the set of patches that you wish to submit.
- Commit and sign these groups of changes (signing required by Linux developers).
  - `git commit -s`
  - Make sure your first description line is a useful summary and starts with the name of the modified subsystem. This first description line will appear in your e-mails
- The easiest way is to look at previous commit summaries on the main file you modify
  - `git log --pretty=oneline <path-to-file>`
- Examples subject lines (`[PATCH]` omitted):

```
Documentation: prctl/seccomp_filter
PCI: release busn when removing bus
ARM: add support for xz kernel decompression
```

Contribute to the Linux Kernel (4)

- Remove previously generated patches
  - `rm 00*.patch`
- Have git generate patches corresponding to your branch (assuming it is the current branch)
  - If your branch is based on mainline
    - `git format-patch master`
  - If your branch is based on a remote branch
    - `git format-patch <remote>/<branch>`
- Make sure your patches pass `checkpatch.pl` checks:
  - `scripts/checkpatch.pl --strict 00*.patch`
- Now, send your patches to yourself
  - `git send-email --compose --to me@mydomain.com 00*.patch`
- If you have just one patch, or a trivial patch, you can remove the empty line after `In-Reply-To:`. This way, you won't add a summary e-mail introducing your changes (recommended otherwise).

Contribute to the Linux Kernel (5)

- Check that you received your e-mail properly, and that it looks good.
- Now, find the maintainers for your patches

```
scripts/get_maintainer.pl ~/patches/00*.patch
Russell King <linux@arm.linux.org.uk> (maintainer:ARM PORT)
Nicolas Pitre <nicolas.pitre@linaro.org>
(commit_signer:1/1=100%)
linux-arm-kernel@lists.infradead.org (open list:ARM PORT)
linux-kernel@vger.kernel.org (open list)
```

- Now, send your patches to each of these people and lists
  - `git send-email --compose --to linux@arm.linux.org.uk --to nicolas.pitre@linaro.org --cc linux-arm-kernel@lists.infradead.org --cc linux-kernel@vger.kernel.org 00*.patch`
- Wait for replies about your changes, take the comments into account, and resubmit if needed, until your changes are eventually accepted.

Contribute to the Linux Kernel (6)

- If you use `git format-patch` to produce your patches, you will need to update your branch and may need to group your changes in a different way (one patch per commit).
- Here's what we recommend
  - Update your master branch
    - `git checkout master; git pull`
  - Back to your branch, implement the changes taking community feedback into account. Commit these changes.
  - Still in your branch: reorganize your commits and commit messages
    - `git rebase --interactive origin/master`
    - `git rebase` allows to rebase (replay) your changes starting from the latest commits in master. In interactive mode, it also allows you to merge, edit and even reorder commits, in an interactive way.
  - Third, generate the new patches with `git format-patch`.

Kernel Resources

Kernel Development News

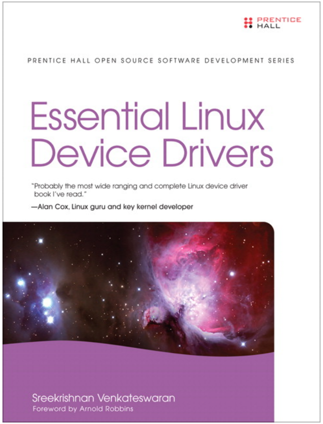
Linux Weekly News

- https://lwn.net/
- The weekly digest off all Linux and free software information sources
- In depth technical discussions about the kernel
- Subscribe to finance the editors ($7 / month)
- Articles available for non subscribers after 1 week.

Useful Reading (1)

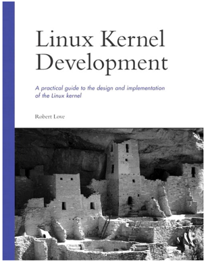
Essential Linux Device Drivers, April 2008

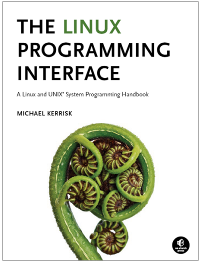
- https://elinuxdd.com/
- By Sreekrishnan Venkateswaran, an embedded IBM engineer with more than 10 years of experience
- Covers a wide range of topics not covered by LDD: serial drivers, input drivers, I2C, PCMCIA, PCI, USB, video drivers, audio drivers, block drivers, network drivers, Bluetooth, IrDA, MTD, drivers in user space, kernel debugging, etc.
- *Probably the most wide ranging and complete Linux device driver book I've read* – Alan Cox



Useful Reading (2)

- Linux Kernel Development, 3rd Edition, Jun 2010
  - Robert Love, Novell Press
  - https://rlove.org
  - A very synthetic and pleasant way to learn about kernel subsystems (beyond the needs of device driver writers)
- The Linux Programming Interface, Oct 2010
  - Michael Kerrisk, No Starch Press
  - https://man7.org/tlpi/
  - A gold mine about the kernel interface and how to use it

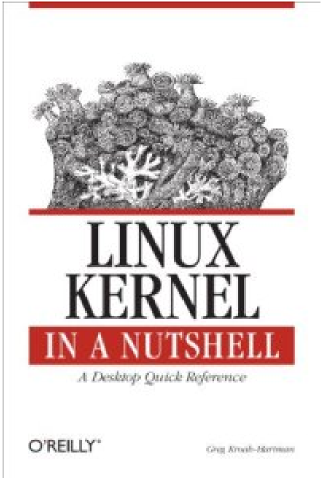




Useful Reading (3)

Linux Kernel in a Nutshell, Dec. 2006

- By Greg Kroah-Hartman, O'Reilly
  http://www.kroah.com/lkn/
- A good reference book and guide on configuring, compiling and managing the Linux kernel sources.
- Freely available on-line!
  Great companion to the printed book for easy electronic searches!
  Available as single PDF file on
  https://bootlin.com/community/kernel/lkn/
- Getting old but still containing useful content.

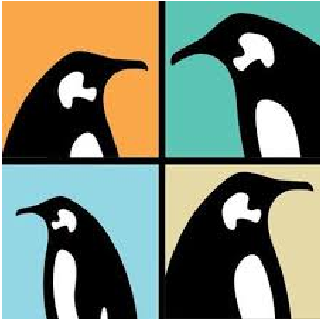


Useful Online Resources

- Kernel documentation
  - https://kernel.org/doc/
- Linux kernel mailing list FAQ
  - http://vger.kernel.org/lkml/
  - Complete Linux kernel FAQ
  - Read this before asking a question to the mailing list
- Kernel Newbies
  - https://kernelnewbies.org/
  - Glossary, articles, presentations, HOWTOs, recommended reading, useful tools for people getting familiar with Linux kernel or driver development.
- Kernel glossary
  - https://kernelnewbies.org/KernelGlossary

International Conferences (1)

- Embedded Linux Conference:
  - https://embeddedlinuxconference.com/
  - Organized by the Linux Foundation
  - Once per year, alternating North America/Europe
  - Very interesting kernel and user space topics for embedded systems developers. Many kernel and embedded project maintainers are present.
  - Presentation slides and videos freely available on https://elinux.org/ELC_Presentations
- Linux Plumbers
  - https://linuxplumbersconf.org
  - About the low-level plumbing of Linux: kernel, audio, power management, device management, multimedia, etc.
  - Not really a conventional conference with formal presentations, but rather a place where contributors on each topic meet, share their progress and make plans for



International Conferences (2)

- Kernel Recipes: https://kernel-recipes.org/
  - Well attended conference in Europe (Paris), only one track at a time, with a format that really allows for discussions.
- linux.conf.au: https://linux.org.au/conf/
  - In Australia / New Zealand
  - Features a few presentations by key kernel hackers.
- Currently, most conferences are available on-line. They are much more affordable and often free.

Continue to learn after the course

Here are a few suggestions:

- Run your labs again on your own hardware. The Nunchuk lab should be rather straightforward, but the serial lab will be quite different if you use a different processor.
- Help with tasks keeping the kernel code clean and up-to-date: `https://kernelnewbies.org/KernelJanitors/Todo`
- Propose fixes for issues reported by the *Coccinelle* tool: `make coccicheck`
- Participate to improving drivers in `drivers/staging/`
- Investigate and do the triage of issues reported by Coverity Scan: `https://scan.coverity.com/projects/linux`
- Learn by reading the kernel code by yourself, ask questions and propose improvements.
- Implement and share drivers for your own hardware, of course!

Last slides

Corrections, suggestions, contributions and translations are welcome!

bootlin

embedded Linux and kernel engineering

Thank you!

And may the Source be with you

Rights to copy

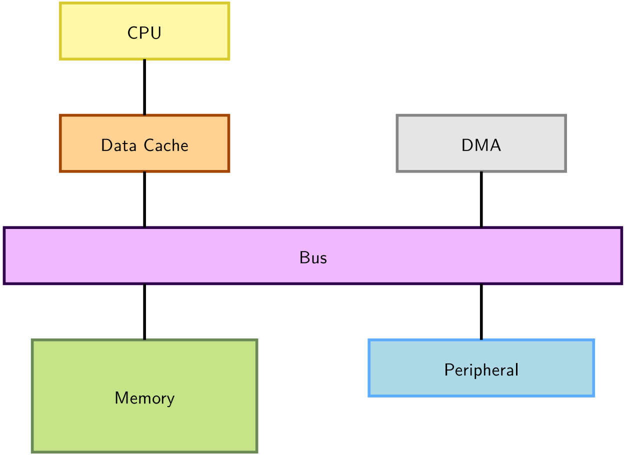
Document sources: https://github.com/bootlin/training-materials/

Backup slides

DMA

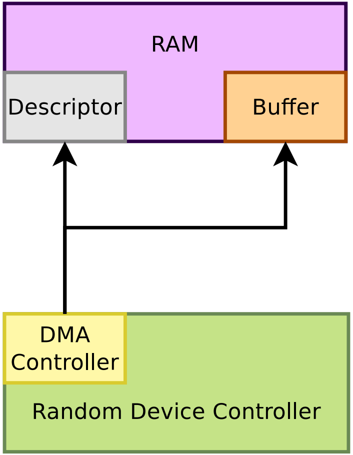
DMA integration

DMA (*Direct Memory Access*) is used to copy data directly between devices and RAM, without going through the CPU.



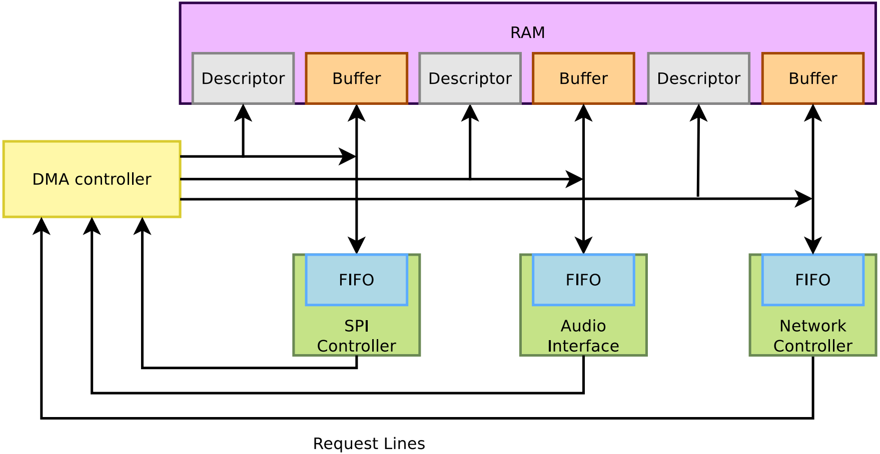
Peripheral DMA

Some device controllers embedded their own DMA controller and therefore can do DMA on their own.



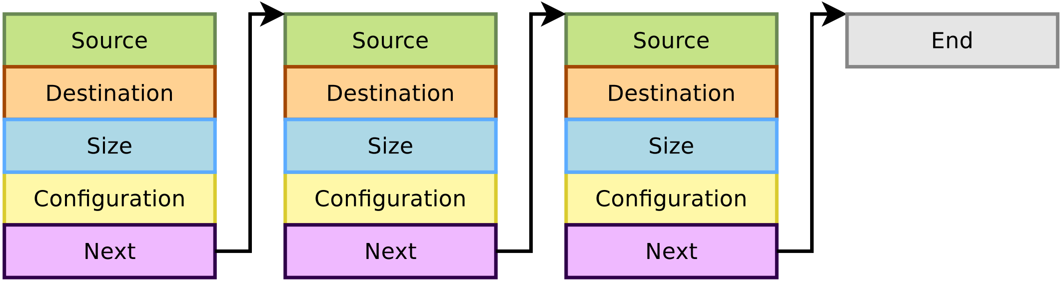
DMA controllers

Other device controllers rely on an external DMA controller (on the SoC). Their drivers need to submit DMA descriptors to this controller.



DMA descriptors

DMA descriptors describe the various attributes of a DMA transfer, and are chained.



DMA usage

Constraints with a DMA

- A DMA deals with physical addresses, so:
  - Programming a DMA requires retrieving a physical address at some point (virtual addresses are usually used)
  - The memory accessed by the DMA shall be physically contiguous
- The CPU can access memory through a data cache
  - Using the cache can be more efficient (faster accesses to the cache than the bus)
  - But the DMA does not access the CPU cache, so one needs to take care of cache coherency (cache content vs. memory content)
  - Either clean (write to memory) or invalidate the cache lines corresponding to the buffer accessed by DMA and processor at the right times

DMA memory constraints

- Need to use contiguous memory in physical space.
- Can use any memory allocated by `kmalloc()` (up to 128 KB) or `__get_free_pages()` (up to 8MB).
- Can use block I/O and networking buffers, designed to support DMA.
- Can not use `vmalloc()` memory (would have to setup DMA on each individual physical page).

Memory synchronization issues

Memory caching could interfere with DMA

- Before DMA to device
  - Need to make sure that all writes to the DMA buffer are done (corresponding cache lines cleaned)
- After DMA from device
  - Before drivers read from a DMA buffer, need to make sure that the corresponding cache lines are invalidated.
- Bidirectional DMA
  - Need to do both of the above operations

Linux DMA API

The kernel DMA utilities can take care of:

- Either allocating a buffer in a cache coherent area,
- Or making sure caches are handled when required,
- Managing the DMA mappings and IOMMU (if any).
- See `core-api/dma-api` for details about DMA and the Linux DMA generic API.
- Most subsystems (such as PCI or USB) supply their own DMA API, derived from the generic one. May be sufficient for most needs.

Coherent or streaming DMA mappings

- Coherent mappings
  - The kernel allocates a suitable buffer and sets the mapping for the driver.
  - Can simultaneously be accessed by the CPU and device.
  - So, has to be in a cache coherent memory area.
  - Usually allocated for the whole time the module is loaded.
  - Can be expensive to setup and use on some platforms.
- Streaming mappings
  - The kernel just sets the mapping for a buffer provided by the driver.
  - Use an already allocated buffer
  - Mapping set up for each transfer. Keeps DMA registers free on the hardware.

Allocating coherent mappings

The kernel takes care of both buffer allocation and mapping

```
#include <asm/dma-mapping.h>

void *                          /* Output: buffer address */
    dma_alloc_coherent(
         struct device *dev, /* device structure */
         size_t size,        /* Needed buffer size in bytes */
         dma_addr_t *handle, /* Output: DMA bus address */
         gfp_t gfp           /* Standard GFP flags */
);

void dma_free_coherent(struct device *dev,
    size_t size, void *cpu_addr, dma_addr_t handle);
```

Note: called *consistent mappings* on PCI
(`pci_alloc_consistent()` and `pci_free_consistent()`)

Setting up streaming mappings

Works on already allocated buffers

```
#include <linux/dmapool.h>

dma_addr_t dma_map_single(
      struct device *,         /* device structure */
      void *,                  /* input: buffer to use */
      size_t,                  /* buffer size */
      enum dma_data_direction /* Either DMA_BIDIRECTIONAL,
                               * DMA_TO_DEVICE or
                               * DMA_FROM_DEVICE */
);

void dma_unmap_single(struct device *dev, dma_addr_t handdle,
    size_t size, enum dma_data_direction dir);
```

DMA notes

Streaming mapping notes:

- When the mapping is active: only the device should access the buffer (potential cache issues otherwise).
- The CPU can access the buffer only after unmapping!
- Another reason: if required, this API can create an intermediate bounce buffer (used if the given buffer is not usable for DMA).
- The Linux API also supports scatter / gather DMA streaming mappings.

Commented network driver example:

- See `https://bootlin.com/pub/drivers/r6040-network-driver-with-comments.c` for a commmented network driver, which both streaming and coherent mappings.

DMA transfers

Starting DMA transfers

- If the device you're writing a driver for is doing peripheral DMA, no external API is involved.
- If it relies on an external DMA controller, you'll need to
  - Ask the hardware to use DMA, so that it will drive its request line
  - Use Linux DMAEngine framework, especially its slave API

DMAEngine slave API 1/2

In order to start a DMA transfer with DMAEngine, you need to call the following functions from your driver

1. Request a channel for exclusive use with `dma_request_channel()`, or one of its variants
2. Configure it for our use case, by filling a `struct dma_slave_config` structure with various parameters (source and destination adresses, accesses width, etc.) and passing it as an argument to `dmaengine_slave_config()`
3. Start a new transaction with `dmaengine_prep_slave_single()` or `dmaengine_prep_slave_sg()`
4. Put the transaction in the driver pending queue using `dmaengine_submit()`
5. And finally ask the driver to process all pending transactions using `dma_async_issue_pending()`

DMAEngine slave API 2/2

- Of course, all this needs to be done in addition to the DMA mapping seen previously
- Some frameworks abstract it away, such as *SPI* and *ASoC*
- Example usage of the slave API: look at the code for `stm32_i2c_prep_dma_xfer()`.

Details in kernel documentation: `driver-api/dmaengine/client`

mmap

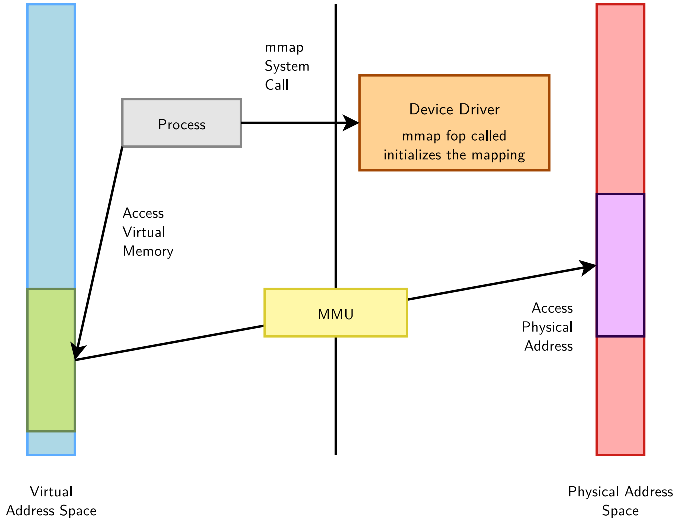
mmap

- Possibility to have parts of the virtual address space of a program mapped to the contents of a file
- Particularly useful when the file is a device file
- Allows to access device I/O memory and ports without having to go through (expensive) read, write or ioctl calls
- One can access to current mapped files by two means:
  - `/proc/<pid>/maps`
  - `pmap <pid>`

/proc/<pid>/maps

```
       start-end          perm offset major:minor inode  mapped file name
...
7f4516d04000-7f4516d06000 rw-s 1152a2000 00:05 8406   /dev/dri/card0
7f4516d07000-7f4516d0b000 rw-s 120f9e000 00:05 8406   /dev/dri/card0
...
7f4518728000-7f451874f000 r-xp 00000000 08:01 268909  /lib/x86_64-linux-gnu/libexpat.so.1.5.2
7f451874f000-7f451894f000 ---p 00027000 08:01 268909  /lib/x86_64-linux-gnu/libexpat.so.1.5.2
7f451894f000-7f4518951000 r--p 00027000 08:01 268909  /lib/x86_64-linux-gnu/libexpat.so.1.5.2
7f4518951000-7f4518952000 rw-p 00029000 08:01 268909  /lib/x86_64-linux-gnu/libexpat.so.1.5.2
...
7f451da4f000-7f451dc3f000 r-xp 00000000 08:01 1549    /usr/bin/Xorg
7f451de3e000-7f451de41000 r--p 001ef000 08:01 1549    /usr/bin/Xorg
7f451de41000-7f451de4c000 rw-p 001f2000 08:01 1549    /usr/bin/Xorg
...
```

mmap overview



How to Implement mmap - User space

- Open the device file
- Call the mmap system call (see man mmap for details):

```
void * mmap(
    void *start,   /* Often 0, preferred starting address */
    size_t length, /* Length of the mapped area */
    int prot,      /* Permissions: read, write, execute */
    int flags,     /* Options: shared mapping, private copy... */
    int fd,        /* Open file descriptor */
    off_t offset   /* Offset in the file */
);
```

- You get a virtual address you can write to or read from.

How to Implement mmap - Kernel space

- Character driver: implement an `mmap` file operation and add it to the driver file operations:

```
int (*mmap) (
    struct file *,              /* Open file structure */
    struct vm_area_struct *     /* Kernel VMA structure */
);
```

- Initialize the mapping.
  - Can be done in most cases with the `remap_pfn_range()` function, which takes care of most of the job.

remap_pfn_range()

- *pfn*: page frame number
- The most significant bits of the page address (without the bits corresponding to the page size).

```
#include <linux/mm.h>

int remap_pfn_range(
    struct vm_area_struct *, /* VMA struct */
    unsigned long virt_addr, /* Starting user
                              * virtual address */
    unsigned long pfn,       /* pfn of the starting
                              * physical address */
    unsigned long size,      /* Mapping size */
    pgprot_t prot            /* Page permissions */
);
```

Simple mmap implementation

```
static int acme_mmap
    (struct file * file, struct vm_area_struct *vma)
{
      size = vma->vm_end - vma->vm_start;

      if (size > ACME_SIZE)
          return -EINVAL;

      if (remap_pfn_range(vma,
                    vma->vm_start,
                    ACME_PHYS >> PAGE_SHIFT,
                    size,
                    vma->vm_page_prot))
          return -EAGAIN;

      return 0;
    }
```

devmem2

- https://bootlin.com/pub/mirror/devmem2.c, by Jan-Derk Bakker
- Very useful tool to directly peek (read) or poke (write) I/O addresses mapped in physical address space from a shell command line!
  - Very useful for early interaction experiments with a device, without having to code and compile a driver.
  - Uses `mmap` to `/dev/mem`.
  - Examples (`b`: byte, `h`: half, `w`: word)
    - `devmem2 0x000c0004 h` (reading)
    - `devmem2 0x000c0008 w 0xffffffff` (writing)
  - `devmem` is now available in BusyBox, making it even easier to use.

mmap summary

- The device driver is loaded. It defines an `mmap` file operation.
- A user space process calls the `mmap` system call.
- The `mmap` file operation is called.
- It initializes the mapping using the device physical address.
- The process gets a starting address to read from and write to (depending on permissions).
- The MMU automatically takes care of converting the process virtual addresses into physical ones.
- Direct access to the hardware without any expensive `read` or `write` system calls