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Embedded Linux

Linux-based Embedded System Component Stack

Goals

To illustrate the main components of a Linux-based embedded system

To analyze the bootstrap process

Summary

Introduction

Bootloader

Kernel

Device tree

System programs

Application

Root filesystem

Summary

Introduction → component ที่ make up ของ embedded system

Bootloader

Kernel

Device tree

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Linux-based Embedded System Components

Bootloader

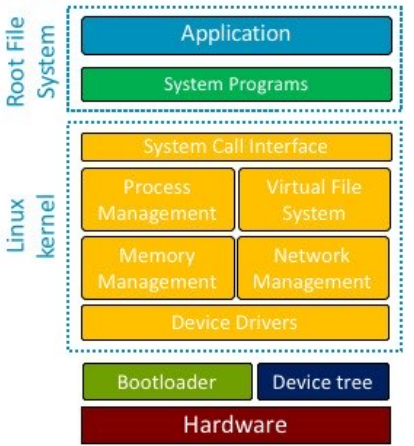
- Software executed at power-up to set-up the hardware to run the operating system

Device tree

- A tree data structure with nodes that describe the physical devices in the hardware needed by the Linux kernel to initialize properly the device drivers

Linux Kernel (main component)

- The operating system code providing all the services to manage the hardware resources



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Linux-based Embedded System Components

System programs

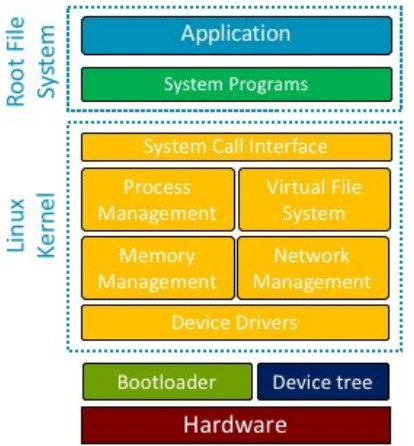
- User-friendly utilities to access operating system services

Application

- Software implementing the functionalities to be delivered to the embedded system user

Root filesystem

- Container for the Linux Kernel configuration files, the system programs, and the application



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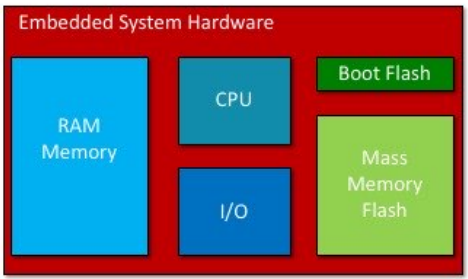
Reference Hardware Model

Embedded System Hardware components:

- RAM memory: volatile memory storing data/code
- CPU: processor running software
- I/O: peripherals to get inputs from the user, and to provide outputs to the user
- Boot Flash: small non-volatile memory needed at power-up (discussed later)
- Mass Memory Flash: large non-volatile memory (discussed later)



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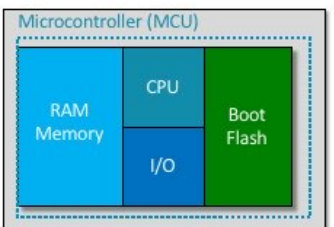
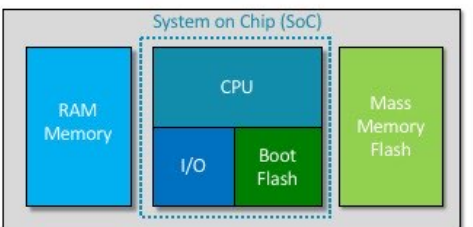
Reference Hardware Model Implementations

Multiple implementations of the reference hardware model are possible. For example:

- Microcontroller-based implementation: a single device hosts most of the reference model components (e.g. CPU, RAM memory, boot flash).
- System-on-Chip implementation: most of the reference model components are discrete components, while the CPU is integrated with some of them (e.g. I/O, boot flash).





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CPU Memory Map

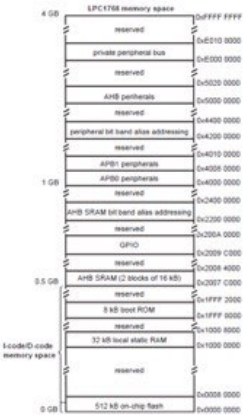
The CPU generates 2^N different addresses ($0 \rightarrow 2^N-1$).

- N=number of bits of the address bus

Each device (memory, I/O, etc.) is associated with a range of addresses.

The memory map describes this association for all the devices.

Memory map of NXP LPC1768 (Cortex-M3)



Summary

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The Role of the Bootloader

A processor is designed to run software from “somewhere”.

To start running the software, the processor needs to know:

- Where the software is located
- How to get access to the software location
- Where the stack is located

The Role of the Bootloader

ต้องรันเป็นอันแรก

When powered-up, the processor needs a simple way to get the information it needs.

- Where the software is located
- How to get access to the software location
- Where the stack is located

pointer ต่อ address ที่เก็บคำสั่งแรกที่ต้องทำงานของ firmware

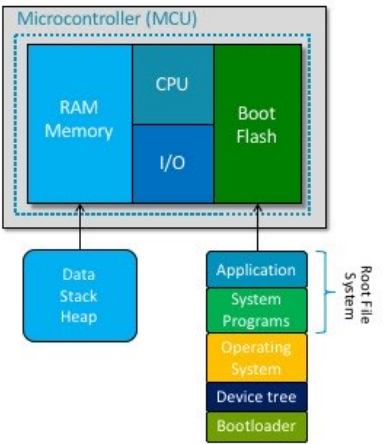
At power-up, the program counter is set to a default known value, the reset vector.

- The software starting at the reset vector, which will load the bootloader, takes care of providing the processor all the needed information.
- The operations performed depend on the system architecture.

Possible Scenarios

Scenario 1, typical of microcontrollers

- All the sw (bootloader + device tree + operating system + root filesystem) is stored in persistent storage (boot flash) embedded in the microcontroller.
- All the sw is executed from the persistent storage.
- The CPU reset vector is located in the boot flash.
- The RAM Memory is embedded in the microcontroller and is used for data, stack and heap only.



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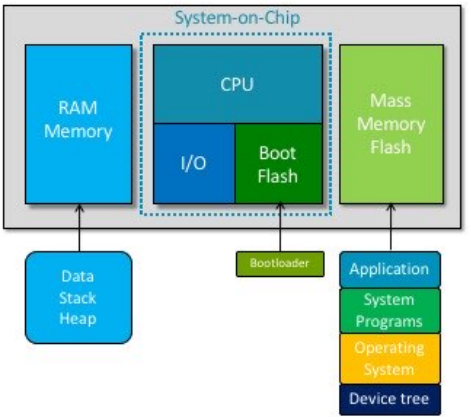
Possible Scenarios

Scenario 2, typical of System-on-Chip

- The bootloader is stored into the boot flash.
- The CPU reset vector is located in the boot flash.
- The root filesystem, operating systems, and device tree are stored in the mass memory flash and loaded in RAM memory by the bootloader.
- The RAM memory is external to the SoC. It will store the operating system + application software, root filesystem (if configured as RAM disk), data, stack, and heap.



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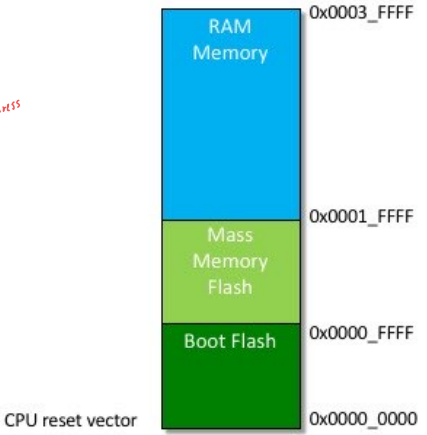
An Example of Bootloader Operations

Let's consider Scenario 2 for a given SoC with the following memory map:

- RAM memory 512 kbytes (arranged as 128 kwords, each 32 bytes long), from 0x0002_0000 to 0x0003_FFFF
- Mass memory flash 256 kbytes (same organization as before), from 0x0001_0000 to 0x0001_FFFF
- Boot flash 256 kbytes (same organization as before), from 0x000_0000 to 0x0000_FFFF



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An Example of Bootloader Operations

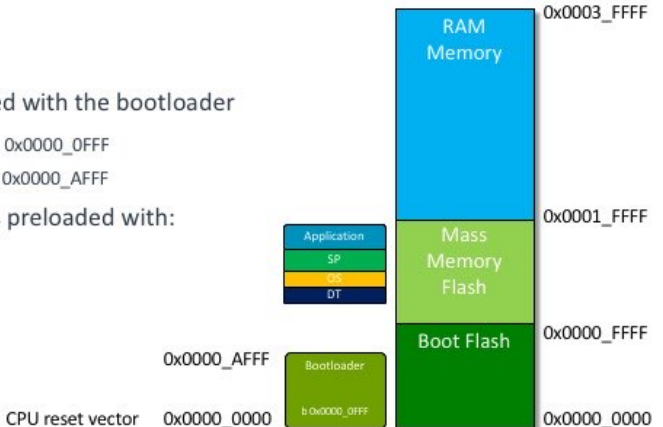
Time = before power up

The boot flash is preloaded with the bootloader

- First bootloader instruction at 0x0000_0FFF
- Last bootloader instruction at 0x0000_AFFF

The mass memory flash is preloaded with:

- Device tree (DT)
- Operating systems (OS)
- System programs (SP)
- Application



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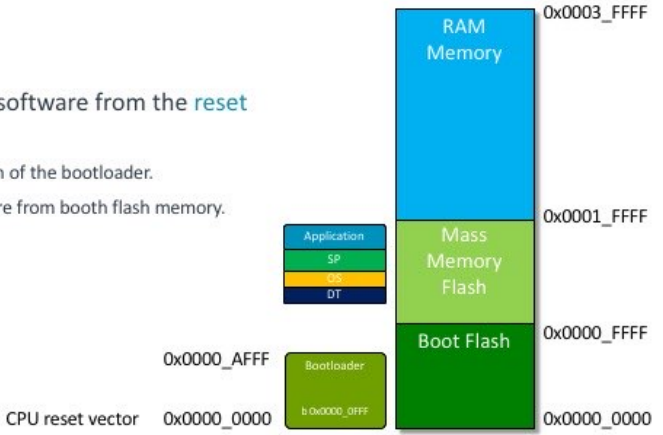
An Example of Bootloader Operations

Time = power up

The CPU starts executing software from the reset vector:

- It jumps to the first instruction of the bootloader.
- It runs the bootloader software from booth flash memory.



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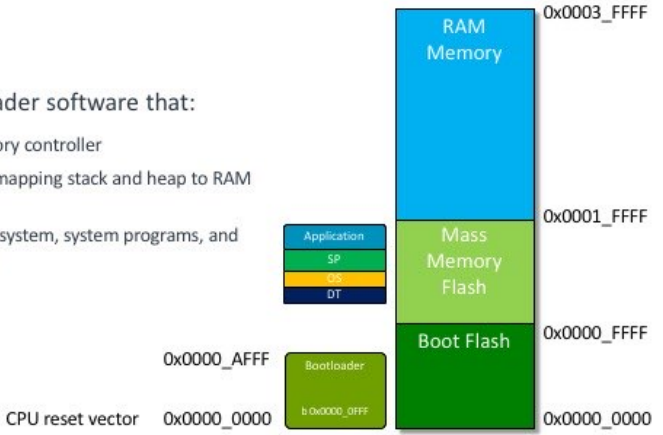
An Example of Bootloader Operations

Time = during bootstrap

The CPU executes bootloader software that:

- Initializes the CPU RAM memory controller
- Sets up the CPU registers for mapping stack and heap to RAM memory
- Copies device tree, operating system, system programs, and applications to RAM memory



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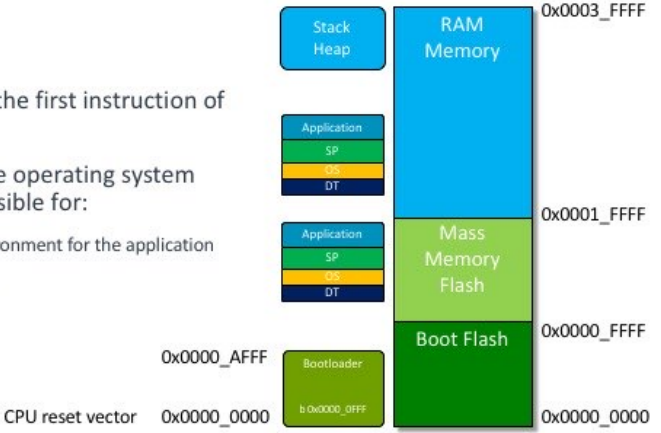
An Example of Bootloader Operations

Time = end of bootstrap

The bootloader jumps to the first instruction of the operating system.

The CPU now executes the operating system software, which is responsible for:

- Setting-up the execution environment for the application
- Starting application execution



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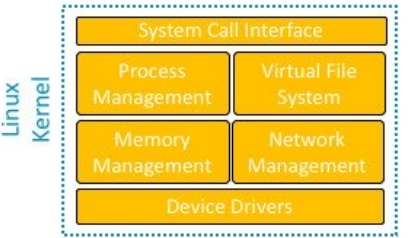
Linux Kernel

The Linux Kernel is the software responsible for optimally managing the embedded system's hardware resources.

It offers services such as:

- Process management → task scheduling
- Process scheduling
- Inter-process communication → share data
- Memory management → share memory in block sizes
- I/O management (device drivers)
- File system
- Networking
- And more



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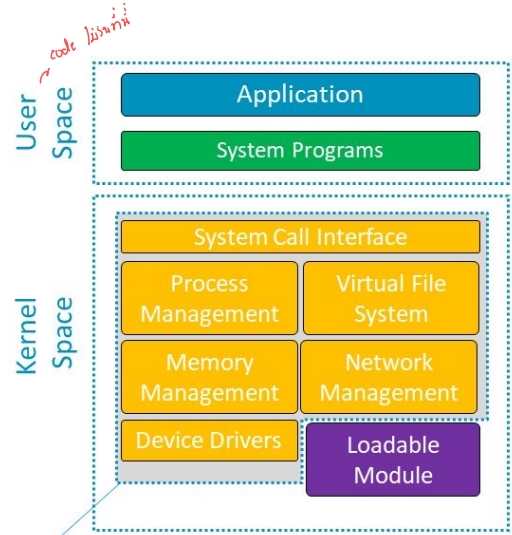
Linux Kernel

The Linux kernel adopts a layered operating system architecture:

- The operating system is divided into two layers, one (user space) built on top of the other (Kernel space).
- User space and Kernel space are different address spaces.
- Basic services are delivered by a single executable, monolithic Kernel.
- Services can be extended at run-time through loadable Kernel modules



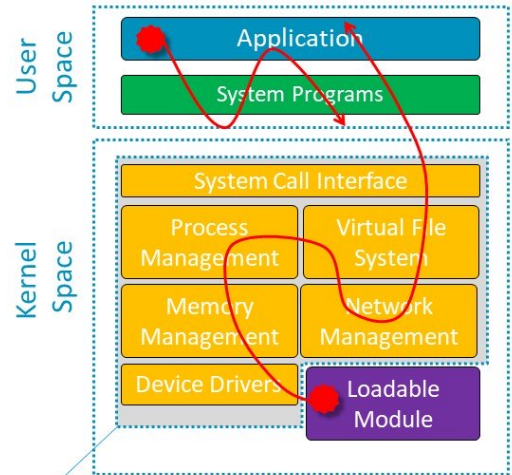
Linux Kernel

Advantage

- Good separation between application/system programs and kernel. Bugs in the user space do not corrupt the kernel.

Disadvantages

- Bugs in one Kernel component (e.g. a new device driver) can crash the whole system.



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Device Tree

To manage hardware resources, the Kernel must know which resources are available in the embedded system (i.e. the hardware description: I/O devices, memory, etc).

There are two ways to provide this information to the Kernel:

- Hardcode it into the Kernel binary code. Each modification to the hardware definition requires recompiling the source code.
- Provide it to the Kernel when the bootloader uses a binary file, the device tree blob.

A device tree blob (DTB) file is produced from a device tree source (DTS).

- A hardware definition can be changed more easily as only DTS recompilation is needed.
- Kernel recompilation is not needed upon changes to the hardware definition. This is a big time saver.

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System Programs

System programs provide a convenient environment for program development and execution.

They can be divided into:

- Status information
- File modification
- Programming language support
- Program loading and execution
- Communications
- Application programs

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Application

The application is the software required to provide the end user service for which the embedded system was conceived.

Examples can be found in many different products:

- Network Attached Storage (NAS)
- Network router
- In-vehicle infotainment
- Specialized lab equipment
- And more

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Root Filesystem

The Linux Kernel needs a file system, called a root filesystem, at startup.

- It contains the configuration file needed to prepare the execution environment for the application (e.g. setting up the Ethernet address).
- It contains the first user-level process (init).

The root filesystem can be:

- A portion of the RAM treated as a file system known as Initial RAM Disk (initrd), if the embedded system does not need to store data persistently during its operations
- A persistent storage in the embedded system, if the embedded system has to store data persistently during its operations
- A persistent storage accessed over the network, if developing a Linux-based embedded system

Typical Layout of the Root Filesystem

```
/                                   # Disk root
        /bin                        # Repository for binary files
        /lib                        # Repository for library files
        /dev                        # Repository for device files
                console c 5 1       # Console device file
                null c 1 3          # Null device file
                zero c 1 5          # All-zero device file
                tty c 5 0           # Serial console device file
                tty0 c 4 0          # Serial terminal device file
                tty1 c 4 1          #
                tty2 c 4 2          #
                tty3 c 4 3          #
                tty4 c 4 4          #
                tty5 c 4 5          #
        /etc                        # Repository for config files
                inittab             # The inittab
                /init.d             # Repository for init config files
                        rcS         # The script run at sysinit
        /proc                       # The /proc file system
        /sbin                       # Repository for accessory binary files
        /tmp                        # Repository for temporary files
        /var                        # Repository for optional config files
        /usr                        # Repository for user files
        /sys                        # Repository for system service files
        /media                      # Mount point for removable storage
```