Embedded Linux kernel and driver development training
On-site training, 5 days
Latest update: August 29, 2023

Title	**Embedded Linux kernel and driver development training**
Training objectives	• Be able to configure, build and install the Linux kernel on an embedded system. • Be able to understand the overall architecture of the Linux kernel, and how user-space applications interact with the Linux kernel. • Be able to develop simple but complete Linux kernel device drivers, thanks to the development from scratch of two drivers for two different hardware devices, that illustrate all the major concepts of the course. • Be able to navigate through the device drivers mechanisms of the Linux kernel: Device Tree, device model, bus infrastructures. • Be able to develop device drivers that communicate with hardware devices. • Be able to develop drivers that expose functionality of hardware devices to Linux user-space applications: character devices, kernel subsystems. • Be able to use the major kernel mechanisms needed for device driver development: memory management, locking, interrupt handling, sleeping, DMA. • Be able to debug Linux kernel issues, using a variety of debugging techniques and mechanisms.
Duration	**Five** days - 40 hours (8 hours per day)
Pedagogics	• Lectures delivered by the trainer: 50% of the duration • Practical labs done by participants: 50% of the duration • Electronic copies of presentations, lab instructions and data files. They are freely available at https://bootlin.com/doc/training/linux-kernel.
Trainer	One of the engineers listed on: https://bootlin.com/training/trainers/
Language	Oral lectures: English, French. Materials: English.

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Audience	People developing devices using the Linux kernel People supporting embedded Linux system developers.
Prerequisites	• **Solid experience with the C programming language**: participants must be familiar with the usage of complex data types and structures, pointers, function pointers, and the C pre-processor. • **Knowledge and practice of UNIX or GNU/Linux commands**: participants must be familiar with the Linux command line. Participants lacking experience on this topic should get trained by themselves, for example with our freely available on-line slides at bootlin.com/blog/command-line/. • **Minimal experience in embedded Linux development**: participants should have a minimal understanding of the architecture of embedded Linux systems: role of the Linux kernel vs. user-space, development of Linux user-space applications in C. Following Bootlin's *Embedded Linux* course at bootlin.com/training/embedded-linux/ allows to fulfill this pre-requisite. • **Minimal English language level: B1**, according to the *Common European Framework of References for Languages*, for our sessions in English. See bootlin.com/pub/training/cefr-grid.pdf for self-evaluation.
Required equipment	• Video projector • One PC computer on each desk (for one or two persons) with at least 8 GB of RAM, and Ubuntu Linux 22.04 / 20.04 installed in a **free partition of at least 30 GB** • Distributions other than Ubuntu Linux 22.04 / 20.04 are not supported, and using Linux in a virtual machine is not supported. • **Unfiltered and fast connection to Internet**: at least 50 Mbit/s of download bandwidth, and no filtering of web sites or protocols. • **PC computers with valuable data must be backed up** before being used in our sessions.
Certificate	Only the participants who have attended all training sessions, and who have scored over 50% of correct answers at the final evaluation will receive a training certificate from Bootlin.
Disabilities	Participants with disabilities who have special needs are invited to contact us at *training@bootlin.com* to discuss adaptations to the training course.

Hardware

The hardware platform used for the practical labs of this training session is the **BeagleBone Black** board, which features:

- An ARM AM335x processor from Texas Instruments (Cortex-A8 based), 3D acceleration, etc.
- 512 MB of RAM
- 2 GB of on-board eMMC storage (4 GB in Rev C)
- USB host and device
- HDMI output
- 2 x 46 pins headers, to access UARTs, SPI buses, I2C buses and more.
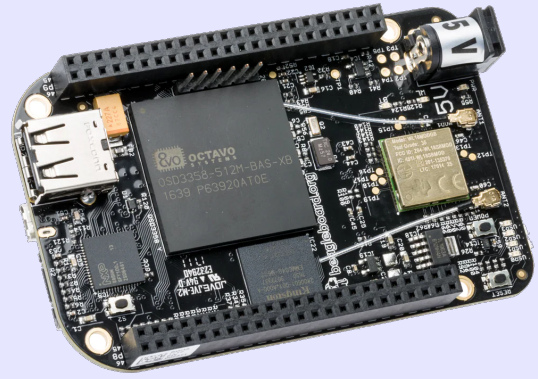
Labs

The practical labs of this training session use the following hardware peripherals to illustrate the development of Linux device drivers:

- A Wii Nunchuk, which is connected over the I2C bus to the BeagleBone Black board. Its driver will use the Linux *input* subsystem.
- An additional UART, which is memory-mapped, and will use the Linux *misc* subsystem.

While our explanations will be focused on specifically the Linux subsystems needed to implement these drivers, they will always be generic enough to convey the general design philosophy of the Linux kernel. The information learnt will therefore apply beyond just I2C, input or memory-mapped devices.

Day 1 - Morning

Lecture - Introduction to the Linux kernel	**Lab - Downloading the Linux kernel source code**
• Roles of the Linux kernel • Kernel user interface (/proc and /sys) • Overall architecture • Versions of the Linux kernel • Kernel source tree organization	• Download the Linux kernel code from Git

Lecture - Linux kernel source code	**Lab - Kernel sources**
• Specifics of Linux kernel development • Coding standards • Stability of interfaces • Licensing aspects • User-space drivers	• Making searches in the Linux kernel sources: looking for C definitions, for definitions of kernel configuration parameters, and for other kinds of information. • Using the UNIX command line and then kernel source code browsers.

Day 1 - Afternoon

Lecture - Configuring, compiling and booting the Linux kernel	**Lab - Kernel configuration, cross-compiling and booting on NFS**
• Kernel configuration. • Native and cross compilation. Generated files. • Booting the kernel. Kernel booting parameters. • Mounting a root filesystem on NFS.	*Using the BeagleBone Black board* • Configuring, cross-compiling and booting a Linux kernel with NFS boot support.

Lecture - Linux kernel modules

- Linux device drivers
- A simple module
- Programming constraints
- Loading, unloading modules
- Module dependencies
- Adding sources to the kernel tree

Lab - Writing modules

Using the BeagleBone Black board
- Write a kernel module with several capabilities.
- Access kernel internals from your module.
- Set up the environment to compile it

Day 2 - Morning

Lecture - Describing hardware devices

- Discoverable hardware: USB, PCI
- Non-discoverable hardware
- Extensive details on Device Tree: overall syntax, properties, design principles, examples

Lab - Describing hardware devices

Using the BeagleBone Black board
- Create your own Device Tree file
- Configure LEDs connected to GPIOs
- Describe an I2C-connected device in the Device Tree

Lecture - Pin muxing

- Understand the *pinctrl* framework of the kernel
- Understand how to configure the muxing of pins

Lab - Pin muxing

Using the BeagleBone Black board
- Configure the pinmuxing for the I2C bus used to communicate with the Nunchuk
- Validate that the I2C communication works using user space tools

Day 2 - Afternoon

Lecture - Linux device model

- Understand how the kernel is designed to support device drivers
- The device model
- Binding devices and drivers
- Platform devices, Device Tree
- Interface in user space: `/sys`

Lecture - Introduction to the I2C API

- The I2C subsystem of the kernel
- Details about the API provided to kernel drivers to interact with I2C devices

Lab - Communicate with the Nunchuk over I2C

Using the BeagleBone Black board
- Explore the content of `/dev` and `/sys` and the devices available on the embedded hardware platform.
- Implement a driver that registers as an I2C driver.
- Communicate with the Nunchuk and extract data from it.

Day 3 - Morning

Lecture - Kernel frameworks

- Block vs. character devices
- Interaction of user space applications with the kernel
- Details on character devices, `file_operations`, `ioctl()`, etc.
- Exchanging data to/from user space
- The principle of kernel frameworks

Lecture - The input subsystem

- Principle of the kernel *input* subsystem
- API offered to kernel drivers to expose input devices capabilities to user space applications
- User space API offered by the *input* subsystem

Lab - Expose the Nunchuk functionality to user space

Using the BeagleBone Black board
- Extend the Nunchuk driver to expose the Nunchuk features to user space applications, as a *input* device.
- Test the operation of the Nunchuk using `evtest`

Day 3 - Afternoon

Lecture - Memory management

- Linux: memory management - Physical and virtual (kernel and user) address spaces.
- Linux memory management implementation.
- Allocating with `kmalloc()`.
- Allocating by pages.
- Allocating with `vmalloc()`.

Lecture - I/O memory

- I/O memory range registration.
- I/O memory access.
- Memory ordering and barriers

Lab - Minimal platform driver and access to I/O memory

Using the BeagleBone Black board
- Implement a minimal platform driver
- Modify the Device Tree to instantiate the new serial port device.
- Reserve the I/O memory addresses used by the serial port.
- Read device registers and write data to them, to send characters on the serial port.

Day 4 - Morning

Lecture - The misc kernel subsystem

- What the *misc* kernel subsystem is useful for
- API of the *misc* kernel subsystem, both the kernel side and user space side

Lab - Output-only serial port driver

Using the BeagleBone Black board
- Extend the driver started in the previous lab by registering it into the *misc* subsystem
- Implement serial port output functionality through the *misc* subsystem
- Test serial output from user space

Lecture - Processes, scheduling, sleeping and interrupts

- Process management in the Linux kernel.
- The Linux kernel scheduler and how processes sleep.
- Interrupt handling in device drivers: interrupt handler registration and programming, scheduling deferred work.

Lab - Sleeping and handling interrupts in a device driver

Using the BeagleBone Black board
- Adding read capability to the character driver developed earlier.
- Register an interrupt handler.
- Waiting for data to be available in the `read()` file operation.
- Waking up the code when data is available from the device.
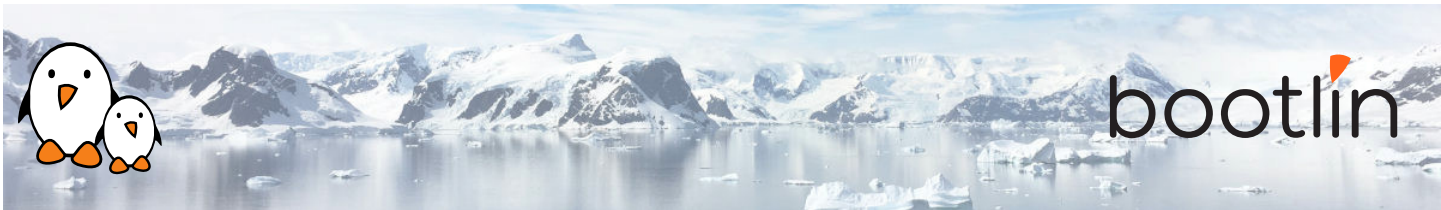
Day 4 - Afternoon

Lecture - Locking	**Lab - Locking**
• Issues with concurrent access to shared resources • Locking primitives: mutexes, semaphores, spinlocks. • Atomic operations. • Typical locking issues. • Using the lock validator to identify the sources of locking problems.	*Using the BeagleBone Black board* • Add locking to the current driver

Lecture - DMA: Direct Memory Access	**Lab - DMA: Direct Memory Access**
• Peripheral DMA vs. DMA controllers • DMA constraints: caching, addressing • Kernel APIs for DMA: `dma-mapping`, `dmaengine`, `dma-buf`	• Setup streaming mappings with the `dma` API • Configure a DMA controller with the `dmaengine` API • Configure the hardware to trigger DMA transfers • Wait for DMA completion

Day 5 - Morning

Lecture - Driver debugging techniques	**Lab - Investigating kernel faults**
• Debugging with printing functions • Using Debugfs • Analyzing a kernel oops • Using kgdb, a kernel debugger • Using the Magic SysRq commands	*Using the BeagleBone Black board* • Studying a broken driver. • Analyzing a kernel fault message and locating the problem in the source code.

Day 5 - Afternoon

Lecture - ARM board support and SoC support

- Understand the organization of the ARM support code
- Understand how the kernel can be ported to a new hardware board

Lecture - Power management

- Overview of the power management features of the kernel
- Topics covered: clocks, suspend and resume, dynamic frequency scaling, saving power during idle, runtime power management, regulators, etc.

Lecture - The Linux kernel development process

- Organization of the kernel community
- The release schedule and process: release candidates, stable releases, long-term support, etc.
- Legal aspects, licensing.
- How to submit patches to contribute code to the community.
- Kernel resources: books, websites, conferences

Lecture - If time left

- mmap

Questions and Answers

- Questions and answers with the audience about the course topics
- Extra presentations if time is left, according what most participants are interested in.