

Embedded Linux system development

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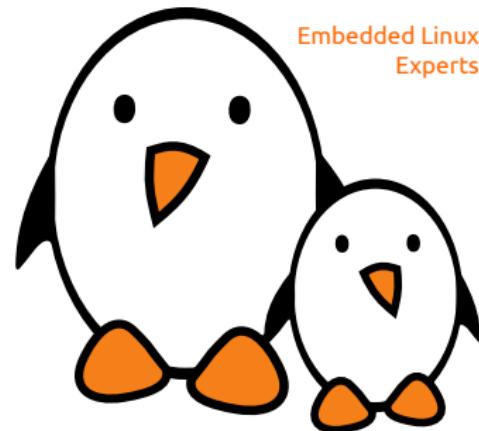
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Document updates and sources:

<http://free-electrons.com/doc/training/embedded-linux>

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There are many hyperlinks in the document

- ▶ Regular hyperlinks:

<http://kernel.org/>

- ▶ Kernel documentation links:

[Documentation/kmemcheck.txt](#)

- ▶ Links to kernel source files and directories:

[drivers/input](#)

[include/linux/fb.h](#)

- ▶ Links to the declarations, definitions and instances of kernel symbols (functions, types, data, structures):

[platform_get_irq\(\)](#)

[GFP_KERNEL](#)

[struct file_operations](#)

- ▶ An employee-owned, software engineering company from Berlin
- ▶ We do: Application Engineering, Platform Engineering, Open Source Compliance & Guidance
- ▶ Head count: 15 (from 5 countries)
- ▶ Recent activities:
 - ▶ fleet development (1.0.0 yay!)
<https://github.com/coreos/fleet>
 - ▶ Immmr to the Cloud
<http://coreosfest2016.sched.org/event/6T0b>
 - ▶ MultipathTCP in connman
<https://endocode.com/blog/2016/03/22/multipathtcp-support-for-connman/>

Generic course information

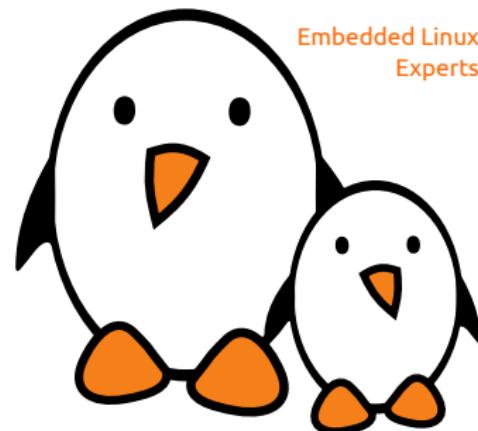
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Using Atmel SAMA5D3 Xplained boards in all practical labs

- ▶ SAMA5D36 (Cortex A5) CPU from Atmel
- ▶ USB powered!
- ▶ 256 MB DDR2 RAM, 256 MB NAND flash
- ▶ 2 Ethernet ports (Gigabit + 100 Mbit)
- ▶ 2 USB 2.0 host, 1 USB device
- ▶ 1 MMC/SD slot
- ▶ 3.3 V serial port (like Beaglebone Black)
- ▶ Misc: Arduino R3-compatible header, JTAG, buttons, LEDs
- ▶ Currently sold at 69 EUR by Mouser (V.A.T. not included)



Board and CPU documentation, design files, software:
<http://www.atmel.com/sama5d3xplained>

During the lectures...

- ▶ Don't hesitate to ask questions. Other people in the audience may have similar questions too.
- ▶ This helps the trainer to detect any explanation that wasn't clear or detailed enough.
- ▶ Don't hesitate to share your experience, for example to compare Linux / Android with other operating systems used in your company.
- ▶ Your point of view is most valuable, because it can be similar to your colleagues' and different from the trainer's.
- ▶ Your participation can make our session more interactive and make the topics easier to learn.

During practical labs...

- ▶ Open the electronic copy of your lecture materials, and use it throughout the practical labs to find the slides you need again.
- ▶ Don't hesitate to copy and paste commands from the PDF slides and labs.

During practical labs, write down all your commands in a text file.

- ▶ You can save a lot of time re-using commands in later labs.
- ▶ This helps to replay your work if you make significant mistakes.
- ▶ You build a reference to remember commands in the long run.
- ▶ That's particular useful to keep kernel command line settings that you used earlier.
- ▶ Also useful to get help from the instructor, showing the commands that you run.

gedit ~/lab-history.txt

Lab commands

```
Cross-compiling kernel:  
export ARCH=arm  
export CROSS_COMPILE=arm-linux-  
make sama5_defconfig  
  
Booting kernel through tftp:  
setenv bootargs console=ttyS0 root=/dev/nfs  
setenv bootcmd tftp 0x21000000 zImage; tftp  
0x22000000 dtb; bootz 0x21000000 - 0x2200...
```

```
Making ubifs images:  
mkfs.ubifs -d rootfs -o root.ubifs -e 124KiB  
-m 2048 -c 1024
```

Encountered issues:
Restart NFS server after editing /etc/exports!

As in the Free Software and Open Source community, cooperation during practical labs is valuable in this training session:

- ▶ If you complete your labs before other people, don't hesitate to help other people and investigate the issues they face. The faster we progress as a group, the more time we have to explore extra topics.
- ▶ Explain what you understood to other participants when needed. It also helps to consolidate your knowledge.
- ▶ Don't hesitate to report potential bugs to your instructor.
- ▶ Don't hesitate to look for solutions on the Internet as well.

Introduction into Linux

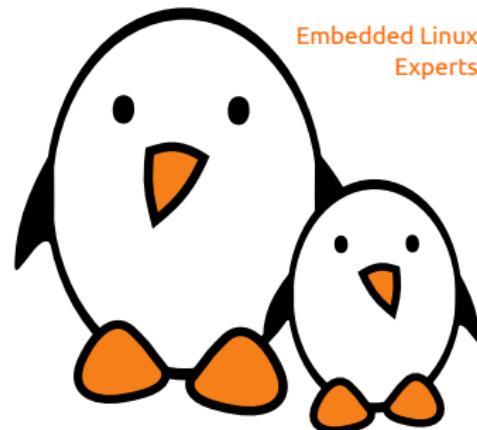
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- ▶ An Unix-like and mostly POSIX-compliant operating system
- ▶ More specific: an operating system kernel
- ▶ Linux distribution: kernel bundled with software (GNU)

- ▶ 1991 started by Linus Torvalds as a hobby project
- ▶ 1992 version 0.99 released under GPL
- ▶ 1993 first Linux distribution released: Slackware
- ▶ 1993 first release of Debian GNU/Linux distribution
- ▶ 1995, Linux is more and more popular on server systems
- ▶ 2000, Linux is more and more popular on **embedded systems**
- ▶ 2008, Linux is more and more popular on mobile devices
- ▶ 2010, Linux is more and more popular on phones

- ▶ Any good and sufficiently recent **Linux desktop distribution** can be used for the development workstation
 - ▶ Ubuntu, Debian, Fedora, openSUSE, Red Hat, etc.
- ▶ We recommend Ubuntu, as it is a **widely used and easy to use** desktop Linux distribution
- ▶ I personally prefer Debian GNU/Linux



Defined by the Filesystem Hierarchy Standard :

<http://www.pathname.com/fhs/>

- / Toplevel directory (root of the filesystem)
- /bin Basic programs
- /boot Kernel image (only when the kernel is loaded from a filesystem, not common on non-x86 architectures)
- /dev Device files (covered later)
- /etc System-wide configuration
- /home Directory for the users home directories
- /lib Basic libraries
- /media Mount points for removable media
- /mnt Mount points for static media
- /proc Mount point for the proc virtual filesystem

- /root Home directory of the root user
- /sbin Basic system programs
- /sys Mount point of the sysfs virtual filesystem
- /tmp Temporary files
- /usr "Unix system resources"
 - /usr/bin Non-basic programs
 - /usr/lib Non-basic libraries
- /usr/local Software installed by the sysadmin
- /usr/sbin Non-basic system programs
- /var Variable data files. This includes spool directories and files, administrative and logging data, and transient and temporary files

Almost everything in Linux is a file.

Regular files

Directories Directories are files listing a set of files

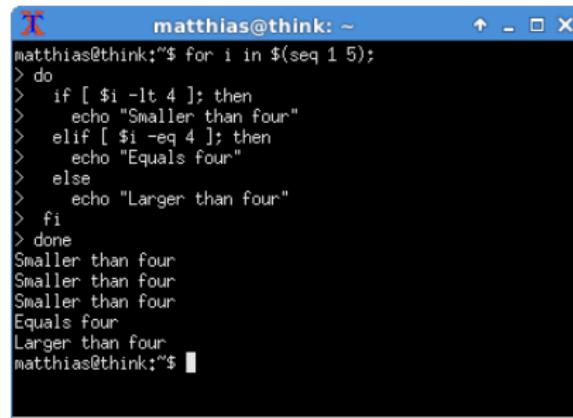
Symbolic links File referring to the name of another file

Devices Read and Write from devices as from regular files

Pipes Cascade programs `cat *.log | grep err`

Sockets Inter process communication

- ▶ Shell: tool to execute user commands
- ▶ Commands are typed into a text terminal
- ▶ Results are also displayed on the text terminal
- ▶ Shells can be scripted (variables, conditionals, iterations...)



A screenshot of a terminal window titled "matthias@think: ~". The window contains the following text:

```
matthias@think:~$ for i in $(seq 1 5);
> do
>   if [ $i -lt 4 ]; then
>     echo "Smaller than four."
>   elif [ $i -eq 4 ]; then
>     echo "Equals four"
>   else
>     echo "Larger than four"
>   fi
> done
Smaller than four
Smaller than four
Smaller than four
Equals four
Larger than four
matthias@think:~$
```

- ▶ sh: The Bourne Shell (traditional Unix shell)
- ▶ bash: Bourne Again SHell (improved implementation of sh)
- ▶ zsh: "extended Bourne Shell"
- ▶ csh: C Shell (c-like syntax)
- ▶ mksh: MirBSD Korn Shell (fork ksh, now default on Android)

Please download and use this cheat sheet:

http://free-electrons.com/doc/command_memento_de.pdf



- ▶ Linux is a multi-user operating system
 - ▶ The **root user is the administrator**, and it can do privileged operations such as: mounting filesystems, configuring the network, creating device files, changing the system configuration, installing or removing software
 - ▶ All **other users are unprivileged**, and cannot perform these administrator-level operations
- ▶ On an Ubuntu system, it is not possible to log in as `root`, only as a normal user.
- ▶ The system has been configured so that the user account created first is allowed to run privileged operations through a program called `sudo`.
 - ▶ Example: `sudo mount /dev/sda2 /mnt/disk`

Don't work as root all the time. It's dangerous.
Better use sudo.

- ▶ `sudo -l` Show what commands are allowed
- ▶ `sudo less /var/log/syslog` Read a logfile

```
ls -l /bin/bash
-rwxr-xr-x 1 root root 1029624 Nov 13 2014 /bin/bash
three types of access rights
```

- r Read access
- w Write access
- x Execute rights

three types of access levels

- u User: owner of the file
- g Group: list of users
- o Other: all other users

Maintain permissions of files

`chmod -w file` make the file readonly for all

`chmod u+w file` make the file writeable for the owner

`chmod +x file` make the file executeable for all

`chmod go-w file` make the file readonly for group and others

Maintain ownership of files

`chown matthias file` Set the owner of the file to matthias

`chown matthias.dialout file` Set the owner of the file to
matthias and the group to dialout

`chgrp dialout file` Set the group of the file to dialout

- ▶ The distribution mechanism for software in GNU/Linux is different from the one in Windows
- ▶ Linux distributions provides a central and coherent way of installing, updating and removing applications and libraries: **packages**
- ▶ Packages contains the application or library files, and associated meta-information, such as the version and the dependencies
 - ▶ .deb on Debian and Ubuntu, .rpm on Red Hat, Fedora, openSUSE
- ▶ Packages are stored in **repositories**, usually on HTTP or FTP servers
- ▶ You should only use packages from official repositories for your distribution, unless strictly required.

Instructions for Debian based GNU/Linux systems (Debian, Ubuntu...)

- ▶ Package repositories are specified in `/etc/apt/sources.list`
- ▶ To update package repository lists:
`sudo apt-get update`
- ▶ To find the name of a package to install, the best is to use the search engine on <http://packages.debian.org> or on <http://packages.ubuntu.com>. You may also use:
`apt-cache search <keyword>`

- ▶ To install a given package:
`sudo apt-get install <package>`
- ▶ To remove a given package:
`sudo apt-get remove <package>`
- ▶ To install all available package updates:
`sudo apt-get dist-upgrade`
- ▶ Get information about a package:
`apt-cache show <package>`
- ▶ Graphical interfaces
 - ▶ Synaptic for GNOME
 - ▶ KPackageKit for KDE

Further details on package management:

<http://www.debian.org/doc/manuals/apt-howto/>

Introduction to Embedded Linux

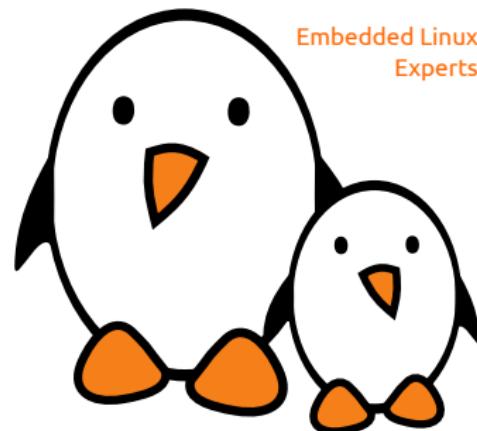
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- ▶ 1983, Richard Stallman, **GNU project** and the **free software** concept. Beginning of the development of *gcc*, *gdb*, *glibc* and other important tools
- ▶ 1991, Linus Torvalds, **Linux kernel project**, a Unix-like operating system kernel. Together with GNU software and many other open-source components: a completely free operating system, GNU/Linux
- ▶ 1995, Linux is more and more popular on server systems
- ▶ 2000, Linux is more and more popular on **embedded systems**
- ▶ 2008, Linux is more and more popular on mobile devices
- ▶ 2010, Linux is more and more popular on phones

- ▶ A program is considered **free** when its license offers to all its users the following **four** freedoms
 - ▶ Freedom to run the software for any purpose
 - ▶ Freedom to study the software and to change it
 - ▶ Freedom to redistribute copies
 - ▶ Freedom to distribute copies of modified versions
- ▶ These freedoms are granted for both commercial and non-commercial use
- ▶ They imply the availability of source code, software can be modified and distributed to customers
- ▶ **Good match for embedded systems!**

Embedded Linux is the usage of the **Linux kernel** and various **open-source** components in embedded systems

Advantages of Linux and open-source for embedded systems

- ▶ The key advantage of Linux and open-source in embedded systems is the **ability** to re-use components
- ▶ The open-source ecosystem already provides many components for standard features, from hardware support to network protocols, going through multimedia, graphic, cryptographic libraries, etc.
- ▶ As soon as a hardware device, or a protocol, or a feature is wide-spread enough, high chance of having open-source components that support it.
- ▶ Allows to quickly design and develop complicated products, based on existing components.
- ▶ No-one should re-develop yet another operating system kernel, TCP/IP stack, USB stack or another graphical toolkit library.
- ▶ **Allows to focus on the added value of your product.**

- ▶ Free software can be duplicated on as many devices as you want, free of charge.
- ▶ If your embedded system uses only free software, you can reduce the cost of software licenses to zero. Even the development tools are free, unless you choose a commercial embedded Linux edition.
- ▶ **Allows to have a higher budget for the hardware or to increase the company's skills and knowledge**

- ▶ With open-source, you have the source code for all components in your system
- ▶ Allows unlimited modifications, changes, tuning, debugging, optimization, for an unlimited period of time
- ▶ Without lock-in or dependency from a third-party vendor
 - ▶ To be true, non open-source components must be avoided when the system is designed and developed
- ▶ **Allows to have full control over the software part of your system**

- ▶ Many open-source components are widely used, on millions of systems
- ▶ Usually higher quality than what an in-house development can produce, or even proprietary vendors
- ▶ Of course, not all open-source components are of good quality, but most of the widely-used ones are.
- ▶ **Allows to design your system with high-quality components at the foundations**

- ▶ Open-source being freely available, it is easy to get a piece of software and evaluate it
- ▶ Allows to easily study several options while making a choice
- ▶ Much easier than purchasing and demonstration procedures needed with most proprietary products
- ▶ **Allows to easily explore new possibilities and solutions**

- ▶ Open-source software components are developed by communities of developers and users
- ▶ This community can provide a high-quality support: you can directly contact the main developers of the component you are using. The likelihood of getting an answer doesn't depend what company you work for.
- ▶ Often better than traditional support, but one needs to understand how the community works to properly use the community support possibilities
- ▶ **Allows to speed up the resolution of problems when developing your system**

- ▶ Possibility of taking part into the development community of some of the components used in the embedded systems: bug reporting, test of new versions or features, patches that fix bugs or add new features, etc.
- ▶ Most of the time the open-source components are not the core value of the product: it's the interest of everybody to contribute back.
- ▶ For the *engineers*: a very **motivating** way of being recognized outside the company, communication with others in the same field, **opening of new possibilities**, etc.
- ▶ For the *managers*: **motivation factor** for engineers, allows the company to be **recognized** in the open-source community and therefore get support more easily and be **more attractive** to open-source developers

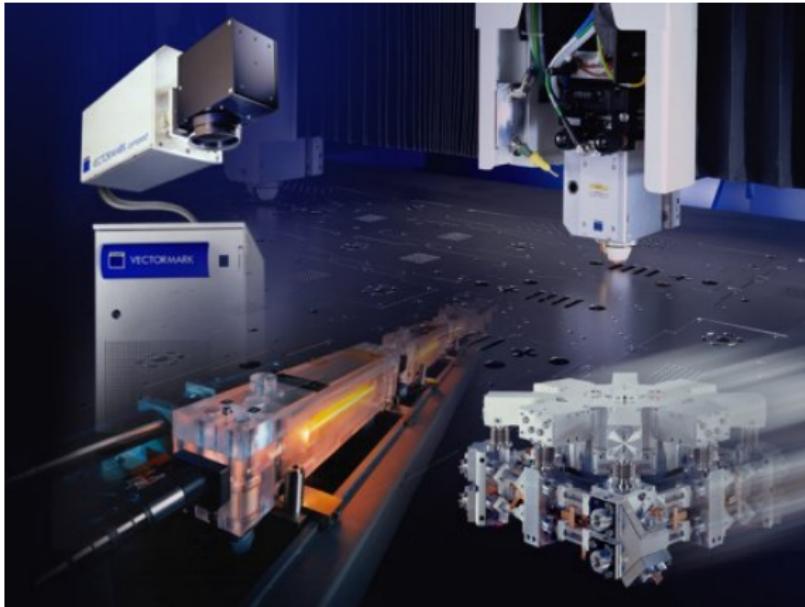
A few examples of embedded systems running Linux





ENDO CODE Point of sale terminal







Embedded hardware for Linux systems

The Linux kernel and most other architecture-dependent components support a wide range of 32 and 64 bits architectures

- ▶ x86 and x86-64, as found on PC platforms, but also embedded systems (multimedia, industrial)
- ▶ ARM, with hundreds of different SoC (multimedia, industrial)
- ▶ PowerPC (mainly real-time, industrial applications)
- ▶ MIPS (mainly networking applications)
- ▶ SuperH (mainly set top box and multimedia applications)
- ▶ Blackfin (DSP architecture)
- ▶ Microblaze (soft-core for Xilinx FPGA)
- ▶ Coldfire, SCore, Tile, Xtensa, Cris, FRV, AVR32, M32R

- ▶ Both MMU and no-MMU architectures are supported, even though no-MMU architectures have a few limitations.
- ▶ Linux is not designed for small microcontrollers.
- ▶ Besides the toolchain, the bootloader and the kernel, all other components are generally **architecture-independent**

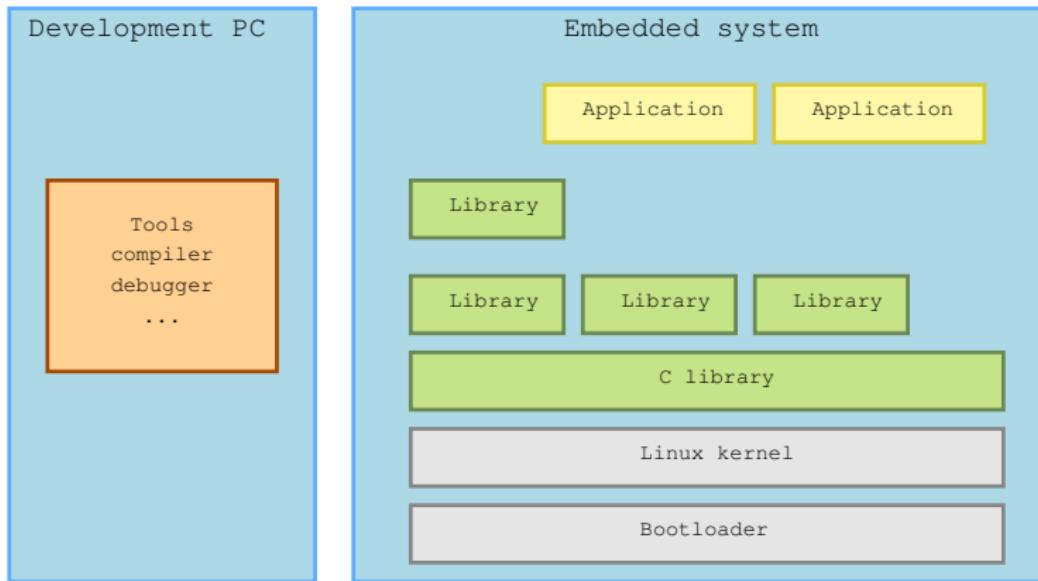
- ▶ **RAM:** a very basic Linux system can work within 8 MB of RAM, but a more realistic system will usually require at least 32 MB of RAM. Depends on the type and size of applications.
- ▶ **Storage:** a very basic Linux system can work within 4 MB of storage, but usually more is needed.
 - ▶ Flash storage is supported, both NAND and NOR flash, with specific filesystems
 - ▶ Block storage including SD/MMC cards and eMMC is supported
- ▶ Not necessarily interesting to be too restrictive on the amount of RAM/storage: having flexibility at this level allows to re-use as many existing components as possible.

- ▶ The Linux kernel has support for many common communication buses
 - ▶ I2C
 - ▶ SPI
 - ▶ CAN
 - ▶ 1-wire
 - ▶ SDIO
 - ▶ USB
- ▶ And also extensive networking support
 - ▶ Ethernet, Wifi, Bluetooth, CAN, etc.
 - ▶ IPv4, IPv6, TCP, UDP, SCTP, DCCP, etc.
 - ▶ Firewalling, advanced routing, multicast

- ▶ **Evaluation platforms** from the SoC vendor. Usually expensive, but many peripherals are built-in. Generally unsuitable for real products.
- ▶ **Component on Module**, a small board with only CPU/RAM/flash and a few other core components, with connectors to access all other peripherals. Can be used to build end products for small to medium quantities.
- ▶ **Community development platforms**, to make a particular SoC popular and easily available. These are ready-to-use and low cost, but usually have less peripherals than evaluation platforms. To some extent, can also be used for real products.
- ▶ **Custom platform**. Schematics for evaluation boards or development platforms are more and more commonly freely available, making it easier to develop custom platforms.

- ▶ Make sure the hardware you plan to use is already supported by the Linux kernel, and has an open-source bootloader, especially the SoC you're targeting.
- ▶ Having support in the official versions of the projects (kernel, bootloader) is a lot better: quality is better, and new versions are available.
- ▶ Some SoC vendors and/or board vendors do not contribute their changes back to the mainline Linux kernel. Ask them to do so, or use another product if you can. A good measurement is to see the delta between their kernel and the official one.
- ▶ **Between properly supported hardware in the official Linux kernel and poorly-supported hardware, there will be huge differences in development time and cost.**

Embedded Linux system architecture



- ▶ Cross-compilation toolchain
 - ▶ Compiler that runs on the development machine, but generates code for the target
- ▶ Bootloader
 - ▶ Started by the hardware, responsible for basic initialization, loading and executing the kernel
- ▶ Linux Kernel
 - ▶ Contains the process and memory management, network stack, device drivers and provides services to user space applications
- ▶ C library
 - ▶ The interface between the kernel and the user space applications
- ▶ Libraries and applications
 - ▶ Third-party or in-house

Several distinct tasks are needed when deploying embedded Linux in a product:

- ▶ **Board Support Package development**

- ▶ A BSP contains a bootloader and kernel with the suitable device drivers for the targeted hardware

- ▶ **System integration**

- ▶ Integrate all the components, bootloader, kernel, third-party libraries and applications and in-house applications into a working system
 - ▶ Purpose of *this* training

- ▶ **Development of applications**

- ▶ Normal Linux applications, but using specifically chosen libraries

Embedded Linux development environment

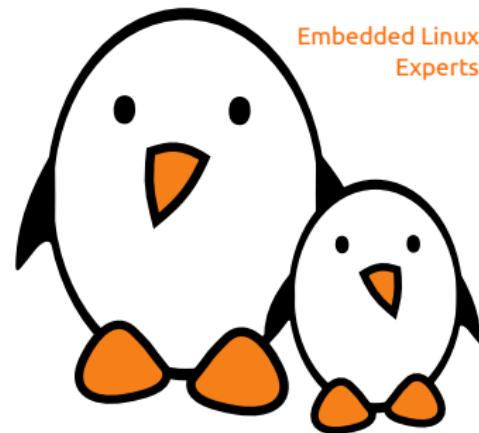
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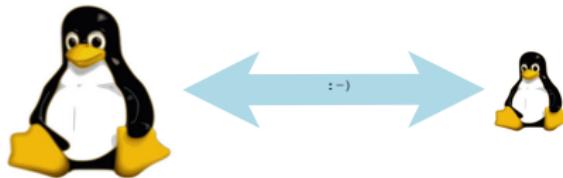
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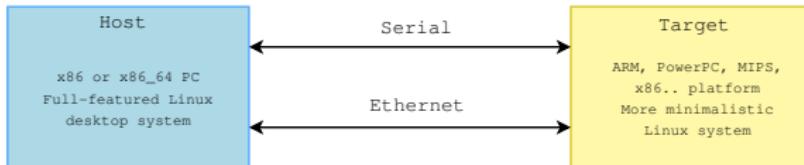


- ▶ Two ways to switch to embedded Linux
 - ▶ Use **solutions provided and supported by vendors** like MontaVista, Wind River or TimeSys. These solutions come with their own development tools and environment. They use a mix of open-source components and proprietary tools.
 - ▶ Use **community solutions**. They are completely open, supported by the community.
- ▶ In this training sessions, we do not promote a particular vendor, and therefore use community solutions
 - ▶ However, knowing the concepts, switching to vendor solutions will be easy

- ▶ We strongly recommend to use Linux as the desktop operating system to embedded Linux developers, for multiple reasons.
- ▶ All community tools are developed and designed to run on Linux. Trying to use them on other operating systems (Windows, Mac OS X) will lead to trouble, and their usage on these systems is generally not supported by community developers.
- ▶ As Linux also runs on the embedded device, all the knowledge gained from using Linux on the desktop will apply similarly to the embedded device.



- ▶ When doing embedded development, there is always a split between
 - ▶ The *host*, the development workstation, which is typically a powerful PC
 - ▶ The *target*, which is the embedded system under development
- ▶ They are connected by various means: almost always a serial line for debugging purposes, frequently an Ethernet connection, sometimes a JTAG interface for low-level debugging



- ▶ An essential tool for embedded development is a serial line communication program, like HyperTerminal in Windows.
- ▶ There are multiple options available in Linux: Minicom, Picocom, Gtkterm, Putty, etc.
- ▶ In this training session, we recommend using the simplest of them: picocom
 - ▶ Installation with `sudo apt-get install picocom`
 - ▶ Run with `picocom -b BAUD_RATE /dev/SERIAL_DEVICE`
 - ▶ Exit with Control-A Control-X
- ▶ SERIAL_DEVICE is typically
 - ▶ `ttyUSBx` for USB to serial converters
 - ▶ `ttySx` for real serial ports

- ▶ Using the command line is mandatory for many operations needed for embedded Linux development
- ▶ It is a very powerful way of interacting with the system, with which you can save a lot of time.
- ▶ Some useful tips
 - ▶ You can use several tabs in the Gnome Terminal
 - ▶ Remember that you can use relative paths (for example: `../../linux`) in addition to absolute paths (for example: `/home/user`)
 - ▶ In a shell, hit `[Control] [r]`, then a keyword, will search through the command history. Hit `[Control] [r]` again to search backwards in the history
 - ▶ You can copy/paste paths directly from the file manager to the terminal by drag-and-drop.



Prepare your lab environment

- ▶ Download and extract the lab archive

Cross-compiling toolchains

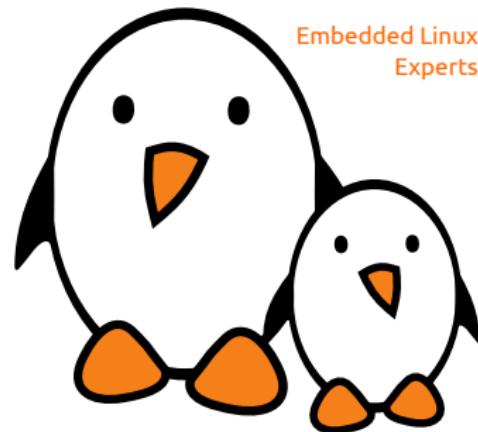
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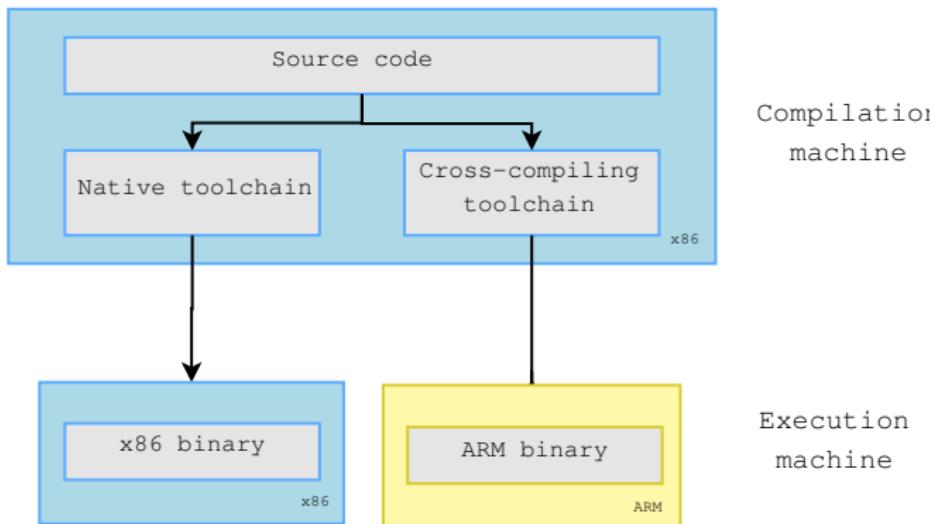


Definition and Components

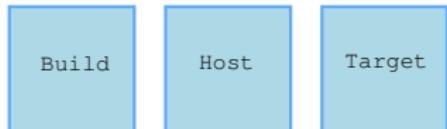
Definition (1)

- ▶ The usual development tools available on a GNU/Linux workstation is a **native toolchain**
- ▶ This toolchain runs on your workstation and generates code for your workstation, usually x86
- ▶ For embedded system development, it is usually impossible or not interesting to use a native toolchain
 - ▶ The target is too restricted in terms of storage and/or memory
 - ▶ The target is very slow compared to your workstation
 - ▶ You may not want to install all development tools on your target.
- ▶ Therefore, **cross-compiling toolchains** are generally used. They run on your workstation but generate code for your target.

Definition (2)



- ▶ Three machines must be distinguished when discussing toolchain creation
 - ▶ The **build** machine, where the toolchain is built.
 - ▶ The **host** machine, where the toolchain will be executed.
 - ▶ The **target** machine, where the binaries created by the toolchain are executed.
- ▶ Four common build types are possible for toolchains



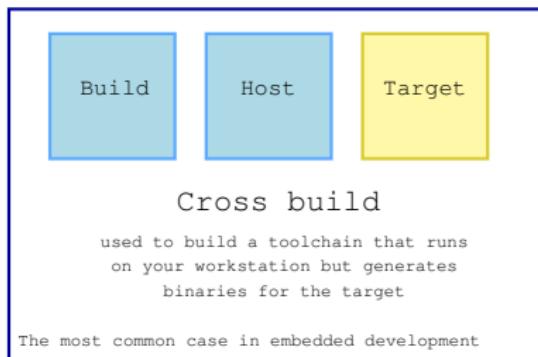
Native build

used to build the normal gcc
of a workstation



Cross-native build

used to build a toolchain that runs on your
target and generates binaries for the target



Cross build

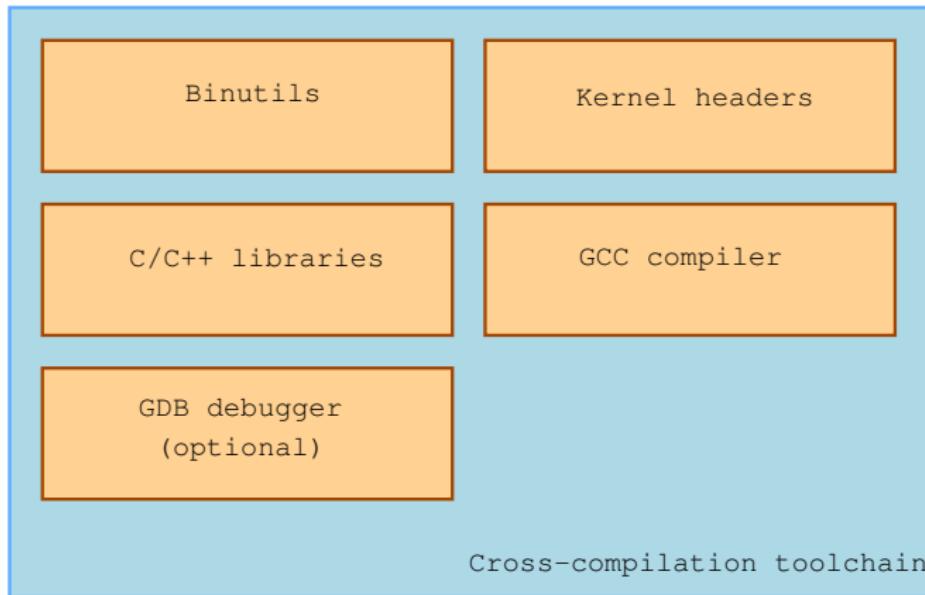
used to build a toolchain that runs
on your workstation but generates
binaries for the target

The most common case in embedded development



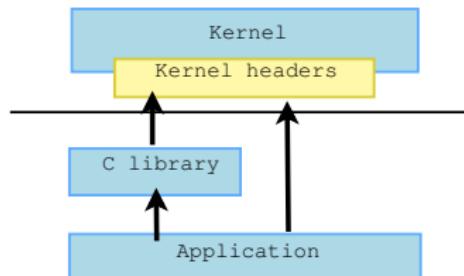
Canadian build

used to build on architecture A a
toolchain that runs on architecture B
and generates binaries for architecture C



- ▶ **Binutils** is a set of tools to generate and manipulate binaries for a given CPU architecture
 - ▶ `as`, the assembler, that generates binary code from assembler source code
 - ▶ `ld`, the linker
 - ▶ `ar`, `ranlib`, to generate `.a` archives, used for libraries
 - ▶ `objdump`, `readelf`, `size`, `nm`, `strings`, to inspect binaries.
Very useful analysis tools!
 - ▶ `strip`, to strip parts of binaries that are just needed for debugging (reducing their size).
- ▶ <http://www.gnu.org/software/binutils/>
- ▶ GPL license

- ▶ The C library and compiled programs needs to interact with the kernel
 - ▶ Available system calls and their numbers
 - ▶ Constant definitions
 - ▶ Data structures, etc.
- ▶ Therefore, compiling the C library requires kernel headers, and many applications also require them.
- ▶ Available in `<linux/...>` and `<asm/...>` and a few other directories corresponding to the ones visible in `include/` in the kernel sources



- ▶ System call numbers, in <asm/unistd.h>

```
#define __NR_exit          1
#define __NR_fork           2
#define __NR_read            3
```

- ▶ Constant definitions, here in <asm-generic/fcntl.h>, included from <asm/fcntl.h>, included from <linux/fcntl.h>

```
#define O_RDWR 00000002
```

- ▶ Data structures, here in <asm/stat.h>

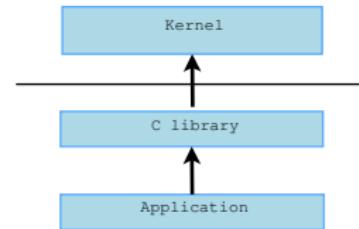
```
struct stat {
    unsigned long st_dev;
    unsigned long st_ino;
    [...]
};
```

- ▶ The kernel to user space ABI is **backward compatible**
 - ▶ Binaries generated with a toolchain using kernel headers older than the running kernel will work without problem, but won't be able to use the new system calls, data structures, etc.
 - ▶ Binaries generated with a toolchain using kernel headers newer than the running kernel might work on if they don't use the recent features, otherwise they will break
 - ▶ Using the latest kernel headers is not necessary, unless access to the new kernel features is needed
- ▶ The kernel headers are extracted from the kernel sources using the `headers_install` kernel Makefile target.

- ▶ GNU Compiler Collection, the famous free software compiler
- ▶ Can compile C, C++, Ada, Fortran, Java, Objective-C, Objective-C++, and generate code for a large number of CPU architectures, including ARM, AVR, Blackfin, CRIS, FRV, M32, MIPS, MN10300, PowerPC, SH, v850, i386, x86_64, IA64, Xtensa, etc.
- ▶ <http://gcc.gnu.org/>
- ▶ Available under the GPL license, libraries under the LGPL.



- ▶ The C library is an essential component of a Linux system
 - ▶ Interface between the applications and the kernel
 - ▶ Provides the well-known standard C API to ease application development
- ▶ Several C libraries are available:
glibc, uClibc, musl, dietlibc, newlib, etc.
- ▶ The choice of the C library must be made at the time of the cross-compiling toolchain generation, as the GCC compiler is compiled against a specific C library.



C Libraries

- ▶ License: LGPL
- ▶ C library from the GNU project
- ▶ Designed for performance, standards compliance and portability
- ▶ Found on all GNU / Linux host systems
- ▶ Of course, actively maintained
- ▶ By default, quite big for small embedded systems: approx 2.5 MB on ARM (version 2.9 - `libc`: 1.5 MB, `libm`: 750 KB)
- ▶ But some features not needed in embedded systems can be configured out (merged from the old `eglibc` project).
- ▶ <http://www.gnu.org/software/libc/>



- ▶ <http://uclibc-ng.org/>
- ▶ A continuation of the old uClibc project
- ▶ License: LGPL
- ▶ Lightweight C library for small embedded systems
 - ▶ High configurability: many features can be enabled or disabled through a menuconfig interface
 - ▶ Supports most embedded architectures
 - ▶ Supports no-MMU architectures (ARM Cortex-M, Blackfin, etc.)
 - ▶ No guaranteed binary compatibility. May need to recompile applications when the library configuration changes.
 - ▶ Focus on size rather than performance
 - ▶ Small compile time

- ▶ Most of the applications compile with uClibc-ng. This applies to all applications used in embedded systems.
- ▶ Size (arm): 3.5 times smaller than glibc!
 - ▶ uClibc-ng 1.0.14: approx. 716kB (libuClibc: 282kB, libm: 73kB)
 - ▶ glibc 2.22: approx 2.5 MB
- ▶ Some features not available or limited: priority-inheritance mutexes, fixed Name Service Switch functionality, etc.
- ▶ Used on a large number of production embedded products, including consumer electronic devices

- ▶ Executable size comparison on ARM, tested with *glibc* 2.22 and *uClibc-ng* 1.0.14
- ▶ Plain “hello world” program (stripped):

helloworld	static	dynamic
<i>uClibc</i>	33.4kB	2.5kB
<i>uClibc</i> with Thumb-2	25.4kB	2.5kB
<i>eglibc</i> with Thumb-2	479kB	2.7kB

- ▶ Busybox (stripped):

busybox	static	dynamic
<i>uClibc</i>	818kB	664kB
<i>uClibc</i> with Thumb-2	602kB	504kB
<i>eglibc</i> with Thumb-2	1206kB	503kB

<http://www.musl-libc.org/>

- ▶ A lightweight, fast and simple library for embedded systems
- ▶ Created while uClibc's development was stalled
- ▶ In particular, great at making small static executables
- ▶ Permissive license (MIT)
- ▶ Compare features with other C libraries:
http://www.etalabs.net/compare_libcs.html
- ▶ Supported by build systems such as Buildroot

- ▶ Several other smaller C libraries have been developed, but none of them have the goal of allowing the compilation of large existing applications
- ▶ They can run only relatively simple programs, typically to make very small static executables and run in very small root filesystems.
- ▶ Choices:
 - ▶ Dietlibc, <http://fefe.de/dietlibc/>. Approximately 70 KB.
 - ▶ Newlib, <http://sourceware.org/newlib/>
 - ▶ Klibc, <http://www.kernel.org/pub/linux/libs/klibc/>, designed for use in an *initramfs* or *initrd* at boot time.

Toolchain Options

- ▶ When building a toolchain, the ABI used to generate binaries needs to be defined
- ▶ ABI, for *Application Binary Interface*, defines the calling conventions (how function arguments are passed, how the return value is passed, how system calls are made) and the organization of structures (alignment, etc.)
- ▶ All binaries in a system must be compiled with the same ABI, and the kernel must understand this ABI.
- ▶ On ARM, two main ABIs: *OABI* and *EABI*
 - ▶ Nowadays everybody uses *EABI*
- ▶ On MIPS, several ABIs: *o32*, *o64*, *n32*, *n64*
- ▶ http://en.wikipedia.org/wiki/Application_Binary_Interface

- ▶ Some processors have a floating point unit, some others do not.
 - ▶ For example, many ARMv4 and ARMv5 CPUs do not have a floating point unit. Since ARMv7, a VFP unit is mandatory.
- ▶ For processors having a floating point unit, the toolchain should generate *hard float* code, in order to use the floating point instructions directly
- ▶ For processors without a floating point unit, two solutions
 - ▶ Generate *hard float code* and rely on the kernel to emulate the floating point instructions. This is very slow.
 - ▶ Generate *soft float code*, so that instead of generating floating point instructions, calls to a user space library are generated
- ▶ Decision taken at toolchain configuration time
- ▶ Also possible to configure which floating point unit should be used

- ▶ A set of cross-compiling tools is specific to a CPU architecture (ARM, x86, MIPS, PowerPC)
- ▶ However, with the `-march=`, `-mcpu=`, `-mtune=` options, one can select more precisely the target CPU type
 - ▶ For example, `-march=armv7 -mcpu=cortex-a8`
- ▶ At the toolchain compilation time, values can be chosen. They are used:
 - ▶ As the default values for the cross-compiling tools, when no other `-march`, `-mcpu`, `-mtune` options are passed
 - ▶ To compile the C library
- ▶ Even if the C library has been compiled for armv5t, it doesn't prevent from compiling other programs for armv7

Obtaining a Toolchain

Building a cross-compiling toolchain by yourself is a difficult and painful task! Can take days or weeks!

- ▶ Lots of details to learn: many components to build, complicated configuration
- ▶ Lots of decisions to make (such as C library version, ABI, floating point mechanisms, component versions)
- ▶ Need kernel headers and C library sources
- ▶ Need to be familiar with current `gcc` issues and patches on your platform
- ▶ Useful to be familiar with building and configuring tools
- ▶ See the *Crosstool-NG* docs/ directory for details on how toolchains are built.

- ▶ Solution that many people choose
 - ▶ Advantage: it is the simplest and most convenient solution
 - ▶ Drawback: you can't fine tune the toolchain to your needs
- ▶ Make sure the toolchain you find meets your requirements: CPU, endianness, C library, component versions, ABI, soft float or hard float, etc.
- ▶ Possible choices
 - ▶ Toolchains packaged by your distribution
 - Ubuntu examples:
`sudo apt-get install gcc-arm-linux-gnueabi`
`sudo apt-get install gcc-arm-linux-gnueabihf`
 - ▶ Sourcery CodeBench toolchains, now only supporting MIPS, NIOS-II, AMD64, Hexagon. Old versions with ARM support still available through build systems (Buildroot...)
 - ▶ Toolchain provided by your hardware vendor.

Another solution is to use utilities that **automate the process of building the toolchain**

- ▶ Same advantage as the pre-compiled toolchains: you don't need to mess up with all the details of the build process
- ▶ But also offers more flexibility in terms of toolchain configuration, component version selection, etc.
- ▶ They also usually contain several patches that fix known issues with the different components on some architectures
- ▶ Multiple tools with identical principle: shell scripts or Makefile that automatically fetch, extract, configure, compile and install the different components

▶ Crosstool-ng

- ▶ Rewrite of the older Crosstool, with a menuconfig-like configuration system
- ▶ Feature-full: supports uClibc, glibc, musl, hard and soft float, many architectures
- ▶ Actively maintained
- ▶ <http://crosstool-ng.org/>

Many root filesystem build systems also allow the construction of a cross-compiling toolchain

- ▶ **Buildroot**

- ▶ Makefile-based. Can build (e)glibc, uClibc and musl based toolchains, for a wide range of architectures.
- ▶ <http://www.buildroot.net>

- ▶ **PTXdist**

- ▶ Makefile-based, uClibc or glibc, maintained mainly by *Pengutronix*
- ▶ <http://pengutronix.de/software/ptxdist/>

- ▶ **OpenEmbedded / Yocto**

- ▶ A featureful, but more complicated build system
- ▶ <http://www.openembedded.org/>
- ▶ <https://www.yoctoproject.org/>

- ▶ Installation of Crosstool-NG can be done system-wide, or just locally in the source directory. For local installation:

```
./configure --enable-local  
make  
make install
```

- ▶ Some sample configurations for various architectures are available in samples, they can be listed using

```
./ct-ng list-samples
```

- ▶ To load a sample configuration

```
./ct-ng <sample-name>
```

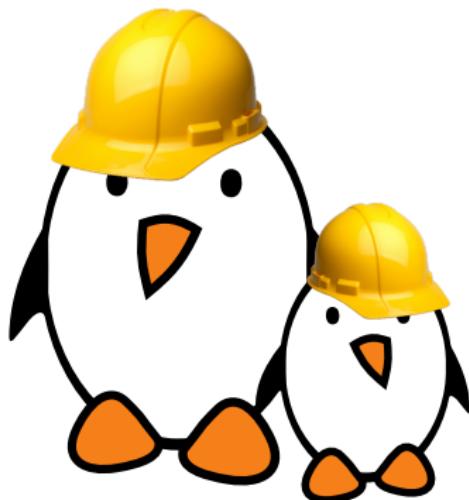
- ▶ To adjust the configuration

```
./ct-ng menuconfig
```

- ▶ To build the toolchain

```
./ct-ng build
```

- ▶ The cross compilation tool binaries, in `bin/`
 - ▶ This directory should be added to your PATH to ease usage of the toolchain
- ▶ One or several *sysroot*, each containing
 - ▶ The C library and related libraries, compiled for the target
 - ▶ The C library headers and kernel headers
- ▶ There is one *sysroot* for each variant: toolchains can be *multilib* if they have several copies of the C library for different configurations (for example: ARMv4T, ARMv5T, etc.)
 - ▶ Old CodeSourcery ARM toolchains were multilib, the sysroots in:
`arm-none-linux-gnueabi/libc/`,
`arm-none-linux-gnueabi/libc/armv4t/`,
`arm-none-linux-gnueabi/libc/thumb2`
 - ▶ Crosstool-NG toolchains can be multilib too (still experimental), otherwise the sysroot is in
`arm-unknown-linux-uclibcgnueabi/sysroot`



Time to build your toolchain

- ▶ Configure Crosstool-NG
- ▶ Run it to build your own cross-compiling toolchain

Bootloaders

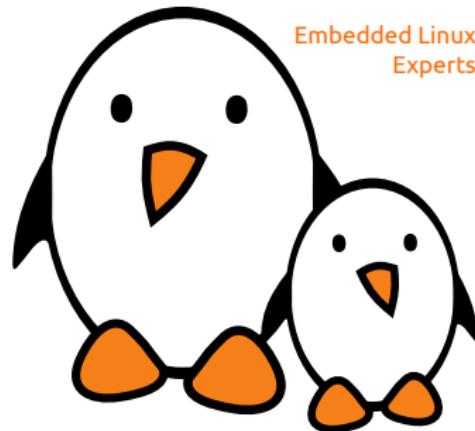
Endocode AG

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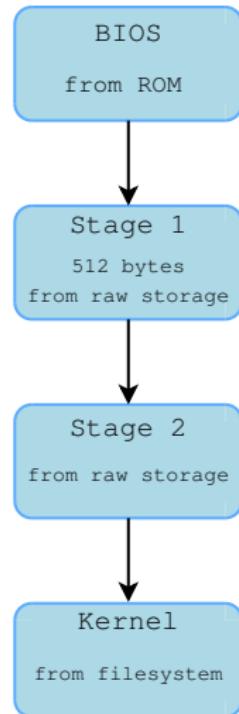
Corrections, suggestions, contributions and translations are welcome!



Boot Sequence

- ▶ The bootloader is a piece of code responsible for
 - ▶ Basic hardware initialization
 - ▶ Loading of an application binary, usually an operating system kernel, from flash storage, from the network, or from another type of non-volatile storage.
 - ▶ Possibly decompression of the application binary
 - ▶ Execution of the application
- ▶ Besides these basic functions, most bootloaders provide a shell with various commands implementing different operations.
 - ▶ Loading of data from storage or network, memory inspection, hardware diagnostics and testing, etc.

- ▶ The x86 processors are typically bundled on a board with a non-volatile memory containing a program, the BIOS.
- ▶ On old BIOS-based x86 platforms: the BIOS is responsible for basic hardware initialization and loading of a very small piece of code from non-volatile storage.
- ▶ This piece of code is typically a 1st stage bootloader, which will load the full bootloader itself.
- ▶ It typically understands filesystem formats so that the kernel file can be loaded directly from a normal filesystem.
- ▶ This sequence is different for modern EFI-based systems.

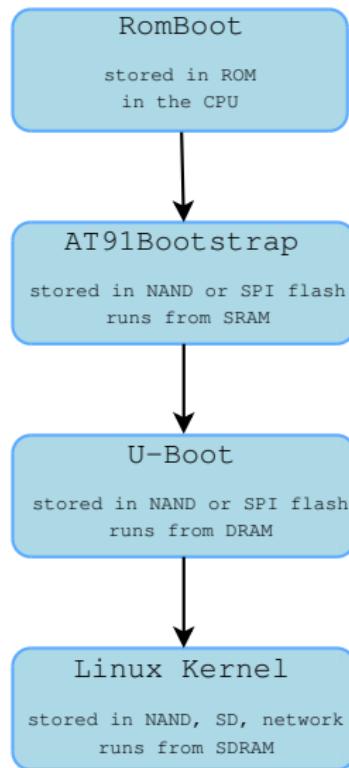


- ▶ GRUB, Grand Unified Bootloader, the most powerful one.
<http://www.gnu.org/software/grub/>
 - ▶ Can read many filesystem formats to load the kernel image and the configuration, provides a powerful shell with various commands, can load kernel images over the network, etc.
 - ▶ See our dedicated presentation for details:
<http://free-electrons.com/docs/grub/>
- ▶ Syslinux, for network and removable media booting (USB key, CD-ROM)
<http://www.kernel.org/pub/linux/utils/boot/syslinux/>

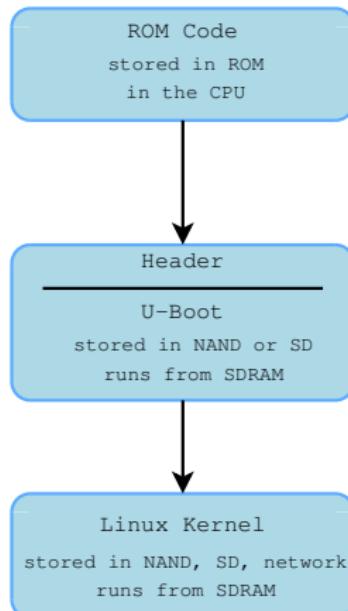
- ▶ When powered, the CPU starts executing code at a fixed address
- ▶ There is no other booting mechanism provided by the CPU
- ▶ The hardware design must ensure that a NOR flash chip is wired so that it is accessible at the address at which the CPU starts executing instructions
- ▶ The first stage bootloader must be programmed at this address in the NOR
- ▶ NOR is mandatory, because it allows random access, which NAND doesn't allow
- ▶ **Not very common anymore** (unpractical, and requires NOR flash)



- ▶ The CPU has an integrated boot code in ROM
 - ▶ BootROM on AT91 CPUs, “ROM code” on OMAP, etc.
 - ▶ Exact details are CPU-dependent
- ▶ This boot code is able to load a first stage bootloader from a storage device into an internal SRAM (DRAM not initialized yet)
 - ▶ Storage device can typically be: MMC, NAND, SPI flash, UART (transmitting data over the serial line), etc.
- ▶ The first stage bootloader is
 - ▶ Limited in size due to hardware constraints (SRAM size)
 - ▶ Provided either by the CPU vendor or through community projects
- ▶ This first stage bootloader must initialize DRAM and other hardware devices and load a second stage bootloader into RAM



- ▶ **RomBoot:** tries to find a valid bootstrap image from various storage sources, and load it into SRAM (DRAM not initialized yet). Size limited to 4 KB. No user interaction possible in standard boot mode.
- ▶ **AT91Bootstrap:** runs from SRAM. Initializes the DRAM, the NAND or SPI controller, and loads the secondary bootloader into RAM and starts it. No user interaction possible.
- ▶ **U-Boot:** runs from RAM. Initializes some other hardware devices (network, USB, etc.). Loads the kernel image from storage or network to RAM and starts it. Shell with commands provided.
- ▶ **Linux Kernel:** runs from RAM. Takes over the system completely (bootloaders no longer exists).



- ▶ **ROM Code:** tries to find a valid bootstrap image from various storage sources, and load it into RAM. The RAM configuration is described in a CPU-specific header, prepended to the bootloader image.
- ▶ **U-Boot:** runs from RAM. Initializes some other hardware devices (network, USB, etc.). Loads the kernel image from storage or network to RAM and starts it. Shell with commands provided. File called `u-boot.kwb`.
- ▶ **Linux Kernel:** runs from RAM. Takes over the system completely (bootloaders no longer exists).

- ▶ We will focus on the generic part, the main bootloader, offering the most important features.
- ▶ There are several open-source generic bootloaders. Here are the most popular ones:
 - ▶ **U-Boot**, the universal bootloader by Denx

The most used on ARM, also used on PPC, MIPS, x86, m68k, NIOS, etc. The de-facto standard nowadays. We will study it in detail.

<http://www.denx.de/wiki/U-Boot>
 - ▶ **Barebox**, a new architecture-neutral bootloader, written as a successor of U-Boot. Better design, better code, active development, but doesn't yet have as much hardware support as U-Boot.

<http://www.barebox.org>
- ▶ There are also a lot of other open-source or proprietary bootloaders, often architecture-specific
 - ▶ RedBoot, Yaboot, PMON, etc.

The U-boot bootloader

U-Boot is a typical free software project

- ▶ License: GPLv2 (same as Linux)
- ▶ Freely available at <http://www.denx.de/wiki/U-Boot>
- ▶ Documentation available at
<http://www.denx.de/wiki/U-Boot/Documentation>
- ▶ The latest development source code is available in a Git repository: <http://git.denx.de/?p=u-boot.git;a=summary>
- ▶ Development and discussions happen around an open mailing-list <http://lists.denx.de/pipermail/u-boot/>
- ▶ Since the end of 2008, it follows a fixed-interval release schedule. Every three months, a new version is released. Versions are named YYYY.MM.

- ▶ Get the source code from the website, and uncompress it
- ▶ The `configs/` directory contains one configuration file for each supported board
 - ▶ It defines the CPU type, the peripherals and their configuration, the memory mapping, the U-Boot features that should be compiled in, etc.
- ▶ Note: U-Boot is migrating from board configuration defined in header files (`include/configs/`) to `defconfig` like in the Linux kernel (`configs/`)
 - ▶ Not all boards have been converted to the new configuration system.
 - ▶ Older U-Boot releases provided by hardware vendors may not yet use this new configuration system.

CHIP_defconfig

```
CONFIG_ARM=y
CONFIG_ARCH_SUNXI=y
CONFIG_MACH_SUN5I=y
CONFIG_DRAM_TIMINGS_DDR3_800E_1066G_1333J=y
# CONFIG_MMU is not set
CONFIG_USB0_VBUS_PIN="PB10"
CONFIG_VIDEO_COMPOSITE=y
CONFIG_DEFAULT_DEVICE_TREE="sun5i-r8-chip"
CONFIG_SPL=y
CONFIG_SYS_EXTRA_OPTIONS="CONS_INDEX=2"
# CONFIG_CMD_IMLS is not set
CONFIG_CMD_DFU=y
CONFIG_CMD_USB_MASS_STORAGE=y
CONFIG_AXP_ALD03_VOLT=3300
CONFIG_AXP_ALD04_VOLT=3300
CONFIG_USB_MUSB_GADGET=y
CONFIG_USB_GADGET=y
CONFIG_USB_GADGET_DOWNLOAD=y
CONFIG_G_DNL_MANUFACTURER="Allwinner Technology"
CONFIG_G_DNL_VENDOR_NUM=0x1f3a
CONFIG_G_DNL_PRODUCT_NUM=0x1010
CONFIG_USB_EHCI_HCD=y
```

- ▶ U-Boot must be configured before being compiled
 - ▶ `make BOARDNAME_defconfig`
 - ▶ Where `BOARDNAME` is the name of a configuration, as visible in the `configs/` directory.
 - ▶ You can then run `make menuconfig` to further customize U-Boot's configuration!
- ▶ Make sure that the cross-compiler is available in PATH
- ▶ Compile U-Boot, by specifying the cross-compiler prefix.
Example, if your cross-compiler executable is `arm-linux-gcc`:
`make CROSS_COMPILE=arm-linux-`
- ▶ The main result is a `u-boot.bin` file, which is the U-Boot image. Depending on your specific platform, there may be other specialized images: `u-boot.img`, `u-boot.kwb`, `MLO`, etc.

U-Boot must usually be installed in flash memory to be executed by the hardware. Depending on the hardware, the installation of U-Boot is done in a different way:

- ▶ The CPU provides some kind of specific boot monitor with which you can communicate through serial port or USB using a specific protocol
- ▶ The CPU boots first on removable media (MMC) before booting from fixed media (NAND). In this case, boot from MMC to reflash a new version
- ▶ U-Boot is already installed, and can be used to flash a new version of U-Boot. However, be careful: if the new version of U-Boot doesn't work, the board is unusable
- ▶ The board provides a JTAG interface, which allows to write to the flash memory remotely, without any system running on the board. It also allows to rescue a board if the bootloader doesn't work.

U-boot prompt

- ▶ Connect the target to the host through a serial console.
- ▶ Power-up the board. On the serial console, you will see something like:

```
U-Boot 2016.05 (May 17 2016 - 12:41:15 -0400)
```

```
CPU: SAMA5D36
Crystal frequency:      12 MHz
CPU clock       :      528 MHz
Master clock     :      132 MHz
DRAM: 256 MiB
NAND: 256 MiB
MMC: mci: 0
```

```
In:   serial
Out:  serial
Err:  serial
Net:  gmac0
```

```
Hit any key to stop autoboot: 0
=>
```

- ▶ The U-Boot shell offers a set of commands. We will study the most important ones, see the documentation for a complete reference or the `help` command.

Flash information (NOR and SPI flash)

```
U-Boot> flinfo
DataFlash:AT45DB021
Nb pages: 1024
Page Size: 264
Size= 270336 bytes
Logical address: 0xC0000000
Area 0: C0000000 to C0001FFF (RO) Bootstrap
Area 1: C0002000 to C0003FFF Environment
Area 2: C0004000 to C0041FFF (RO) U-Boot
```

NAND flash information

```
U-Boot> nand info
Device 0: nand0, sector size 128 KiB
  Page size      2048 b
  OOB size       64 b
  Erase size    131072 b
```

Version details

```
U-Boot> version
U-Boot 2016.05 (May 17 2016 - 12:41:15 -0400)
```

- ▶ The exact set of commands depends on the U-Boot configuration
- ▶ `help` and `help` command
- ▶ `ext2load`, loads a file from an ext2 filesystem to RAM
 - ▶ And also `ext2ls` to list files, `ext2info` for information
- ▶ `fatload`, loads a file from a FAT filesystem to RAM
 - ▶ And also `fatls` and `fatinfo`
- ▶ `tftp`, loads a file from the network to RAM
- ▶ `ping`, to test the network
- ▶ `boot`, runs the default boot command, stored in `bootcmd`
- ▶ `bootz <address>`, starts a kernel image loaded at the given address in RAM

- ▶ `loadb`, `loads`, `loady`, load a file from the serial line to RAM
- ▶ `usb`, to initialize and control the USB subsystem, mainly used for USB storage devices such as USB keys
- ▶ `mmc`, to initialize and control the MMC subsystem, used for SD and microSD cards
- ▶ `nand`, to erase, read and write contents to NAND flash
- ▶ `erase`, `protect`, `cp`, to erase, modify protection and write to NOR flash
- ▶ `md`, displays memory contents. Can be useful to check the contents loaded in memory, or to look at hardware registers.
- ▶ `mm`, modifies memory contents. Can be useful to modify directly hardware registers, for testing purposes.

- ▶ U-Boot can be configured through environment variables
 - ▶ Some specific environment variables affect the behavior of the different commands
 - ▶ Custom environment variables can be added, and used in scripts
- ▶ Environment variables are loaded from flash to RAM at U-Boot startup, can be modified and saved back to flash for persistence
- ▶ There is a dedicated location in flash (or in MMC storage) to store the U-Boot environment, defined in the board configuration file

Commands to manipulate environment variables:

- ▶ `printenv`
Shows all variables
- ▶ `printenv <variable-name>`
Shows the value of a variable
- ▶ `setenv <variable-name> <variable-value>`
Changes the value of a variable, only in RAM
- ▶ `editenv <variable-name>`
Edits the value of a variable, only in RAM
- ▶ `saveenv`
Saves the current state of the environment to flash

```
u-boot # printenv
baudrate=19200
ethaddr=00:40:95:36:35:33
netmask=255.255.255.0
ipaddr=10.0.0.11
serverip=10.0.0.1
stdin=serial
stdout=serial
stderr=serial
u-boot # printenv serverip
serverip=10.0.0.1
u-boot # setenv serverip 10.0.0.100
u-boot # saveenv
```

- ▶ bootcmd, contains the command that U-Boot will automatically execute at boot time after a configurable delay (bootdelay), if the process is not interrupted
- ▶ bootargs, contains the arguments passed to the Linux kernel, covered later
- ▶ serverip, the IP address of the server that U-Boot will contact for network related commands
- ▶ ipaddr, the IP address that U-Boot will use
- ▶ netmask, the network mask to contact the server
- ▶ ethaddr, the MAC address, can only be set once
- ▶ autostart, if yes, U-Boot starts automatically an image that has been loaded into memory
- ▶ filesize, the size of the latest copy to memory (from tftp, fatload, nand read...)

- ▶ Environment variables can contain small scripts, to execute several commands and test the results of commands.
 - ▶ Useful to automate booting or upgrade processes
 - ▶ Several commands can be chained using the ; operator
 - ▶ Tests can be done using

```
if command ; then ... ; else ... ; fi
```
 - ▶ Scripts are executed using run <variable-name>
 - ▶ You can reference other variables using \${variable-name}
- ▶ Example
 - ▶

```
setenv mmc-boot 'if fatload mmc 0 80000000 boot.ini;
then source; else if fatload mmc 0 80000000 zImage;
then run mmc-do-boot; fi; fi'
```

- ▶ U-Boot is mostly used to load and boot a kernel image, but it also allows to change the kernel image and the root filesystem stored in flash.
- ▶ Files must be exchanged between the target and the development workstation. This is possible:
 - ▶ Through the network if the target has an Ethernet connection, and U-Boot contains a driver for the Ethernet chip. This is the fastest and most efficient solution.
 - ▶ Through a USB key, if U-Boot supports the USB controller of your platform
 - ▶ Through a SD or microSD card, if U-Boot supports the MMC controller of your platform
 - ▶ Through the serial port

- ▶ Network transfer from the development workstation to U-Boot on the target takes place through TFTP
 - ▶ *Trivial File Transfer Protocol*
 - ▶ Somewhat similar to FTP, but without authentication and over UDP
- ▶ A TFTP server is needed on the development workstation
 - ▶ `sudo apt-get install tftpd-hpa`
 - ▶ All files in `/var/lib/tftpboot` are then visible through TFTP
 - ▶ A TFTP client is available in the `tftp-hpa` package, for testing
- ▶ A TFTP client is integrated into U-Boot
 - ▶ Configure the `ipaddr` and `serverip` environment variables
 - ▶ Use `tftp <address> <filename>` to load a file



Time to start the practical lab!

- ▶ Communicate with the board using a serial console
- ▶ Configure, build and install *U-Boot*
- ▶ Learn *U-Boot* commands
- ▶ Set up *TFTP* communication with the board

Linux kernel introduction

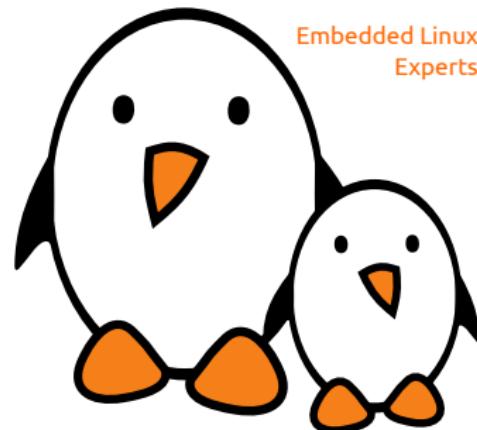
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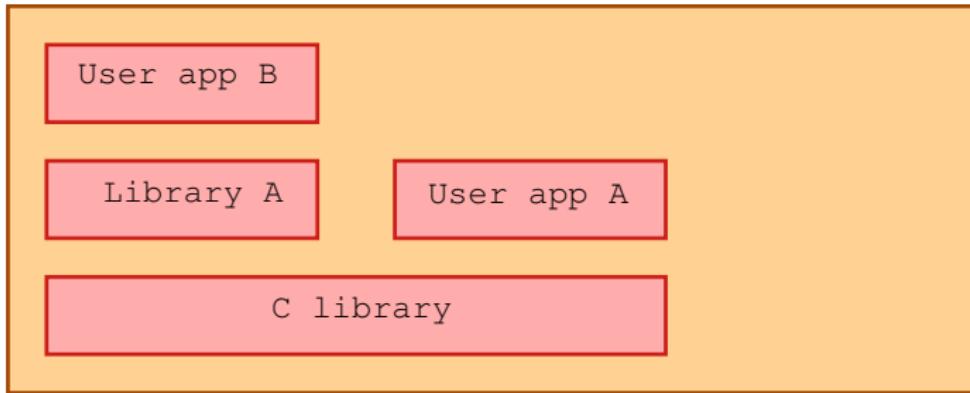
Corrections, suggestions, contributions and translations are welcome!



Linux features

- ▶ The Linux kernel is one component of a system, which also requires libraries and applications to provide features to end users.
- ▶ The Linux kernel was created as a hobby in 1991 by a Finnish student, Linus Torvalds.
 - ▶ Linux quickly started to be used as the kernel for free software operating systems
- ▶ Linus Torvalds has been able to create a large and dynamic developer and user community around Linux.
- ▶ Nowadays, more than one thousand people contribute to each kernel release, individuals or companies big and small.

- ▶ Portability and hardware support. Runs on most architectures.
- ▶ Scalability. Can run on super computers as well as on tiny devices (4 MB of RAM is enough).
- ▶ Compliance to standards and interoperability.
- ▶ Exhaustive networking support.
- ▶ Security. It can't hide its flaws. Its code is reviewed by many experts.
- ▶ Stability and reliability.
- ▶ Modularity. Can include only what a system needs even at run time.
- ▶ Easy to program. You can learn from existing code. Many useful resources on the net.



Call to services

Event notification information exposi

Linux kernel

Manage hardware

Event notification

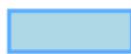
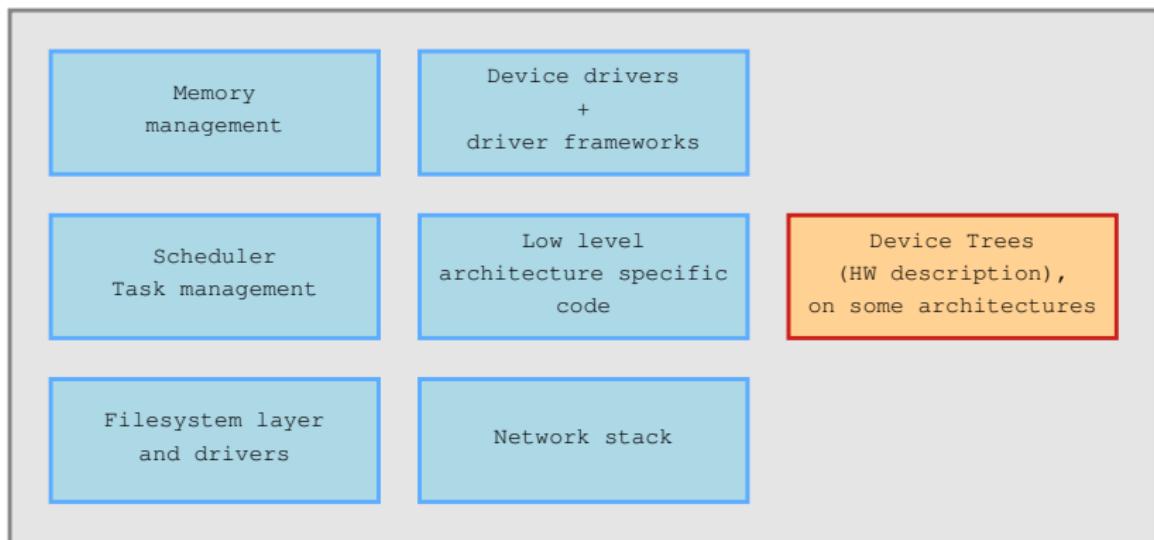
Hardware

- ▶ **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 to “multiplex” the hardware resource.

- ▶ The main interface between the kernel and user space is the set of system calls
- ▶ About 300 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 interface is stable over time: only new system calls can be added by the kernel developers
- ▶ 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

- ▶ 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 set of devices and buses.
Information about these devices.

Linux Kernel



Implemented mainly in C,
a little bit of assembly.



Written in a Device Tree
specific language.

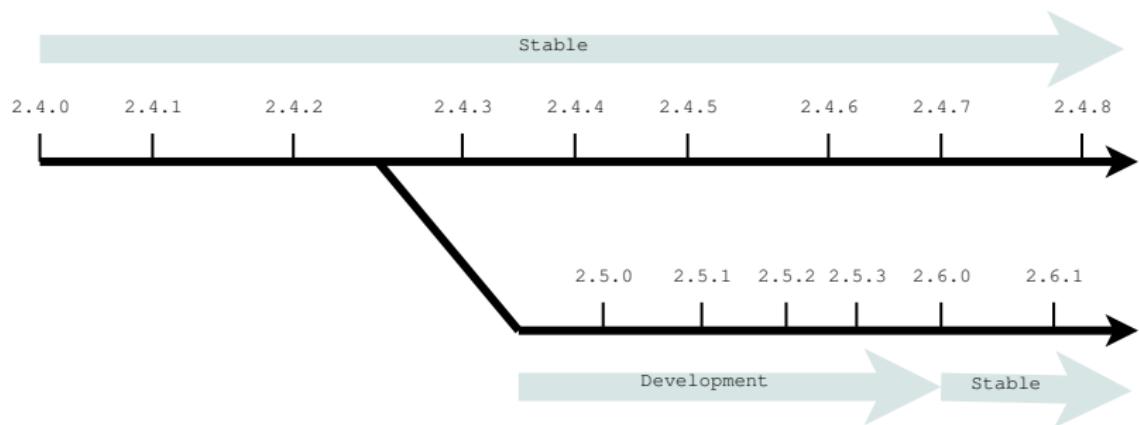
- ▶ The whole Linux sources are Free Software released under the GNU General Public License version 2 (GPL v2).
- ▶ For the Linux kernel, this basically implies that:
 - ▶ When you receive or buy a device with Linux on it, you should receive the Linux sources, with the right to study, modify and redistribute them.
 - ▶ When you produce Linux based devices, you must release the sources to the recipient, with the same rights, with no restriction.

- ▶ See the arch/ directory in the kernel sources
- ▶ Minimum: 32 bit processors, with or without MMU, and gcc support
- ▶ 32 bit architectures (arch/ subdirectories)
Examples: arm, avr32, blackfin, c6x, m68k, microblaze, score, um
- ▶ 64 bit architectures:
Examples: alpha, arm64, ia64, tile
- ▶ 32/64 bit architectures
Examples: mips, powerpc, sh, sparc, x86
- ▶ Find details in kernel sources: arch/<arch>/Kconfig, arch/<arch>/README, or Documentation/<arch>/

Linux versioning scheme and development process

- ▶ One stable major branch every 2 or 3 years
 - ▶ Identified by an even middle number
 - ▶ Examples: 1.0.x, 2.0.x, 2.2.x, 2.4.x
- ▶ One development branch to integrate new functionalities and major changes
 - ▶ Identified by an odd middle number
 - ▶ Examples: 2.1.x, 2.3.x, 2.5.x
 - ▶ After some time, a development version becomes the new base version for the stable branch
- ▶ Minor releases once in while: 2.2.23, 2.5.12, etc.

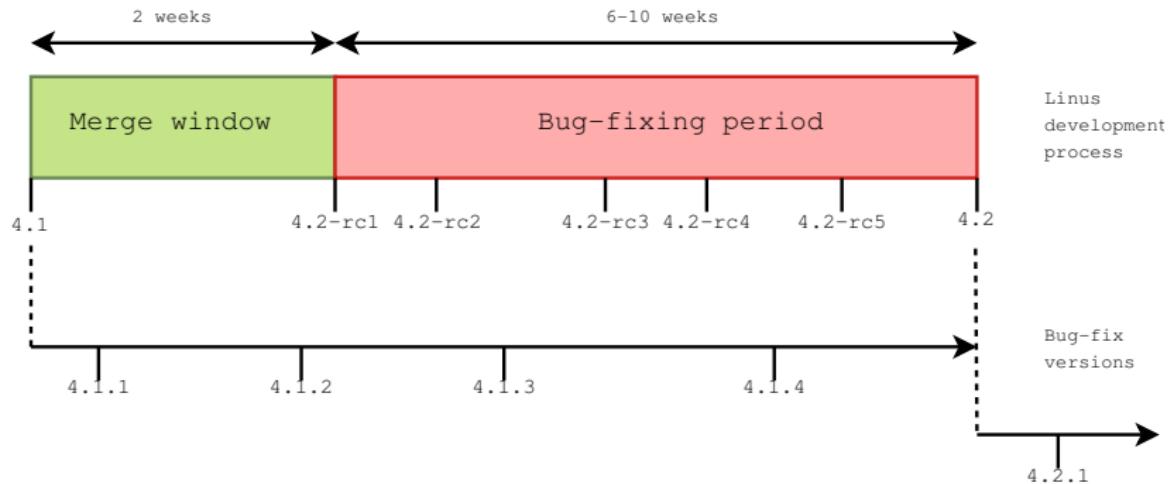
ENDO CODE Until 2.6 (2)



- ▶ Since 2.6.0, kernel developers have been able to introduce lots of new features one by one on a steady pace, without having to make disruptive changes to existing subsystems.
- ▶ Since then, there has been no need to create a new development branch massively breaking compatibility with the stable branch.
- ▶ Thanks to this, **more features are released to users at a faster pace.**

- ▶ From 2003 to 2011, the official kernel versions were named 2.6.x.
- ▶ Linux 3.0 was released in July 2011
- ▶ Linux 4.0 was released in April 2015
- ▶ This is only a change to the numbering scheme
 - ▶ Official kernel versions are now named x.y (3.0, 3.1, 3.2, ..., 3.19, 4.0, 4.1, etc.)
 - ▶ Stabilized versions are named x.y.z (3.0.2, 4.2.7, etc.)
 - ▶ It effectively only removes a digit compared to the previous numbering scheme

Using merge and bug fixing windows



- ▶ Issue: bug and security fixes only released for most recent stable kernel versions.
- ▶ Some people need to have a recent kernel, but with long term support for security updates.
- ▶ You could get long term support from a commercial embedded Linux provider.
- ▶ You could reuse sources for the kernel used in Ubuntu Long Term Support releases (5 years of free security updates).
- ▶ The <http://kernel.org> front page shows which versions will be supported for some time (up to 2 or 3 years), and which ones won't be supported any more ("EOL: End Of Life")

mainline:	4.4-rc4	2015-12-06
stable:	4.3.2	2015-12-10
stable:	4.2.7	2015-12-09
longterm:	4.1.14	2015-12-09
longterm:	3.18.24	2015-10-31
longterm:	3.14.58	2015-12-09
longterm:	3.12.51	2015-11-25
longterm:	3.10.94	2015-12-09
longterm:	3.4.110	2015-10-22
longterm:	3.2.74	2015-11-27
longterm:	2.6.32.69	2015-12-05
linux-next:	next-20151211	2015-12-11

The official list of changes for each Linux release is just a huge list of individual patches!

```
commit aa6e52a35d388e730f4df0ec2ec48294590cc459
Author: Thomas Petazzoni <thomas.petazzoni@free-electrons.com>
Date:   Wed Jul 13 11:29:17 2011 +0200
```

at91: at91-ohci: support overcurrent notification

Several USB power switches (AIC1526 or MIC2026) have a digital output that is used to notify that an overcurrent situation is taking place. This digital outputs are typically connected to GPIO inputs of the processor and can be used to be notified of these overcurrent situations.

Therefore, we add a new overcurrent_pin[] array in the at91_usbh_data structure so that boards can tell the AT91 OHCI driver which pins are used for the overcurrent notification, and an overcurrent_supported boolean to tell the driver whether overcurrent is supported or not.

The code has been largely borrowed from ohci-da8xx.c and ohci-s3c2410.c.

Signed-off-by: Thomas Petazzoni <thomas.petazzoni@free-electrons.com>
Signed-off-by: Nicolas Ferre <nicolas.ferre@atmel.com>

Very difficult to find out the key changes and to get the global picture out of individual changes.

Fortunately, there are some useful resources available

- ▶ <http://wiki.kernelnewbies.org/LinuxChanges>
(some versions are missing)
- ▶ <http://lwn.net>
- ▶ <http://www.linux-arm.info>
News about Linux on ARM, including kernel changes.
- ▶ <http://www.heise.de/open/kernel-log-3007.html>, for German readers

Linux kernel sources

- ▶ The official versions of the Linux kernel, as released by Linus Torvalds, are available at <http://www.kernel.org>
 - ▶ These versions follow the development model of the kernel
 - ▶ However, they may not contain the latest development from a specific area yet. Some features in development might not be ready for mainline inclusion yet.
- ▶ Many chip vendors supply their own kernel sources
 - ▶ Focusing on hardware support first
 - ▶ Can have a very important delta with mainline Linux
 - ▶ Useful only when mainline hasn't caught up yet.
- ▶ Many kernel sub-communities maintain their own kernel, with usually newer but less stable features
 - ▶ Architecture communities (ARM, MIPS, PowerPC, etc.), device drivers communities (I2C, SPI, USB, PCI, network, etc.), other communities (real-time, etc.)
 - ▶ No official releases, only development trees are available.

- ▶ The kernel sources are available from <http://kernel.org/pub/linux/kernel> as **full tarballs** (complete kernel sources) and **patches** (differences between two kernel versions).
- ▶ However, more and more people use the `git` version control system. Absolutely needed for kernel development!
 - ▶ Fetch the entire kernel sources and history

```
git clone git://git.kernel.org/pub/scm/linux/kernel/  
git/torvalds/linux.git
```
 - ▶ Create a branch that starts at a specific stable version

```
git checkout -b <name-of-branch> v3.11
```
 - ▶ Web interface available at <http://git.kernel.org/cgit/linux/kernel/git/torvalds/linux.git/tree/>.
 - ▶ Read more about Git at <http://git-scm.com/>

- ▶ Linux 4.6 sources:
Raw size: 730 MB (53,600 files, approx 21,400,000 lines)
`gzip` compressed tar archive: 130 MB
`xz` compressed tar archive: 85 MB
- ▶ Minimum Linux 3.17 compiled kernel size, booting on the ARM Versatile board (hard drive on PCI, ext2 filesystem, ELF executable support, framebuffer console and input devices):
876 KB (compressed), 2.3 MB (raw)
- ▶ 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!

As of kernel version 4.6 (in lines).

- ▶ drivers/: 57.0%
- ▶ arch/: 16.3%
- ▶ fs/: 5.5%
- ▶ sound/: 4.4%
- ▶ net/: 4.3%
- ▶ include/: 3.5%
- ▶ Documentation/: 2.8%
- ▶ tools/: 1.3%
- ▶ kernel/: 1.2%
- ▶ firmware/: 0.6%
- ▶ lib/: 0.5%
- ▶ mm/: 0.5%
- ▶ scripts/: 0.4%
- ▶ crypto/: 0.4%
- ▶ security/: 0.3%
- ▶ block/: 0.1%
- ▶ ...

- ▶ **Full tarballs**
 - ▶ Contain the complete kernel sources: long to download and uncompress, but must be done at least once
 - ▶ Example:
`http://www.kernel.org/pub/linux/kernel/v3.x/linux-3.10.9.tar.xz`
 - ▶ Extract command:
`tar xf linux-3.10.9.tar.xz`
- ▶ **Incremental patches between versions**
 - ▶ It assumes you already have a base version and you apply the correct patches in the right order. Quick to download and apply
 - ▶ Examples:
`http://www.kernel.org/pub/linux/kernel/v3.x/patch-3.10.xz`
(3.9 to 3.10)
`http://www.kernel.org/pub/linux/kernel/v3.x/patch-3.10.9.xz`
(3.10 to 3.10.9)
- ▶ All previous kernel versions are available in
`http://kernel.org/pub/linux/kernel/`

- ▶ A patch is the difference between two source trees
 - ▶ Computed with the `diff` tool, or with more elaborate version control systems
- ▶ They are very common in the open-source community
- ▶ Excerpt from a patch:

```
diff -Nru a/Makefile b/Makefile
--- a/Makefile 2005-03-04 09:27:15 -08:00
+++ b/Makefile 2005-03-04 09:27:15 -08:00
@@ -1,7 +1,7 @@
VERSION = 2
PATCHLEVEL = 6
SUBLEVEL = 11
-EXTRAVERSION =
+EXTRAVERSION = .1
NAME=Woozy Numbat

# *DOCUMENTATION*
```

- ▶ One section per modified file, starting with a header

```
diff -Nru a/Makefile b/Makefile
--- a/Makefile 2005-03-04 09:27:15 -08:00
+++ b/Makefile 2005-03-04 09:27:15 -08:00
```

- ▶ One sub-section per modified part of the file, starting with header with the affected line numbers

```
@@ -1,7 +1,7 @@
```

- ▶ Three lines of context before the change

```
VERSION = 2
```

```
PATCHLEVEL = 6
```

```
SUBLEVEL = 11
```

- ▶ The change itself

```
-EXTRAVERSION =
```

```
+EXTRAVERSION = .1
```

- ▶ Three lines of context after the change

```
NAME=Woozy Numbat
```

```
# *DOCUMENTATION*
```

The patch command:

- ▶ Takes the patch contents on its standard input
- ▶ Applies the modifications described by the patch into the current directory

patch usage examples:

- ▶ `patch -p<n> < diff_file`
- ▶ `cat diff_file | patch -p<n>`
- ▶ `xzcat diff_file.xz | patch -p<n>`
- ▶ `bzcat diff_file.bz2 | patch -p<n>`
- ▶ `zcat diff_file.gz | patch -p<n>`
- ▶ Notes:
 - ▶ n: number of directory levels to skip in the file paths
 - ▶ You can reverse apply a patch with the `-R` option
 - ▶ You can test a patch with `--dry-run` option

- ▶ Two types of Linux patches:
 - ▶ Either to be applied to the previous stable version (from 3.<x-1> to 3.x)
 - ▶ Or implementing fixes to the current stable version (from 3.x to 3.x.y)
- ▶ Can be downloaded in gzip, bzip2 or xz (much smaller) compressed files.
- ▶ Always produced for n=1 (that's what everybody does... do it too!)
- ▶ Need to run the `patch` command inside the kernel source directory
- ▶ Linux patch command line example:

```
cd linux-3.9
xzcat ../patch-3.10.xz | patch -p1
xzcat ../patch-3.10.9.xz | patch -p1
cd ..; mv linux-3.9 linux-3.10.9
```



Time to start the practical lab!

- ▶ Get the Linux kernel sources
- ▶ Apply patches

Kernel configuration

- ▶ 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-3.6.x/`
 - ▶ `make <target>`

- ▶ 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 your hardware (for device drivers, etc.)
 - ▶ On the capabilities you would like to give to your kernel (network capabilities, filesystems, real-time, etc.)

- ▶ The configuration is stored in the `.config` file at the root of kernel sources
 - ▶ Simple text file, `key=value` style
- ▶ As options have dependencies, typically never edited by hand, but through graphical or text interfaces:
 - ▶ `make xconfig`, `make gconfig` (graphical)
 - ▶ `make menuconfig`, `make nconfig` (text)
 - ▶ You can switch from one to another, they all load/save the same `.config` file, and show the same set of options
- ▶ To modify a kernel in a GNU/Linux distribution: the configuration files are usually released in `/boot/`, together with kernel images: `/boot/config-3.2.0-31-generic`

- ▶ 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 included 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

There are different types of options

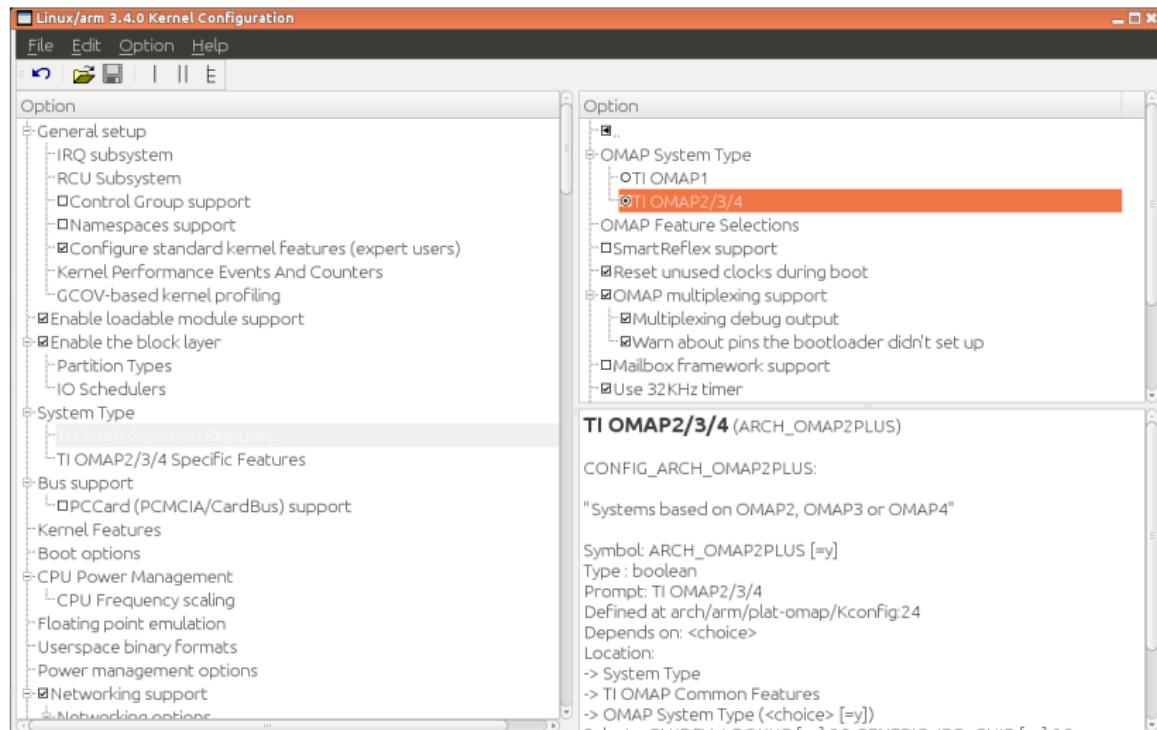
- ▶ `bool` options, they are either
 - ▶ `true` (to include the feature in the kernel) or
 - ▶ `false` (to exclude the feature from the kernel)
- ▶ `tristate` options, they are either
 - ▶ `true` (to include the feature in the kernel image) or
 - ▶ `module` (to include the feature as a kernel module) or
 - ▶ `false` (to exclude the feature)
- ▶ `int` options, to specify integer values
- ▶ `hex` options, to specify hexadecimal values
- ▶ `string` options, to specify string values

- ▶ There are dependencies between kernel options
- ▶ For example, enabling a network driver requires the network stack to be enabled
- ▶ Two types of dependencies
 - ▶ depends on dependencies. In this case, option A that depends on option B is not visible until option B is enabled
 - ▶ select dependencies. In this case, with option A depending on option B, when option A is enabled, option B is automatically enabled
- ▶ make xconfig allows to see all options, even the ones that cannot be selected because of missing dependencies. In this case, they are displayed in gray.

make xconfig

- ▶ The most common graphical interface to configure the kernel.
- ▶ Make sure you read
`help -> introduction: useful options!`
- ▶ File browser: easier to load configuration files
- ▶ Search interface to look for parameters
- ▶ Required Debian / Ubuntu packages: `qt5-default g++`
`pkg-config`

ENDO CODE make xconfig screenshot



Option

- .
- OMAP System Type
 - OTI OMAP1
 - OTI OMAP2/3/4
- OMAP Feature Selections
 - SmartReflex support
 - Reset unused clocks during boot
 - OMAP multiplexing support
 - Multiplexing debug output
 - Warn about pins the bootloader didn't set up
 - Mailbox framework support
 - Use 32KHz timer

TI OMAP2/3/4 (ARCH_OMAP2PLUS)

CONFIG_ARCH_OMAP2PLUS:

"Systems based on OMAP2, OMAP3 or OMAP4"

Symbol: ARCH_OMAP2PLUS [=y]

Type : boolean

Prompt: TI OMAP2/3/4

Defined at arch/arm/plat-omap/Kconfig:24

Depends on: <choice>

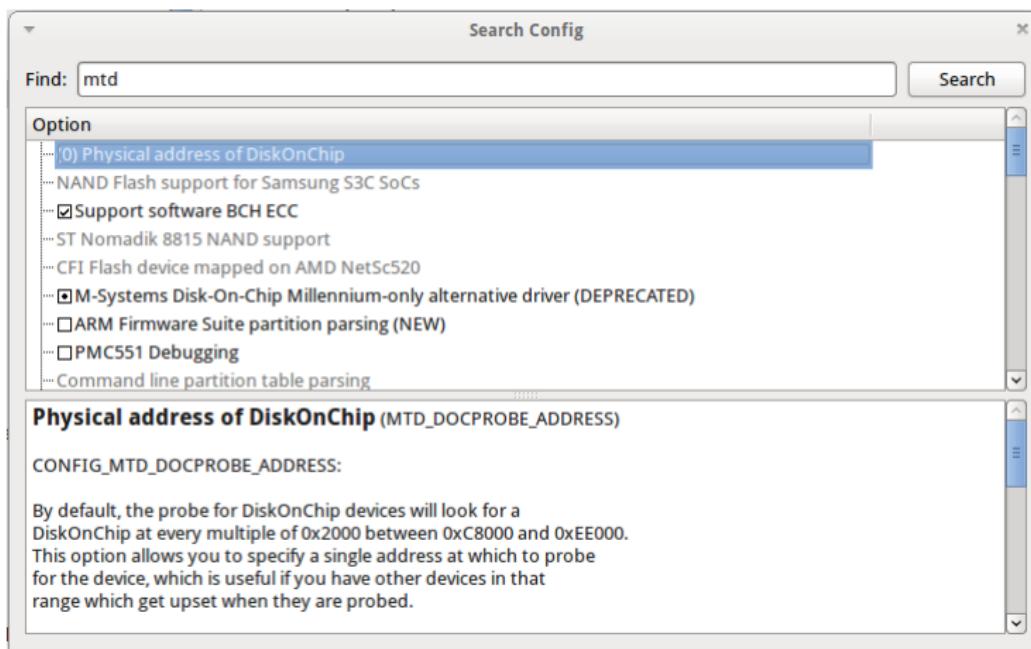
Location:

-> System Type

-> TI OMAP Common Features

-> OMAP System Type (<choice> [=y])

Looks for a keyword in the parameter name. Allows to select or unselect found parameters.



Compiled as a module (separate file)

CONFIG_ISO9660_FS=m

Driver options

CONFIG_JOLIET=y

CONFIG_ZISOFS=y

Compiled statically into the kernel

CONFIG_UDF_FS=y

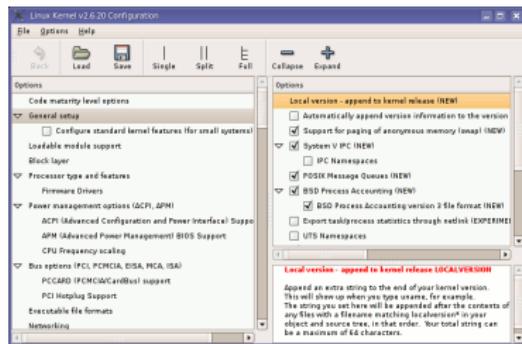
- ISO 9660 CDROM file system support
 - Microsoft Joliet CDROM extensions
 - Transparent decompression extension
 - UDF file system support

Options are grouped by sections and are prefixed with CONFIG_.

```
#  
# CD-ROM/DVD Filesystems  
#  
CONFIG_ISO9660_FS=m  
CONFIG_JOLIET=y  
CONFIG_ZISOFS=y  
CONFIG_UDF_FS=y  
CONFIG_UDF_NLS=y  
  
#  
# DOS/FAT/NT Filesystems  
#  
# CONFIG_MSdos_FS is not set  
# CONFIG_VFAT_FS is not set  
CONFIG_NTFS_FS=m  
# CONFIG_NTFS_DEBUG is not set  
CONFIG_NTFS_RW=y
```

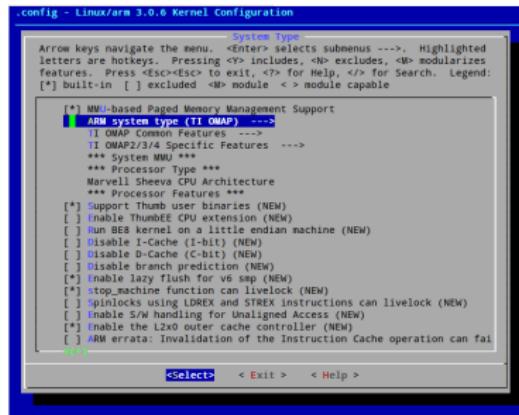
make gconfig

- ▶ GTK based graphical configuration interface.
Functionality similar to that of make xconfig.
- ▶ Just lacking a search functionality.
- ▶ Required Debian packages:
`libglade2-dev`



make menuconfig

- ▶ Useful when no graphics are available. Pretty convenient too!
- ▶ Same interface found in other tools: BusyBox, Buildroot...
- ▶ Required Debian packages: libncurses-dev



make nconfig

- ▶ A newer, similar text interface
- ▶ More user friendly (for example, easier to access help information).
- ▶ Required Debian packages:
`libncurses-dev`



make oldconfig

- ▶ Needed very often!
- ▶ Useful to upgrade a .config file from an earlier kernel release
- ▶ Issues warnings for configuration parameters that no longer exist in the new kernel.
- ▶ Asks for values for new parameters (while xconfig and menuconfig silently set default values for new parameters).

If you edit a .config file by hand, it's strongly recommended to run make oldconfig afterwards!

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 interfaces of the kernel (xconfig, menuconfig, oldconfig...) keep this `.config.old` backup copy.

- ▶ The set of configuration options is architecture dependent
 - ▶ Some configuration options are very architecture-specific
 - ▶ Most of the configuration options (global kernel options, network subsystem, filesystems, most of the device drivers) are visible in all architectures.
- ▶ By default, the kernel build system assumes that the kernel is being built for the host architecture, i.e. native compilation
- ▶ The architecture is not defined inside the configuration, but at a higher level
- ▶ We will see later how to override this behaviour, to allow the configuration of kernels for a different architecture

Compiling and installing the kernel for the host system

- ▶ make
 - ▶ in the main kernel source directory
 - ▶ Remember to run multiple jobs in parallel if you have multiple CPU cores. Example: `make -j 4`
 - ▶ No need to run as root!
- ▶ Generates
 - ▶ `vmlinux`, the raw uncompressed kernel image, in the ELF format, useful for debugging purposes, but cannot be booted
 - ▶ `arch/<arch>/boot/*Image`, the final, usually compressed, kernel image that can be booted
 - ▶ `bzImage` for x86, `zImage` for ARM, `vmImage.gz` for Blackfin, etc.
 - ▶ `arch/<arch>/boot/dts/*.dtb`, compiled Device Tree files (on some architectures)
 - ▶ All kernel modules, spread over the kernel source tree, as `.ko` (*Kernel Object*) files.

- ▶ make install
 - ▶ Does the installation for the host system by default, so needs to be run as root. Generally not used when compiling for an embedded system, as it installs files on the development workstation.
- ▶ Installs
 - ▶ /boot/vmlinuz-<version>
Compressed kernel image. Same as the one in arch/<arch>/boot
 - ▶ /boot/System.map-<version>
Stores kernel symbol addresses
 - ▶ /boot/config-<version>
Kernel configuration for this version
- ▶ Typically re-runs the bootloader configuration utility to take the new kernel into account.

- ▶ 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
Module aliases for module loading utilities. Example line:
alias sound-service-?-0 snd_mixer_oss
 - ▶ modules.dep, modules.dep.bin (binary hashed)
Module dependencies
 - ▶ modules.symbols, modules.symbols.bin (binary hashed)
Tells which module a given symbol belongs to.

- ▶ Clean-up generated files (to force re-compilation):
`make clean`
- ▶ Remove all generated files. Needed when switching from one architecture to another.
Caution: it also removes your `.config` file!
`make mrproper`
- ▶ Also remove editor backup and patch reject files (mainly to generate patches):
`make distclean`
- ▶ If you are in a git tree, remove all files not tracked (and ignored) by git:
`git clean -fdx`



Cross-compiling the kernel

When you compile a Linux kernel for another CPU architecture

- ▶ Much faster than compiling natively, when the target system is much slower than your GNU/Linux workstation.
- ▶ Much easier as development tools for your GNU/Linux workstation are much easier to find.
- ▶ To make the difference with a native compiler, cross-compiler executables are prefixed by the name of the target system, architecture and sometimes library. Examples:
`mips-linux-gcc`, the prefix is `mips-linux-`
`arm-linux-gnueabi-gcc`, the prefix is `arm-linux-gnueabi-`

The CPU architecture and cross-compiler prefix are defined through the `ARCH` and `CROSS_COMPILE` variables in the toplevel Makefile.

- ▶ `ARCH` is the name of the architecture. It is defined by the name of the subdirectory in `arch/` in the kernel sources
 - ▶ Example: `arm` if you want to compile a kernel for the arm architecture.
- ▶ `CROSS_COMPILE` is the prefix of the cross compilation tools
 - ▶ Example: `arm-linux-` if your compiler is `arm-linux-gcc`

Two solutions to define 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. If you only work on a single architecture with always the same toolchain, you could even put these settings in your `~/.bashrc` file to make them permanent and visible from any terminal.

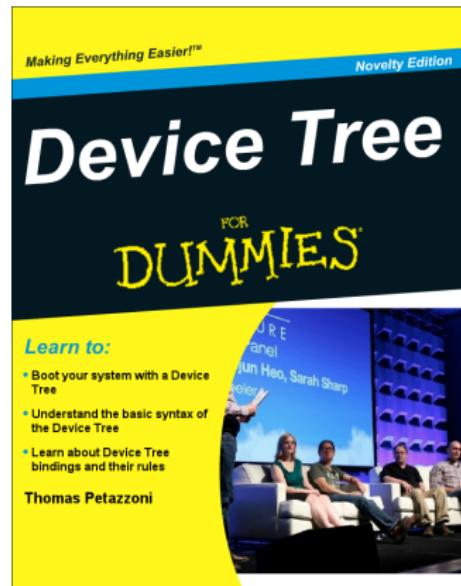
- ▶ Default configuration files available, per board or per-CPU family
 - ▶ They are stored in `arch/<arch>/configs/`, and are just minimal `.config` files
 - ▶ This is the most common way of configuring a kernel for embedded platforms
- ▶ Run `make help` to find if one is available for your platform
- ▶ To load a default configuration file, just run
`make acme_defconfig`
 - ▶ This will overwrite your existing `.config` file!
- ▶ To create your own default configuration file
 - ▶ `make savedefconfig`, to create a minimal configuration file
 - ▶ `mv defconfig arch/<arch>/configs/myown_defconfig`

- ▶ After loading a default configuration file, you can adjust the configuration to your needs with the normal `xconfig`, `gconfig` or `menuconfig` interfaces
- ▶ As the architecture is different from your host architecture
 - ▶ Some options will be different from the native configuration (processor and architecture specific options, specific drivers, etc.)
 - ▶ Many options will be identical (filesystems, network protocols, architecture-independent drivers, etc.)

- ▶ Many embedded architectures have a lot of non-discoverable hardware.
- ▶ Depending on the architecture, such hardware is either described using C code directly within the kernel, or using a special hardware description language in a *Device Tree*.
- ▶ ARM, PowerPC, OpenRISC, ARC, Microblaze are examples of architectures using the Device Tree.
- ▶ A *Device Tree Source*, written by kernel developers, is compiled into a binary *Device Tree Blob*, passed at boot time to the kernel.
 - ▶ There is one different Device Tree for each board/platform supported by the kernel, available in arch/arm/boot/dts/<board>.dtb.
 - ▶ The bootloader must load both the kernel image and the Device Tree Blob in memory before starting the kernel.

Often needed for embedded board users:

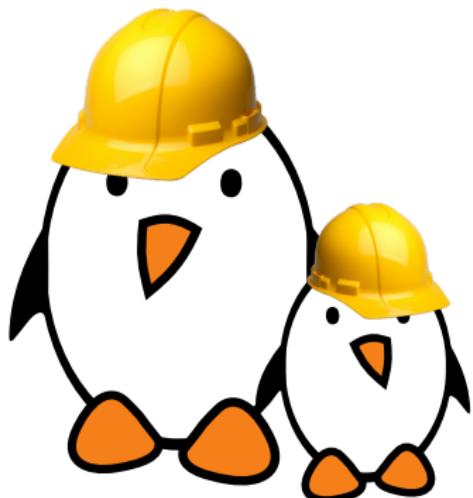
- ▶ To describe external devices attached to non-discoverable busses (such as I2C) and configure them.
- ▶ To configure pin muxing: choosing what SoC signals are made available on the board external connectors.
- ▶ To configure some system parameters: flash partitions, kernel command line (other ways exist)
- ▶ Useful reference: Device Tree for Dummies, Thomas Petazzoni (Apr. 2014): <http://j.mp/1jQU6NR>



- ▶ Run `make`
- ▶ Copy the final kernel image to the target storage
 - ▶ can be `zImage`, `vmlinux`, `bzImage` in `arch/<arch>/boot`
 - ▶ copying the Device Tree Blob might be necessary as well, they are available in `arch/<arch>/boot/dts`
- ▶ `make install` is rarely used in embedded development, as the kernel image is a single file, easy to handle
 - ▶ It is however possible to customize the `make install` behaviour in `arch/<arch>/boot/install.sh`
- ▶ `make modules_install` is used even in embedded development, as it installs many modules and description files
 - ▶ `make INSTALL_MOD_PATH=<dir>/ modules_install`
 - ▶ The `INSTALL_MOD_PATH` variable is needed to install the modules in the target root filesystem instead of your host root filesystem.

- ▶ Recent versions of U-Boot can boot the `zImage` binary.
- ▶ Older versions require a special kernel image format: `uImage`
 - ▶ `uImage` is generated from `zImage` using the `mkimage` tool. It is done automatically by the kernel make `uImage` target.
 - ▶ On some ARM platforms, make `uImage` requires passing a `LOADADDR` environment variable, which indicates at which physical memory address the kernel will be executed.
- ▶ In addition to the kernel image, U-Boot can also pass a *Device Tree Blob* to the kernel.
- ▶ The typical boot process is therefore:
 1. Load `zImage` or `uImage` at address X in memory
 2. Load `<board>.dtb` at address Y in memory
 3. Start the kernel with `bootz X - Y` (`zImage` case), or `bootm X - Y` (`uImage` case)
The `-` in the middle indicates no *initramfs*

- ▶ In addition to the compile time configuration, the kernel behaviour 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
 - ▶ Many more exist. The most important ones are documented in `Documentation/kernel-parameters.txt` in kernel sources.
- ▶ This kernel command line is either
 - ▶ Passed by the bootloader. In U-Boot, the contents of the `bootargs` environment variable is automatically passed to the kernel
 - ▶ Built into the kernel, using the `CONFIG_CMDLINE` option.



- ▶ Set up the cross-compiling environment
- ▶ Configure and cross-compile the kernel for an `arm` platform
- ▶ On this platform, interact with the bootloader and boot your kernel

Using kernel 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.

- ▶ Some kernel modules can depend on other modules, which need to be loaded first.
- ▶ Example: the `usb-storage` module depends on the `scsi_mod`, `libusual` and `usbcore` modules.
- ▶ Dependencies are described both in
`/lib/modules/<kernel-version>/modules.dep` and in
`/lib/modules/<kernel-version>/modules.dep.bin`
These files are generated when you run
`make modules_install`.

When a new module is loaded, related information is available in the kernel log.

- ▶ The kernel keeps its messages in a circular buffer (so that it doesn't consume more memory with many messages)
- ▶ Kernel log messages are available through the `dmesg` command (**diagnostic message**)
- ▶ Kernel log messages are also displayed in the system console (console messages can be filtered by level using the `loglevel` kernel parameter, or completely disabled with the `quiet` parameter).
- ▶ Note that you can write to the kernel log from user space too:
`echo "<n>Debug info" > /dev/kmsg`

<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.
- ▶ `sudo insmod <module_path>.ko`
Tries to load the given module. The full path to the module
object file must be given.

- ▶ 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
```

- ▶ `sudo modprobe <module_name>`
Most common usage of `modprobe`: tries to load all the modules the given module depends on, 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`!

- ▶ `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 <module_name>`
Tries to remove the given module and all dependent modules (which are no longer needed after removing the module)

- ▶ 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 driver is built statically into the kernel:

```
usb-storage.delay_use=0
```

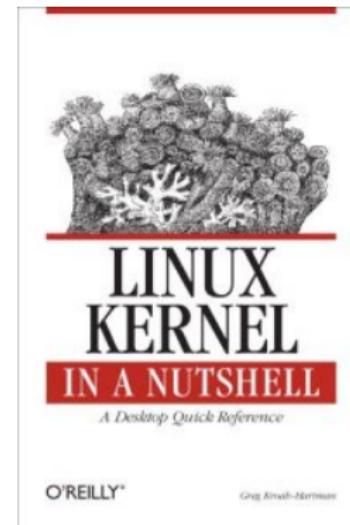
- ▶ *usb-storage* is the *driver name*
- ▶ *delay_use* is the *driver parameter name*. It specifies a delay before accessing a USB storage device (useful for rotating devices).
- ▶ *0* is the *driver parameter value*

How to find 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.

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
<http://free-electrons.com/community/kernel/lkn/>



Linux Root Filesystem

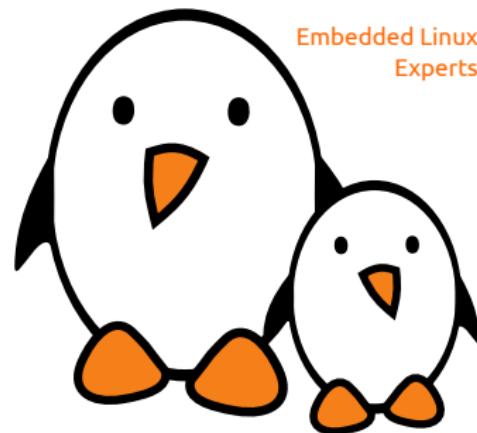
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Embedded Linux
Experts

Principle and solutions

- ▶ Filesystems are used to organize data in directories and files on storage devices or on the network. The directories and files are organized as a hierarchy
- ▶ In Unix systems, applications and users see a **single global hierarchy** of files and directories, which can be composed of several filesystems.
- ▶ Filesystems are **mounted** in a specific location in this hierarchy of directories
 - ▶ When a filesystem is mounted in a directory (called *mount point*), the contents of this directory reflects the contents of the storage device
 - ▶ When the filesystem is unmounted, the *mount point* is empty again.
- ▶ This allows applications to access files and directories easily, regardless of their exact storage location

- ▶ Create a mount point, which is just a directory

```
$ mkdir /mnt/usbkey
```

- ▶ It is empty

```
$ ls /mnt/usbkey  
$
```

- ▶ Mount a storage device in this mount point

```
$ mount -t vfat /dev/sda1 /mnt/usbkey  
$
```

- ▶ You can access the contents of the USB key

```
$ ls /mnt/usbkey  
docs prog.c picture.png movie.avi  
$
```

mount / umount

- ▶ mount allows to mount filesystems
 - ▶ `mount -t type device mountpoint`
 - ▶ `type` is the type of filesystem
 - ▶ `device` is the storage device, or network location to mount
 - ▶ `mountpoint` is the directory where files of the storage device or network location will be accessible
 - ▶ `mount` with no arguments shows the currently mounted filesystems
- ▶ umount allows to unmount filesystems
 - ▶ This is needed before rebooting, or before unplugging a USB key, because the Linux kernel caches writes in memory to increase performance. `umount` makes sure that these writes are committed to the storage.

- ▶ A particular filesystem is mounted at the root of the hierarchy, identified by /
- ▶ This filesystem is called the **root filesystem**
- ▶ As mount and umount are programs, they are files inside a filesystem.
 - ▶ They are not accessible before mounting at least one filesystem.
- ▶ As the root filesystem is the first mounted filesystem, it cannot be mounted with the normal `mount` command
- ▶ It is mounted directly by the kernel, according to the `root=kernel` option
- ▶ When no root filesystem is available, the kernel panics

Please append a correct "root=" boot option

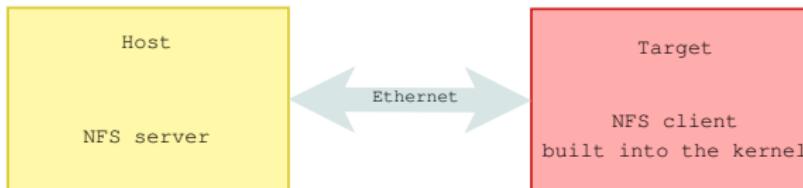
Kernel panic - not syncing: VFS: Unable to mount root fs on unknown block(0,0)

- ▶ It can be mounted from different locations
 - ▶ From the partition of a hard disk
 - ▶ From the partition of a USB key
 - ▶ From the partition of an SD card
 - ▶ From the partition of a NAND flash chip or similar type of storage device
 - ▶ From the network, using the NFS protocol
 - ▶ From memory, using a pre-loaded filesystem (by the bootloader)
 - ▶ etc.
- ▶ It is up to the system designer to choose the configuration for the system, and configure the kernel behaviour with `root=`

- ▶ Partitions of a hard disk or USB key
 - ▶ `root=/dev/sdXY`, where X is a letter indicating the device, and Y a number indicating the partition
 - ▶ `/dev/sdb2` is the second partition of the second disk drive (either USB key or ATA hard drive)
- ▶ Partitions of an SD card
 - ▶ `root=/dev/mmcblkXpY`, where X is a number indicating the device and Y a number indicating the partition
 - ▶ `/dev/mmcblk0p2` is the second partition of the first device
- ▶ Partitions of flash storage
 - ▶ `root=/dev/mtdblockX`, where X is the partition number
 - ▶ `/dev/mtdblock3` is the fourth partition of a NAND flash chip (if only one NAND flash chip is present)

Once networking works, your root filesystem could be a directory on your GNU/Linux development host, exported by NFS (Network File System). This is very convenient for system development:

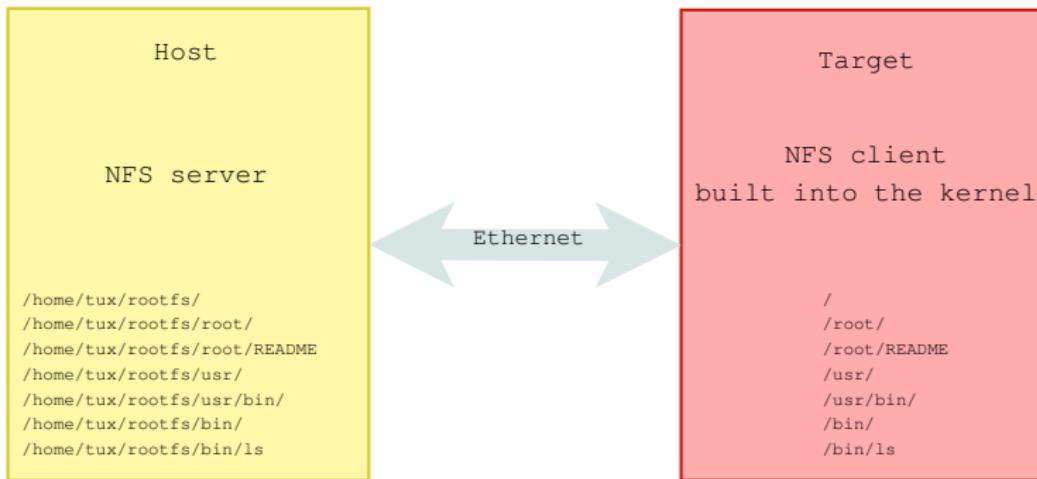
- ▶ Makes it very easy to update files on the root filesystem, without rebooting. Much faster than through the serial port.
- ▶ Can have a big root filesystem even if you don't have support for internal or external storage yet.
- ▶ The root filesystem can be huge. You can even build native compiler tools and build all the tools you need on the target itself (better to cross-compile though).



On the development workstation side, a NFS server is needed

- ▶ Install an NFS server (example: Debian, Ubuntu)
`sudo apt-get install nfs-kernel-server`
- ▶ Add the exported directory to your /etc/exports file:
`/home/tux/rootfs 192.168.1.111(rw,no_root_squash,no_subtree_check)`
 - ▶ 192.168.1.111 is the client IP address
 - ▶ rw,no_root_squash,no_subtree_check are the NFS server options for this directory export.
- ▶ Start or restart your NFS server (example: Debian, Ubuntu)
`sudo /etc/init.d/nfs-kernel-server restart`

- ▶ On the target system
- ▶ The kernel must be compiled with
 - ▶ CONFIG_NFS_FS=y (NFS support)
 - ▶ CONFIG_IP_PNP=y (configure IP at boot time)
 - ▶ CONFIG_ROOT_NFS=y (support for NFS as rootfs)
- ▶ The kernel must be booted with the following parameters:
 - ▶ root=/dev/nfs (we want rootfs over NFS)
 - ▶ ip=192.168.1.111 (target IP address)
 - ▶ nfsroot=192.168.1.110:/home/tux/rootfs/ (NFS server details)



- ▶ It is also possible to have the root filesystem integrated into the kernel image
- ▶ It is therefore loaded into memory together with the kernel
- ▶ This mechanism is called **initramfs**
 - ▶ It integrates a compressed archive of the filesystem into the kernel image
 - ▶ Variant: the compressed archive can also be loaded separately by the bootloader.
- ▶ It is useful for two cases
 - ▶ Fast booting of very small root filesystems. As the filesystem is completely loaded at boot time, application startup is very fast.
 - ▶ As an intermediate step before switching to a real root filesystem, located on devices for which drivers not part of the kernel image are needed (storage drivers, filesystem drivers, network drivers). This is always used on the kernel of desktop/server distributions to keep the kernel image size reasonable.

Kernel code and data

Root filesystem stored
as a compressed cpio
archive

Kernel image (`zImage`, `bzImage`, etc.)

- ▶ The contents of an initramfs are defined at the kernel configuration level, with the `CONFIG_INITRAMFS_SOURCE` option
 - ▶ Can be the path to a directory containing the root filesystem contents
 - ▶ Can be the path to a cpio archive
 - ▶ Can be a text file describing the contents of the initramfs (see documentation for details)
- ▶ The kernel build process will automatically take the contents of the `CONFIG_INITRAMFS_SOURCE` option and integrate the root filesystem into the kernel image
- ▶ Details (in kernel sources):
`Documentation/filesystems/ramfs-rootfs-initramfs.txt`
`Documentation/early-userspace/README`

Contents

- ▶ The organization of a Linux root filesystem in terms of directories is well-defined by the **Filesystem Hierarchy Standard**
- ▶ <http://www.linuxfoundation.org/collaborate/workgroups/lsb/fhs>
- ▶ Most Linux systems conform to this specification
 - ▶ Applications expect this organization
 - ▶ It makes it easier for developers and users as the filesystem organization is similar in all systems

- /bin Basic programs
- /boot Kernel image (only when the kernel is loaded from a filesystem, not common on non-x86 architectures)
- /dev Device files (covered later)
- /etc System-wide configuration
- /home Directory for the users home directories
- /lib Basic libraries
- /media Mount points for removable media
- /mnt Mount points for static media
- /proc Mount point for the proc virtual filesystem

/root Home directory of the root user

/sbin Basic system programs

/sys Mount point of the sysfs virtual filesystem

/tmp Temporary files

/usr /usr/bin Non-basic programs

 /usr/lib Non-basic libraries

 /usr/sbin Non-basic system programs

/var Variable data files. This includes spool directories and files, administrative and logging data, and transient and temporary files

- ▶ Basic programs are installed in `/bin` and `/sbin` and basic libraries in `/lib`
- ▶ All other programs are installed in `/usr/bin` and `/usr/sbin` and all other libraries in `/usr/lib`
- ▶ In the past, on Unix systems, `/usr` was very often mounted over the network, through NFS
- ▶ In order to allow the system to boot when the network was down, some binaries and libraries are stored in `/bin`, `/sbin` and `/lib`
- ▶ `/bin` and `/sbin` contain programs like `ls`, `ifconfig`, `cp`, `bash`, etc.
- ▶ `/lib` contains the C library and sometimes a few other basic libraries
- ▶ All other programs and libraries are in `/usr`

Device Files

- ▶ One of the kernel important role is to **allow applications to access hardware devices**
- ▶ In the Linux kernel, most devices are presented to user space applications through two different abstractions
 - ▶ **Character** device
 - ▶ **Block** device
- ▶ Internally, the kernel identifies each device by a triplet of information
 - ▶ **Type** (character or block)
 - ▶ **Major** (typically the category of device)
 - ▶ **Minor** (typically the identifier of the device)

- ▶ Block devices
 - ▶ A device composed of fixed-sized blocks, that can be read and written to store data
 - ▶ Used for hard disks, USB keys, SD cards, etc.
- ▶ Character devices
 - ▶ Originally, an infinite stream of bytes, with no beginning, no end, no size. The pure example: a serial port.
 - ▶ Used for serial ports, terminals, but also sound cards, video acquisition devices, frame buffers
 - ▶ Most of the devices that are not block devices are represented as character devices by the Linux kernel

- ▶ 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

Example of device files in a Linux system

```
$ ls -l /dev/ttys0 /dev/tty1 /dev/sda1 /dev/sda2 /dev/zero
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
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

```
int fd;
fd = open("/dev/ttys0", O_RDWR);
write(fd, "Hello", 5);
close(fd);
```

- ▶ 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 known to the kernel. The `CONFIG_DEV TMPFS_MOUNT` kernel configuration option makes the kernel mount it automatically at boot time, except when booting on an initramfs.

Pseudo Filesystems

- ▶ The `proc` virtual filesystem exists since the beginning of Linux
- ▶ It allows
 - ▶ The kernel to expose statistics about running processes in the system
 - ▶ The user to adjust at runtime various system parameters about process management, memory management, etc.
- ▶ The `proc` filesystem is used by many standard user space applications, and they expect it to be mounted in `/proc`
- ▶ Applications such as `ps` or `top` would not work without the `proc` filesystem
- ▶ Command to mount `/proc`:
`mount -t proc nodev /proc`
- ▶ Documentation/filesystems/proc.txt in the kernel sources
- ▶ `man proc`

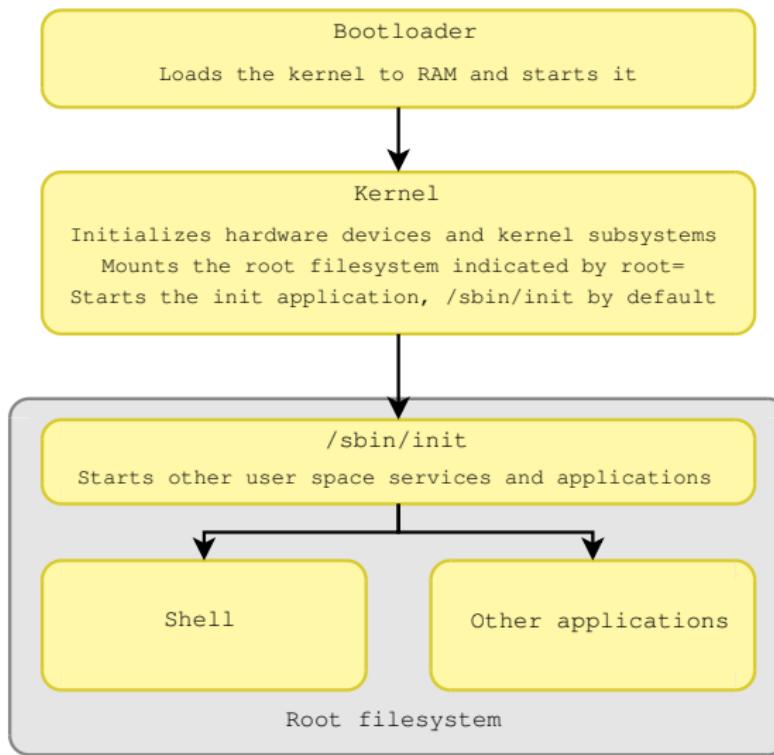
- ▶ One directory for each running process in the system
 - ▶ `/proc/<pid>`
 - ▶ `cat /proc/3840/cmdline`
 - ▶ It contains details about the files opened by the process, the CPU and memory usage, etc.
- ▶ `/proc/interrupts`, `/proc/devices`, `/proc/iomem`, `/proc/ioports` contain general device-related information
- ▶ `/proc/cmdline` contains the kernel command line
- ▶ `/proc/sys` contains many files that can be written to to adjust kernel parameters
 - ▶ They are called *sysctl*. See Documentation/sysctl/ in kernel sources.
 - ▶ Example

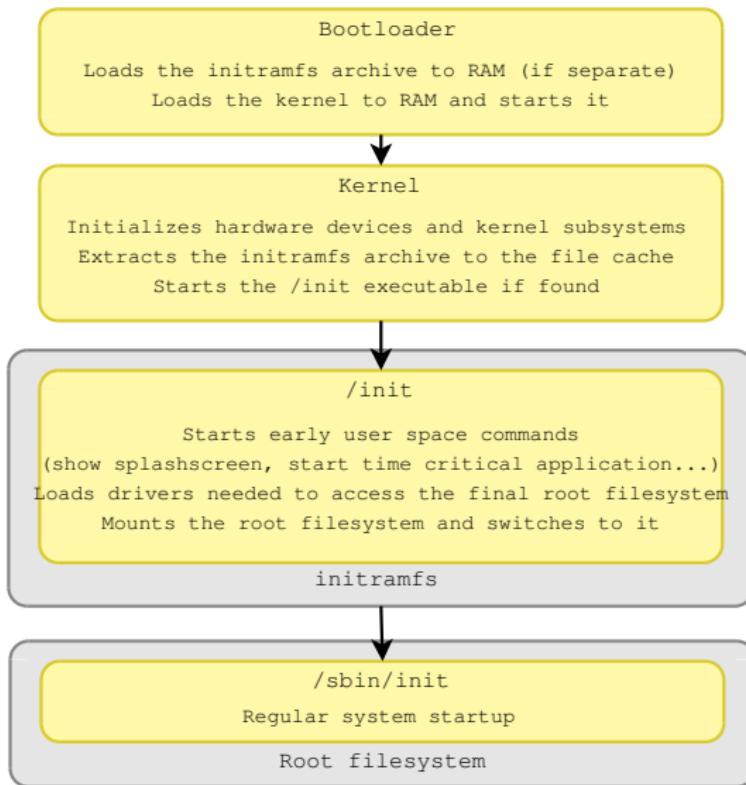
```
echo 3 > /proc/sys/vm/drop_caches
```

- ▶ The `sysfs` filesystem is a feature integrated in the 2.6 Linux kernel
- ▶ It allows to represent in user space the vision that the kernel has of the buses, devices and drivers in the system
- ▶ It is useful for various user space applications that need to list and query the available hardware, for example `udev` or `mdev`.
- ▶ All applications using `sysfs` expect it to be mounted in the `/sys` directory
- ▶ Command to mount `/sys`:
`mount -t sysfs nodev /sys`
- ▶ `$ ls /sys/`
`block bus class dev devices firmware`
`fs kernel module power`

Minimal filesystem

- ▶ In order to work, a Linux system needs at least a few applications
- ▶ An `init` application, which is the first user space application started by the kernel after mounting the root filesystem
 - ▶ The kernel tries to run `/sbin/init`, `/bin/init`, `/etc/init` and `/bin/sh`.
 - ▶ In the case of an `initramfs`, it will only look for `/init`. Another path can be supplied by the `rdinit` kernel argument.
 - ▶ If none of them are found, the kernel panics and the boot process is stopped.
 - ▶ The `init` application is responsible for starting all other user space applications and services
- ▶ A shell, to implement scripts, automate tasks, and allow a user to interact with the system
- ▶ Basic Unix applications, to copy files, move files, list files (commands like `mv`, `cp`, `mkdir`, `cat`, etc.)
- ▶ These basic components have to be integrated into the root filesystem to make it usable





Busybox

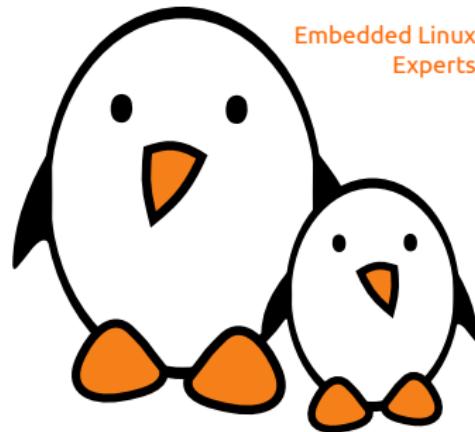
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Corrections, suggestions, contributions and translations are welcome!



- ▶ A Linux system needs a basic set of programs to work
 - ▶ An init program
 - ▶ A shell
 - ▶ Various basic utilities for file manipulation and system configuration
- ▶ In normal Linux systems, these programs are provided by different projects
 - ▶ coreutils, bash, grep, sed, tar, wget, modutils, etc. are all different projects
 - ▶ A lot of different components to integrate
 - ▶ Components not designed with embedded systems constraints in mind: they are not very configurable and have a wide range of features
- ▶ Busybox is an alternative solution, extremely common on embedded systems

- ▶ Rewrite of many useful Unix command line utilities
 - ▶ Integrated into a single project, which makes it easy to work with
 - ▶ Designed with embedded systems in mind: highly configurable, no unnecessary features
- ▶ All the utilities are compiled into a single executable, /bin/busybox
 - ▶ Symbolic links to /bin/busybox are created for each application integrated into Busybox
- ▶ For a fairly featureful configuration, less than 500 KB (statically compiled with uClibc) or less than 1 MB (statically compiled with glibc).
- ▶ <http://www.busybox.net/>

Commands available in BusyBox 1.13

[, [[, addgroup, adduser, adjtimex, ar, arp, arping, ash, awk, basename, bbconfig, bbsht, brctl, bunzip2, busybox, bzcat, bzip2, cal, cat, catv, chat, chattr, chcon, chgrp, chmod, chown, chpasswd, chpst, chroot, chrt, chvt, cksum, clear, cmp, comm, cp, cpio, crond, crontab, cryptpw, cttyhack, cut, date, dc, dd, deallocvt, delgroup, deluser, depmod, devfsd, df, dhcprelay, diff, dirname, dmesg, dnsd, dos2unix, dpkg, dpkg_deb, du, dumpkmap, dumpleases, e2fsck, echo, ed, egrep, eject, env, envdir, envuidgid, ether_wake, expand, expr, fakeidentd, false, fbset, fbsplash, fdflush, fdformat, fdisk, fetchmail, fgrep, find, findfs, fold, free, freeramdisk, fsck, fsck_minix, ftpget, ftpput, fuser, getenforce, getopt, getsebool, getty, grep, gunzip, gzip, halt, hd, hdparm, head, hexdump, hostid, hostname, httpd, hush, hwclock, id, ifconfig, ifdown, ifenslave, ifup, inetd, init, inotifyd, insmod, install, ip, ipaddr, ipcalc, ipcrm, ipcs, iplink, iproute, iprule, iptunnel, kbd_mode, kill, killall, killall5, klogd, lash, last, length, less, linux32, linux64, linuxrc, ln, load_policy, loadfont, loadkmap, logger, login, logname, logread, losetup, lpd, lpq, lpr, ls, lsattr, lsmod, lzmacat, makedevs, man, matchpathcon, md5sum, mdev, mesg, microcom, mkdir, mke2fs, mkfifo, mkfs_minix, mknod, mkswap, mkttemp, modprobe, more, mount, mountpoint, msh, mt, mv, nameif, nc, netstat, nice, nmeter, nohup, nslookup, od, openvt, parse, passwd, patch, pgrep, pidof, ping, ping6, pipe_progress, pivot_root, pkill, poweroff, printenv, printf, ps, pscan, pwd, raidautorun, rdate, rdev, readahead, readlink, readprofile, realpath, reboot, renice, reset, resize, restorecon, rm, rmdir, rmmod, route, rpm, rpm2cpio, rtcwake, run_parts, runcon, runlevel, runsv, runsvdir, rx, script, sed, selinuxenabled, sendmail, seq, sestatus, setarch, setconsole, setenforce, setfiles, setfont, setkeycodes, setlogcons, setsebool, setsid, setuidgid, sh, sha1sum, showkey, slattach, sleep, softlimit, sort, split, start_stop_daemon, stat, strings, stty, su, slogin, sum, sv, svlogd, swapoff, swapon, switch_root, sync, sysctl, syslogd, tac, tail, tar, taskset, tcpsvd, tee, telnet, telnetd, test, tftp, tftpd, time, top, touch, tr, traceroute, true, tty, ttysize, tune2fs, udhcpc, udhcpd, udpsvd, umount, uname, uncompress, unexpand, uniq, unix2dos, unlzma, unzip, uptime, usleep, uudecode, uuencode, vconfig, vi, vlock, watch, watchdog, wc, wget, which, who, whoami, xargs, yes, zcat, zcip

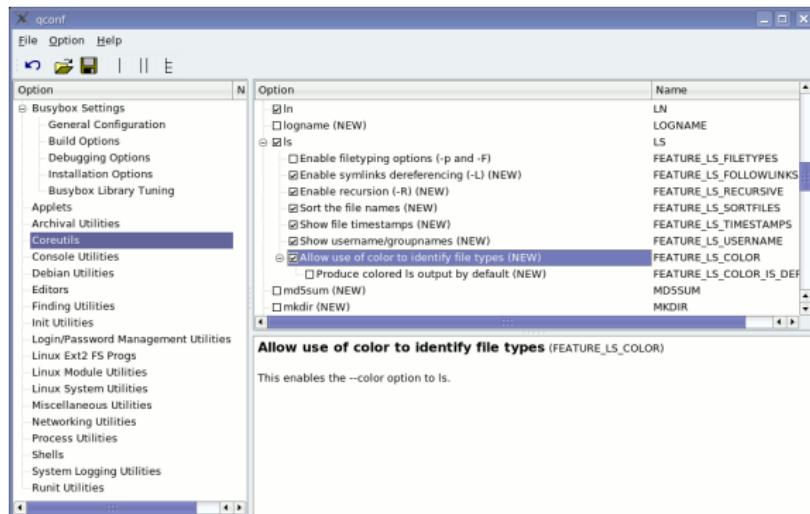
- ▶ Busybox provides an implementation of an `init` program
- ▶ Simpler than the `init` implementation found on desktop/server systems: no runlevels are implemented
- ▶ A single configuration file: `/etc/inittab`
 - ▶ Each line has the form `<id>:<action>:<process>`
- ▶ Allows to run services at startup, and to make sure that certain services are always running on the system
- ▶ See `examples/inittab` in Busybox for details on the configuration

- ▶ If you are using BusyBox, adding `vi` support only adds 20K.
(built with shared libraries, using uClibc).
- ▶ You can select which exact features to compile in.
- ▶ Users hardly realize that they are using a lightweight `vi` version!
- ▶ Tip: you can learn `vi` on the desktop, by running the `vimtutor` command.

- ▶ Get the latest stable sources from <http://busybox.net>
- ▶ Configure BusyBox (creates a `.config` file):
 - ▶ `make defconfig`
Good to begin with BusyBox.
Configures BusyBox with all options for regular users.
 - ▶ `make allnoconfig`
Unselects all options. Good to configure only what you need.
- ▶ `make xconfig` (graphical, needs the `libqt3-mt-dev` package)
or `make menuconfig` (text)
Same configuration interfaces as the ones used by the Linux kernel (though older versions are used).

You can choose:

- ▶ the commands to compile,
- ▶ and even the command options and features that you need!



- ▶ Set the cross-compiler prefix in the configuration interface:

BusyBox Settings -> Build Options -

> Cross Compiler prefix

Example: arm-linux-

- ▶ Set the installation directory in the configuration interface:

BusyBox Settings -> Installation Options -

> BusyBox installation prefix

- ▶ Add the cross-compiler path to the PATH environment variable:

```
export PATH=/home/<user>/x-tools/arm-unknown-linux-  
uclibcgnueabi/bin:$PATH
```

- ▶ Compile BusyBox:

make

- ▶ Install it (this creates a Unix directory structure symbolic links to the busybox executable):

make install



- ▶ Make Linux boot on a directory on your workstation, shared by NFS
- ▶ Create and configure a minimalistic Linux embedded system
- ▶ Install and use BusyBox
- ▶ System startup with `/sbin/init`
- ▶ Set up a simple web interface
- ▶ Use shared libraries

Flash filesystems

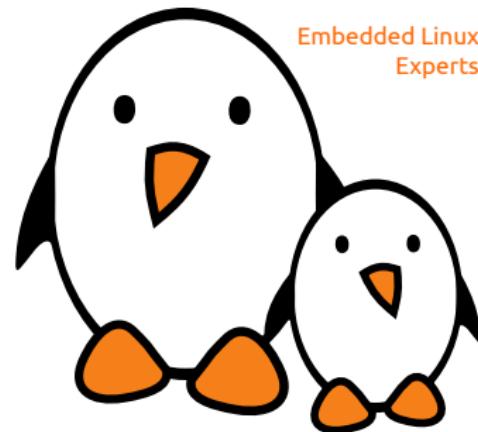
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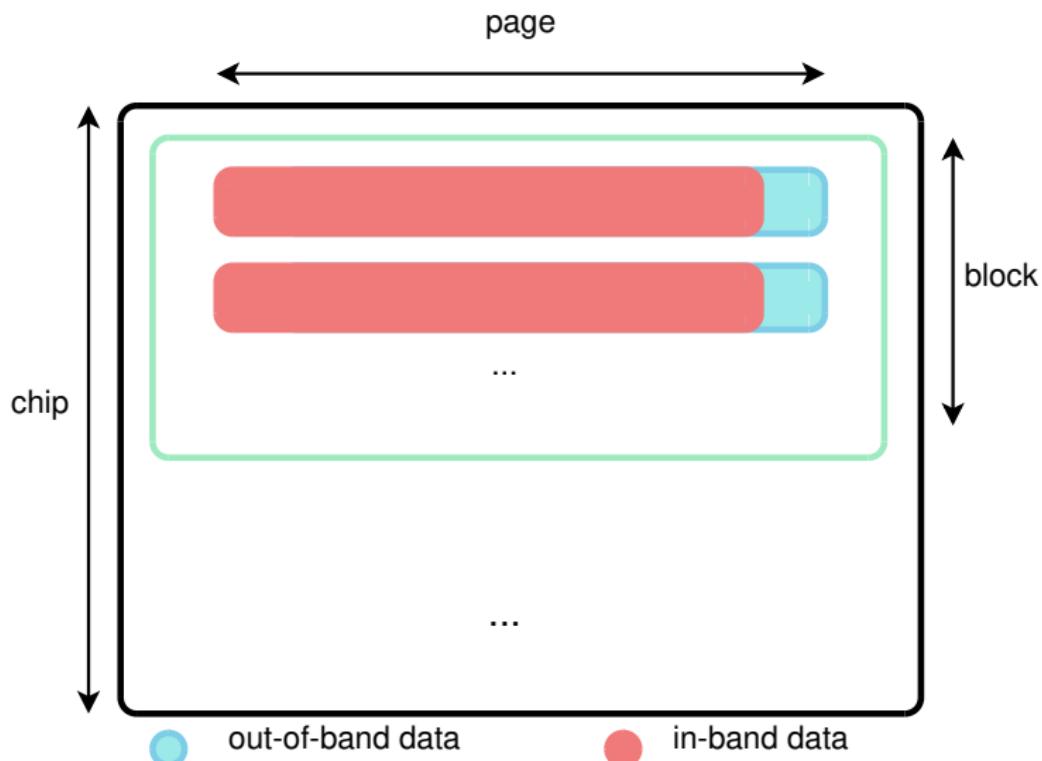
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Corrections, suggestions, contributions and translations are welcome!



- ▶ Block devices:
 - ▶ Allow for random data access using fixed size blocks
 - ▶ Do not require special care when writing on the media
 - ▶ Block size is relatively small (minimum 512 bytes, can be increased for performance reasons)
 - ▶ Considered as reliable (if the storage media is not, some hardware or software parts are supposed to make it reliable)
- ▶ Flash devices:
 - ▶ Allow for random data access too
 - ▶ Require special care before writing on the media (erasing the region you are about to write on)
 - ▶ Erase, write and read operation might not use the same block size
 - ▶ Reliability depends on the flash technology

- ▶ Encode bits with voltage levels
- ▶ Start with all bits set to 1
- ▶ Programming implies changing some bits from 1 to 0
- ▶ Restoring bits to 1 is done via the ERASE operation
- ▶ Programming and erasing is not done on a per bit or per byte basis
- ▶ Organization
 - ▶ Page: minimum unit for PROGRAM operation
 - ▶ Block: minimum unit for ERASE operation



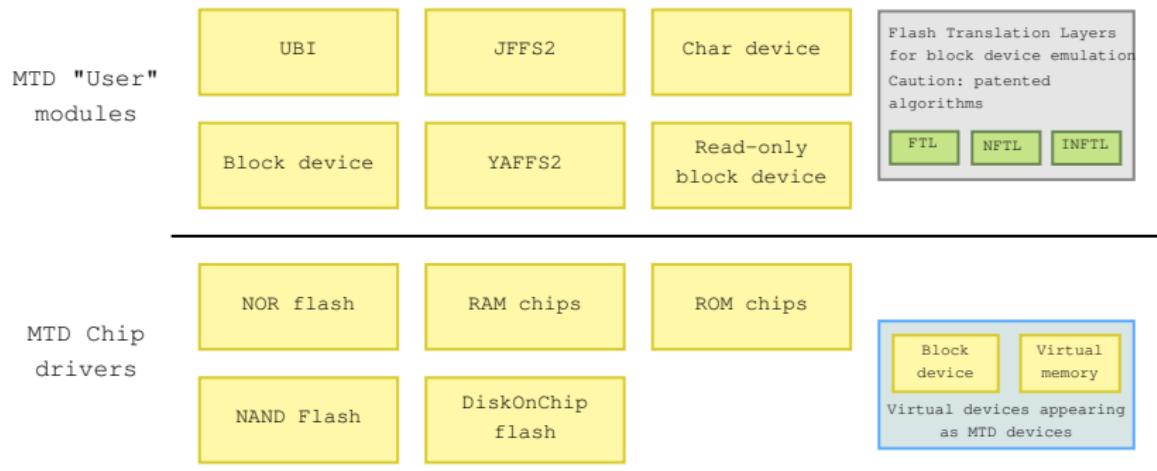
- ▶ Reliability
 - ▶ Far less reliable than NOR flash
 - ▶ Reliability depends on the NAND flash technology (SLC, MLC)
 - ▶ Require additional mechanisms to recover from bit flips: ECC (Error Correcting Code)
 - ▶ ECC information stored in the OOB (Out-of-band area)
- ▶ Lifetime
 - ▶ Short lifetime compared to other storage media
 - ▶ Lifetime depends on the NAND flash technology (SLC, MLC): between 1000000 and 1000 erase cycles per block
 - ▶ Wear leveling mechanisms are required
 - ▶ Bad block detection/handling required too
- ▶ Despite the number of constraints brought by NAND they are widely used in embedded systems for several reasons:
 - ▶ Cheaper than other flash technologies
 - ▶ Provide high capacity storage
 - ▶ Provide good performance (both in read and write access)

- ▶ ECC partly addresses the reliability problem on NAND flash
- ▶ Operates on blocks (usually 512 or 1024 bytes)
- ▶ ECC data are stored in the OOB area
- ▶ Three algorithms:
 - ▶ Hamming: can fixup a single bit per block
 - ▶ Reed-Solomon: can fixup several bits per block
 - ▶ BCH: can fixup several bits per block
- ▶ BCH and Reed-Solomon strength depends on the size allocated for ECC data, which in turn depends on the OOB size
- ▶ NAND manufacturers specify the required ECC strength in their datasheets: ignoring these requirements might compromise data integrity

- ▶ MTD stands for *Memory Technology Devices*
- ▶ Generic subsystem dealing with all types of storage media that are not fitting in the block subsystem
- ▶ Supported media types: RAM, ROM, NOR flash, NAND flash, Dataflash
- ▶ Independent of the communication interface (drivers available for parallel, SPI, direct memory mapping, ...)
- ▶ Abstract storage media characteristics and provide a simple API to access MTD devices
- ▶ MTD device characteristics exposed to users:
 - ▶ erasesize: minimum erase size unit
 - ▶ writesize: minimum write size unit
 - ▶ oobsize: extra size to store metadata or ECC data
 - ▶ size: device size
 - ▶ flags: information about device type and capabilities
- ▶ Various kind of MTD users: file-systems, block device emulation layers, user space interfaces...

ENDO CODE The MTD subsystem (2)

Linux filesystem interface



- ▶ MTD devices are usually partitioned
 - ▶ It allows to use different areas of the flash for different purposes: read-only filesystem, read-write filesystem, backup areas, bootloader area, kernel area, etc.
- ▶ Unlike block devices, which contains their own partition table, the partitioning of MTD devices is described externally (don't want to put it in a flash sector which could become bad)
 - ▶ Specified in the board Device Tree
 - ▶ Hard-coded into the kernel code (if no Device Tree)
 - ▶ Specified through the kernel command line
- ▶ Each partition becomes a separate MTD device
 - ▶ Different from block device labeling (`hda3`, `sda2`)
 - ▶ `/dev/mtd1` is either the second partition of the first flash device, or the first partition of the second flash device
 - ▶ Note that the master MTD device (the device those partitions belongs to) is not exposed in `/dev`

The Device Tree is the standard place to define MTD partitions for platforms with Device Tree support.

Example from arch/arm/boot/dts/omap3-igep.dtsi:

```
nand@0 {
    linux,mtd-name= "micron,mt29c4g96maz";
^^I^^I[...]
    partition@0 {
        label = "SPL";
        reg = <0 0x100000>;
    };
    partition@0x80000 {
        label = "U-Boot";
        reg = <0x100000 0x180000>;
    };
^^I^^I[...]
    partition@0x780000 {
        label = "Filesystem";
        reg = <0x680000 0x1f980000>;
    };
}
```

- ▶ U-Boot also provides a way to define MTD partitions on flash devices
- ▶ Named partitions are easier to use, and much less error prone than using offsets.
- ▶ U-Boot partition definitions can also be used by Linux too, eliminating the risk of mismatches between Linux and U-Boot.
- ▶ Use flash specific commands (detailed soon), and pass partition names instead of numerical offsets
- ▶ Example: nand erase.part <partname>

- ▶ Example:

```
setenv mtdids nand0=omap2-nand.0
setenv mtdparts=omap2-nand.0:512k(X-Loader)ro,1536k(U-Boot)ro,512k(Env),4m(Kernel),-(RootFS)
```

- ▶ This defines 5 partitions in the omap2-nand.0 device:
 - ▶ 1st stage bootloader (512 KiB, read-only)
 - ▶ U-Boot (1536 KiB, read-only)
 - ▶ U-Boot environment (512 KiB)
 - ▶ Kernel (4 MiB)
 - ▶ Root filesystem (Remaining space)
- ▶ Partition sizes must be multiple of the erase block size. You can use sizes in hexadecimal too. Remember the below sizes:
 $0x20000 = 128k$, $0x100000 = 1m$, $0x1000000 = 16m$
- ▶ ro lists the partition as read only
- ▶ - is used to use all the remaining space.

Details about the two environment variables needed by U-Boot:

- ▶ `mtdids` attaches an *mtdid* to a flash device.

```
setenv mtdids <devid>=<mtdid>[,<devid>=<mtdid>]
```

- ▶ `devid`: **U-Boot** device identifier (from `nand info` or `flinfo`)
- ▶ `mtdid`: **Linux** mtd identifier. Displayed when booting the Linux kernel:

```
NAND device: Manufacturer ID: 0x2c, Chip ID: 0xbc (Micron NAND 512MiB 1,8V 16-bit)
Creating 5 MTD partitions on "omap2-nand.0":
0x000000000000-0x000000080000 : "X-Loader"
0x000000080000-0x000000200000 : "U-Boot"
0x000000200000-0x000000280000 : "Environment"
0x000000280000-0x000000580000 : "Kernel"
0x000000580000-0x000020000000 : "File System"
```

- ▶ `mtdparts` defines partitions for the different devices

```
setenv mtdparts mtdparts=<mtdid>:
```

```
<partition>[,partition]
```

```
partition format: <size>[@offset](<name>)[ro]
```

Use the `mtdparts` command to setup the configuration specified by the `mtdids` and `mtdparts` variables

Linux understands U-Boot's `mtdparts` partition definitions.

Here is a recommended way to pass them from U-Boot to Linux:

- ▶ Define a `bootargs_base` environment variable:

```
setenv bootargs_base console=ttyS0 root=....
```

- ▶ Define the final kernel command line (`bootargs`) through the `bootcmd` environment variable:

```
setenv bootcmd 'setenv bootargs ${bootargs_base}  
${mtdparts}; <rest of bootcmd>'
```

U-Boot provides a set of commands to manipulate NAND devices, grouped under the `nand` command

- ▶ `nand info`
Show available NAND devices and characteristics
- ▶ `nand device [dev]`
Select or display the active NAND device
- ▶ `nand read[.option] <addr> <offset|partname> <size>`
Read data from NAND
- ▶ `nand write[.option] <addr> <offset|partname> <size>`
Write data on NAND
 - ▶ Use `nand write.trimffs` to avoid writing empty pages (those filled with `0xff`)
- ▶ `nand erase <offset> <size>`
Erase a NAND region
- ▶ `nand erase.part <partname>`
Erase a NAND partition
- ▶ More commands for debugging purposes

- ▶ U-Boot provides a set of commands to manipulate NOR devices
- ▶ Memory mapped NOR devices
 - ▶ `flinfo [devid]`
Display information of all NOR devices or a specific one if `devid` is provided
 - ▶ `cp.[bw1] <src> <target> <count>`
Read/write data from/to the NOR device
 - ▶ `erase <start> <end>` or `erase <start> +<len>`
Erase a memory region
 - ▶ `erase bank <bankid>`
Erase a memory bank
 - ▶ `erase all`
Erase all banks
 - ▶ `protect on|off <range-description>`
Protect a memory range

- ▶ SPI NOR devices
 - ▶ Grouped under the `sf` command
 - ▶ `sf probe [[bus:]cs] [hz] [mode]`
Probe a NOR device on
 - ▶ `sf read|write <addr> <offset> <len>`
Read/write data from/to a SPI NOR
 - ▶ `sf erase <offset> +<len>`
Erase a memory region
 - ▶ `sf update <addr> <offset> <len>`
Erase + write operation

- ▶ MTD devices are visible in `/proc/mtd`
- ▶ The user space only see MTD partitions, not the flash device under those partitions
- ▶ The **mtdchar** driver creates a character device for each MTD device/partition of the system
 - ▶ Usually named `/dev/mtdX` or `/dev/mtdXro`
 - ▶ Provide `ioctl()` to erase and manage the flash
 - ▶ Used by the *mtd-utils* utilities

- ▶ `mtd-utils` is a set of utilities to manipulate MTD devices
 - ▶ `mtdinfo` to get detailed information about an MTD device
 - ▶ `flash_erase` to partially or completely erase a given MTD device
 - ▶ `flashcp` to write to NOR flash
 - ▶ `nandwrite` to write to NAND flash
 - ▶ Flash filesystem image creation tools: `mkfs.jffs2`,
`mkfs.ubifs`, `ubinize`, etc.
- ▶ On your workstation: usually available as the `mtd-utils` package in your distribution.
- ▶ On your embedded target: most commands now also available in BusyBox.
- ▶ See <http://www.linux-mtd.infradead.org/>.

- ▶ Wear leveling consists in distributing erases over the whole flash device to avoid quickly reaching the maximum number of erase cycles on blocks that are written really often
- ▶ Can be done in:
 - ▶ the filesystem layer (JFFS2, YAFFS2, ...)
 - ▶ an intermediate layer dedicated to wear leveling (UBI)
- ▶ The wear leveling implementation is what makes your flash lifetime good or not

Flash users should also take the limited lifetime of flash devices into account by taking additional precautions

- ▶ Do not use your flash storage as swap area (rare in embedded systems anyway)
- ▶ Mount your filesystems as read-only, or use read-only filesystems (SquashFS), whenever possible.
- ▶ Keep volatile files in RAM (tmpfs)
- ▶ Don't use the `sync` mount option (commits writes immediately). Use the `fsync()` system call for per-file synchronization.

- ▶ 'Standard' file systems are meant to work on block devices
- ▶ Specific file systems have been developed to deal flash constraints
- ▶ These file systems are relying on the MTD layer to access flash chips
- ▶ There are several legacy flash filesystems which might be useful for specific usage: JFFS2, YAFFS2.
- ▶ Nowadays, UBI/UBIFS is the de facto standard for medium to large capacity NANDs (above 128MB)

- ▶ Supports on the fly compression
- ▶ Wear leveling, power failure resistant
- ▶ Available in the official Linux kernel
- ▶ Boot time depends on the filesystem size:
doesn't scale well for large partitions.
- ▶ <http://www.linux-mtd.infradead.org/doc/jffs2.html>

Standard file
API

— — — —
JFFS2
filesystem

— — — —
MTD
driver

— — — —



Flash chip

- ▶ Mainly supports NAND flash
- ▶ No compression
- ▶ Wear leveling, power failure resistant
- ▶ Fast boot time
- ▶ Not part of the official Linux kernel: code only available separately
(Dual GPL / Proprietary license for non Linux operating systems)
- ▶ <http://www.yaffs.net/>

Standard file

API

YAFFS2

filesystem

MTD

driver



Flash chip

- ▶ Aimed at replacing JFFS2 by addressing its limitations
- ▶ Design choices:
 - ▶ Split the wear leveling and filesystem layers
 - ▶ Add some flexibility
 - ▶ Focus on scalability, performance and reliability
- ▶ Drawback: introduces noticeable space overhead, especially when used on small devices or partitions.

Standard file

API

UBIFS

filesystem

UBI

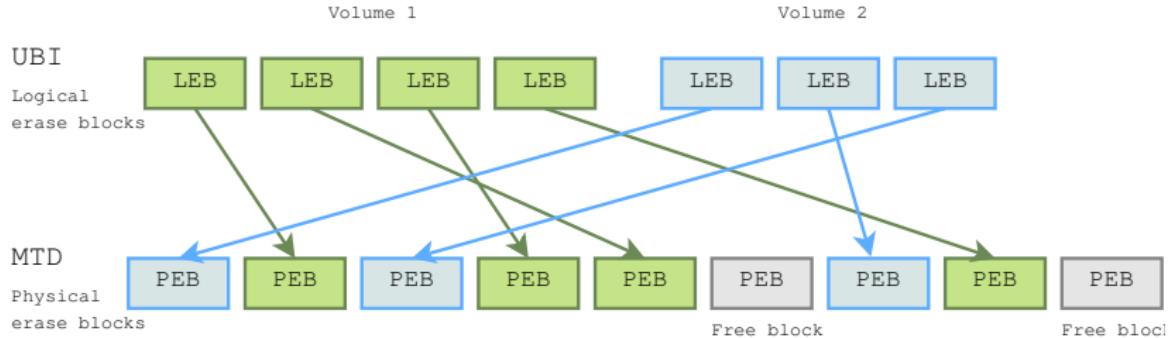
MTD
driver

Flash chip

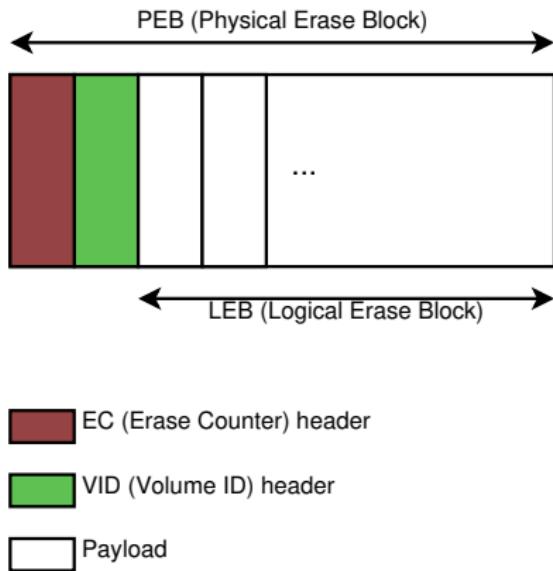
Unsorted Block Images

- ▶ <http://www.linux-mtd.infradead.org/doc/ubi.html>
- ▶ Volume management system on top of MTD devices (similar to what LVM provides for block devices)
- ▶ Allows to create multiple logical volumes and spread writes across all physical blocks
- ▶ Takes care of managing the erase blocks and wear leveling. Makes filesystems easier to implement
- ▶ Wear leveling can operate on the whole storage, not only on individual partitions (strong advantage)
- ▶ Volumes can be dynamically resized or, on the opposite, can be read-only (static)

ENDO CODE UBI (2)

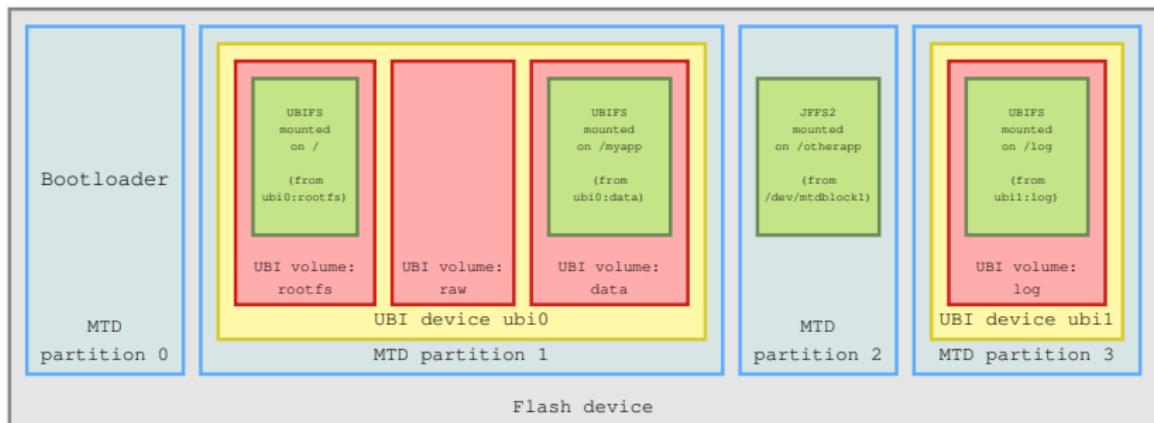


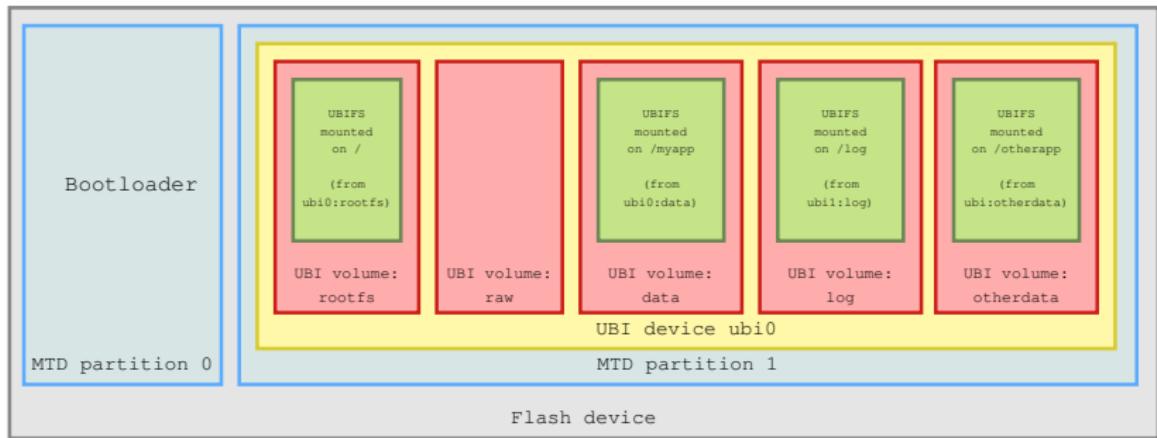
- ▶ UBI is storing its metadata in-band
- ▶ In each MTD erase block
 - ▶ One page is reserved to count the number of erase cycles
 - ▶ Another page is reserved to attach the erase block to a UBI volume
 - ▶ The remaining pages are used to store payload data
- ▶ If the device supports subpage write, the EC and VID headers can be stored on the same page



- ▶ UBI is responsible for distributing writes all over the flash device: the more space you assign to a partition attached to the UBI layer the more efficient the wear leveling will be
- ▶ If you need partitioning, use UBI volumes not MTD partitions
- ▶ Some partitions will still have to be MTD partitions: e.g. the bootloaders and bootloader environments
- ▶ If you need extra MTD partitions, try to group them at the end or the beginning of the flash device

UBI layout: bad example





Unsorted Block Images File System

- ▶ <http://www.linux-mtd.infradead.org/doc/ubifs.html>
- ▶ The filesystem part of the UBI/UBIFS couple
- ▶ Works on top of UBI volumes
- ▶ Journaling file system providing better performance than JFFS2 and addressing its scalability issues
- ▶ See this paper for more technical details about UBIFS internals http://www.linux-mtd.infradead.org/doc/ubifs_whitepaper.pdf

- ▶ ubinize is the only host tool for the UBI layer
- ▶ Creates a UBI image to be flashed on an MTD partition
- ▶ Takes the following arguments:
 - ▶ `-o <output-file-path>`
Path to the output image file
 - ▶ `-p <peb-size>`
The PEB size (MTD erase block size)
 - ▶ `-m <min-io-size>`
The minimum write unit size (e.g. MTD write size)
 - ▶ `-s <subpage-size>`
Subpage size, only needed if both your flash and your flash controller are supporting subpage writes
 - ▶ The last argument is a path to a UBI image description file
(see next page for an example)
- ▶ Example:

```
ubinize -o ubi.img -p 16KiB -m 512 -s 256 cfg.ini
```

- ▶ Can contain several sections
- ▶ Each section is describing a UBI volume
- ▶ Example:

```
[kernel-volume]
mode=ubi
image=zImage
vol_id=1
vol_type=static
vol_name=kernel
```

```
[rootfs-volume]
mode=ubi
image=rootfs.squashfs
vol_id=2
vol_type=static
vol_name=rootfs
```

```
[data-volume]
mode=ubi
image=data.ubifs
vol_id=3
vol_size=30MiB
vol_type=dynamic
vol_name=data
vol_flags=autoresize
```

Grouped under the ubi command

- ▶ `ubi part <part-name>`
Attach an MTD partition to the UBI layer
- ▶ `ubi info [layout]`
Display UBI device information
(or volume information if the layout string is passed)
- ▶ `ubi check <vol-name>`
Check if a volume exists
- ▶ `ubi readvol <dest-addr> <vol-name> [<size>]`
Read volume contents
- ▶ U-Boot also provides tools to update the UBI device contents
- ▶ Using them is highly discouraged (the U-Boot UBI implementation is not entirely stable, and using commands that do not touch the UBI metadata is safer)
 - ▶ `ubi createvol <vol-name> [<size>] [<type>]`
 - ▶ `ubi removevol <vol-name>`
 - ▶ `ubi writevol <src-addr> <vol-name> <size>`

- ▶ Tools used on the target to dynamically create and modify UBI elements
- ▶ UBI device management:
 - ▶ `ubiformat <MTD-device-id>`
Format an MTD partition and preserve Erase Counter information if any
 - ▶ `ubiattach -m <MTD-device-id> /dev/ubi_ctrl`
Attach an MTD partition/device to the UBI layer, and create a UBI device
 - ▶ `ubidetach -m <MTD-device-id> /dev/ubi_ctrl`
Detach an MTD partition/device from the UBI layer, and remove the associated UBI device

UBI volume management:

- ▶ `ubimkvol /dev/ubi<UBI-device-id> -N <name> -s <size>`
Create a new volume. Use `-m` in place of `-s <size>` if you want to assign all the remaining space to this volume.
- ▶ `ubirmvol /dev/ubi<UBI-device-id> -N <name>`
Delete a UBI volume
- ▶ `ubiupdatevol /dev/ubi<UBI-device-id>_<UBI-vol-id> [-s <size>] <vol-image-file>`
Update volume contents
- ▶ `ubirsvol /dev/ubi<UBI-device-id> -N <name> -s <size>`
Resize a UBI volume
- ▶ `ubirename /dev/ubi<UBI-device-id>_<UBI-vol-id> <old-name> <new-size>`
Rename a UBI volume

Beware that the implementation of UBI commands in BusyBox is still incomplete. For example:

- ▶ `ubirsvol` doesn't support `-N <name>`. You have to use specify the volume to resize by its id (`-n num`):

```
ubirsvol /dev/ubi0 -n 4 -s 64 MiB
```

- ▶ Same constraint for `ubirmvol`:

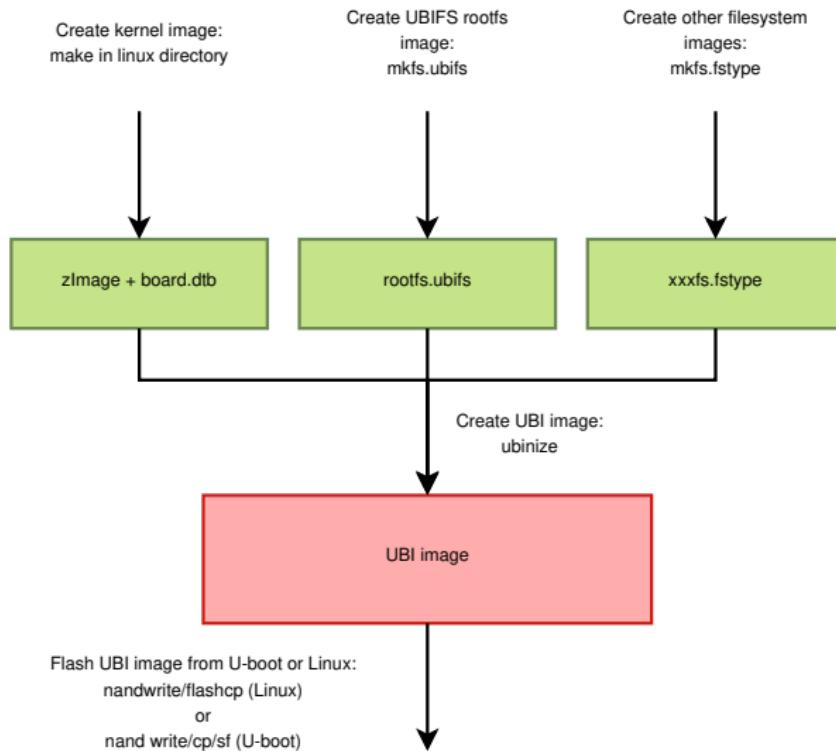
```
ubirmvol /dev/ubi0 -n 4
```

UBIFS filesystems images can be created using `mkfs.ubifs`

- ▶ `mkfs.ubifs -m 4096 -e 258048 -c 1000 -r rootfs/ ubifs.img`
 - ▶ `-m 4096`, minimal I/O size
(see `/sys/class/mtd/mtdx/writesize`).
 - ▶ `-e 258048`, logical erase block size (smaller than PEB size, can be found in the kernel log after running `ubiaattach`)
 - ▶ `-c 1000`, maximum size of the UBI volume the image will be flashed into, in number of logical erase blocks. Do not make this number unnecessary big, otherwise the UBIFS data structures will be bigger than needed and performance will be degraded. Details:
http://linux-mtd.infradead.org/faq/ubifs.html#L_max_leb_cnt

- ▶ Once created
 - ▶ Can be written to a UBI volume from the target using `ubiupdatevol`
 - ▶ Or, can be included in a UBI image (using `ubinize` on the host)

- ▶ No specific tools are required to manipulate a UBIFS filesystem
- ▶ Mounting a UBIFS filesystem is done with `mount`:
`mount -t ubifs <ubi-device-id>:<volume-name> <mount-point>`
- ▶ Example:
`mount -t ubifs ubi0:data /data`



- ▶ You just have to pass the following information on the kernel command line:
 - ▶ ubi.mtd=1
Attach /dev/mtd1 to the UBI layer and create ubi0
 - ▶ rootfstype=ubifs root=ubi0:rootfs
Mount the rootfs volume on ubi0 as a UBIFS filesystem
- ▶ Example: rootfstype=ubifs ubi.mtd=1 root=ubi0:rootfs

In U-Boot:

- ▶ Define partitions:

```
setenv mtdids ...
```

```
setenv mtdparts ...
```

- ▶ Define the base Linux kernel bootargs, specifying booting on UBIFS, the UBI volume used as root filesystem, and the MTD partition attached to UBI. Example:

```
setenv bootargs_base console=ttyS0 rootfstype=ubifs  
root=ubi0:rootfs ubi.mtd=2 ...
```

- ▶ Define the boot command sequence, loading the U-Boot partition definitions, loading kernel and DTB images from UBI partitions, and adding `mtdparts` to the kernel command line. Example:

```
setenv bootcmd 'mtdparts; ubi part UBI; ubi readvol  
0x81000000 kernel; ubi readvol 0x82000000 dtb;  
setenv bootargs ${bootargs_base} ${mtdparts}; bootz  
0x81000000 - 0x82000000'
```

- ▶ Sometimes we need block devices to re-use existing block filesystems, especially read-only ones like SquashFs
- ▶ Linux provides two block emulation layers:
 - ▶ `mtdblock`: block devices emulated on top of MTD devices
 - ▶ `ubiblock`: block devices emulated on top of UBI volumes

- ▶ The `mtdblock` layer creates a block device for each MTD device of the system
- ▶ Usually named `/dev/mtdblockX`.
- ▶ Allows read/write block-level access. However bad blocks are not handled, and no wear leveling is done for writes.
- ▶ For historical reasons, JFFS2 and YAFFS2 filesystems require a block device for the `mount` command.
- ▶ **Do not write on `mtdblock` devices**

- ▶ Implemented by Ezequiel Garcia from Free Electrons.
- ▶ Preferred over `mtdblock` if UBI is available (UBI accounts for data retention and wear leveling issues, while MTD does not)
- ▶ The `ubiblock` layer creates **read-only** block devices on demand
- ▶ The user specifies which static volumes (`s`)he would like to attach to `ubiblock`
 - ▶ Through the kernel command line: by passing`ubi.block=<ubi-dev-id>,<volume-name>`
 - ▶ Using the `ubiblock` utility provided by `mtd-utils`:
`ubiblock --create <ubi-volume-dev-file>`
- ▶ Usually named `/dev/ubiblockX_Y`, where X is the UBI device id and Y is the UBI volume id

- ▶ Managing flash storage with Linux:
<http://free-electrons.com/blog/managing-flash-storage-with-linux/>
- ▶ Documentation on the linux-mtd website:
<http://www.linux-mtd.infradead.org/>
- ▶ Details about creating UBI and UBIFS images:
<http://free-electrons.com/blog/creating-flashing-ubi-ubifs-images/>



- ▶ Creating partitions in your internal flash storage
- ▶ Creating a UBI image with several volumes and flashing it from U-Boot
- ▶ Manipulating UBI volumes from Linux

Embedded Linux system development

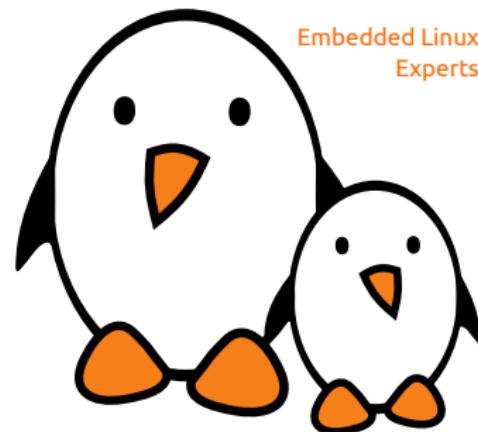
Endocode AG

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Corrections, suggestions, contributions and translations are welcome!



- ▶ Using open-source components
- ▶ Tools for the target device
 - ▶ Networking
 - ▶ System utilities
 - ▶ Language interpreters
 - ▶ Audio, video and multimedia
 - ▶ Graphical toolkits
 - ▶ Databases
 - ▶ Web browsers
- ▶ System building

Leveraging open-source components in an Embedded Linux system

- ▶ One of the advantages of embedded Linux is the wide range of third-party libraries and applications that one can leverage in its product
 - ▶ They are freely available, freely distributable, and thanks to their open-source nature, they can be analyzed and modified according to the needs of the project
- ▶ However, efficiently re-using these components is not always easy. One must:
 - ▶ Find these components
 - ▶ Choose the most appropriate ones
 - ▶ Cross-compile them
 - ▶ Integrate them in the embedded system and with the other applications

- ▶ Free Software Directory
<http://directory.fsf.org>
- ▶ Look at other embedded Linux products, and see what their components are
- ▶ Look at the list of software packaged by embedded Linux build systems
 - ▶ These are typically chosen for their suitability to embedded systems
- ▶ Ask the community or Google
- ▶ This presentation will also feature a list of components for common needs

Not all free software components are necessarily good to re-use.

One must pay attention to:

- ▶ **Vitality** of the developer and user communities. This vitality ensures long-term maintenance of the component, and relatively good support. It can be measured by looking at the mailing-list traffic and the version control system activity.
- ▶ **Quality** of the component. Typically, if a component is already available through embedded build systems, and has a dynamic user community, it probably means that the quality is relatively good.
- ▶ **License**. The license of the component must match your licensing constraints. For example, GPL libraries cannot be used in proprietary applications.
- ▶ **Technical requirements**. Of course, the component must match your technical requirements. But don't forget that you can improve the existing components if a feature is missing!

- ▶ All software that are under a free software license give four freedoms to all users
 - ▶ Freedom to use
 - ▶ Freedom to study
 - ▶ Freedom to copy
 - ▶ Freedom to modify and distribute modified copies
- ▶ See <http://www.gnu.org/philosophy/free-sw.html> for a definition of Free Software
- ▶ Open Source software, as per the definition of the Open Source Initiative, are technically similar to Free Software in terms of freedoms
- ▶ See <http://www.opensource.org/docs/osd> for the definition of Open Source Software

- ▶ Free Software licenses fall in two main categories
 - ▶ The copyleft licenses
 - ▶ The non-copyleft licenses
- ▶ The concept of *copyleft* is to ask for reciprocity in the freedoms given to a user.
- ▶ The result is that when you receive a software under a copyleft free software license and distribute modified versions of it, you must do so under the same license
 - ▶ Same freedoms to the new users
 - ▶ It's an incentive to contribute back your changes instead of keeping them secret
- ▶ Non-copyleft licenses have no such requirements, and modified versions can be kept proprietary, but they still require attribution

- ▶ **GNU General Public License**
- ▶ Covers around 55% of the free software projects
 - ▶ Including the Linux kernel, Busybox and many applications
- ▶ Is a copyleft license
 - ▶ Requires derivative works to be released under the same license
 - ▶ Programs linked with a library released under the GPL must also be released under the GPL
- ▶ Some programs covered by version 2 (Linux kernel, Busybox and others)
- ▶ More and more programs covered by version 3, released in 2007
 - ▶ Major change for the embedded market: the requirement that the user must be able to **run** the modified versions on the device, if the device is a *consumer* device

- ▶ No obligation when the software is not distributed
 - ▶ You can keep your modifications secret until the product delivery
- ▶ It is then authorized to distribute binary versions, if one of the following conditions is met:
 - ▶ Convey the binary with a copy of the source on a physical medium
 - ▶ Convey the binary with a written offer valid for 3 years that indicates how to fetch the source code
 - ▶ Convey the binary with the network address of a location where the source code can be found
 - ▶ See section 6. of the GPL license
- ▶ In all cases, the attribution and the license must be preserved
 - ▶ See section 4. and 5.

- ▶ **GNU Lesser General Public License**
- ▶ Covers around 10% of the free software projects
- ▶ A copyleft license
 - ▶ Modified versions must be released under the same license
 - ▶ But, programs linked against a library under the LGPL do not need to be released under the LGPL and can be kept proprietary.
 - ▶ However, the user must keep the ability to update the library independently from the program. Dynamic linking is the easiest solution. Statically linked executables are only possible if the developer provides a way to relink with an update (with source code or linkable object files).
- ▶ Used instead of the GPL for most of the libraries, including the C libraries
 - ▶ Some exceptions: MySQL, or Qt <= 4.4
- ▶ Also available in two versions, v2 and v3

- ▶ You make modifications to the Linux kernel (to add drivers or adapt to your board), to Busybox, U-Boot or other GPL software
 - ▶ You must release the modified versions under the same license, and be ready to distribute the source code to your customers
- ▶ You make modifications to the C library or any other LGPL library
 - ▶ You must release the modified versions under the same license
- ▶ You create an application that relies on LGPL libraries
 - ▶ You can keep your application proprietary, but you must link dynamically with the LGPL libraries
- ▶ You make modifications to a non-copyleft licensed software
 - ▶ You can keep your modifications proprietary, but you must still credit the authors

- ▶ A large family of non-copyleft licenses that are relatively similar in their requirements
- ▶ A few examples
 - ▶ Apache license (around 4%)
 - ▶ BSD license (around 6%)
 - ▶ MIT license (around 4%)
 - ▶ X11 license
 - ▶ Artistic license (around 9 %)

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Redistribution and use in source and binary forms, with or without modification, are permitted provided that the following conditions are met:

- * Redistributions of source code must retain the above copyright notice, this list of conditions and the following disclaimer.
- * Redistributions in binary form must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution.
- * Neither the name of the <organization> nor the names of its contributors may be used to endorse or promote products derived from this software without specific prior written permission.

[...]

- ▶ Most of the free software projects are covered by 10 well-known licenses, so it is fairly easy for the majority of project to get a good understanding of the license
- ▶ Otherwise, read the license text
- ▶ Check Free Software Foundation's opinion
<http://www.fsf.org/licensing/licenses/>
- ▶ Check Open Source Initiative's opinion
<http://www.opensource.org/licenses>

- ▶ Free Software is not public domain software, the distributors have obligations due to the licenses
 - ▶ **Before** using a free software component, make sure the license matches your project constraints
 - ▶ Make sure to keep a complete list of the free software packages you use, the original version numbers you used, and to keep your modifications and adaptations well-separated from the original version.
 - ▶ Buildroot and Yocto Project can generate this list for you!
 - ▶ Conform to the license requirements before shipping the product to the customers.
- ▶ Free Software licenses have been enforced successfully in courts. Organizations which can help:
 - ▶ Software Freedom Law Center,
<http://www.softwarefreedom.org/>
 - ▶ Software Freedom Conservancy, <http://sfconservancy.org/>
- ▶ Ask your legal department!

- ▶ When integrating existing open-source components in your project, it is sometimes needed to make modifications to them
 - ▶ Better integration, reduced footprint, bug fixes, new features, etc.
- ▶ Instead of mixing these changes, it is much better to keep them separate from the original component version
 - ▶ If the component needs to be upgraded, easier to know what modifications were made to the component
 - ▶ If support from the community is requested, important to know how different the component we're using is from the upstream version
 - ▶ Makes contributing the changes back to the community possible
- ▶ It is even better to keep the various changes made on a given component separate
 - ▶ Easier to review and to update to newer versions

- ▶ The simplest solution is to use Quilt
 - ▶ Quilt is a tool that allows to maintain a stack of patches over source code
 - ▶ Makes it easy to add, remove modifications from a patch, to add and remove patches from stack and to update them
 - ▶ The stack of patches can be integrated into your version control system
 - ▶ <https://savannah.nongnu.org/projects/quilt/>
- ▶ Another solution is to use a version control system
 - ▶ Import the original component version into your version control system
 - ▶ Maintain your changes in a separate branch

Tools for the target device: Networking

<http://matt.ucc.asn.au/dropbear/dropbear.html>

- ▶ Very small memory footprint ssh server for embedded systems
- ▶ Satisfies most needs. Both client and server!
- ▶ Size: 110 KB, statically compiled with uClibc on i386.
(OpenSSH client and server: approx 1200 KB, dynamically compiled with glibc on i386)
- ▶ Useful to:
 - ▶ Get a remote console on the target device
 - ▶ Copy files to and from the target device (`scp` or `rsync -e ssh`).
- ▶ An alternative to OpenSSH, used on desktop and server systems.

Many network enabled devices can just have a network interface

- ▶ Examples: modems / routers, IP cameras, printers...
- ▶ No need to develop drivers and applications for computers connected to the device. No need to support multiple operating systems!
- ▶ Just need to develop static or dynamic HTML pages (possibly with powerful client-side JavaScript).
Easy way of providing access to device information and parameters.
- ▶ Reduced hardware costs (no LCD, very little storage space needed)

- ▶ *BusyBox http server:* `http://busybox.net`
 - ▶ Tiny: only adds 9 K to BusyBox (dynamically linked with glibc on i386, with all features enabled.)
 - ▶ Sufficient features for many devices with a web interface, including CGI, http authentication and script support (like PHP, with a separate interpreter).
 - ▶ License: GPL
- ▶ Other possibilities: lightweight servers like *Boa*, *thttpd*, *lighttpd*, *nginx*, etc
- ▶ Some products are using *Node.js*, which is lightweight enough to be used.



- ▶ **avahi** is an implementation of Multicast DNS Service Discovery, that allows programs to publish and discover services on a local network
- ▶ **bind**, a DNS server
- ▶ **iptables**, the user space tools associated to the Linux firewall, Netfilter
- ▶ **iw and wireless tools**, the user space tools associated to Wireless devices
- ▶ **netsnmp**, implementation of the SNMP protocol
- ▶ **openntpd**, implementation of the Network Time Protocol, for clock synchronization
- ▶ **openssl**, a toolkit for SSL and TLS connections

- ▶ **pppd**, implementation of the Point to Point Protocol, used for dial-up connections
- ▶ **samba**, implements the SMB and CIFS protocols, used by Windows to share files and printers
- ▶ **coherence**, a UPnP/DLNA implementation
- ▶ **vsftpd**, proftpd, FTP servers

Tools for the target device: System utilities

- ▶ **dbus**, an inter-application object-oriented communication bus
- ▶ **gpsd**, a daemon to interpret and share GPS data
- ▶ **libraw1394**, raw access to Firewire devices
- ▶ **libusb**, a user space library for accessing USB devices without writing an in-kernel driver
- ▶ Utilities for kernel subsystems: **i2c-tools** for I2C, **input-tools** for input, **mtd-utils** for MTD devices, **usbutils** for USB devices

Tools for the target device: Language interpreters

- ▶ Interpreters for the most common scripting languages are available. Useful for
 - ▶ Application development
 - ▶ Web services development
 - ▶ Scripting
- ▶ Languages supported
 - ▶ Lua
 - ▶ Python
 - ▶ Perl
 - ▶ Ruby
 - ▶ TCL
 - ▶ PHP

Tools for the target device: Audio,
video and multimedia

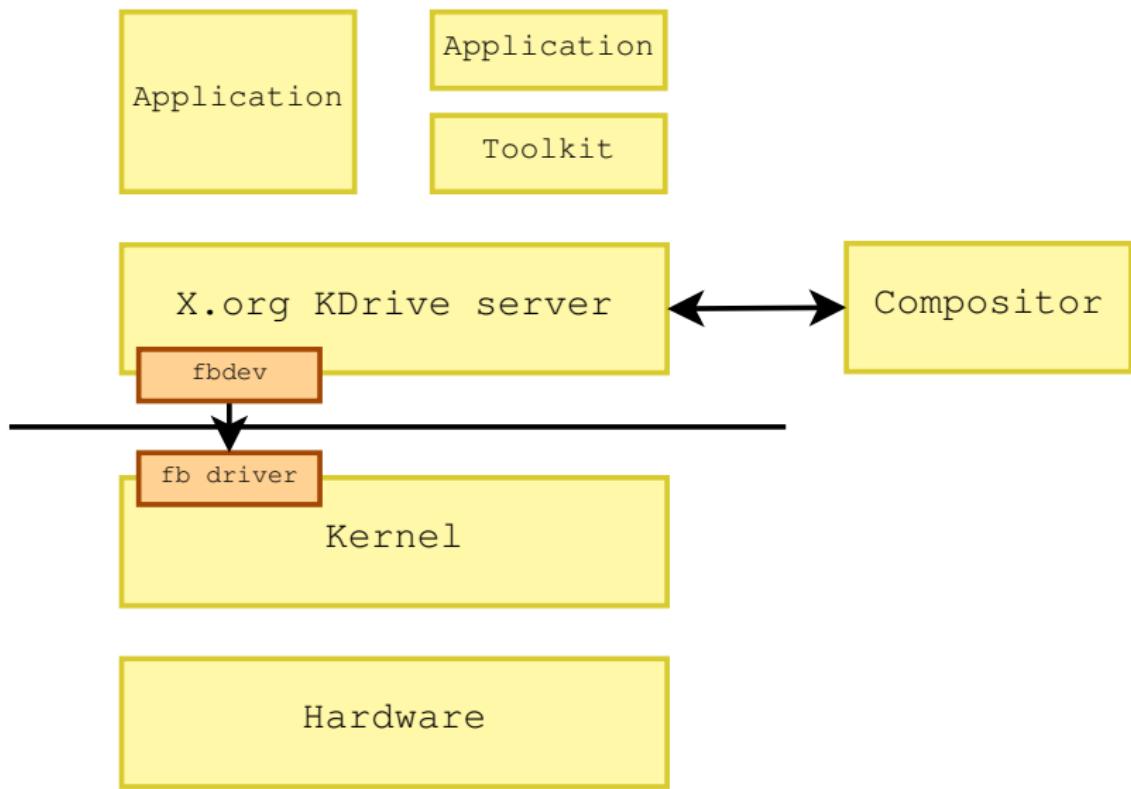
- ▶ **GStreamer**, a multimedia framework
 - ▶ Allows to decode/encode a wide variety of codecs.
 - ▶ Supports hardware encoders and decoders through plugins, proprietary/specific plugins are often provided by SoC vendors.
- ▶ **alsa-lib**, the user space tools associated to the ALSA sound kernel subsystem
- ▶ Directly using encoding and decoding libraries, if you decide not to use GStreamer:
libavcodec, libogg, libtheora, libvpx, flac, libvorbis, libmad, libsndfile, speex, etc.

Tools for the target device: Graphical toolkits

Graphical toolkits: “Low-level” solutions and layers



- ▶ Stand-alone simplified version of the X server, for embedded systems
 - ▶ Formerly known as Tiny-X
 - ▶ Kdrive is integrated in the official X.org server
- ▶ Works on top of the Linux frame buffer, thanks to the Xfbdev variant of the server
- ▶ Real X server
 - ▶ Fully supports the X11 protocol: drawing, input event handling, etc.
 - ▶ Allows to use any existing X11 application or library
- ▶ Actively developed and maintained.
- ▶ X11 license
- ▶ <http://www.x.org>

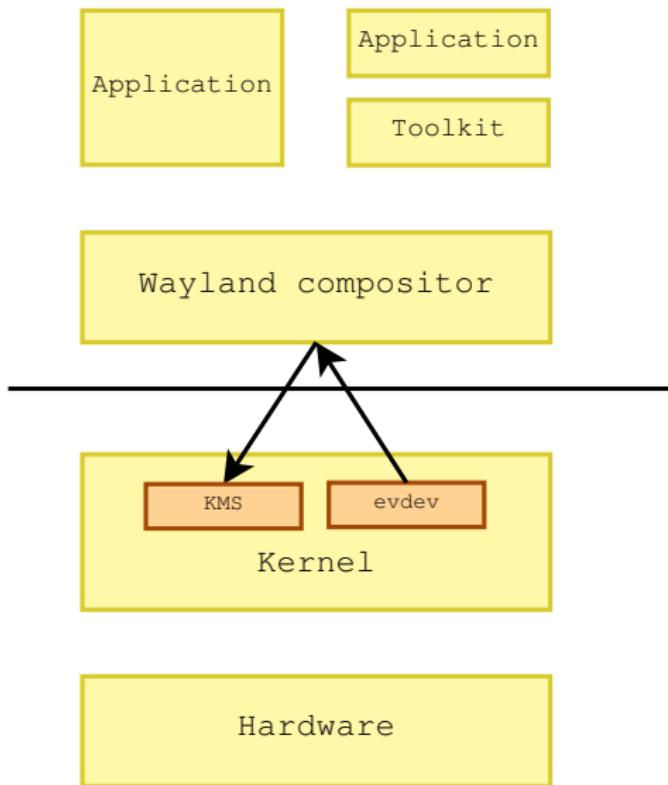


- ▶ Can be directly programmed using Xlib / XCB
 - ▶ Low-level graphic library, rarely used
- ▶ Or, usually used with a toolkit on top of it
 - ▶ Gtk
 - ▶ Qt
 - ▶ Enlightenment Foundation Libraries
 - ▶ Others: Fltk, WxEmbedded, etc



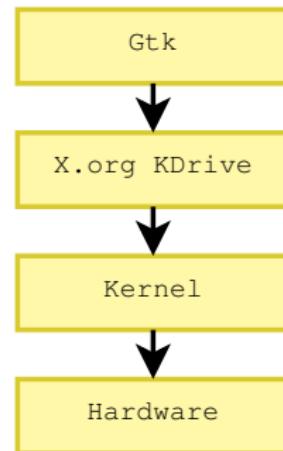
- ▶ Intended to be a simpler replacement for X
- ▶ *Wayland is a protocol for a compositor to talk to its clients as well as a C library implementation of that protocol.*
- ▶ Weston: a minimal and fast reference implementation of a Wayland compositor, and is suitable for many embedded and mobile use cases.
- ▶ Not fully deployed yet. However, the ports of Gtk and Qt to Wayland are complete.
- ▶ <http://wayland.freedesktop.org/>

ENDO CODE Wayland: architecture



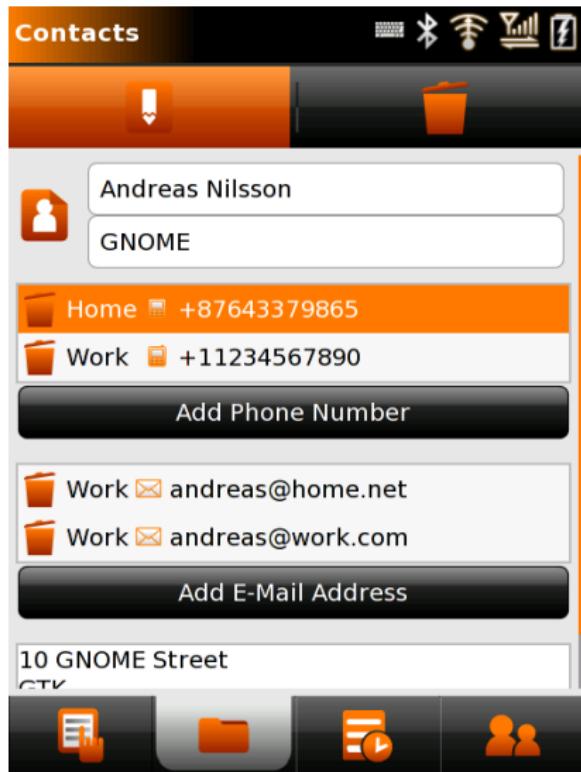
Graphical toolkits: “High-level” solutions

- ▶ The famous toolkit, providing widget-based high-level APIs to develop graphical applications
- ▶ Standard API in C, but bindings exist for various languages: C++, Python, etc.
- ▶ Works on top of X.org.
- ▶ No windowing system, a lightweight window manager needed to run several applications. Possible solution: Matchbox.
- ▶ License: LGPL
- ▶ <http://www.gtk.org>



- ▶ **Glib**, core infrastructure
 - ▶ Object-oriented infrastructure GObject
 - ▶ Event loop, threads, asynchronous queues, plug-ins, memory allocation, I/O channels, string utilities, timers, date and time, internationalization, simple XML parser, regular expressions
 - ▶ Data types: memory slices and chunks, linked lists, arrays, trees, hash tables, etc.
- ▶ **Pango**, internationalization of text handling
- ▶ **ATK**, accessibility toolkit
- ▶ **Cairo**, vector graphics library
- ▶ **Gtk+**, the widget library itself
- ▶ *The Gtk stack is a complete framework to develop applications*

ENDO CODE Gtk examples (1)



Openmoko phone interface



Maemo tablet / phone interface

GTK is losing traction, however: Mer, the descendent of Maemo, is now implemented in EFL (see next slides).

- ▶ The other famous toolkit, providing widget-based high-level APIs to develop graphical applications
- ▶ Implemented in C++
 - ▶ the C++ library is required on the target system
 - ▶ standard API in C++, but with bindings for other languages
- ▶ Works either on top of
 - ▶ Framebuffer
 - ▶ X11
 - ▶ Wayland

- ▶ Qt is more than just a graphical toolkit, it also offers a complete development framework: data structures, threads, network, databases, XML, etc.
- ▶ See our presentation *Qt for non graphical applications* presentation at ELCE 2011 (Thomas Petazzoni):
<http://j.mp/W4PK85>
- ▶ Qt Embedded has an integrated windowing system, allowing several applications to share the same screen
- ▶ Very well documented
- ▶ Since version 4.5, available under the LGPL, allowing proprietary applications



Qt on the Dash Express
navigation system



Qt on the Netflix player by Roku

- ▶ Enlightenment Foundation Libraries (EFL)
 - ▶ Very powerful. Supported by Samsung, Intel and Free.fr.
 - ▶ Work on top of X or Wayland.
 - ▶ <http://www.enlightenment.org/p.php?p=about/efl>

Tools for the target device: Databases

<http://www.sqlite.org>

- ▶ SQLite is a small C library that implements a self-contained, embeddable, lightweight, zero-configuration SQL database engine
- ▶ The database engine of choice for embedded Linux systems
 - ▶ Can be used as a normal library
 - ▶ Can be directly embedded into a application, even a proprietary one since SQLite is released in the public domain

Tools for the target device: Web browsers

<http://webkit.org/>



- ▶ Web browser engine. Application framework that can be used to develop web browsers.
- ▶ License: portions in LGPL and others in BSD. Proprietary applications allowed.
- ▶ Used by many web browsers: Safari, iPhone and Android default browsers ... Google Chrome now uses a fork of its WebCore component). Used by e-mail clients too to render HTML:

[http://trac.webkit.org/wiki/
Applications%20using%20WebKit](http://trac.webkit.org/wiki/Applications%20using%20WebKit)

- ▶ Multiple graphical back-ends: Qt4, GTK, EFL...
- ▶ You could use it to create your custom browser.

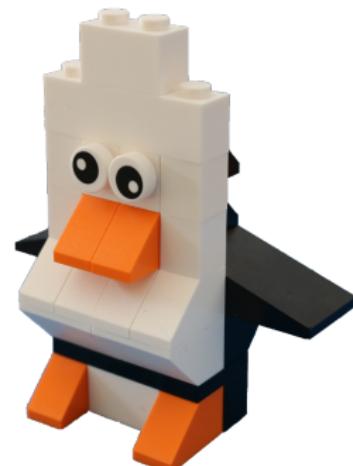
System building

- ▶ Goal

- ▶ Integrate all the software components, both third-party and in-house, into a working root filesystem
- ▶ It involves the download, extraction, configuration, compilation and installation of all components, and possibly fixing issues and adapting configuration files

- ▶ Several solutions

- ▶ Manually
- ▶ System building tools
- ▶ Distributions or ready-made filesystems



Penguin picture: <http://bit.ly/1PwDklz>

- ▶ Manually building a target system involves downloading, configuring, compiling and installing all the components of the system.
- ▶ All the libraries and dependencies must be configured, compiled and installed in the right order.
- ▶ Sometimes, the build system used by libraries or applications is not very cross-compile friendly, so some adaptations are necessary.
- ▶ There is no infrastructure to reproduce the build from scratch, which might cause problems if one component needs to be changed, if somebody else takes over the project, etc.

- ▶ Manual system building is not recommended for production projects
- ▶ However, using automated tools often requires the developer to dig into specific issues
- ▶ Having a basic understanding of how a system can be built manually is therefore very useful to fix issues encountered with automated tools
 - ▶ We will first study manual system building, and during a practical lab, create a system using this method
 - ▶ Then, we will study the automated tools available, and use one of them during a lab

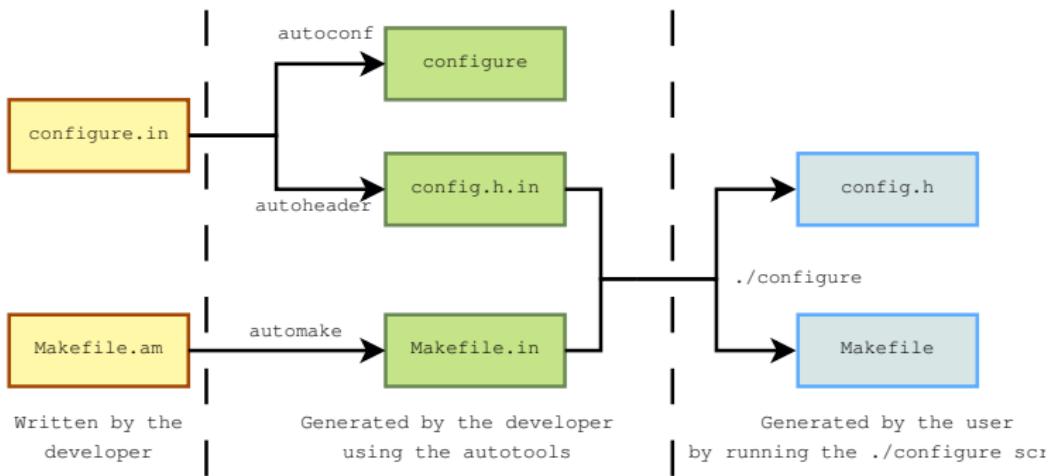
- ▶ A basic root file system needs at least
 - ▶ A traditional directory hierarchy, with `/bin`, `/etc`, `/lib`, `/root`,
`/usr/bin`, `/usr/lib`, `/usr/share`, `/usr/sbin`, `/var`, `/sbin`
 - ▶ A set of basic utilities, providing at least the `init` program, a shell and other traditional Unix command line tools. This is usually provided by *Busybox*
 - ▶ The C library and the related libraries (thread, math, etc.) installed in `/lib`
 - ▶ A few configuration files, such as `/etc/inittab`, and initialization scripts in `/etc/init.d`
- ▶ On top of this foundation common to most embedded Linux system, we can add third-party or in-house components

- ▶ The system foundation, Busybox and C library, are the core of the target root filesystem
- ▶ However, when building other components, one must distinguish two directories
 - ▶ The *target* space, which contains the target root filesystem, everything that is needed for **execution** of the application
 - ▶ The *build* space, which will contain a lot more files than the *target* space, since it is used to keep everything needed to **compile** libraries and applications. So we must keep the headers, documentation, and other configuration files

Each open-source component comes with a mechanism to configure, compile and install it

- ▶ A basic Makefile
 - ▶ Need to read the *Makefile* to understand how it works and how to tweak it for cross-compilation
- ▶ A build system based on the *Autotools*
 - ▶ As this is the most common build system, we will study it in details
- ▶ CMake, <http://www.cmake.org/>
 - ▶ Newer and simpler than the *autotools*. Used by large projects such as KDE or Second Life
- ▶ Scons, <http://www.scons.org/>
- ▶ Waf, <http://code.google.com/p/waf/>
- ▶ Other manual build systems

- ▶ A family of tools, which associated together form a complete and extensible build system
 - ▶ **autoconf** is used to handle the configuration of the software package
 - ▶ **automake** is used to generate the Makefiles needed to build the software package
 - ▶ **pkgconfig** is used to ease compilation against already installed shared libraries
 - ▶ **libtool** is used to handle the generation of shared libraries in a system-independent way
- ▶ Most of these tools are old and relatively complicated to use, but they are used by a majority of free software packages today. One must have a basic understanding of what they do and how they work.



- ▶ Files written by the developer
 - ▶ `configure.in` describes the configuration options and the checks done at configure time
 - ▶ `Makefile.am` describes how the software should be built
- ▶ The `configure` script and the `Makefile.in` files are generated by `autoconf` and `automake` respectively.
 - ▶ They should never be modified directly
 - ▶ They are usually shipped pre-generated in the software package, because there are several versions of `autoconf` and `automake`, and they are not completely compatible
- ▶ The `Makefile` files are generated at configure time, before compiling
 - ▶ They are never shipped in the software package.

- ▶ The traditional steps to configure and compile an autotools based package are
 - ▶ Configuration of the package
`./configure`
 - ▶ Compilation of the package
`make`
 - ▶ Installation of the package
`make install`
- ▶ Additional arguments can be passed to the `./configure` script to adjust the component configuration.
- ▶ Only the `make install` needs to be done as root if the installation should take place system-wide

- ▶ For cross-compilation, things are a little bit more complicated.
- ▶ At least some of the environment variables AR, AS, LD, NM, CC, GCC, CPP, CXX, STRIP, OBJCOPY must be defined to point to the proper cross-compilation tools. The host tuple is also by default used as prefix.
- ▶ configure script arguments:
 - ▶ --host: mandatory but a bit confusing. Corresponds to the *target* platform the code will run on. Example:
--host=arm-linux
 - ▶ --build: build system. Automatically detected.
 - ▶ --target is only for tools generating code.
- ▶ It is recommended to pass the --prefix argument. It defines from which location the software will run in the target environment. Usually, /usr is fine.

- ▶ If one simply runs `make install`, the software will be installed in the directory passed as `--prefix`. For cross-compiling, one must pass the `DESTDIR` argument to specify where the software must be installed.
- ▶ Making the distinction between the prefix (as passed with `--prefix` at configure time) and the destination directory (as passed with `DESTDIR` at installation time) is very important.
- ▶ Example:

```
export PATH=/usr/local/arm-linux/bin:$PATH
export CC=arm-linux-gcc
export STRIP=arm-linux-strip
./configure --host=arm-linux --prefix=/usr
make
make DESTDIR=$HOME/work/rootfs install
```

- ▶ The autotools based software packages provide both a `install` and `install-strip` make targets, used to install the software, either stripped or unstripped.
- ▶ For applications, the software is usually installed in `<prefix>/bin`, with configuration files in `<prefix>/etc` and data in `<prefix>/share/<application>/`
- ▶ The case of libraries is a little more complicated:
 - ▶ In `<prefix>/lib`, the library itself (a `.so.<version>`), a few symbolic links, and the libtool description file (a `.la` file)
 - ▶ The `pkgconfig` description file in `<prefix>/lib/pkgconfig`
 - ▶ Include files in `<prefix>/include/`
 - ▶ Sometimes a `<libname>-config` program in `<prefix>/bin`
 - ▶ Documentation in `<prefix>/share/man` or `<prefix>/share/doc/`

Contents of `usr/lib` after installation of *libpng* and *zlib*

- ▶ *libpng* libtool description files

`./lib/libpng12.la`
`./lib/libpng.la -> libpng12.la`

- ▶ *libpng* static version

`./lib/libpng12.a`
`./lib/libpng.a -> libpng12.a`

- ▶ *libpng* dynamic version

`./lib/libpng.so.3.32.0`
`./lib/libpng12.so.0.32.0`
`./lib/libpng12.so.0 -> libpng12.so.0.32.0`
`./lib/libpng12.so -> libpng12.so.0.32.0`
`./lib/libpng.so -> libpng12.so`
`./lib/libpng.so.3 -> libpng.so.3.32.0`

- ▶ *libpng* pkg-config description files

`./lib/pkgconfig/libpng12.pc`
`./lib/pkgconfig/libpng.pc -> libpng12.pc`

- ▶ *zlib* dynamic version

`./lib/libz.so.1.2.3`
`./lib/libz.so -> libz.so.1.2.3`
`./lib/libz.so.1 -> libz.so.1.2.3`

- ▶ From all these files, everything except documentation is necessary to build an application that relies on libpng.
 - ▶ These files will go into the *build space*
- ▶ However, only the library .so binaries in <prefix>/lib and some symbolic links are needed to execute the application on the target.
 - ▶ Only these files will go in the *target space*
- ▶ The build space must be kept in order to build other applications or recompile existing applications.

- ▶ `pkg-config` is a tool that allows to query a small database to get information on how to compile programs that depend on libraries
- ▶ The database is made of `.pc` files, installed by default in `<prefix>/lib/pkgconfig/`.
- ▶ `pkg-config` is used by the `configure` script to get the library configurations
- ▶ It can also be used manually to compile an application:
`arm-linux-gcc -o test test.c $(pkg-config --libs --cflags thelib)`
- ▶ By default, `pkg-config` looks in `/usr/lib/pkgconfig` for the `*.pc` files, and assumes that the paths in these files are correct.
- ▶ `PKG_CONFIG_PATH` allows to set another location for the `*.pc` files and `PKG_CONFIG_SYSROOT_DIR` to prepend a prefix to the paths mentioned in the `.pc` files.

- ▶ When compiling an application or a library that relies on other libraries, the build process by default looks in `/usr/lib` for libraries and `/usr/include` for headers.

- ▶ The first thing to do is to set the `CFLAGS` and `LDLFLAGS` environment variables:

```
export CFLAGS=-I/my/build/space/usr/include/  
export LDLFLAGS=-L/my/build/space/usr/lib
```

- ▶ The libtool files (`.la` files) must be modified because they include the absolute paths of the libraries:

- `libdir='/usr/lib'`
+ `libdir='/my/build/space/usr/lib'`

- ▶ The `PKG_CONFIG_PATH` environment variable must be set to the location of the `.pc` files and the `PKG_CONFIG_SYSROOT_DIR` variable must be set to the build space directory.



- ▶ Manually cross-compiling applications and libraries
- ▶ Learning about common techniques and issues.

- ▶ Different tools are available to automate the process of building a target system, including the kernel, and sometimes the toolchain.
- ▶ They automatically download, configure, compile and install all the components in the right order, sometimes after applying patches to fix cross-compiling issues.
- ▶ They already contain a large number of packages, that should fit your main requirements, and are easily extensible.
- ▶ The build becomes reproducible, which allows to easily change the configuration of some components, upgrade them, fix bugs, etc.

Large choice of tools

- ▶ **Buildroot**, developed by the community
<http://www.buildroot.net> See our dedicated course and training materials: <http://free-electrons.com/training/buildroot/>
- ▶ **PTXdist**, developed by Pengutronix
<http://pengutronix.de/software/ptxdist/>
- ▶ **OpenWRT**, originally a fork of Buildroot for wireless routers, now a more generic project
<http://www.openwrt.org>
- ▶ **LTIB**. Good support for Freescale boards, but small community
<http://ltib.org/>
- ▶ **OpenEmbedded**, more flexible but also far more complicated
<http://www.openembedded.org>, its industrialized version **Yocto Project** and vendor-specific derivatives such as **Arago**.
See our dedicated course and training materials:
<http://free-electrons.com/training/yocto/>.
- ▶ Vendor specific tools (silicon vendor or embedded Linux vendor)

- ▶ Allows to build a toolchain, a root filesystem image with many applications and libraries, a bootloader and a kernel image
 - ▶ Or any combination of the previous items
- ▶ Supports building uClibc, glibc and musl toolchains, either built by Buildroot, or external
- ▶ Over 1200+ applications or libraries integrated, from basic utilities to more elaborate software stacks: X.org, GStreamer, Qt, Gtk, WebKit, Python, PHP, etc.
- ▶ Good for small to medium embedded systems, with a fixed set of features
 - ▶ No support for generating packages (.deb or .ipk)
 - ▶ Needs complete rebuild for most configuration changes.
- ▶ Active community, releases published every 3 months.

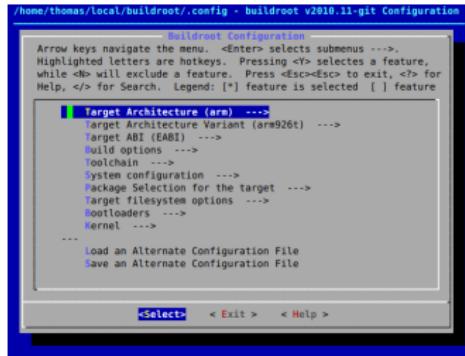
- ▶ Configuration takes place through a `*config` interface similar to the kernel

`make menuconfig`

- ▶ Allows to define

- ▶ Architecture and specific CPU
- ▶ Toolchain configuration
- ▶ Set of applications and libraries to integrate
- ▶ Filesystem images to generate
- ▶ Kernel and bootloader configuration

- ▶ Build by just running
`make`



- ▶ A package allows to integrate a user application or library to Buildroot
- ▶ Each package has its own directory (such as `package/gqview`). This directory contains:
 - ▶ A `Config.in` file (mandatory), describing the configuration options for the package. At least one is needed to enable the package. This file must be sourced from `package/Config.in`
 - ▶ A `gqview.mk` file (mandatory), describing how the package is built.
 - ▶ Patches (optional). Each file of the form `gqview-*.patch` will be applied as a patch.

- ▶ For a simple package with a single configuration option to enable/disable it, the `Config.in` file looks like:

```
config BR2_PACKAGE_GQVIEW
    bool "gqview"
    depends on BR2_PACKAGE_LIBGTK2
    help
        GQview is an image viewer for Unix operating systems
        http://prdownloads.sourceforge.net/gqview
```

- ▶ It must be sourced from `package/Config.in`:

```
source "package/gqview/Config.in"
```

- ▶ Create the gqview.mk file to describe the build steps

```
GQVIEW_VERSION = 2.1.5
GQVIEW_SOURCE = gqview-$(GQVIEW_VERSION).tar.gz
GQVIEW_SITE = http://prdownloads.sourceforge.net/gqview
GQVIEW_DEPENDENCIES = host-pkgconf libgtk2
GQVIEW_CONF_ENV = LIBS="-lm"

$(eval $(autotools-package))
```

- ▶ The package directory and the prefix of all variables must be identical to the suffix of the main configuration option
BR2_PACKAGE_GQVIEW
- ▶ The autotools-package infrastructure knows how to build autotools packages. A more generic generic-package infrastructure is available for packages not using the autotools as their build system.

- ▶ The most versatile and powerful embedded Linux build system
 - ▶ A collection of recipes (.bb files)
 - ▶ A tool that processes the recipes: bitbake
- ▶ Integrates 2000+ application and libraries, is highly configurable, can generate binary packages to make the system customizable, supports multiple versions/variants of the same package, no need for full rebuild when the configuration is changed.
- ▶ Configuration takes place by editing various configuration files
- ▶ Good for larger embedded Linux systems, or people looking for more configurability and extensibility
- ▶ Drawbacks: very steep learning curve, very long first build.

Debian GNU/Linux, <http://www.debian.org>



- ▶ Provides the easiest environment for quickly building prototypes and developing applications. Countless runtime and development packages available.
- ▶ But probably too costly to maintain and unnecessarily big for production systems.
- ▶ Available on ARM (armel, armhf, arm64), MIPS and PowerPC architectures
- ▶ Software is compiled natively by default.

Fedora

- ▶ <http://fedoraproject.org/wiki/Architectures/ARM>
- ▶ Supported on various recent ARM boards (such as Beaglebone Black). Pidora supports Raspberry Pi too.
- ▶ Supports QEMU emulated ARM boards too (Versatile Express board)
- ▶ Shipping the same version as for desktops!



Ubuntu

- ▶ Had some releases for ARM mobile multimedia devices, but stopped at version 12.04. Now focusing on ARM servers only.



Distributions designed for specific types of devices

- ▶ **Android:** <http://www.android.com/>
Google's distribution for phones and tablet PCs.
Except the Linux kernel, very different user space
than other Linux distributions. Very successful, lots
of applications available (many proprietary).
- ▶ **Ångström:**
<http://www.angstrom-distribution.org/>
Produces nightly built images for a nice list of ARM
and x86 systems (see <http://dominion.thruhere.net/angstrom/nightlies/>)



Ångström

Not real distributions you can download. Instead, they implement middleware running on top of the Linux kernel and allowing to develop applications.

- ▶ **Mer:** <http://merproject.org/>
Fork from the Meego project.
Targeting mobile devices.
Supports x86, ARM and MIPS.
See [http://en.wikipedia.org/wiki/Mer_\(software_distribution\)](http://en.wikipedia.org/wiki/Mer_(software_distribution))

- ▶ **Tizen:** <https://www.tizen.org/>
Targeting smartphones, tablets, netbooks, smart TVs and In Vehicle Infotainment devices.
Supported by big phone manufacturers and operators
HTML5 base application framework.
See <http://en.wikipedia.org/wiki/Tizen>





- ▶ Rebuild the same system, this time with Buildroot.
- ▶ See how easier it gets!

Embedded Linux application development

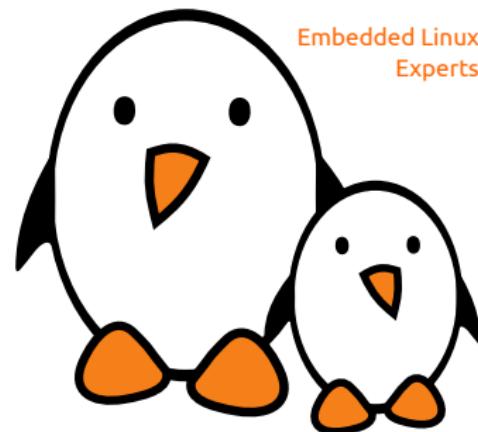
Endocode AG

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Corrections, suggestions, contributions and translations are welcome!



- ▶ Application development
 - ▶ Developing applications on embedded Linux
 - ▶ Building your applications
- ▶ Source management
 - ▶ Integrated development environments (IDEs)
 - ▶ Version control systems
- ▶ Debugging and analysis tools
 - ▶ Debuggers
 - ▶ Memory checkers
 - ▶ System analysis

Developing applications on embedded Linux

- ▶ An embedded Linux system is just a normal Linux system, with usually a smaller selection of components
- ▶ In terms of application development, developing on embedded Linux is exactly the same as developing on a desktop Linux system
- ▶ All existing skills can be re-used, without any particular adaptation
- ▶ All existing libraries, either third-party or in-house, can be integrated into the embedded Linux system
 - ▶ Taking into account, of course, the limitation of the embedded systems in terms of performance, storage and memory

- ▶ The default programming language for system-level application in Linux is usually C
 - ▶ The C library is already present on your system, nothing to add
- ▶ C++ can be used for larger applications
 - ▶ The C++ library must be added to the system
 - ▶ Some libraries, including Qt, are developed in C++ so they need the C++ library on the system anyway
- ▶ Scripting languages can also be useful for quick application development, web applications or scripts
 - ▶ But they require an interpreter on the embedded system and have usually higher memory consumption and slightly lower performance
- ▶ Languages: Python, Perl, Lua, Ada, Fortran, etc.

- ▶ For many applications, the C library already provides a relatively large set of features
 - ▶ file and device I/O, networking, threads and synchronization, inter-process communication
 - ▶ Thoroughly described in the glibc manual, or in any *Linux system programming* book
 - ▶ However, the API carries a lot of history and is not necessarily easy to grasp for new comers
- ▶ Therefore, using a higher level framework, such as Qt or the Gtk stack, might be a good idea
 - ▶ These frameworks are not only graphical libraries, their core is separate from the graphical part
 - ▶ But of course, these libraries have some memory and storage footprint, in the order of a few megabytes

- ▶ For simple applications that do not need to be really portable or provide compile-time configuration options, a simple Makefile will be sufficient
- ▶ For more complicated applications, or if you want to be able to run your application on a desktop Linux PC and on the target device, using a build system is recommended
 - ▶ *autotools* is ancient, complicated but very widely used.
 - ▶ We recommend to invest in *CMake* instead: modern, simpler, smaller but growing user base.
- ▶ The QT library is a special case, since it comes with its own build system for applications, called *qmake*.

- ▶ Case of an application that only uses the C library, contains two source files and generates a single binary

```
CROSS_COMPILE?=arm-linux-
CC=$(CROSS_COMPILE)gcc
OBJS=foo.o bar.o

all: foobar

foobar: $(OBJS)
        $(CC) -o $@ $^

clean:
        $(RM) -f foobar $(OBJS)
```

ENDO CODE Simple Makefile (2)

- ▶ Case of an application that uses the Glib and the GPS libraries

```
CROSS_COMPILE?=arm-linux-
LIBS=libgps glib-2.0
OBJS=foo.o bar.o

CC=$(CROSS_COMPILE)gcc
CFLAGS=$(shell pkg-config --cflags $(LIBS))
LDFLAGS=$(shell pkg-config --libs $(LIBS))

all: foobar

foobar: $(OBJS)
        $(CC) -o $@ $^ $(LDFLAGS)

clean:

        $(RM) -f foobar $(OBJS)
```

Integrated Development Environments (IDE)

<http://kdevelop.org>



- ▶ A full featured IDE!
- ▶ License: GPL
- ▶ Supports many languages: Ada, C, C++, Database, Java, Perl, PHP, Python, Ruby, Shell
- ▶ Supports many kinds of projects: KDE, but also GTK, Gnome, kernel drivers, embedded (Opie)...
- ▶ Many features: editor, syntax highlighting, code completion, compiler interface, debugger interface, file manager, class browser...

Nice overview:

<http://en.wikipedia.org/wiki/Kdevelop>

ENDO CODE KDevelop screenshot

The screenshot shows the KDevelop IDE interface with a Ruby debugger session. The title bar indicates the project is "trymain" and the file is "main.rb".

The left pane displays the variable inspector, showing the current state of variables:

- app: A KDE::Application object.
- children: An array of 5 elements, each a Qt::Object.
- metaObject: A KDE::MetaObject for "trymain".
- name: "trymain".
- receivers: A hash containing a single entry for "aboutToQuit".
- aboutToQuit[0]: A connection object for the "shutDown" signal.
- args: An empty array.
- description: "A KDE Application".

The right pane shows the code editor with the following Ruby code:

```
description = I18N_NOOP("A KDE Application")
version = "0.1"
options = [ [ "+[URL]", I18N_NOOP("Document to open") ], "" ]

about = KDE::AboutData.new("trymain", I18N_NOOP("TryMain"),
                           KDE::AboutData.License_GPL, "(C) 2005",
                           Richard Dale, nil, "Richard_Dale@tipitina.net",
                           KDE::CmdlineArgs.init(ARGV, about),
                           KDE::CmdlineArgs.addCmdLineOptions(options))
app = KDE::Application.new

# register ourselves as a dcop client
app.dcopClient().registerAs(app.name, false)

# see if we are starting with session management
if app.restored?
    RESTORE(TryMain)
else
    # no session.. just start up normally
    args = KDE::CmdlineArgs.parsedArgs
    if args.count == 0
        widget = TryMain.new
        widget.show
    else
        for i in 0...args.count do
            #1 /home/duke/play/testit/trymain/src/main.rb:22
    end
end
```

The bottom status bar shows the current thread and file path: "1 #<Thread:0x3005b798 run> /home/duke/play/testit/trymain/src/main.rb:22".

Ruby debugger

<http://www.eclipse.org/>



- ▶ An extensible, plug-in based software development kit, typically used for creating IDEs.
- ▶ Supported by the Eclipse foundation, a non-profit consortium of major software industry vendors (IBM, Intel, Borland, Nokia, Wind River, Zend, Computer Associates...).
- ▶ Free Software license (Eclipse Public License). Incompatible with the GPL.
- ▶ Supported platforms: GNU/Linux, Unix, Windows

Extremely popular: created a lot of attraction.

- ▶ Eclipse is actually a platform composed of many projects:
<http://www.eclipse.org/projects/>
 - ▶ Some projects are dedicated to integrating into Eclipse features useful for embedded developers (cross-compilation, remote development, remote debugging, etc.)
- ▶ The platform is used by major embedded Linux software vendors for their (proprietary) system development kits: MontaVista DevRocket, TimeSys TimeStorm, Wind River Workbench, Sysgo ELinOS.
- ▶ Used by free software build systems and development environments too, such as Yocto and Buildroot.

Eclipse is a huge project. It would require an entire training session!

- ▶ Many embedded Linux developers simply use **Vim** or **Emacs**. They can integrate with debuggers, source code browsers such as *cscope*, offer syntax highlighting and more.
 - ▶ **Geany** is an easy-to-use graphical code editor.
 - ▶ **CodeBlocks** is also quite popular, since it's also available on the Windows platform.

All these editors are available in most Linux distributions, simply install them and try them out!

Vim

Emacs

Version control systems

Real projects can't do without them

- ▶ Allow multiple developers to contribute on the same project.
Each developer can see the latest changes from the others, or choose to stick with older versions of some components.
- ▶ Allow to keep track of changes, and revert them if needed.
- ▶ Allow developers to have their own development branch (branching)
- ▶ Supposed to help developers resolving conflicts with different branches (merging)

Rely on a central repository. The most popular open-source ones:

- ▶ **CVS - Concurrent Versions System**

- ▶ Still quite popular in enterprise contexts. Almost no longer exists in the open-source community.
- ▶ Should no longer be used for new projects
- ▶ http://en.wikipedia.org/wiki/Concurrent_Versions_System

- ▶ **Subversion**

- ▶ Created as a replacement of CVS, removing many of its limitations.
- ▶ Commits on several files, proper renaming support, better performance, etc.
- ▶ The user interface is very similar to CVS
- ▶ [http://en.wikipedia.org/wiki/Subversion_\(software\)](http://en.wikipedia.org/wiki/Subversion_(software))

No longer have a central repository

- ▶ More adapted to the way the Free Software community develops software and organizes
- ▶ Allows each developer to have a full local history of the project, to create local branches. Makes each developer's work easier.
- ▶ People get working copies from other people's working copies, and exchange changes between themselves. Branching and merging is made easier.
- ▶ Make it easier for new developers to join, making their own experiments without having to apply for repository access.

▶ **Git**

- ▶ Initially designed and developed by Linus Torvalds for Linux kernel development
- ▶ Extremely popular in the community, and used by more and more projects (kernel, U-Boot, Barebox, uClibc, GNOME, X.org, etc.)
- ▶ Outstanding performance, in particular in big projects
- ▶ [http://en.wikipedia.org/wiki/Git_\(software\)](http://en.wikipedia.org/wiki/Git_(software))

▶ **Mercurial**

- ▶ Another system, created with the same goals as Git.
- ▶ Used by some big projects too
- ▶ <http://en.wikipedia.org/wiki/Mercurial>

http://en.wikipedia.org/wiki/Version_control_systems#Distributed_revision_control

Debuggers

The **GNU Project Debugger**

<http://www.gnu.org/software/gdb/>



- ▶ The debugger on GNU/Linux, available for most embedded architectures.
- ▶ Supported languages: C, C++, Pascal, Objective-C, Fortran, Ada...
- ▶ Console interface (useful for remote debugging).
- ▶ Graphical front-ends available.
- ▶ Can be used to control the execution of a program, set breakpoints or change internal variables. You can also use it to see what a program was doing when it crashed (by loading its memory image, dumped into a core file).

See also <http://en.wikipedia.org/wiki/Gdb>

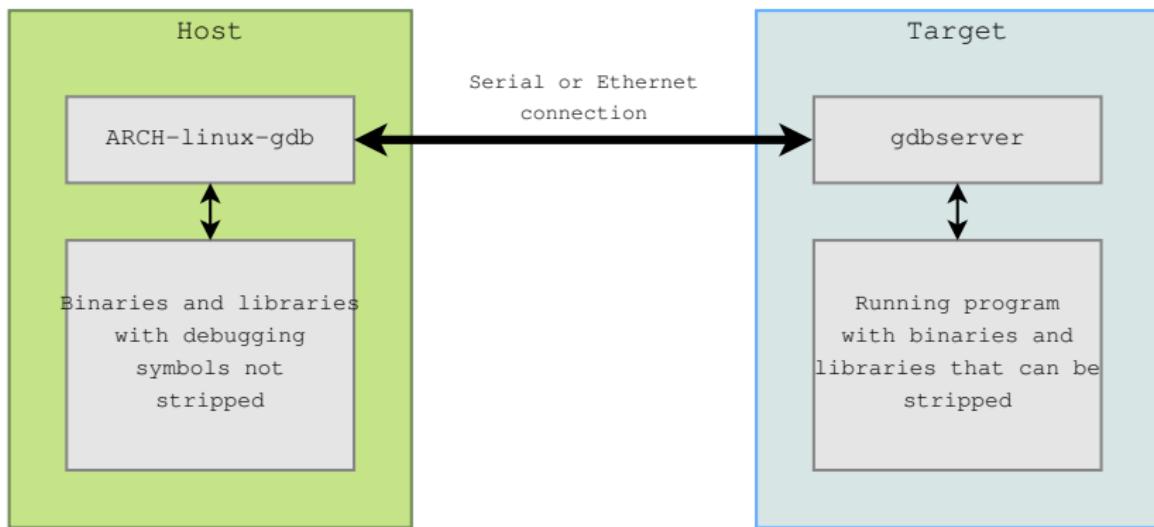
- ▶ A few useful GDB commands
 - ▶ `break foobar`
puts a breakpoint at the entry of function `foobar()`
 - ▶ `break foobar.c:42`
puts a breakpoint in `foobar.c`, line 42
 - ▶ `print var` or `print task->files[0].fd`
prints the variable `var`, or a more complicated reference. GDB can also nicely display structures with all their members
 - ▶ `continue`
continue the execution
 - ▶ `next`
continue to the next line, stepping over function calls
 - ▶ `step`
continue to the next line, entering into subfunctions
 - ▶ `backtrace`
display the program stack

- ▶ **DDD** - Data Display Debugger
<http://www.gnu.org/software/ddd/>
A popular graphical front-end, with advanced data plotting capabilities.
- ▶ **GDB/Insight**
<http://sourceware.org/insight/>
From the GDB maintainers.
- ▶ **KDbg**
<http://www.kdbg.org/>
Another front-end, for the K Display Environment.
- ▶ Integration with other IDEs: Eclipse, Emacs, KDevelop, etc.

Remote debugging

- ▶ In a non-embedded environment, debugging takes place using `gdb` or one of its front-ends.
- ▶ `gdb` has direct access to the binary and libraries compiled with debugging symbols.
- ▶ However, in an embedded context, the target platform environment is often too limited to allow direct debugging with `gdb` (2.4 MB on x86).
- ▶ Remote debugging is preferred
 - ▶ `gdb` is used on the development workstation, offering all its features.
 - ▶ `gdbserver` is used on the target system (only 100 KB on arm).





- ▶ On the target, run a program through `gdbserver`.
Program execution will not start immediately.

```
gdbserver localhost:<port> <executable> <args>  
gdbserver /dev/ttyS0 <executable> <args>
```

- ▶ Otherwise, attach `gdbserver` to an already running program:
`gdbserver --attach localhost:<port> <pid>`
- ▶ Then, on the host, run the `ARCH-linux-gdb` program,
and use the following `gdb` commands:

- ▶ To connect to the target:

```
gdb> target remote <ip-addr>:<port> (networking)  
gdb> target remote /dev/ttyS0 (serial link)
```

- ▶ To tell `gdb` where shared libraries are:

```
gdb> set sysroot <library-path> (without lib/)
```

- ▶ When an application crashes due to a *segmentation fault* and the application was not under control of a debugger, we get no information about the crash
- ▶ Fortunately, Linux can generate a *core* file that contains the image of the application memory at the moment of the crash, and gdb can use this *core* file to let us analyze the state of the crashed application
- ▶ On the target
 - ▶ Use `ulimit -c unlimited` to enable the generation of a *core* file when a crash occurs
- ▶ On the host
 - ▶ After the crash, transfer the *core* file from the target to the host, and run`ARCH-linux-gdb -c core-file application-binary`

Memory checkers

Detect Unintended Memory Access

<http://duma.sourceforge.net/>

- ▶ Fork and replacement for Electric Fence
- ▶ Stops your program on the exact instruction that overruns or underruns a `malloc()` memory buffer.
- ▶ GDB will then display the source-code line that causes the bug.
- ▶ Works by using the virtual-memory hardware to create a red-zone at the border of each buffer - touch that, and your program stops.
- ▶ Works on any platform supported by Linux, whatever the CPU (provided virtual memory support is available).

<http://valgrind.org/>



- ▶ GNU GPL Software suite for debugging and profiling programs.
- ▶ Supported platforms: Linux on x86, x86_64, ppc32, ppc64 and arm (armv7 only: Cortex A8, A9 and A5)
- ▶ Can detect many memory management and threading bugs.
- ▶ Profiler: provides information helpful to speed up your program and reduce its memory usage.
- ▶ The most popular tool for this usage. Even used by projects with hundreds of programmers.



- ▶ Can be used to run any program, without the need to recompile it.
- ▶ Example usage

```
valgrind --leak-check=yes ls -la
```
- ▶ Works by adding its own instrumentation to your code and then running in on its own virtual cpu core.
Significantly slows down execution, but still fine for testing!
- ▶ More details on <http://valgrind.org/info/> and http://valgrind.org/docs/manual/coregrind_core.html#howworks

System analysis

System call tracer

<http://sourceforge.net/projects/strace/>

- ▶ Available on all GNU/Linux systems
Can be built by your cross-compiling toolchain generator.
- ▶ Even easier: drop a ready-made static binary for your architecture, just when you need it. See
<http://git.free-electrons.com/users/michael-opdenacker/static-binaries/tree/strace>
- ▶ Allows to see what any of your processes is doing:
accessing files, allocating memory...
Often sufficient to find simple bugs.
- ▶ Usage:
`strace <command>` (starting a new process)
`strace -p <pid>` (tracing an existing process)

See `man strace` for details.

strace example output

Hint: follow the open file descriptors returned by `open()`. This tells you what files system calls are run on.

A tool to trace library calls used by a program and all the signals it receives

- ▶ Very useful complement to strace, which shows only system calls.
- ▶ Of course, works even if you don't have the sources
- ▶ Allows to filter library calls with regular expressions, or just by a list of function names.
- ▶ Manual page: <http://linux.die.net/man/1/ltrace>

See <http://en.wikipedia.org/wiki/Ltrace> for details

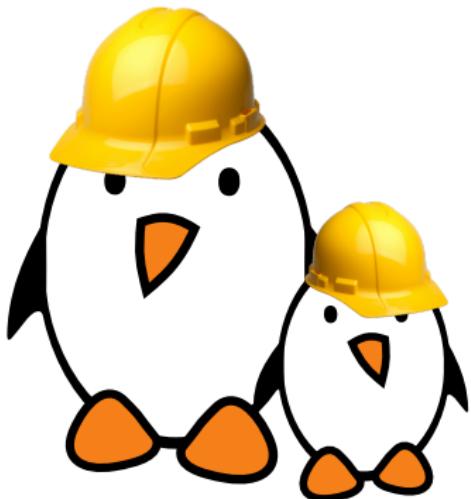
```
ltrace nedit index.html
sscanf(0x8274af1, 0x8132618, 0x8248640, 0xbfaadfe8, 0) = 1
sprintf("const 0", "const %d", 0) = 7
strcmp("startScan", "const 0") = 1
strcmp("ScanDistance", "const 0") = -1
strcmp("const 200", "const 0") = 1
strcmp("$list_dialog_button", "const 0") = -1
strcmp("$shell_cmd_status", "const 0") = -1
strcmp("$read_status", "const 0") = -1
strcmp("$search_end", "const 0") = -1
strcmp("$string_dialog_button", "const 0") = -1
strcmp("$rangeset_list", "const 0") = -1
strcmp("$calltip_ID", "const 0") = -1
```

Example summary at the end of the ltrace output (-c option)

Process 17019 detached					
% time	seconds	usecs/call	calls	errors	syscall
100.00	0.000050	50	1		set_thread_area
0.00	0.000000	0	48		read
0.00	0.000000	0	44		write
0.00	0.000000	0	80	63	open
0.00	0.000000	0	19		close
0.00	0.000000	0	1		execve
0.00	0.000000	0	2	2	access
0.00	0.000000	0	3		brk
0.00	0.000000	0	1		munmap
0.00	0.000000	0	1		uname
0.00	0.000000	0	1		mprotect
0.00	0.000000	0	19		mmap2
0.00	0.000000	0	50	46	stat64
0.00	0.000000	0	18		fstat64
<hr/>					
100.00	0.000050	288	111	total	

<http://oprofile.sourceforge.net>

- ▶ A system-wide profiling tool
- ▶ Can collect statistics like the top users of the CPU.
- ▶ Works without having the sources.
- ▶ Requires a kernel patch to access all features, but is already available in a standard kernel.
- ▶ Requires more investigation to see how it works.
- ▶ Ubuntu/Debian packages: oprofile, oprofile-gui



Application development

- ▶ Compile your own application with the ncurses library

Remote debugging

- ▶ Set up remote debugging tools on the target: strace, ltrace and gdbserver.
- ▶ Debug a simple application running on the target using remote debugging

Boot time: Principles

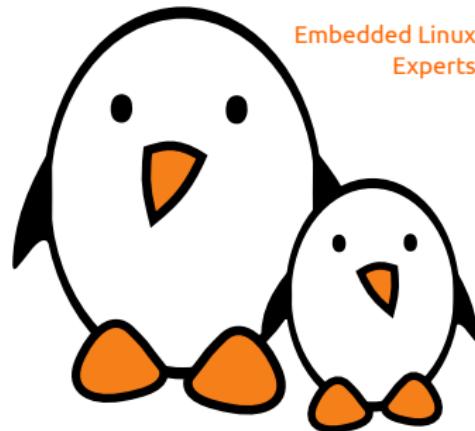
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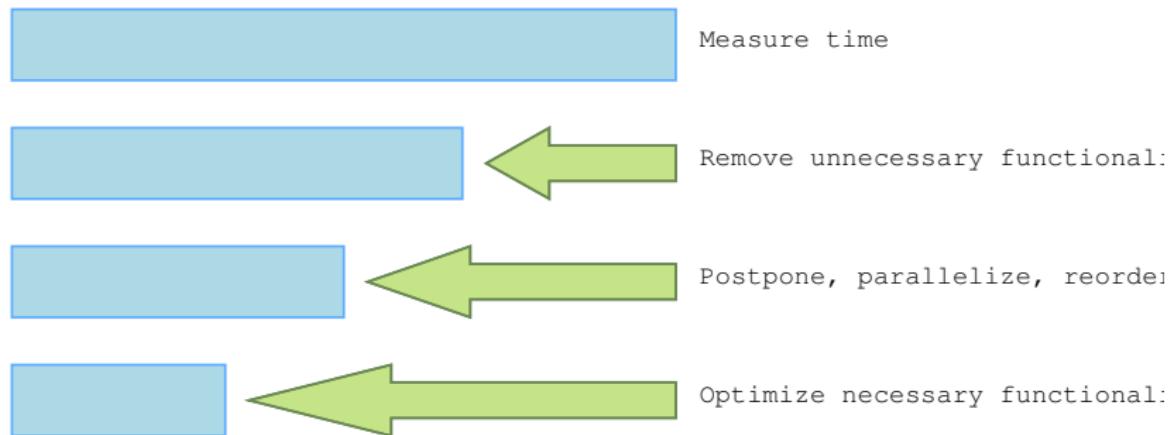
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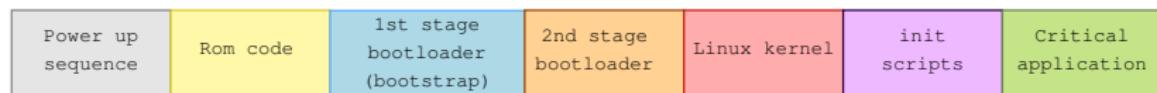


- ▶ Reducing boot time implies measuring boot time!
- ▶ You will have to choose reference events at which you start and stop counting time.
- ▶ What you choose will depend on the goal you want to achieve. Here are typical cases:
 - ▶ Showing a splash screen or an animation, playing a sound to indicate the board is booting
 - ▶ Starting a listening service to handle a particular message
 - ▶ Being fully functional as fast as possible





Generic boot sequence



Example: typical boot sequence on Atmel AT91



We are focusing on reducing *cold* boot time, from power on to the critical application.

Start by optimizing the last steps of the boot process!

- ▶ Don't start by optimizing things that will reduce your ability to make measurements and implement other optimizations.
- ▶ Start by optimizing your applications and startup scripts first.
- ▶ You can then simplify BusyBox, reducing the number of available commands.
- ▶ The next thing to do is simplify and optimize the kernel. This will make you lose debugging and development capabilities, but this is fine as user space has already been simplified.
- ▶ The last thing to do is implement bootloader optimizations, when kernel optimizations are over and when the kernel command line is frozen.

We will follow this order during the practical labs.

Premature optimization is the root of all evil.

Donald Knuth

- ▶ Taking the time to measure time carefully is important.
- ▶ Find the worst consumers of time and address them first.
- ▶ You can waste a lot of time if you start optimizing minor spots first.

- ▶ Very important to automate the way the root filesystem is built, if not done yet. That's always the first thing we do in boot time reduction projects, and it's worth investing 1 or 2 days doing this.
- ▶ Otherwise, you may lose existing optimizations or introduce new bugs when making further optimizations. Without a build system, you will waste a lot of time too.
- ▶ Can be done through build systems such as Buildroot or Yocto, or using the original build automation of the project.
- ▶ Can also be done for kernel and bootloader optimizations, though the need is less critical.

Some ideas to keep in mind while trying to reduce the boot time:

- ▶ The fastest code is code that is not executed
- ▶ A big part of booting is actually loading code and data from the storage to RAM. Reading less means booting faster. I/O are expensive!
- ▶ The root filesystem may take longer to mount if it is bigger.
- ▶ So, even code that is not executed can make your boot time longer.
- ▶ Also, try to benchmark different types of storage. It has happened that booting from SD card was actually faster than booting from NAND.

Measuring

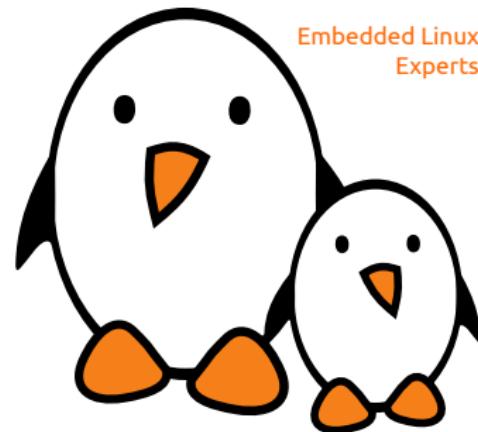
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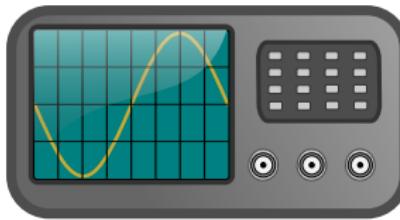
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- ▶ The best equipment is an oscilloscope.
- ▶ Allows to time the "Power on" event (connected to a power rail), or any event (connected to a GPIO pin, for example), all this in a very accurate way.
- ▶ Easy to write to a GPIO at all the stages of system booting.
- ▶ Some oscilloscopes are getting affordable. Example: Bitscope Pocket Analyzer (295 AUD, supported on Linux, <http://www.bitscope.com/product/BS10/>)



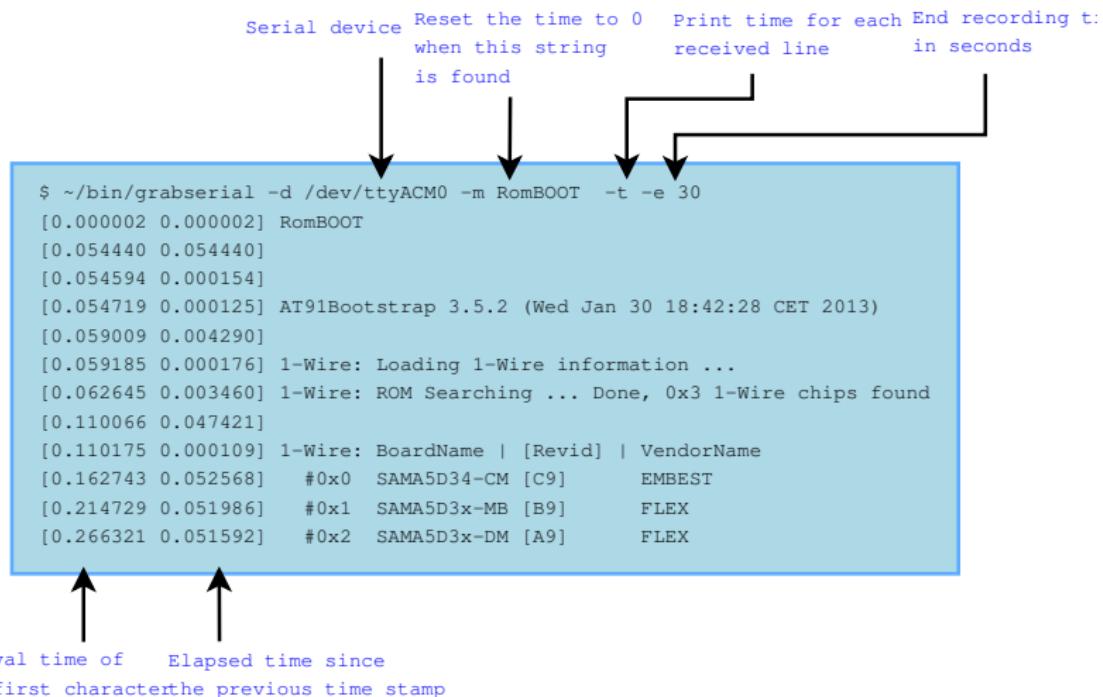
- ▶ Useful when you don't have an oscilloscope, or don't want to make take any risk connecting wires to the hardware.
- ▶ Usually relies on software which times messages received from the board's serial port (serial port absolutely required). Such software runs on a PC connected to the serial port.
- ▶ Need a real serial port (directly connected to the CPU), immediately usable from the earliest parts of the boot process.
- ▶ Limitation: won't be able to time the "Power on" event in an accurate way. But acceptable as you can assume that the time to run the first stage bootloader is constant.



- ▶ Serial ports over USB **device** are fine if there's an on-board serial-to-USB chip directly connected to the CPU serial port (very frequent).
- ▶ Attaching a USB-to-serial dongle to a USB **host** port on the device won't do: USB is available much later and messages go through more complex software stacks (loss of time accuracy).
- ▶ All development boards have a standard or USB serial port.



- ▶ From Tim Bird: <http://elinux.org/Grabserial>
- ▶ A Python script to add timestamps to messages coming from a serial console.
- ▶ Key advantage: starts counting very early (bootstrap and bootloader)
- ▶ Another advantage: no overhead on the target, because run on the host machine.
- ▶ Drawbacks: may not be precise enough. Can't measure power up time.



Caution: `grabserial` shows the arrival time of the **first character** of a line. This doesn't mean that the entire line was received at that time.



- ▶ Time the various components of boot time

Filesystem optimizations

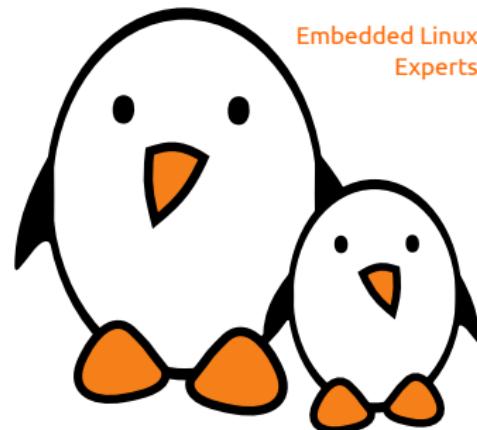
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Tuning the filesystem is usually one of the first things we work on in boot time projects.

- ▶ Different filesystems can have different initialization and mount times. In particular, the type of filesystem for the root filesystem directly impacts boot time.
- ▶ Different filesystems can exhibit different read, write and access time performance, according to the type of filesystem activity and to the type of files in the system.

- ▶ Block storage (including memory cards, eMMC)
 - ▶ ext2, ext3, ext4
 - ▶ xfs, jfs, reiserfs
 - ▶ btrfs
 - ▶ f2fs
 - ▶ SquashFS
- ▶ Raw flash storage
 - ▶ JFFS2
 - ▶ YAFFS2
 - ▶ UBIFS
 - ▶ ubiblock + SquashFS

See our embedded Linux training materials for full details:

<http://free-electrons.com/doc/training/embedded-linux/>

See also our flash filesystem benchmarks:

http://elinux.org/Flash_Filesystem_Benchmarks.

For block storage

- ▶ ext4: best for rather big partitions, good read and write performance.
- ▶ xfs, jfs, reiserfs: can be good in some read or write scenarii as well.
- ▶ btrfs, f2fs: can achieve best read and write performance, taking advantage of the characteristics of flash-based block devices.
- ▶ SquashFS: best mount time and read performance, for read-only partitions. Great for root filesystems which can be read-only.

For raw flash storage

- ▶ Mount time depending on filesystem size: the kernel has to scan the whole filesystem at mount time, to read which block belongs to each file.
- ▶ Need to use the `CONFIG_JFFS2_SUMMARY` kernel option to store such information in flash. This dramatically reduces mount time.
- ▶ Benchmark on ARM:
from 16 s to 0.8 s for a 128 MB partition.
- ▶ Rather poor read and write performance,
compared to YAFFS2 and UBIFS.

For raw flash storage

- ▶ Good mount time
- ▶ Good read and write performance
- ▶ Drawbacks: no compression, not in the mainline Linux kernel

For raw flash storage

- ▶ Advantages:
 - ▶ Good read and write performance (similar to YAFFS2)
 - ▶ Other advantages: better for wear leveling (can operate on the whole UBI space, not only within a single partition).
- ▶ Drawbacks:
 - ▶ Not appropriate for small partitions (too much metadata overhead). Use JFFS2 or JAFFS2 instead.
 - ▶ Not so good mount time, because of the time needed to initialize UBI (*UBI Attach*: at boot time or running `ubi_attach` in user space).
 - ▶ Addressed by *UBI Fastmap*, introduced in Linux 3.7.
See next slides.

- ▶ *UBI Attach*: needs to read UBI metadata by scanning all erase blocks. Time proportional to the storage size.
- ▶ *UBI Fastmap* stores such information in a few flash blocks (typically at UBI detach time during system shutdown) and finds it there at boot time.
- ▶ This makes *UBI Attach* time constant.
- ▶ If *Fastmap* information is invalid (unclean system shutdown, for example), it falls back to scanning (slower, but correct, and *Fastmap* will work again during the next boot).
- ▶ Details: ELCE 2012 presentation from Thomas Gleixner:
http://elinux.org/images/a/ab/UBI_Fastmap.pdf

- ▶ Compile your kernel with `CONFIG_UBI_FASTMAP`
- ▶ Boot your system at least once with the `ubi.fm_autoconvert=1` kernel parameter.
- ▶ Reboot your system in a clean way
- ▶ You can now remove `ubi.fm_autoconvert=1`

- ▶ Measured on the Atmel SAMA5D3 Xplained board (ARM), Linux 3.10
- ▶ UBI space: 216 MB
- ▶ Root filesystem: 80 MB used (Yocto)
- ▶ Average results:

	Attach time	Diff	Total time
Without <i>UBI Fastmap</i>	968 ms		
With <i>UBI Fastmap</i>	238 ms	-731 ms	-665 ms

- ▶ Expect to save more with bigger UBI spaces!

Note: total boot time reduction a bit lower probably because of other kernel threads executing during the attach process.

For raw flash storage

- ▶ *ubiblock*: read-only block device on top of UBI (CONFIG_MTD_UBI_BLOCK). Available in Linux 3.15 (developed on his spare time by Ezequiel Garcia, a Free Electrons contractor).
- ▶ Allows to put SquashFS on a UBI volume.
- ▶ Expecting great boot time and read performance. Great for read-only root filesystems.
- ▶ Benchmarks not available yet.

- ▶ Raw flash storage: UBIFS with CONFIG_UBI_FASTMAP is probably the best solution.
- ▶ Block storage: SquashFS best solution for root filesystems which can be read-only. Btrfs and f2fs probably the best solutions for read/write filesystems.
- ▶ Fortunately, changing filesystem types is quite cheap, and completely transparent for applications. Just try several filesystem options, as see which one works best for you!
- ▶ Do not focus only on boot time.
For systems in which read and write performance matters, we recommend to use separate root filesystem (for quick boot time) and data partitions (for good runtime performance).

Init scripts

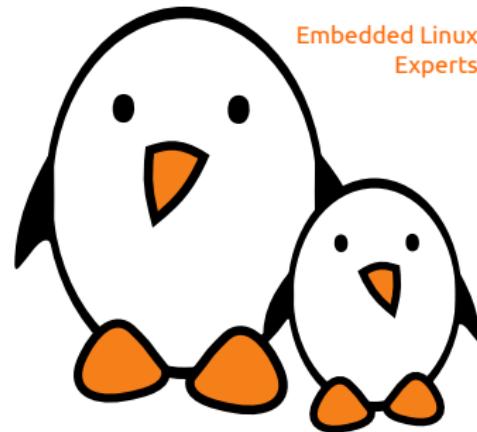
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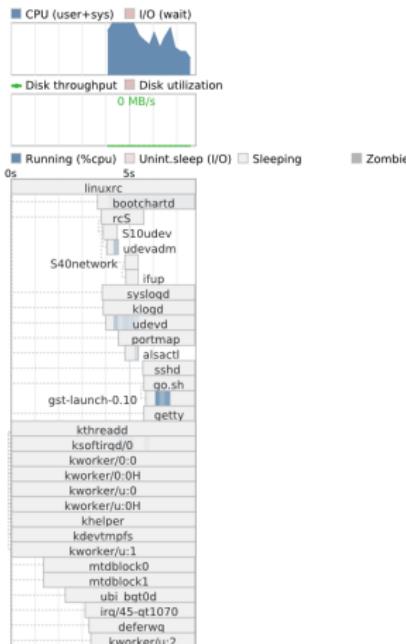
There are multiple ways to reduce the time spent in init scripts before starting the application:

- ▶ Start the application as soon as possible after only the strictly necessary dependencies.
- ▶ Simplify shell scripts
- ▶ Start the application even before `init`

If you want to have a more detailed look at the userland boot sequence than with grabserial, you can use bootchart.

Boot chart for buildroot (Tue Jan 2 21:52:3

uname: Linux 3.6.9+ #1 Wed Jan 30 19:42:51 CET 2013 armv7l
release:
CPU:
kernel options: console=tty0,115200 mtdparts=atmel_nand:8M(bootstr
time: 0:08



- ▶ You can use bootchartd from busybox (CONFIG_BOOTCHARTD=y)
- ▶ Boot your board passing init=/sbin/bootchartd on your kernel command line
- ▶ Copy /var/log/bootlog.tgz from your target to your host
- ▶ Generate the timechart:

```
cd bootchart-<version>
java -jar bootchart.jar bootlog.tgz
```

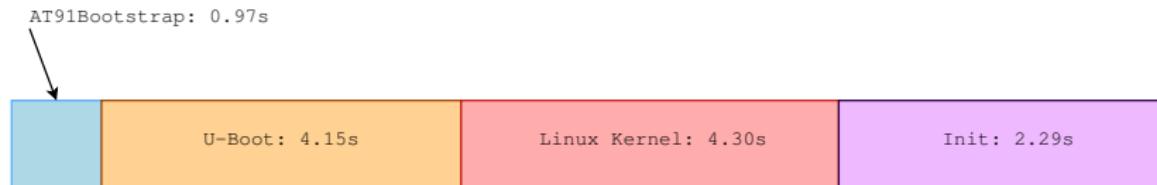
bootchart is available at <http://www.bootchart.org>

If you are using systemd as your init program, you can use `systemd-analyze`. See

<http://www.freedesktop.org/software/systemd/man/systemd-analyze.html>.

```
$ systemd-analyze blame
6207ms udev-settle.service
 735ms NetworkManager.service
 642ms avahi-daemon.service
 600ms abrtd.service
 517ms rtkit-daemon.service
 396ms dbus.service
 390ms rpcidmapd.service
 346ms systemd-tmpfiles-setup.service
 316ms cups.service
 310ms console-kit-log-system-start.service
 309ms libvirtd.service
 303ms rpcbind.service
 298ms ksmtuned.service
 281ms rpcgssd.service
 277ms sshd.service
...
```

In the initial demo, we measure the time taken to get the login prompt (RomBOOT is excluded).



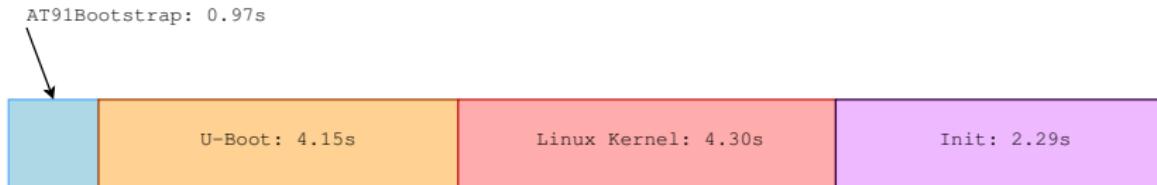
Total: 11.70s.

Starting as soon as possible after all the dependencies are started:

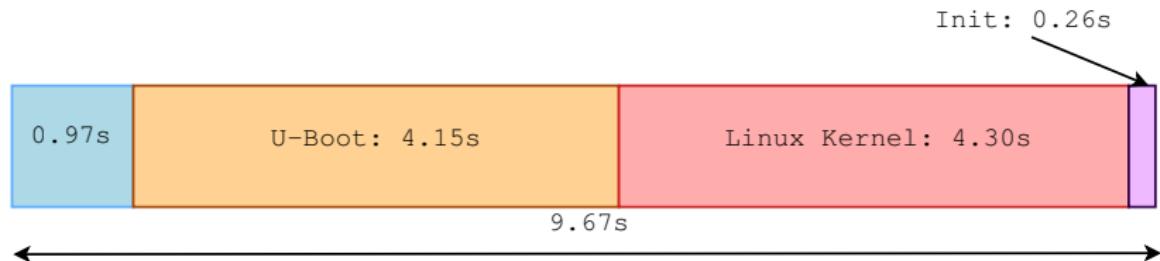
- ▶ Depends on your `init` program. Here we are assuming sysV init scripts.
- ▶ `init` scripts run in alphanumeric order and start with a letter (K for stop (`kill`) and S for `start`).
- ▶ You want to use the lowest number you can for your application.
- ▶ You can even replace `init` with your application!

How fast would we be if we could be the first started application?

Before: 11.70s



After:



- ▶ Start all your services directly from a single startup script (e.g. `/etc/init.d/rcS`). This eliminates multiple calls to `/bin/sh`.
- ▶ Replace `udev` with `mdev`. `mdev` is part of BusyBox. It is not running as a daemon and you can either run it only once or have it handling hotplug events.
- ▶ Remove `udev` (or `mdev`) if you just need it to create device files. Use `devtmpfs` (`CONFIG_DEVTMPFS`) instead, automatically managed by the kernel, and cheaper.

- ▶ fork/exec system calls are very expensive. Because of this, calls to executables from shells are slow.
- ▶ Even an echo in a BusyBox shell results in a fork syscall!
- ▶ Select Shells -> Standalone shell in BusyBox configuration to make the shell call applets whenever possible.
- ▶ Pipes and back-quotes are also implemented by fork/exec. You can reduce their usage in scripts. Example:

```
cat /proc/cpuinfo | grep model
```

Replace it with:

```
grep model /proc/cpuinfo
```

See http://elinux.org/Optimize_RC_Scripts

Replaced:

```
if [ $(expr match "$(cat /proc/cmdline)" '.* debug.*') ]\n    -ne 0 -o -f /root/debug ]; then\nDEBUG=1
```

By a much cheaper command running only one process:

```
res=`grep " debug" /proc/cmdline`\nif [ "$res" -o -f /root/debug ]; then\nDEBUG=1
```

This only optimization allowed to save 87 ms on an ARM AT91SAM9263 system (200 MHz)!

- ▶ Strip your executables and libraries, removing ELF sections only needed for development and debugging. The `strip` command is provided by your cross-compiling toolchain.
BR2_STRIP_strip in Buildroot.
- ▶ superstrip: <http://muppetlabs.com/~breadbox/software/elfkickers.html>.
Goes beyond `strip` and can strip out a few more bits that are not used by Linux to start an executable. BR2_STRIP_sstrip in Buildroot.

- ▶ use `mklibs`, available at
<http://packages.debian.org/sid/mklibs>.
 - ▶ `mklibs` produces cut-down shared libraries that contain only the routines required by a particular set of executables. Really useful with big libraries like OpenGL and QT. It even works without having the source code.
 - ▶ Available in Yocto, but not in Buildroot (at least in 2013.11).
 - ▶ Limitation: `mklibs` could remove `dlopened` libraries (loaded "manually" by applications) because it doesn't see them.



- ▶ Regenerate the root filesystem with Buildroot
- ▶ Use bootchart to measure boot time

C Libraries

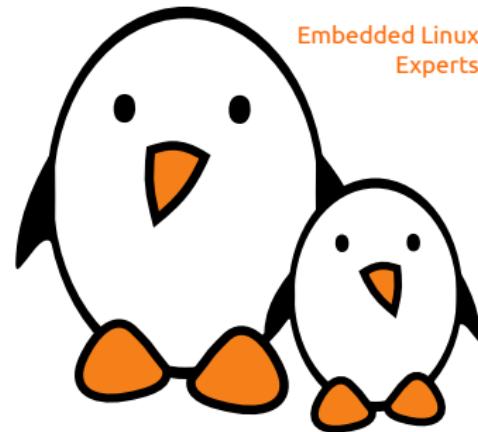
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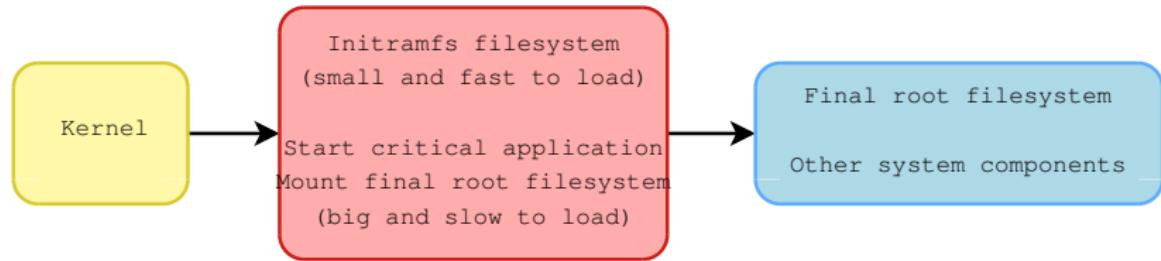
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An idea is to use a very small initramfs, just enough to start the critical application and then switch to the final root filesystem.

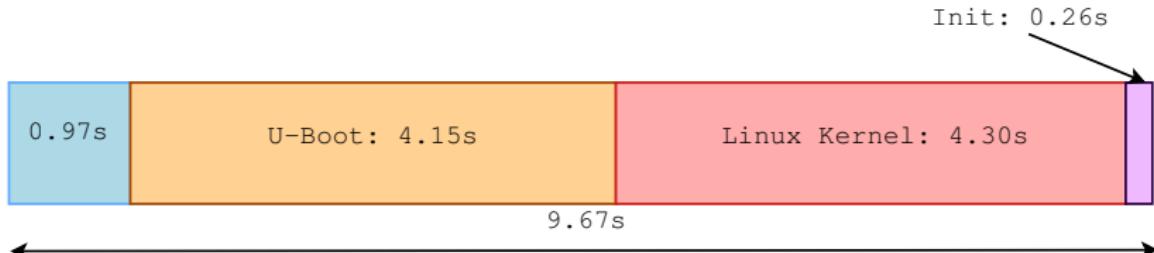


Create the smallest initramfs possible, just enough to start the critical application and then switch to the final root filesystem with `switch_root`:

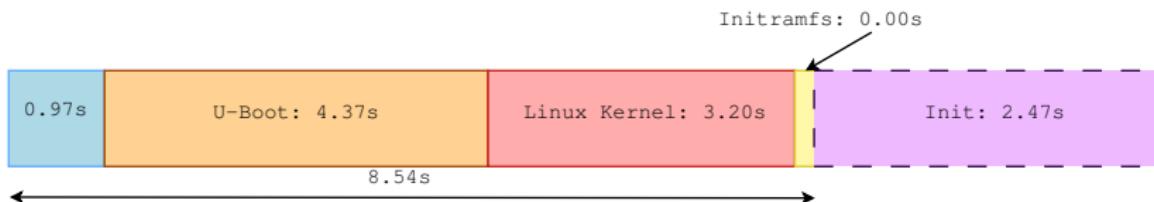
- ▶ Use a light C library reduced to the minimum, *uClibc* if you are not yet using it for your root filesystem
- ▶ Reduce BusyBox to the strict minimum. You could even do without it and implement `/init` in C.
- ▶ Use statically linked applications (less CPU overhead, less libraries to load, smaller initramfs if no libraries at all).
`BR2_PREFER_STATIC_LIB` in Buildroot.

- ▶ Statically linked executables are very useful to reduce size (especially in small initramfs), and require less work to start.
- ▶ However, the LGPL license in libraries (uClibc, glibc), require to leave the user the ability to relink the executable with a modified version of the library.
- ▶ Solution to keep static binaries:
 - ▶ Either provide the executable source code (even proprietary), allowing to recompile it with a modified version of the library. That's what you do when you ship a static BusyBox.
 - ▶ Or also provide a dynamically linked version of the executable (in a separate way), allowing to use another library version.
- ▶ References:
<http://gnu.org/licenses/gpl-faq.html#LGPLStaticVsDynamic>
<http://gnu.org/copyleft/lesser.html#section4>

Before:



After:



- ▶ U-Boot takes more time because the kernel is bigger
- ▶ init is started earlier because UBI is not initialized yet (slow, UBIFS root filesystem)

- ▶ If you ship your initramfs inside a compressed kernel image, don't compress it (enable `CONFIG_INITRAMFS_COMPRESSION_NONE`).
- ▶ Otherwise, your initramfs data will be compressed twice, and the kernel will be slightly bigger and will take a little more time to uncompress.

Tests on Linux 3.13-rc4, measuring the penalty of having a gzip compressed initramfs in a gzip compressed kernel.

Beagle Bone Black (ARM, TI AM3359, 1 GHz)

Mode	Size	Copy	Uncompress	Total	Diff
No initramfs compression	4308200	451 ms	945 ms	5.516 s	
Initramfs compression	4309112	455 ms	947 ms	5.527 s	+ 11 ms

CALAO USB-A9263 (ARM, Atmel AT91SAM9263, 200 MHz)

Mode	Size	Copy	Uncompress	Total	Diff
No initramfs compression	3016192	4.1047 s	1.737 s	8.795 s	
Initramfs compression	3016928	4.1050 s	1.760 s	8.813 s	+ 18 ms

Often the first sign of life that you are showing!

- ▶ You could use the `fbv` program
(<http://freecode.com/projects/fbv>)
to display your splashscreen.
- ▶ On `armel`, you can just use our statically compiled binary:
<http://git.free-electrons.com/users/michael-opdenacker/static-binaries/tree/fbv>
- ▶ However, this is slow:
878 ms on an Atmel AT91SAM9263 system!

- ▶ To do it faster, you can dump the framebuffer contents:

```
fbv -d 1 /root/logo.bmp
cp /dev/fb0 /root/logo.fb
lzop -9 /root/logo.fb
```

- ▶ And then copy it back as early as possible in an initramfs:

```
lzopcat /root/logo.fb.lzo > /dev/fb0
```

Results on an Atmel AT91SAM9263 system:

	fbv	plain copy (dd)	lzopcat
Time	878 ms	54 ms	52.5 ms

<http://free-electrons.com/blog/super-fast-linux-splashscreen/>

Still slow to read and write entire screens. Just draw useful pixels and even create an animation!

- ▶ Create a simple C program that just animates pixels and simple geometric shapes on the framebuffer!
- ▶ Example: <http://free-electrons.com/pub/code/fb/anim.c>.
On a 400 MHz ARM9 system: starts drawing in 10 ms
size: 24 KB, compiled statically).



- ▶ Simplify user space scripts

Applications

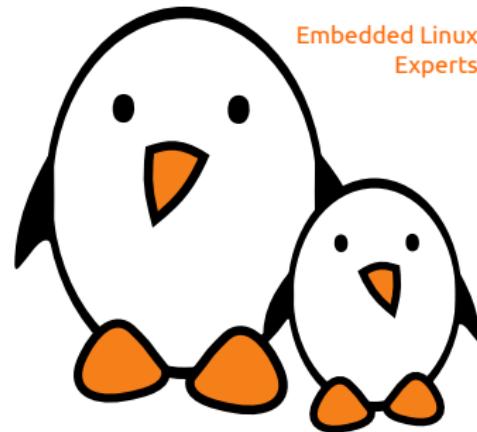
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- ▶ Allows to trace all the system calls made by an application and its children.
- ▶ Useful to:
 - ▶ Understand how time is spent in user space
 - ▶ For example, easy to find file open attempts (`open()`), file access (`read()`, `write()`), and memory allocations (`mmap2()`). Can be done without any access to source code!
 - ▶ Find the biggest time consumers (low hanging fruit)
 - ▶ Find unnecessary work done in applications and scripts.
Example: opening the same file(s) multiple times, or trying to open files that do not exist.
- ▶ Limitation: you can't trace the `init` process!

- ▶ strace can be compiled by your build system
- ▶ Even easier: drop a ready-made static binary for your architecture, just when you need it. See

<http://git.free-electrons.com/users/michael-opdenacker/static-binaries/tree/strace>

- ▶ Recommended usage:

```
strace -f -tt -o strace.log <program> <arguments>
```

- ▶ -f: follow child processes
- ▶ -tt: display timestamps with microsecond accuracy

- ▶ Two ways of working: *legacy mode* and *perf_events mode*
- ▶ *legacy mode*:
 - ▶ Low accuracy, use a kernel driver to profile
 - ▶ `CONFIG_OPROFILE`
 - ▶ User space tools: `opcontrol` and `oprofiled`
- ▶ *perf_events mode*:
 - ▶ Uses hardware performance counters
 - ▶ `CONFIG_PERF_EVENTS` and `CONFIG_HW_PERF_EVENTS`
 - ▶ User space tools: `operf`

oprofile: usage

- ▶ *legacy mode:*

```
^^I^^Iopcontrol --vmlinux=/path/to/vmlinux # optional step  
^^I^^Iopcontrol --start  
^^I^^I/my/command  
^^I^^Iopcontrol --stop  
^^I
```

- ▶ *perf_events mode:*

```
^^I^^Ioperf --vmlinux=/path/to/vmlinux /my/command  
^^I
```

- ▶ Get the results with:

```
^^I^^Iopreport  
^^I
```

```
# opreport
Using /var/lib/oprofile/samples/ for samples directory.
CPU: CPU with timer interrupt, speed 393 MHz (estimated)
Profiling through timer interrupt
      TIMER:0|
samples|      %|
-----
 1540 78.3715 no-vmlinux
 105 5.3435 libQtGui.so.4.8.4
  66 3.3588 libc-2.15.so
  64 3.2570 libQtCore.so.4.8.4
  58 2.9517 ld-2.15.so
  45 2.2901 libgobject-2.0.so.0.3000.3
  37 1.8830 libgstreamer-0.10.so.0.30.0
  13 0.6616 libglib-2.0.so.0.3000.3
   9 0.4580 libQtScript.so.4.8.4
   6 0.3053 libgcc_s.so.1
   4 0.2036 libQtDeclarative.so.4.8.4
   4 0.2036 libstdc++.so.6.0.17
   3 0.1527 libpthread-2.15.so
   2 0.1018 busybox
   2 0.1018 libQtSvg.so.4.8.4
   2 0.1018 libQtWebKit.so.4.9.3
   2 0.1018 libgthread-2.0.so.0.3000.3
   1 0.0509 HomeAutomation
   1 0.0509 libQtNetwork.so.4.8.4
   1 0.0509 libphonon_gstremer.so
```

- ▶ Uses hardware performance counters
- ▶ CONFIG_PERF_EVENTS and CONFIG_HW_PERF_EVENTS
- ▶ User space tool: perf. It is part of the kernel sources so it is always in sync with your kernel.
- ▶ Usage:

```
^^I^^Iperf record /my/command
```

```
^^I
```

- ▶ Get the results with:

```
^^I^^Iperf report
```

```
^^I
```

20.91%	gst-launch-0.10	libavcodec.so.53.35.0	[.] 0x000000000003bdaa1
15.45%	gst-launch-0.10	libgstflump3dec.so	[.] 0x0000000000014b42
3.16%	gst-launch-0.10	libglib-2.0.so.0.3600.2	[.] 0x00000000000882c9
2.99%	gst-launch-0.10	libc-2.17.so	[.] __memcpy_ssse3_back
2.37%	gst-launch-0.10	liboil-0.3.so.0.3.0	[.] 0x000000000004417e
2.24%	gst-launch-0.10	libgobject-2.0.so.0.3600.2	[.] g_type_value_table_peek
1.53%	gst-launch-0.10	libc-2.17.so	[.] vfprintf
1.37%	gst-launch-0.10	libgststreamer-0.10.so.0.30.0	[.] 0x0000000000026fd8
1.29%	gst-launch-0.10	ld-2.17.so	[.] do_lookup_x
0.99%	gst-launch-0.10	libpthread-2.17.so	[.] pthread_mutex_lock
0.98%	gst-launch-0.10	libgobject-2.0.so.0.3600.2	[.] g_type_check_value
0.93%	gst-launch-0.10	libgstavi.so	[.] 0x00000000000119f9
0.88%	gst-launch-0.10	libgststreamer-0.10.so.0.30.0	[.] gst_value_list_get_type
0.85%	gst-launch-0.10	libc-2.17.so	[.] __random
0.66%	gst-launch-0.10	[kernel.kallsyms]	[k] clear_page_c_e
0.62%	gst-launch-0.10	[kernel.kallsyms]	[k] try_to_wake_up
0.61%	gst-launch-0.10	[kernel.kallsyms]	[k] page_fault
0.58%	gst-launch-0.10	libgobject-2.0.so.0.3600.2	[.] g_type_is_a
0.57%	gst-launch-0.10	libc-2.17.so	[.] __strcmp_sse42
0.57%	gst-launch-0.10	[kernel.kallsyms]	[k] radix_tree_lookup_element
0.57%	gst-launch-0.10	libc-2.17.so	[.] malloc
0.57%	gst-launch-0.10	libc-2.17.so	[.] _int_malloc
0.55%	gst-launch-0.10	libgobject-2.0.so.0.3600.2	[.] g_type_check_instance_is_a
0.53%	gst-launch-0.10	[kernel.kallsyms]	[k] __ticket_spin_lock
0.53%	gst-launch-0.10	libgobject-2.0.so.0.3600.2	[.] g_type_check_value_holds
0.53%	gst-launch-0.10	libgstffmpeg.so	[.] 0x000000000001e40c
0.51%	gst-launch-0.10	libgststreamer-0.10.so.0.30.0	[.] gst_structure_id_get_value
0.50%	gst-launch-0.10	libc-2.17.so	[.] _IO_default_xsputn
0.50%	gst-launch-0.10	[kernel.kallsyms]	[k] tg_load_down

Try to use an optimized toolchain for your platform. That is something you'll have to benchmark near the end of your project.

- ▶ gcc version 4.6.3 (Sourcery CodeBench Lite 2012.03-57: 9.63s
- ▶ gcc version 4.7.3 20130226 (prerelease) (crosstool-NG linaro-1.13.1-4.7-2013.03-20130313 - Linaro GCC 2013.03): 9.26s

Results may vary depending on the size/features of your root filesystem. Here, we mainly benchmark the kernel performance as the root filesystem doesn't take much time. Note: Don't compare with a Buildroot toolchain as these are using *glibc* and not *uClibc* and then the initramfs has a quite different size. Compiling the kernel with a Linaro toolchain and using a Buildroot generated root filesystem yields the same results as compiling everything with Buildroot.

Group application code used at startup

- ▶ Find the functions called during startup, for example using the `-finstrument-functions` gcc option.
- ▶ Create a custom linker script to reorder these functions in the call order. You can achieve that by putting each function in their own section using the `-ffunction-sections` gcc option.
- ▶ Particularly useful for flash storage with rather big MTD read blocks. As the whole read blocks are read, you end up reading unnecessary data.

Details:

<http://blogs.linux.ie/caolan/2007/04/24/controlling-symbol-ordering/>

- ▶ Here's a very simple way to find the maximum savings you can expect from this technique:
 - ▶ Start the application once and measure its startup time.
 - ▶ Start the application and measure its startup time again. Its code should still be in the Linux file cache, and the code loading time will be zero.
- ▶ You now know how much time it took to load the application code (and its libraries) the first time. Linker optimizations will save less than this upper limit.
- ▶ You can then decide whether this could be worth the effort. Such optimizations are costly, as the way you compile your applications has to be modified.

- ▶ Prelinking reduces the time needed to start an executable
- ▶ It is extensively used on Android
- ▶ It has to be configured to know which libraries needs to be prelinked and will assign a fixed address for each available symbol thus removing the need to relocate symbols when starting an executable.
- ▶ Be careful of security implications, as executable code is always loaded at the same address.
- ▶ Code and paper at
<http://people.redhat.com/jakub/prelink/>



- ▶ Trace and profile the main application with `strace`

Kernel optimizations

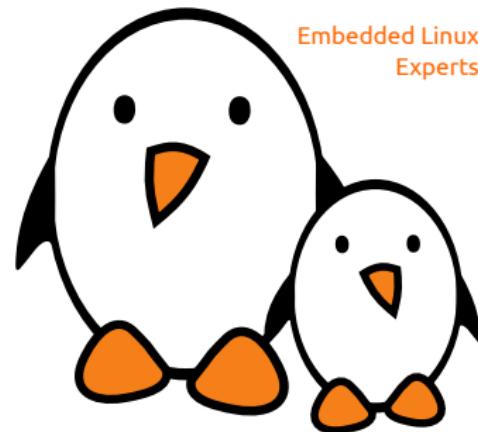
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To find out which kernel initialization functions are the longest to execute, add `initcall_debug` to the kernel command line. Here's what you get on the kernel log:

```
[...]
[ 3.750000] calling ov2640_i2c_driver_init+0x0/0x10 @ 1
[ 3.760000] initcall ov2640_i2c_driver_init+0x0/0x10 returned 0 after 544 usecs
[ 3.760000] calling at91sam9x5_video_init+0x0/0x14 @ 1
[ 3.760000] at91sam9x5-video f0030340.lcdhe01: video device registered @ 0xe0d3e340, irq = 24
[ 3.770000] initcall at91sam9x5_video_init+0x0/0x14 returned 0 after 10388 usecs
[ 3.770000] calling gspca_init+0x0/0x18 @ 1
[ 3.770000] gspca_main: v2.14.0 registered
[ 3.770000] initcall gspca_init+0x0/0x18 returned 0 after 3966 usecs
...
...
```

It is probably a good idea to increase the log buffer size with `CONFIG_LOG_BUF_SHIFT` in your kernel configuration. You will also need `CONFIG_PRINTK_TIME` and `CONFIG_KALLSYMS`.

With `initcall_debug`, you can generate a boot graph making it easy to see which kernel initialization functions take most time to execute.

- ▶ Copy and paste the console output or the output of the `dmesg` command to a file (let's call it `boot.log`)
- ▶ On your workstation, run the `scripts/bootgraph.pl` script in the kernel sources:
`perl scripts/bootgraph.pl boot.log > boot.svg`
- ▶ You can now open the boot graph with a vector graphics editor such as `inkscape`:



Start working on the functions consuming most time first. For each function:

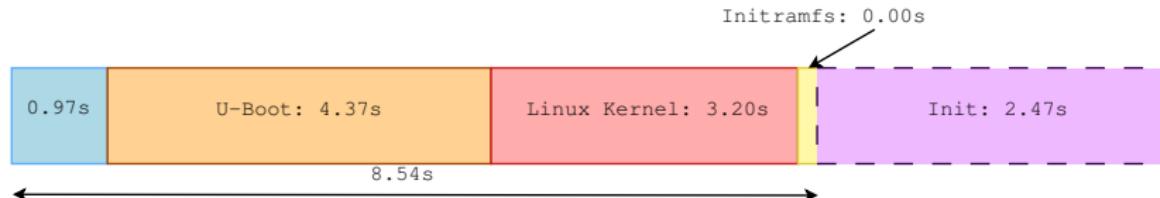
- ▶ Look for its definition in the kernel source code. You can use LXR (for example <http://lxr.free-electrons.com>).
- ▶ Remove unnecessary functionality:
 - ▶ Look for kernel parameters in C sources and Makefiles, starting with `CONFIG_`. Some settings for such parameters could help to remove code complexity or remove unnecessary features.
 - ▶ Find which module (if any) it belongs to. Loading this module could be deferred.

- ▶ Postpone:
 - ▶ Find which module (if any) the function belongs to. Load this module later if possible.
- ▶ Optimize necessary functionality:
 - ▶ Look for parameters which could be used to reduce probe time, looking for the `module_param` macro.
 - ▶ Look for delay loops and calls to functions containing `delay` in their name, which could take more time than needed. You could reduce such delays, and see whether the code still works or not.

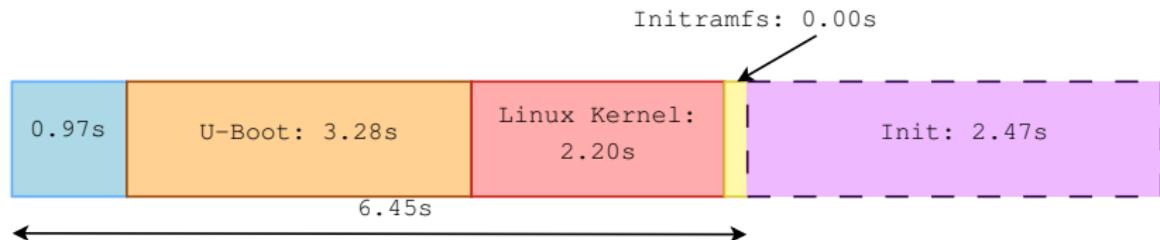
First, we focus on reducing the size without removing features

- ▶ The main mechanism is to use kernel modules
- ▶ Compile everything that is not needed at boot time as a module
- ▶ Two benefits: the kernel will be smaller and load faster, and less initialization code will get executed
- ▶ Remove features that are not used by userland:
`CONFIG_KALLSYMS`, `CONFIG_DEBUG_FS`, `CONFIG_BUG`
- ▶ Use features designed for embedded systems: `CONFIG_SLOB`,
`CONFIG_EMBEDDED`

Before:

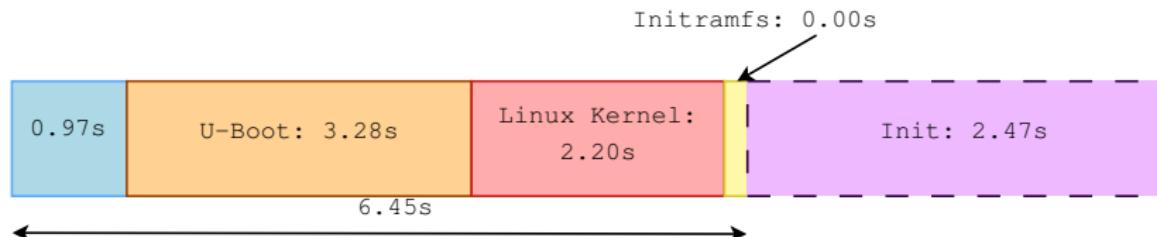


After:

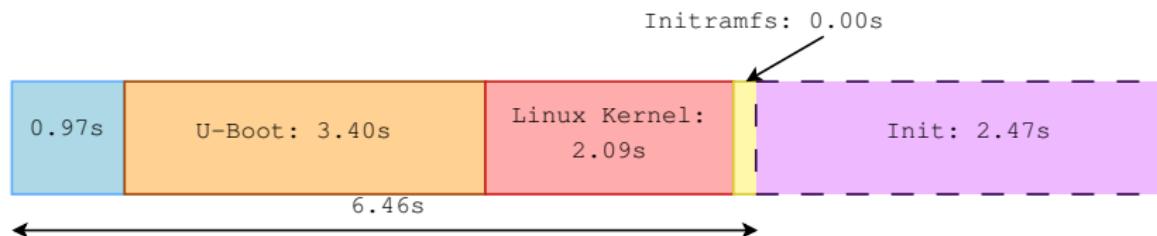


Depending on the balance between your storage reading speed and your CPU power to decompress the kernel, you will need to benchmark different compression algorithms.

Before (gzip):



After (LZO):



Conclusion: don't use LZO for now.

- ▶ If you can't compile a feature as a module (e.g. networking or block subsystem), try `deferred_initcalls`.
- ▶ Your kernel will not shrink but some initializations will be postponed. Once your critical application is ready, you can execute the remaining initcalls.
- ▶ See http://elinux.org/Deferred_Initcalls

- ▶ Console output is actually taking a lot of time (very slow device). Probably not needed in production. Disable it by passing the `quiet` argument on the kernel command line.
- ▶ You will still be able to use `dmesg` to get the kernel messages.
- ▶ Time between starting the kernel and starting the `init` program, on Atmel SAMA5D3 Xplained (ARM), Linux 3.10:

	Time	Diff
Without <code>quiet</code>	2.352 s	
With <code>quiet</code>	1.285 s	-1.067 s

- ▶ Less time will be saved on a reduced kernel, of course.

- ▶ At each boot, the Linux kernel calibrates a delay loop (for the `udelay()` function). This measures a number of loops per jiffy (lpj) value. You just need to measure this once! Find the lpj value in the kernel boot messages:

```
Calibrating delay loop... 262.96 BogoMIPS (lpj=1314816)
```

- ▶ Now, you can add `lpj=<value>` to the kernel command line:

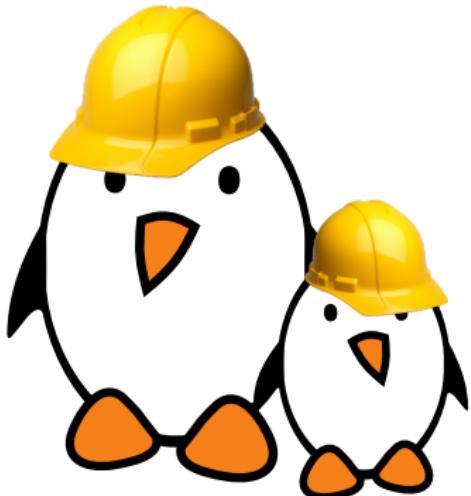
```
Calibrating delay loop (skipped) preset value.. 262.96 BogoMIPS (lpj=1314816)
```

- ▶ Tests on Atmel SAMA5D3 Xplained (ARM), Linux 3.10:

	Time	Diff
Without <code>lpj</code>	71 ms	
With <code>lpj</code>	8 ms	-63 ms

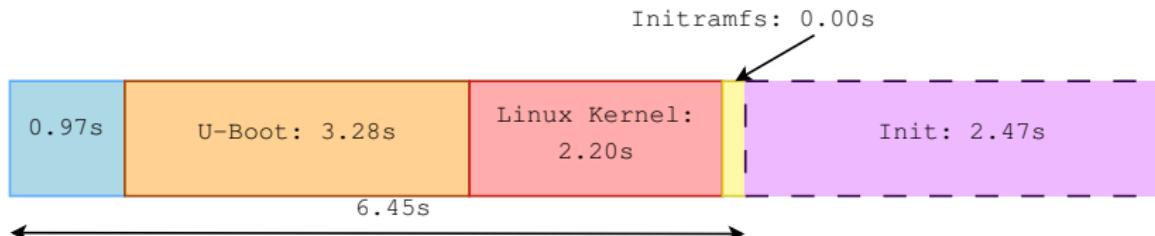
- ▶ This calculation was longer before 2.6.39 (about 200 ms).

- ▶ SMP is quite slow to initialize
- ▶ UP systems may be faster to boot
- ▶ What you can try is to hotplug the other cores after your critical application has started

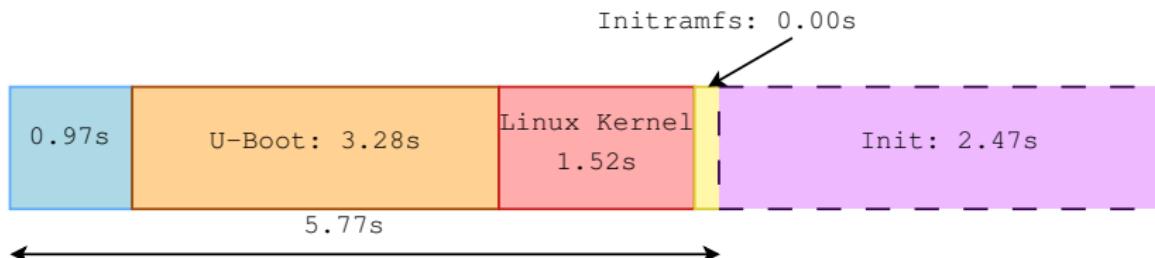


- ▶ Recompile the kernel, switching to an initramfs
- ▶ Use `initcall_debug` to find the biggest time consumers
- ▶ Reduce the number of modules
- ▶ Tune kernel command line parameters

Before (gzip)



After:



Without losing any functionality!

To shave off the last milliseconds, you will probably want to remove unnecessary features:

- ▶ `CONFIG_PRINTK=n` will have the same effect as the `quiet` command line argument but you won't have any access to kernel messages. You will have a significantly smaller kernel though.
- ▶ Try `CONFIG_CC_OPTIMIZE_FOR_SIZE=y`. This will have an impact on performance, you will have to benchmark.

More features you could remove:

- ▶ Module loading/unloading
- ▶ Block layer
- ▶ Network stack
- ▶ USB stack
- ▶ Power management features
- ▶ CONFIG_SYSFS_DEPRECATED
- ▶ Input: keyboards / mice / touchscreens
- ▶ CONFIG_LEGACY_PTY_COUNT or the pty.legacy_count kernel parameter

Bootloader optimizations

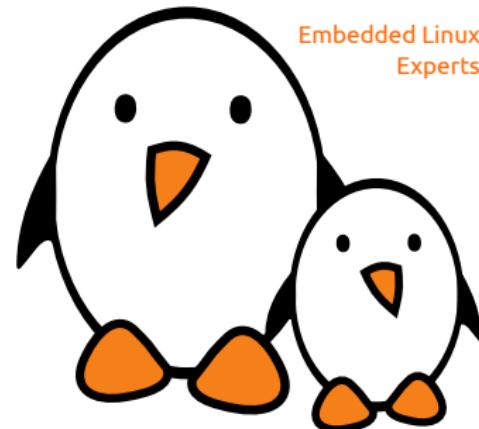
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Corrections, suggestions, contributions and translations are welcome!



- ▶ Remove unnecessary functionality.

Usually, bootloaders include many features needed only for development. Compile your bootloader with less features.

- ▶ Optimize required functionality.

Tune your bootloader for fastest performance.

Switch to another bootloader (if available)

Skip the bootloader and load the kernel right away.

U-Boot optimizations

Recompile U-Boot to remove features not needed in production

- ▶ Disable as many features as possible in
`include/configs/<soc>-<board>.h`
- ▶ Examples: MMC, USB, Ethernet, dhcp, ping, command line
edition, command completion...
- ▶ A smaller and simpler U-Boot is faster to load and faster to
initialize.

- ▶ Remove the boot delay:

```
setenv bootdelay 0
```

- ▶ This usually saves several seconds!
- ▶ Before you do that, recompile U-Boot with
CONFIG_ZERO_BOOTDELAY_CHECK, documented in
doc/README.autoboot. It allows to stop the autoboot process
by hitting a key even if the boot delay is set to 0.

Some boards have over-complicated scripts:

```
bootcmd=run bootf0
bootf0=run ${args0}; setenv bootargs ${bootargs} \
maximasp.kernel=maximasp_nand.0:kernel0; nboot 0x70007fc0 kernel0
```

Let's replace this by:

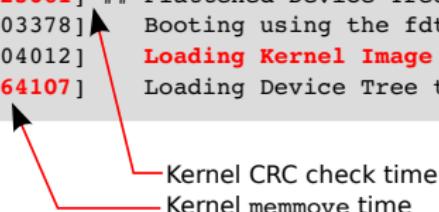
```
setenv bootargs 'mem=128M console=tty0 consoleblank=0
console=ttyS0,57600 \
mtdparts=maximasp_nand.0:2M(u-boot)ro,512k(env0)ro,512k(env1)ro,\
4M(kernel0),4M(kernel1),5M(kernel2),100M(root0),100M(root1),-(other) \
rw ubi.mtd=root0 root=ubi0:rootfs rootfstype=ubifs earlyprintk debug \
user_debug=28 maximasp.board=EEKV1.3.x \
maximasp.kernel=maximasp_nand.0:kernel0'
setenv bootcmd 'nboot 0x70007fc0 kernel0'
```

This saved 56 ms on this ARM9 system (400 MHz)!

- ▶ When copying the kernel from flash to RAM, we still see many systems that copy too many bytes, not taking the exact kernel size into account.
- ▶ In U-Boot, use the `nboot` command:
`nboot ramaddr 0 nandoffset`
- ▶ U-Boot using the kernel size information stored in the `uImage` header to know how many bytes to copy.

- ▶ After copying the kernel uImage to RAM, U-Boot always moves it to the load address specified in the uImage header.
- ▶ A CRC check is also performed.

```
[16.590578 0.003404] ## Booting kernel from Legacy Image at 21000000 ...
[16.595204 0.004626]     Image Name:    Linux-3.10.0+
[16.597986 0.002782]     Image Type:    ARM Linux Kernel Image (uncompressed)
[16.602881 0.004895]     Data Size:    3464112 Bytes = 3.3 MiB
[16.606542 0.003661]     Load Address: 20008000
[16.608903 0.002361]     Entry Point:  20008000
[16.611256 0.002353]     Verifying Checksum ... OK
[17.134317 0.523061] ## Flattened Device Tree blob at 22000000
[17.137695 0.003378]     Booting using the fdt blob at 0x22000000
[17.141707 0.004012]     Loading Kernel Image ... OK
[18.005814 0.864107]     Loading Device Tree to 2bb1a2000, end 2bb1a0b6 ... OK
```



- ▶ You can make U-Boot skip the `memmove` operation by directly loading the `uImage` at the right address.
- ▶ Compute this address:

Addr = Load Address - `uImage` header size

Addr = Load Address - (`size(uImage)` - `size(zImage)`)

Addr = `0x20008000` - `0x40` = `0x20007fc0`

```
[16.590927 0.003407] ## Booting kernel from Legacy Image at 20007fc0 ...
[16.595547 0.004620]     Image Name:    Linux-3.10.0+
[16.598351 0.002804]     Image Type:    ARM Linux Kernel Image (uncompressed)
[16.603228 0.004877]     Data Size:    3464112 Bytes = 3.3 MiB
[16.606907 0.003679]     Load Address: 20008000
[16.609256 0.002349]     Entry Point: 20008000
[16.611619 0.002363]     Verifying Checksum ... OK
[17.135046 0.523427] ## Flattened Device Tree blob at 22000000
[17.138589 0.003543]     Booting using the fdt blob at 0x22000000
[17.142575 0.003986]     XIP Kernel Image ... OK
[17.156358 0.013783]     Loading Device Tree to 2bb12000, end 2bb1a0b6 ... OK
```



Kernel CRC check time

Kernel memmove time (skipped)

Results on Atmel SAMA5D3 Xplained (ARM), Linux 3.10:

	Time	Diff
Default	1.433 s	
Optimum load address	0.583 s	-0.85 s

Measured between Booting kernel and Starting kernel ...

- ▶ Fine in production when you never have data corruption copying the kernel to RAM.
- ▶ Disable CRC checking with a U-boot environment variable:
`setenv verify no`

Results on Atmel SAMA5D3 Xplained (ARM), Linux 3.10:

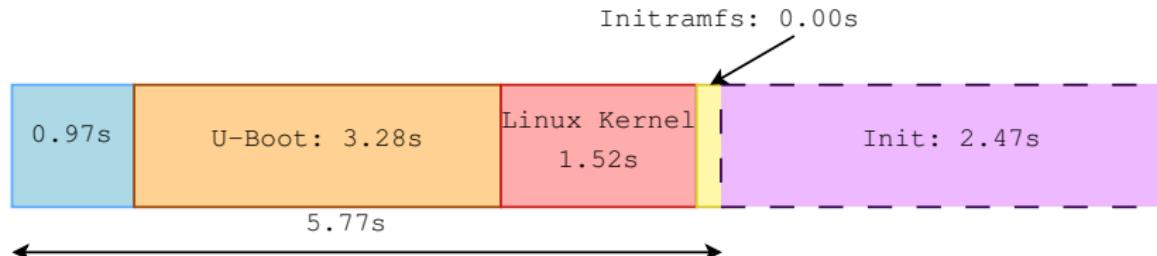
	Time	Diff
With CRC check	583 ms	
Without CRC check	60 ms	-523 ms

Measured between Booting kernel and Starting kernel ...

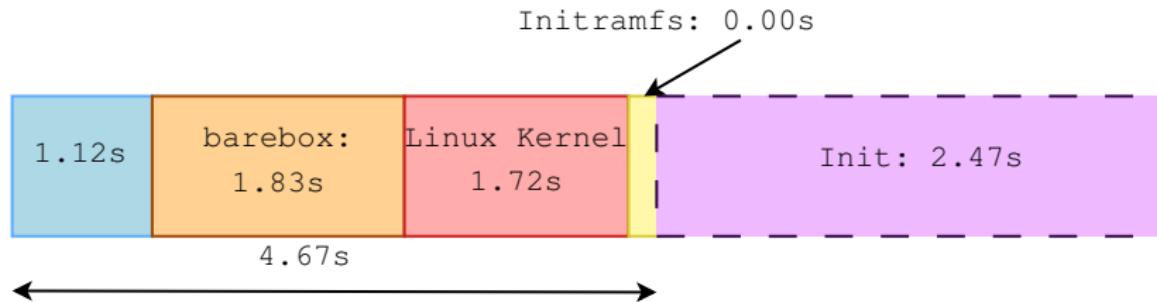
- ▶ Silence U-Boot console output. You will need to compile U-Boot with `CONFIG_SILENT_CONSOLE` and `setenv silent yes`.
See `doc/README.silent` for details.
- ▶ Ultimate solution: use U-Boot's *Falcon* mode.
U-Boot is split in two parts: the SPL (Secondary Program Loader) and the U-Boot image. U-Boot can then configure the SPL to load the Linux kernel directly, instead of the U-Boot image.
See `doc/README.falcon` for details.

Switching to another bootloader

Results with the SAMA5D3x-EK board

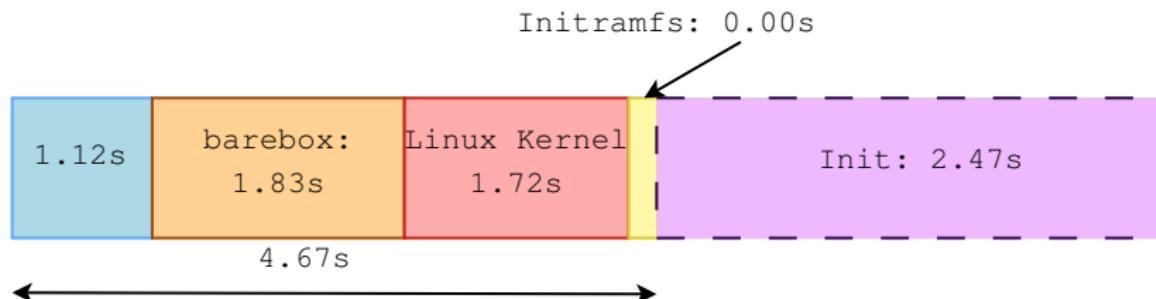


After:

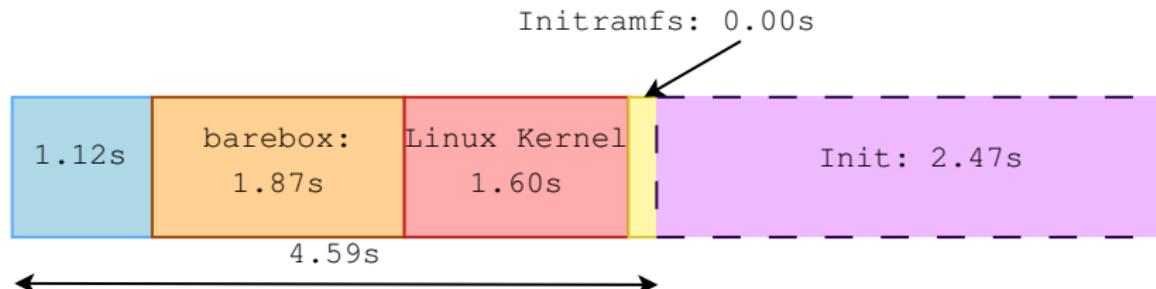


Let's try LZO compression for the kernel again:

Before (gzip):



After (LZO):

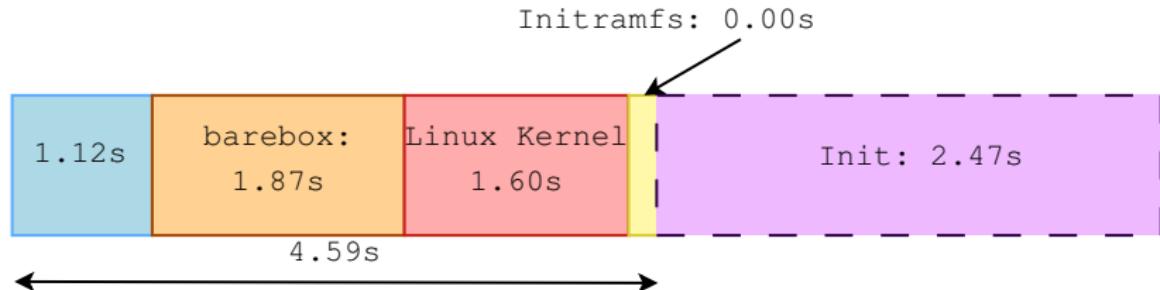


Now, let's limit the features of the bootloader.

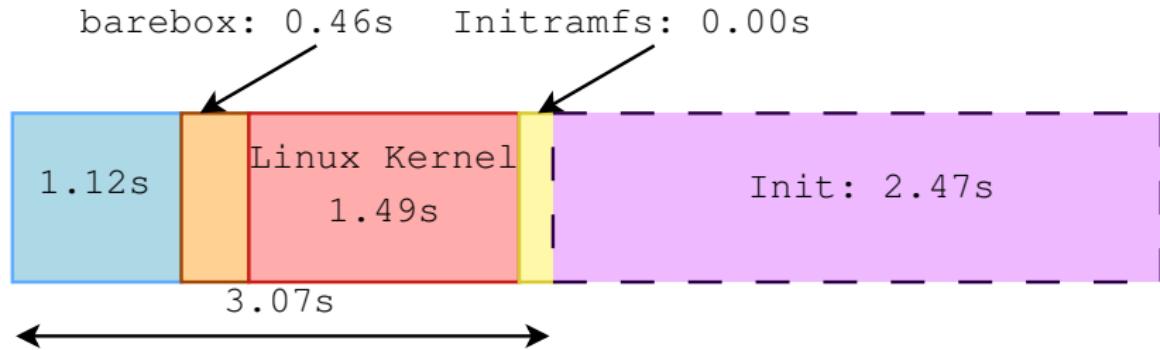
We still keep a way to interact with it when a GPIO has a given value. For example, using the `gpio_direction_input` and `gpio_get_value` commands in a script that would then start an upgrade or boot a rescue kernel.

```
gpio_get_value 42
if [ $? = 0 ]; then
    kdev="/dev/nand0.krescue.bb"
fi
```

Before:



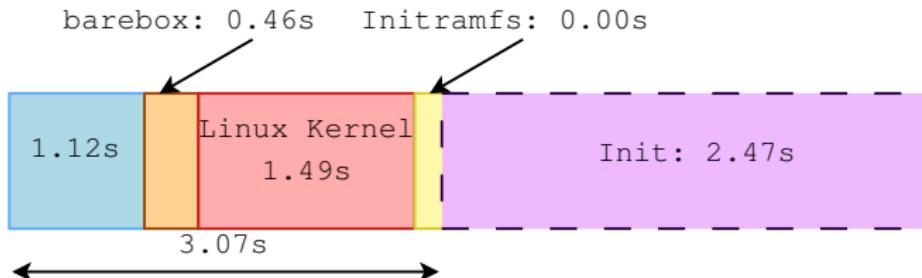
After:



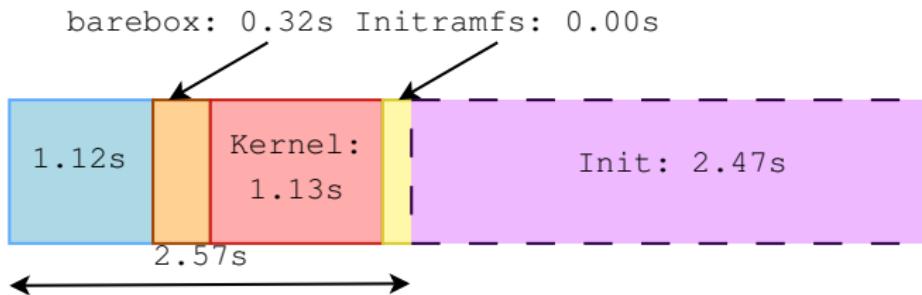
Note: the kernel didn't actually change but we don't get a message on the serial line exactly at the time we switch from the bootloader to the kernel.

Warning: Sometimes, the kernel is relying on the bootloader to initialize the hardware (pinmuxing, clocks, ...) so be careful when removing features.

Before:



After:



Skipping the bootloader

- ▶ Principle: instead of loading the bootloader and then the kernel, load the kernel right away!
- ▶ For example, on Atmel AT91, it is easy to implement with `at91bootstrap v3`. You just need to configure it with one of the `linux` or `linux_dt` configurations:

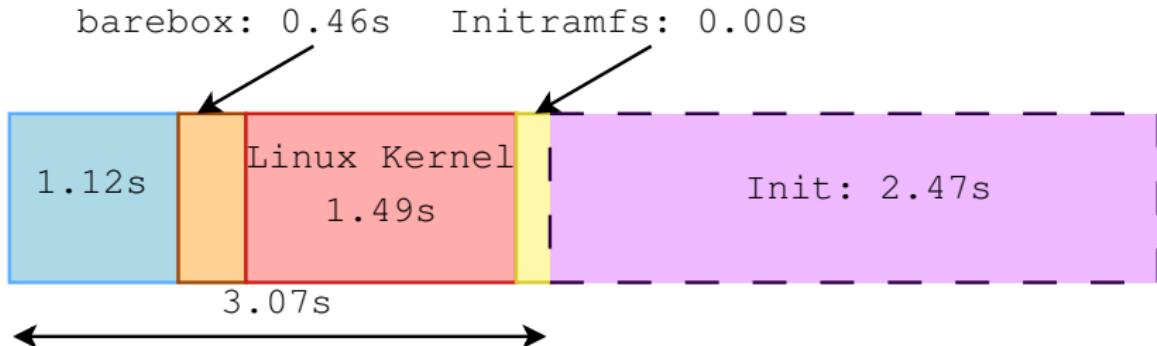
```
make at91sama5d3xecknf_linux_dt_defconfig  
make
```

Full details on

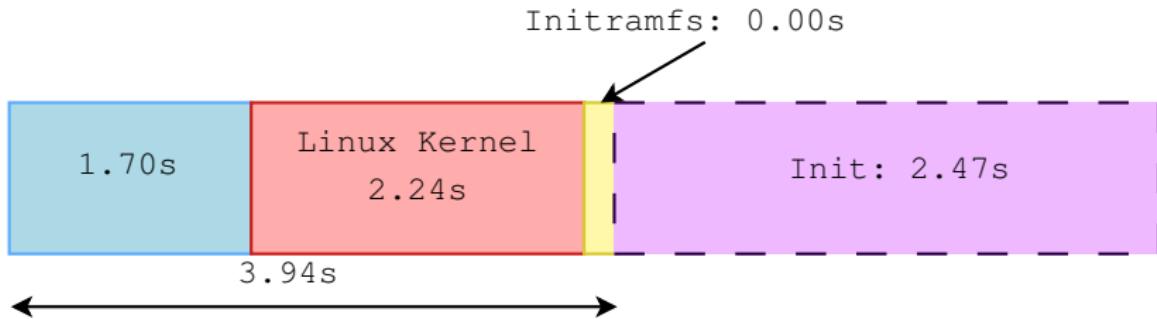
<http://free-electrons.com/blog/startling-linux-directly-from-at91bootstrap3/>

- ▶ In our particular case, though, you will lose the main advantages of using Barebox. It uses the CPU caches while loading the kernel.

Before:



Using AT91bootstrap to boot the Linux kernel:



Kernel compression options

After optimizing the time to load the kernel in the bootloader, we are ready to experiment with kernel options impacting size:

- ▶ Kernel compression options
- ▶ Optimizing kernel code for size

Results on TI AM335x (ARM), 1 GHz, Linux 3.13-rc4

Timestamp	gzip	lzma	xz	lzo	lz4	uncompressed
Size	4308200	3177528	3021928	4747560	5133224	8991104
Copy	0.451 s	0.332 s	0.315 s	0.499 s	0.526 s	0.914 s
Uncompress	0.945 s	2.329 s	2.056 s	0.861 s	0.851 s	0.687 s
Total	5.516 s	6.066 s	5.678 s	5.759 s	6.017 s	8.683 s

Results on Atmel AT91SAM9263 (ARM), 200 MHz, Linux 3.13-rc4

Timestamp	gzip	lzma	xz	lzo	lz4	uncompressed
Size	3016192	2270064	2186056	3292528	3541040	5775472
Copy	4.105 s	3.095 s	2.981 s	4.478 s	4.814	7.836 s
Uncompress	1.737 s	8.691 s	6.531 s	1.073 s	1.225 s	N/A
Total	8.795 s	14.200 s	11.865 s	8.700 s	9.368 s	N/A

Results indeed depend on I/O and CPU performance!

- ▶ CONFIG_CC_OPTIMIZE_FOR_SIZE: possibility to compile the kernel with `gcc -Os` instead of `gcc -O2`.
- ▶ Such optimizations give priority to code size at the expense of code speed.
- ▶ Results: the initial boot time is better (smaller size), but the slower kernel code quickly offsets the benefits. Your system will run slower!

Results on Atmel SAMA5D3 Xplained (ARM), Linux 3.10, gzip compression:

Timestamp	O2	Os	Diff
Starting kernel	4.307 s	4.213 s	-94 ms
Starting init	5.593 s	5.549 s	-44 ms
Login prompt	21.085 s	22.900 s	+ 1.815 s



- ▶ Reduce boot time by using the Barebox bootloader
- ▶ Optimize Barebox

Hardware initialization

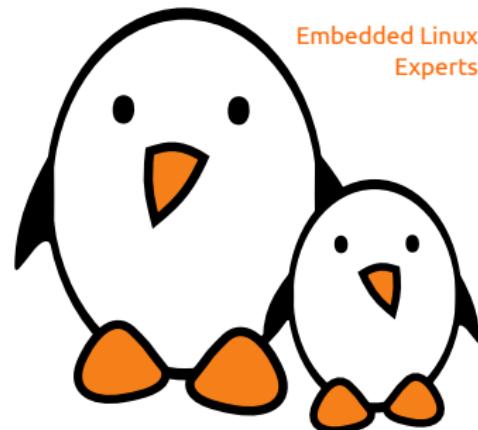
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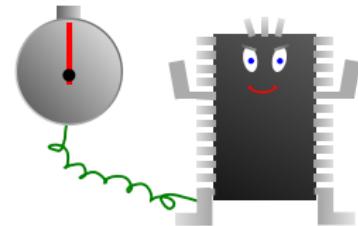
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Corrections, suggestions, contributions and translations are welcome!



The hardware needs time to initialize

- ▶ Voltage regulation, crystal stabilization
- ▶ Can be up to 200 ms
- ▶ As a software developer, you can't do anything about this part.
- ▶ All you can do is measure this time with an oscilloscope and ask the hardware board designers whether they can do anything about this. However, there are delays in the CPU which may not be possible to reduce (see the CPU datasheet).



Real-time in embedded Linux systems

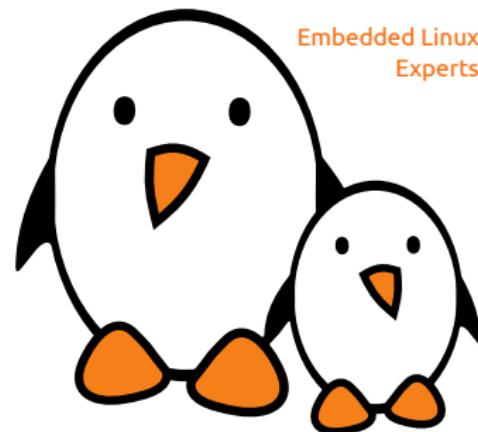
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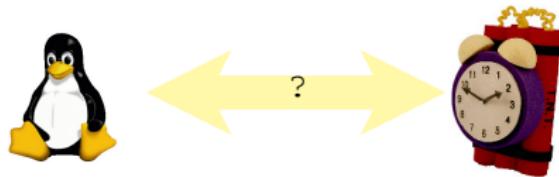
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Corrections, suggestions, contributions and translations are welcome!



Introduction

- ▶ Due to its advantages, Linux and open-source software are more and more commonly used in embedded applications
- ▶ However, some applications also have real-time constraints
- ▶ They, at the same time, want to
 - ▶ Get all the nice advantages of Linux: hardware support, components re-use, low cost, etc.
 - ▶ Get their real-time constraints met



- ▶ Linux is an operating system part of the large Unix family
- ▶ It was originally designed as a time-sharing system
 - ▶ The main goal was to get the best throughput from the available hardware, by making the best possible usage of resources (CPU, memory, I/O)
 - ▶ Time determinism was not taken into account
- ▶ On the opposite, real-time constraints imply time determinism, even at the expense of lower global throughput
- ▶ Best throughput and time determinism are contradictory requirements

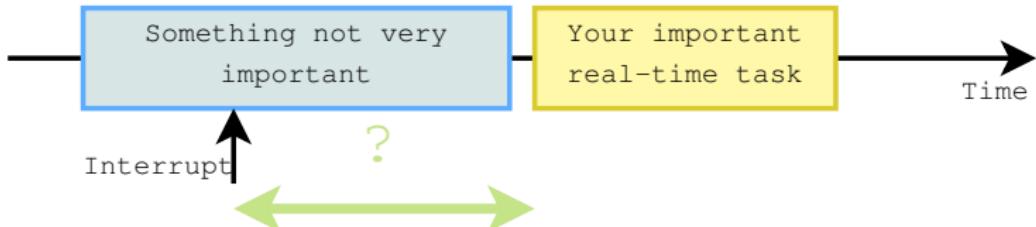
- ▶ Over time, two major approaches have been taken to bring real-time requirements into Linux
- ▶ **Approach 1**
 - ▶ Improve the Linux kernel itself so that it matches real-time requirements, by providing bounded latencies, real-time APIs, etc.
 - ▶ Approach taken by the mainline Linux kernel and the **PREEMPT_RT** project.
- ▶ **Approach 2**
 - ▶ Add a layer below the Linux kernel that will handle all the real-time requirements, so that the behaviour of Linux doesn't affect real-time tasks.
 - ▶ Approach taken by RTLinux, RTAI and **Xenomai**

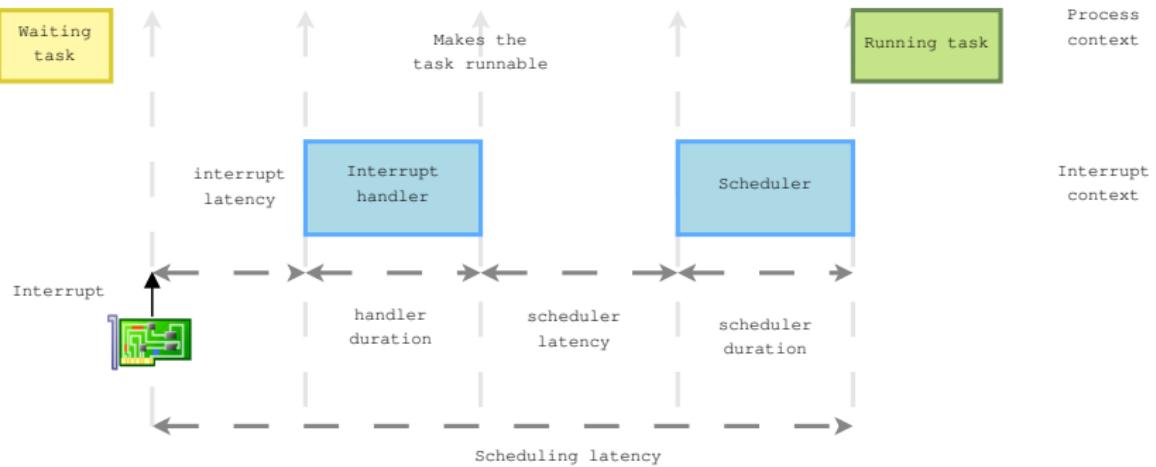
An alternative approach is to use specific hardware to run real-time work on:

- ▶ Dedicating a CPU core to a real-time OS or to a real-time application, using some kind of hypervisor.
- ▶ Running real-time work on an FPGA
- ▶ Running real-time work on a dedicated microcontroller. For example, the TI AM335x CPU (used in the Beaglebone Black) has a "Programmable Real-Time Unit and Industrial Communication Subsystem (PRU-ICSS)", which can be used for real-time processing.

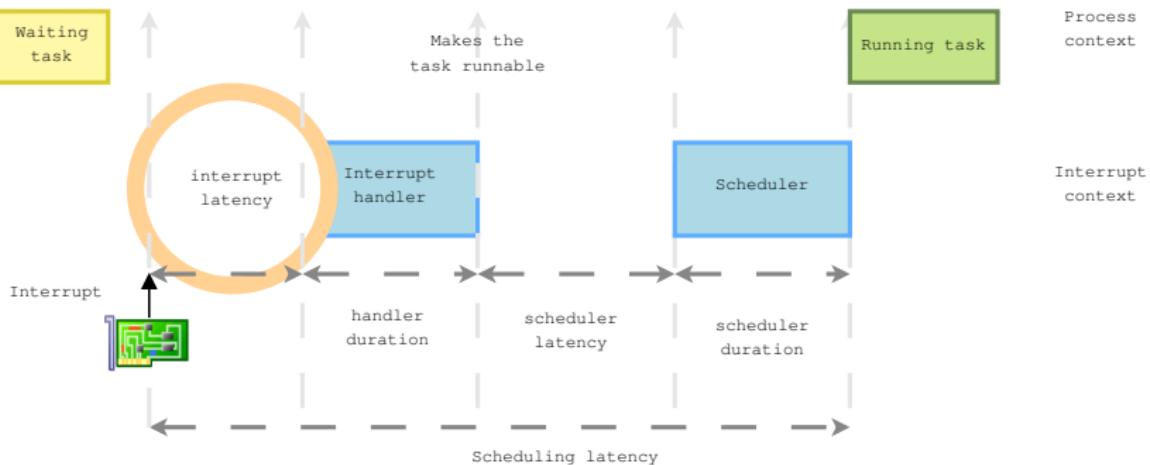
Improving the main Linux kernel with PREEMPT_RT

- ▶ When developing real-time applications with a system such as Linux, the typical scenario is the following
 - ▶ An event from the physical world happens and gets notified to the CPU by means of an interrupt
 - ▶ The interrupt handler recognizes and handles the event, and then wake-up the user space task that will react to this event
 - ▶ Some time later, the user space task will run and be able to react to the physical world event
- ▶ Real-time is about providing guaranteed worst case latencies for this reaction time, called latency

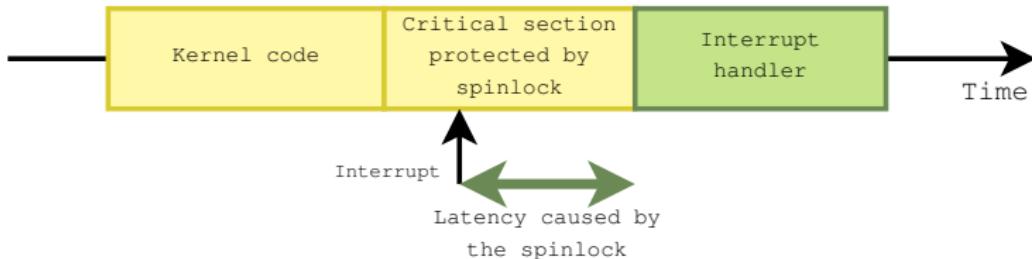


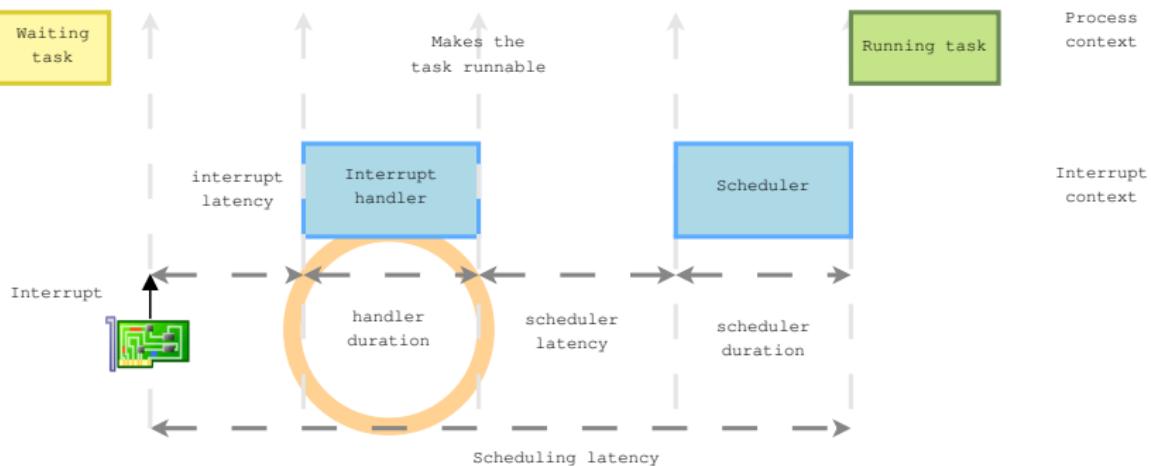


$\text{kernel latency} = \text{interrupt latency} + \text{handler duration} + \text{scheduler latency} + \text{scheduler duration}$

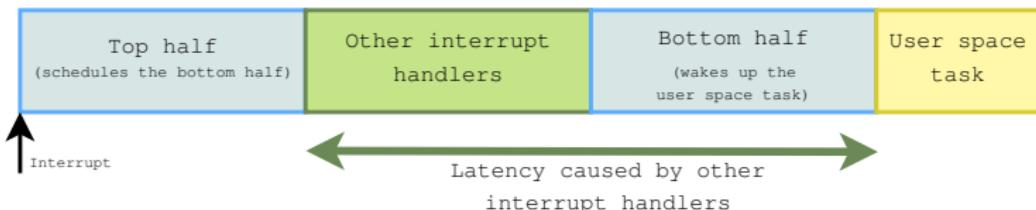


- ▶ One of the concurrency prevention mechanism used in the kernel is the **spinlock**
- ▶ It has several variants, but one of the variant commonly used to prevent concurrent accesses between a process context and an interrupt context works by disabling interrupts
- ▶ Critical sections protected by spinlocks, or other section in which interrupts are explicitly disabled will delay the beginning of the execution of the interrupt handler
 - ▶ The duration of these critical sections is unbounded
- ▶ Other possible source: shared interrupts (not a real problem: mustn't be used for time-critical interrupt-sources anyway).

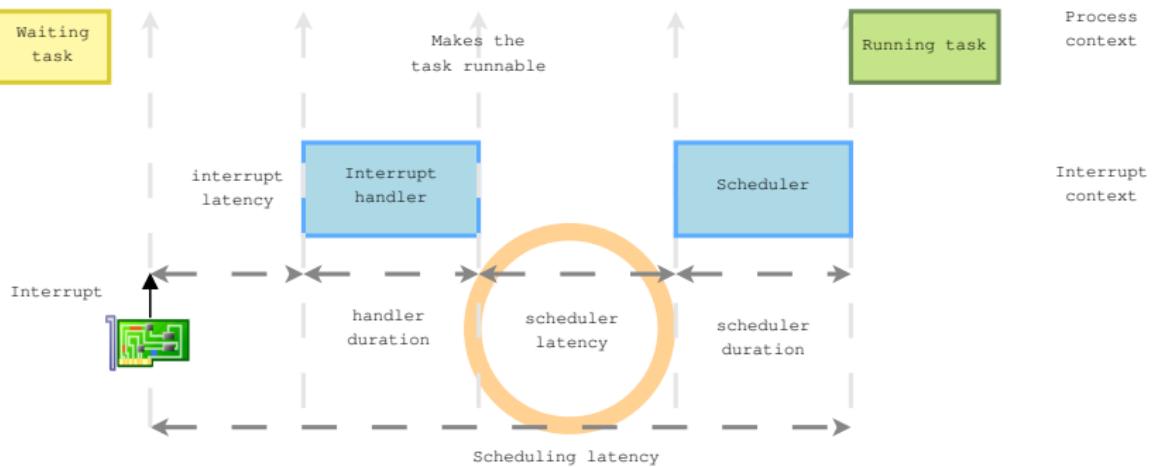




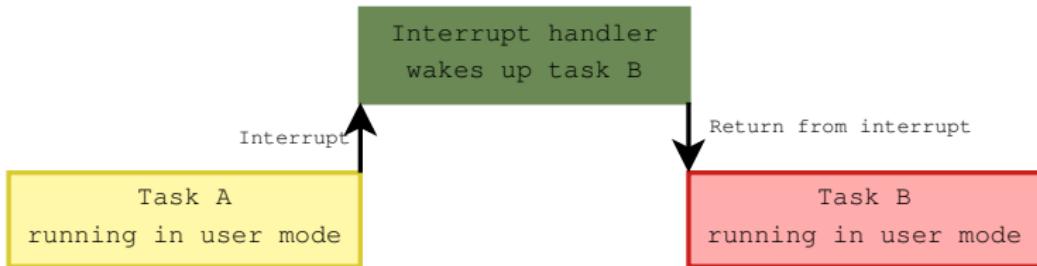
- ▶ In Linux, many interrupt handlers are split in two parts
 - ▶ A top-half, started by the CPU as soon as interrupts are enabled. It runs with the interrupt line disabled and is supposed to complete as quickly as possible.
 - ▶ A bottom-half, scheduled by the top-half, which starts after all pending top-halves have completed their execution.
- ▶ Therefore, for real-time critical interrupts, bottom-halves shouldn't be used: their execution is delayed by all other interrupts in the system.



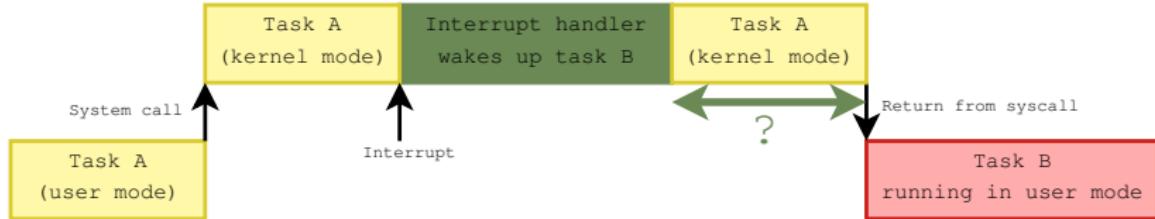
ENDO CODE Scheduler latency



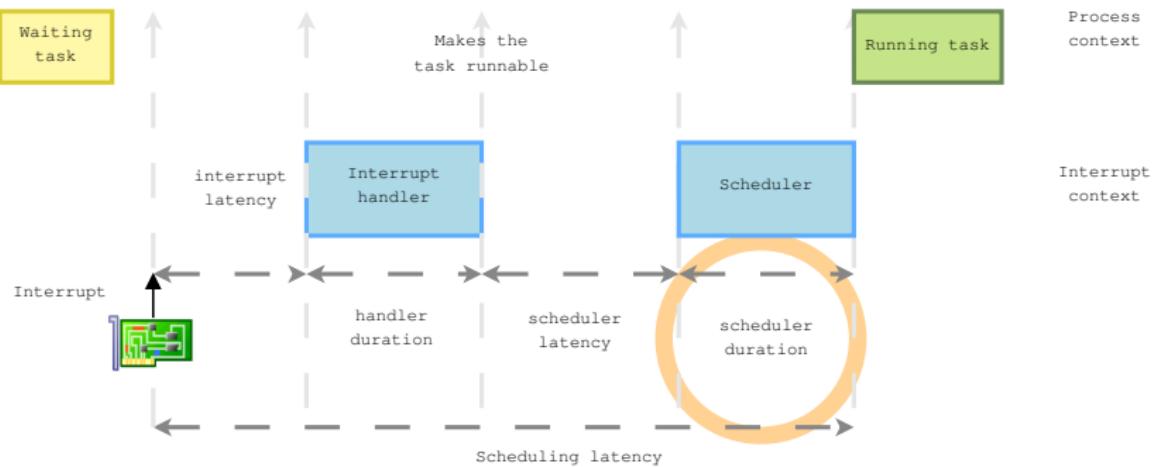
- ▶ The Linux kernel is a preemptive operating system
- ▶ When a task runs in user space mode and gets interrupted by an interruption, if the interrupt handler wakes up another task, this task can be scheduled as soon as we return from the interrupt handler.



- ▶ However, when the interrupt comes while the task is executing a system call, this system call has to finish before another task can be scheduled.
- ▶ By default, the Linux kernel does not do kernel preemption.
- ▶ This means that the time before which the scheduler will be called to schedule another task is unbounded.



ENDO CODE Scheduler duration

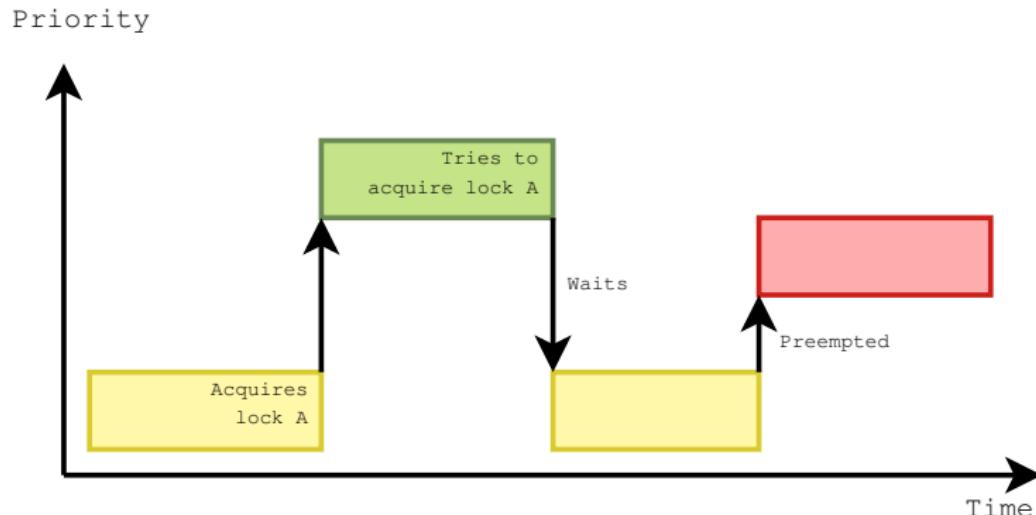


- ▶ Outside of the critical path detailed previously, other non-deterministic mechanisms of Linux can affect the execution time of real-time tasks
- ▶ Linux is highly based on virtual memory, as provided by an MMU, so that memory is allocated on demand. Whenever an application accesses code or data for the first time, it is loaded on demand, which creates huge delays.
- ▶ Many C library services or kernel services are not designed with real-time constraints in mind.

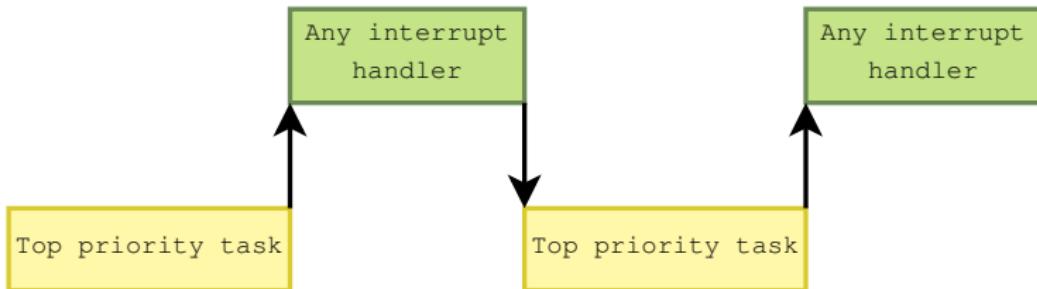
ENDO CODE Priority inversion

A process with a low priority might hold a lock needed by a higher priority process, effectively reducing the priority of this process.

Things can be even worse if a middle priority process uses the CPU.



In Linux, interrupt handlers are executed directly by the CPU interrupt mechanisms, and not under control of the Linux scheduler. Therefore, all interrupt handlers have a higher priority than all tasks running on the system.



- ▶ Long-term project lead by Linux kernel developers Ingo Molnar, Thomas Gleixner and Steven Rostedt
 - ▶ <https://rt.wiki.kernel.org>
- ▶ The goal is to gradually improve the Linux kernel regarding real-time requirements and to get these improvements merged into the mainline kernel
 - ▶ PREEMPT_RT development works very closely with the mainline development
- ▶ Many of the improvements designed, developed and debugged inside PREEMPT_RT over the years are now part of the mainline Linux kernel
 - ▶ The project is a long-term branch of the Linux kernel that ultimately should disappear as everything will have been merged

From the PREEMPT_RT project

- ▶ Since the beginning of 2.6
 - ▶ O(1) scheduler
 - ▶ Kernel preemption
 - ▶ Better POSIX real-time API support
- ▶ Since 2.6.18
 - ▶ Priority inheritance support for mutexes
- ▶ Since 2.6.21
 - ▶ High-resolution timers
- ▶ Since 2.6.30
 - ▶ Threaded interrupts
- ▶ Since 2.6.33
 - ▶ Spinlock annotations

2 new preemption models offered by standard Linux 2.6:

- Preemption Model

- | | |
|--|-------------------|
| ▫ No Forced Preemption (Server) | PREEMPT_NONE |
| ▫ Voluntary Kernel Preemption (Desktop) | PREEMPT_VOLUNTARY |
| ▫ Preemptible Kernel (Low-Latency Desktop) | PREEMPT |

CONFIG_PREEMPT_NONE

Kernel code (interrupts, exceptions, system calls) never preempted.
Default behavior in standard kernels.

- ▶ Best for systems making intense computations, on which overall throughput is key.
- ▶ Best to reduce task switching to maximize CPU and cache usage (by reducing context switching).
- ▶ Still benefits from some Linux 2.6 improvements: O(1) scheduler, increased multiprocessor safety (work on RT preemption was useful to identify hard to find SMP bugs).
- ▶ Can also benefit from a lower timer frequency (100 Hz instead of 250 or 1000).

CONFIG_PREEMPT_VOLUNTARY

Kernel code can preempt itself

- ▶ Typically for desktop systems, for quicker application reaction to user input.
- ▶ Adds explicit rescheduling points throughout kernel code.
- ▶ Minor impact on throughput.
- ▶ Used in: Ubuntu Desktop 15.04, Ubuntu Server 14.04

CONFIG_PREEMPT

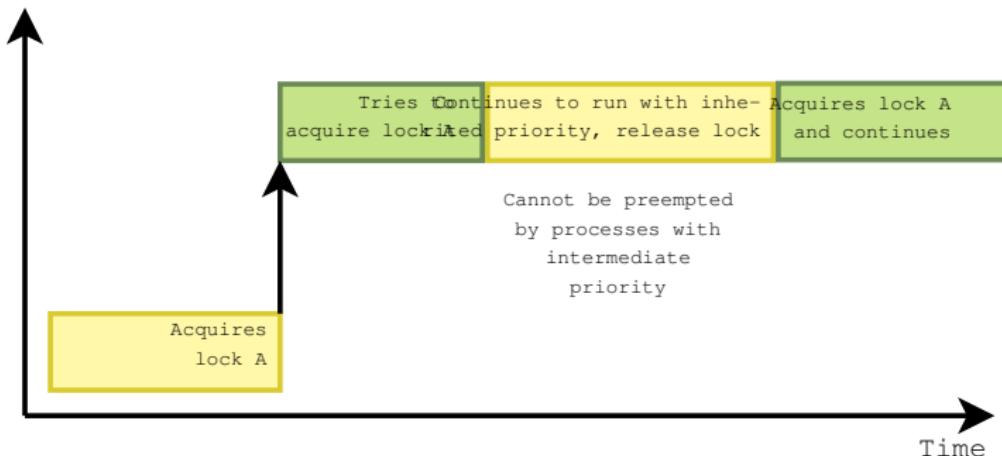
Most kernel code can be involuntarily preempted at any time.

When a process becomes runnable, no more need to wait for kernel code (typically a system call) to return before running the scheduler.

- ▶ Exception: kernel critical sections (holding spinlocks). In a case you hold a spinlock on a uni-processor system, kernel preemption could run another process, which would loop forever if it tried to acquire the same spinlock.
- ▶ Typically for desktop or embedded systems with latency requirements in the milliseconds range.
- ▶ Still a relatively minor impact on throughput.

- ▶ One classical solution to the priority inversion problem is called priority inheritance

Priority



- ▶ In Linux, since 2.6.18, mutexes support priority inheritance
- ▶ In user space, priority inheritance must be explicitly enabled on a per-mutex basis.

- ▶ The resolution of the timers used to be bound to the resolution of the regular system tick
 - ▶ Usually 100 Hz or 250 Hz, depending on the architecture and the configuration
 - ▶ A resolution of only 10 ms or 4 ms.
 - ▶ Increasing the regular system tick frequency is not an option as it would consume too many resources
- ▶ The high-resolution timers infrastructure, merged in 2.6.21, allows to use the available hardware timers to program interrupts at the right moment.
 - ▶ Hardware timers are multiplexed, so that a single hardware timer is sufficient to handle a large number of software-programmed timers.
 - ▶ Usable directly from user space using the usual timer APIs

- ▶ To solve the interrupt inversion problem, PREEMPT_RT has introduced the concept of threaded interrupts
- ▶ The interrupt handlers run in normal kernel threads, so that the priorities of the different interrupt handlers can be configured
- ▶ The real interrupt handler, as executed by the CPU, is only in charge of masking the interrupt and waking-up the corresponding thread
- ▶ The idea of threaded interrupts also allows to use sleeping spinlocks (see later)
- ▶ Merged since 2.6.30, the conversion of interrupt handlers to threaded interrupts is not automatic: drivers must be modified
- ▶ In PREEMPT_RT, all interrupt handlers are switched to threaded interrupts

- ▶ Before Oct. 2015: project stalled because of the lack of funding. Thomas Gleixner still the maintainer but lacked time for further development and mainlining efforts. Patch releases only made for specific kernel releases.
- ▶ Oct. 2015: the Linux Foundation at last got funding for mainlining the patchset into the Linux kernel (see <http://lwn.net/Articles/659193/>).
- ▶ There's at last a good chance for the patchset to be merged by the end of 2016.

PREEMPT_RT specifics

- ▶ The PREEMPT_RT patch adds a new level of preemption, called CONFIG_PREEMPT_RT_FULL
- ▶ This level of preemption replaces all kernel spinlocks by mutexes (or so-called sleeping spinlocks)
 - ▶ Instead of providing mutual exclusion by disabling interrupts and preemption, they are just normal locks: when contention happens, the process is blocked and another one is selected by the scheduler.
 - ▶ Works well with threaded interrupts, since threads can block, while usual interrupt handlers could not.
 - ▶ Some core, carefully controlled, kernel spinlocks remain as normal spinlocks.

- ▶ With CONFIG_PREEMPT_RT_FULL, virtually all kernel code becomes preemptible
 - ▶ An interrupt can occur at any time, when returning from the interrupt handler, the woken up process can start immediately.
- ▶ This is the last big part of PREEMPT_RT that isn't fully in the mainline kernel yet
 - ▶ Part of it has been merged in 2.6.33: the spinlock annotations. The spinlocks that must remain as spinning spinlocks are now differentiated from spinlocks that can be converted to sleeping spinlocks. This has reduced a lot the PREEMPT_RT patch size!

- ▶ The mechanism of threaded interrupts in PREEMPT_RT is still different from the one merged in mainline
- ▶ In PREEMPT_RT, all interrupt handlers are unconditionally converted to threaded interrupts.
- ▶ This is a temporary solution, until interesting drivers in mainline get gradually converted to the new threaded interrupt API that has been merged in 2.6.30.

Setting up PREEMPT_RT

- ▶ PREEMPT_RT is delivered as a patch against the mainline kernel
 - ▶ Best to have a board supported by the mainline kernel, otherwise the PREEMPT_RT patch may not apply and may require some adaptations
- ▶ Not all releases of the Linux kernel are supported. Most recent: 3.4, 3.6, 3.8, 3.10, 3.12, 3.14, 3.18, 4.0, 4.1, 4.4, 4.6
- ▶ Quick set up:
 - ▶ Download the latest PREEMPT_RT patch from <http://www.kernel.org/pub/linux/kernel/projects/rt/>
 - ▶ Download and extract the corresponding mainline kernel version
 - ▶ Apply the patch to the mainline kernel tree

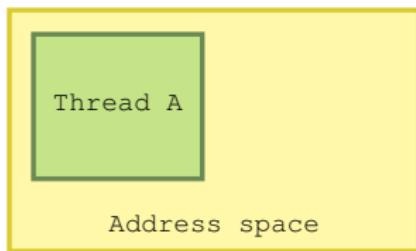
- ▶ In the kernel configuration, be sure to enable
 - ▶ CONFIG_PREEMPT_RT_FULL
 - ▶ High-resolution timers
- ▶ Compile your kernel, and boot
- ▶ You are now running the real-time Linux kernel
- ▶ Of course, some system configuration remains to be done, in particular setting appropriate priorities to the interrupt threads, which depend on your application.

Real-time application development with PREEMPT_RT

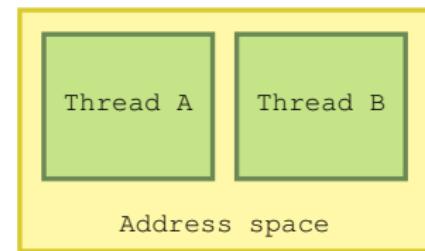
- ▶ No special library is needed, the POSIX real-time API is part of the standard C library
- ▶ The glibc C library is recommended, as support for some real-time features is not mature in other C libraries
 - ▶ Priority inheritance mutexes or NPTL on some architectures, for example
- ▶ Compile a program
 - ▶ `ARCH-linux-gcc -o myprog myprog.c -lrt`
- ▶ To get the documentation of the POSIX API
 - ▶ Install the `manpages-posix-dev` package
 - ▶ Run `man function-name`

- ▶ 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.
 - ▶ One thread, that starts executing the `main()` function.
 - ▶ Upon creation, a process contains one thread
- ▶ 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()`

- ▶ The kernel represents each thread running in the system by a structure of type `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()`



Process after `pthread_create`

- ▶ Linux supports the POSIX thread API
- ▶ To create a new thread

```
pthread_create(pthread_t *thread, pthread_attr_t *attr,  
              void *(*routine)(void*), void *arg);
```

- ▶ The new thread will run in the same address space, but will be scheduled independently
- ▶ Exiting from a thread

```
pthread_exit(void *value_ptr);
```

- ▶ Waiting for the termination of a thread

```
pthread_join(pthread_t *thread, void **value_ptr);
```

- ▶ The Linux kernel scheduler support different scheduling classes
- ▶ The default class, in which processes are started by default is a *time-sharing* class
 - ▶ All processes, regardless of their priority, get some CPU time
 - ▶ The proportion of CPU time they get is dynamic and affected by the *nice* value, which ranges from -20 (highest) to 19 (lowest). Can be set using the `nice` or `renice` commands
- ▶ The real-time classes `SCHED_FIFO` and `SCHED_RR`
 - ▶ The highest priority process gets all the CPU time, until it blocks.
 - ▶ In `SCHED_RR`, round-robin scheduling between the processes of the same priority. All must block before lower priority processes get CPU time.
 - ▶ Priorities ranging from 0 (lowest) to 99 (highest)

- ▶ An existing program can be started in a specific scheduling class with a specific priority using the `chrt` command line tool
 - ▶ Example: `chrt -f 99 ./myprog`
 - f: SCHED_FIFO
 - r: SCHED_RR
- ▶ The `sched_setscheduler()` API can be used to change the scheduling class and priority of a process

```
int sched_setscheduler(pid_t pid, int policy,  
                      const struct sched_param *param);
```

- ▶ `policy` can be SCHED_OTHER, SCHED_FIFO, SCHED_RR, etc.
- ▶ `param` is a structure containing the priority

- ▶ The priority can be set on a per-thread basis when a thread is created

```
struct sched_param parm;  
pthread_attr_t attr;  
  
pthread_attr_init(&attr);  
pthread_attr_setinheritsched(&attr, PTHREAD_EXPLICIT_SCHED);  
pthread_attr_setschedpolicy(&attr, SCHED_FIFO);  
parm.sched_priority = 42;  
pthread_attr_setschedparam(&attr, &parm);
```

- ▶ Then the thread can be created using `pthread_create()`, passing the `attr` structure.
- ▶ Several other attributes can be defined this way: stack size, etc.

- ▶ In order to solve the non-determinism introduced by virtual memory, memory can be locked
 - ▶ Guarantee that the system will keep it allocated
 - ▶ Guarantee that the system has pre-loaded everything into memory
- ▶ `mlockall(MCL_CURRENT | MCL_FUTURE);`
 - ▶ Locks all the memory of the current address space, for currently mapped pages and pages mapped in the future
- ▶ Other, less useful parts of the API: `munlockall`, `mlock`, `munlock`.
- ▶ Watch out for non-currently mapped pages
 - ▶ Stack pages
 - ▶ Dynamically-allocated memory

- ▶ Allows mutual exclusion between two threads in the same address space
- ▶ Initialization/destruction

```
pthread_mutex_init(pthread_mutex_t *mutex,  
                  const pthread_mutexattr_t *mutexattr);  
pthread_mutex_destroy(pthread_mutex_t *mutex);
```

- ▶ Lock/unlock

```
pthread_mutex_lock(pthread_mutex_t *mutex);  
pthread_mutex_unlock(pthread_mutex_t *mutex);
```

- ▶ Priority inheritance must be activated explicitly

```
pthread_mutexattr_t attr;  
pthread_mutexattr_init (&attr);  
pthread_mutexattr_setprotocol(&attr, PTHREAD_PRIO_INHERIT);
```

- ▶ Timer creation

```
timer_create(clockid_t clockid, struct sigevent *evp,  
            timer_t *timerid);
```

- ▶ **clockid** is usually `CLOCK_MONOTONIC`. **sigevent** defines what happens upon timer expiration: send a signal or start a function in a new thread. **timerid** is the returned timer identifier.
- ▶ Configure the timer for expiration at a given time

```
timer_settime(timer_t timerid, int flags,  
              struct itimerspec *newvalue,  
              struct itimerspec *oldvalue);
```

- ▶ Delete a timer

```
timer_delete(timer_t timerid)
```

- ▶ Get the resolution of a clock, `clock_getres`
- ▶ Other functions: `timer_getoverrun()`, `timer_gettime()`

- ▶ Signals are asynchronous notification mechanisms
- ▶ Notification occurs either
 - ▶ By the call of a signal handler. Be careful with the limitations of signal handlers!
 - ▶ By being unblocked from the `sigwait()`, `sigtimedwait()` or `sigwaitinfo()` functions. Usually better.
- ▶ Signal behaviour can be configured using `sigaction()`
- ▶ The mask of blocked signals can be changed with `pthread_sigmask()`
- ▶ Delivery of a signal using `pthread_kill()` or `tgkill()`
- ▶ All signals between `SIGRTMIN` and `SIGRTMAX`, 32 signals under Linux.

▶ **Semaphores**

- ▶ Usable between different processes using named semaphores
- ▶ `sem_open()`, `sem_close()`, `sem_unlink()`, `sem_init()`,
`sem_destroy()`, `sem_wait()`, `sem_post()`, etc.

▶ **Message queues**

- ▶ Allows processes to exchange data in the form of messages.
- ▶ `mq_open()`, `mq_close()`, `mq_unlink()`, `mq_send()`,
`mq_receive()`, etc.

▶ **Shared memory**

- ▶ Allows processes to communicate by sharing a segment of memory
- ▶ `shm_open()`, `ftruncate()`, `mmap()`, `munmap()`, `close()`,
`shm_unlink()`

Debugging latencies in PREEMPT_RT

Infrastructure that can be used for debugging or analyzing latencies and performance issues in the kernel.

- ▶ Very well documented in Documentation/trace/ftrace.txt
- ▶ Negligible overhead when tracing is not enabled at run-time.
- ▶ Can be used to trace any kernel function!

- ▶ Tracing information available through the debugfs virtual fs (CONFIG_DEBUG_FS in the *Kernel Hacking* section)
- ▶ Mount this filesystem as follows:
`mount -t debugfs nodev /sys/kernel/debug`
- ▶ When tracing is enabled (see the next slides), tracing information is available in `/sys/kernel/debug/tracing`.
- ▶ Check available tracers in
`/sys/kernel/debug/tracing/available_tracers`

CONFIG_SCHED_TRACER (*Kernel Hacking* section)

- ▶ Maximum recorded time between waking up a top priority task and its scheduling on a CPU, expressed in us.
- ▶ Check that `wakeup` is listed in
`/sys/kernel/debug/tracing/available_tracers`
- ▶ To select, reset and enable this tracer:

```
echo wakeup > /sys/kernel/debug/tracing/current_tracer
echo 0 > /sys/kernel/debug/tracing/tracing_max_latency
echo 1 > /sys/kernel/debug/tracing/tracing_enabled
```

- ▶ Let your system run, in particular real-time tasks.
Dummy example: `chrt -f 5 sleep 1`
- ▶ Disable tracing:

```
echo 0 > /sys/kernel/debug/tracing/tracing_enabled
```

- ▶ Read the maximum recorded latency and the corresponding trace:

```
cat /sys/kernel/debug/tracing/tracing_max_latency
```

Tests done with `cyclictest`

- ▶ x86 Geode 500 Mhz: 96 us
- ▶ x86 Pentium Dual-core T4500 2.3 Ghz: 36 us
- ▶ ARM Freescale i.MX35 533 Mhz: 120 us
- ▶ ARM Marvell 88FR131 1200 Mhz: 54 us

See more results at <https://www.osadl.org/QA-Farm-Realtime.qa-farm-about.0.html>

About real-time support in the standard Linux kernel

- ▶ Inside the RT patch, Steven Rostedt, Red Hat, ELC 2013
http://elinux.org/images/b/ba/Elc2013_Rostedt.pdf
Video: <http://j.mp/1apUtu6>
- ▶ The Real-Time Linux Wiki: <http://rt.wiki.kernel.org>
“The Wiki Web for the CONFIG_PREEMPT_RT community,
and real-time Linux in general.”
Contains nice and useful documents!
- ▶ See also our books page.

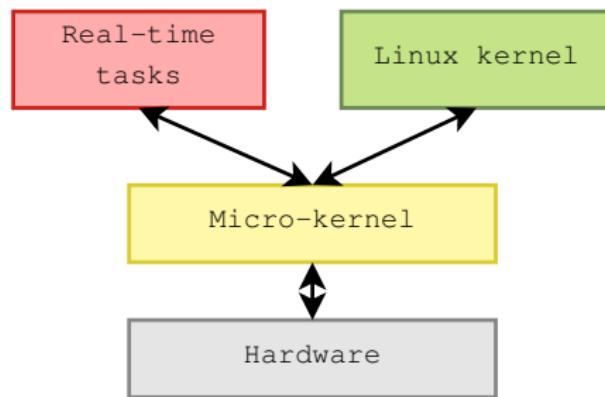
Real-time extensions to the Linux kernel

Three generations

- ▶ RTLinux
- ▶ RTAI
- ▶ Xenomai

A common principle

- ▶ Add an extra layer between the hardware and the Linux kernel, to manage real-time tasks separately.



First real-time extension for Linux, created by Victor Yodaiken.

- ▶ Nice, but the author filed a software patent covering the addition of real-time support to general operating systems as implemented in RTLinux!
- ▶ Its Open Patent License drew many developers away and frightened users. Community projects like RTAI and Xenomai now attract most developers and users.
- ▶ February, 2007: RTLinux rights sold to Wind River. Today, no longer advertised by Wind River.
- ▶ Project completely dead.

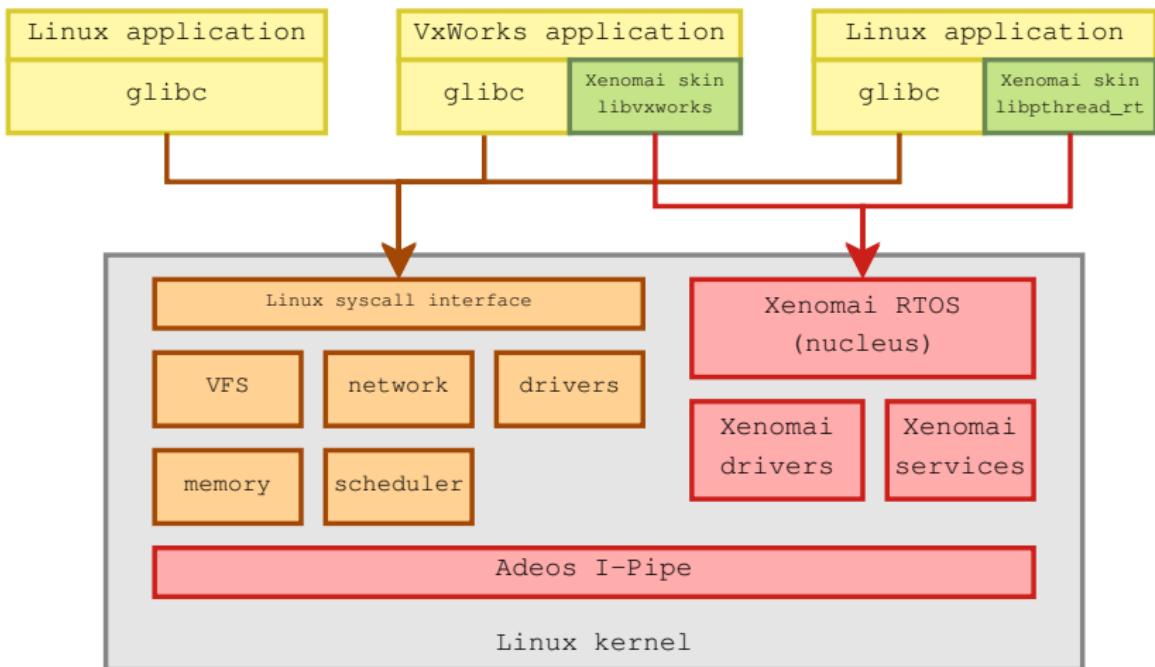
<https://www.rtai.org/> - **Real-Time Application Interface for Linux**

- ▶ Created in 1999, by Prof. Paolo Mantegazza (long time contributor to RTLinux), Dipartimento di Ingegneria Aerospaziale Politecnico di Milano (DIAPM).
- ▶ Community project. Significant user base. Attracted contributors frustrated by the RTLinux legal issues.
- ▶ Only really actively maintained on x86
- ▶ May offer slightly better latencies than Xenomai, at the expense of a less maintainable and less portable code base
- ▶ Since RTAI is not really maintained on ARM and other embedded architectures, our presentation is focused on Xenomai.

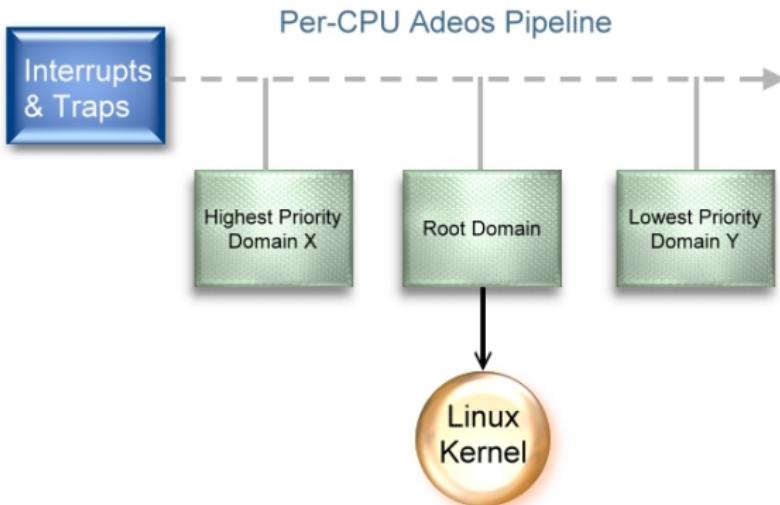
<http://www.xenomai.org/>



- ▶ Started in 2001 as a project aiming at emulating traditional RTOS.
- ▶ Initial goals: facilitate the porting of programs to GNU / Linux.
- ▶ Initially related to the RTAI project (as the RTAI / fusion branch), now independent.
- ▶ Skins mimicking the APIs of traditional RTOS such as VxWorks, pSOS+, and VRTXsa as well as the POSIX API, and a “native” API.
- ▶ Aims at working both as a co-kernel and on top of PREEMPT_RT in future upstream Linux versions.
- ▶ Will never be merged in the mainline kernel.



- ▶ From the Adeos point of view, guest OSes are prioritized domains.
- ▶ For each event (interrupts, exceptions, syscalls, etc...), the various domains may handle the event or pass it down the pipeline.



- ▶ Factored real-time core with skins implementing various real-time APIs
- ▶ Seamless support for hard real-time in user space
- ▶ No second-class citizen, all ports are equivalent feature-wise
- ▶ Xenomai support is as much as possible independent from the Linux kernel version (backward and forward compatible when reasonable)
- ▶ Each Xenomai branch has a stable user/kernel ABI
- ▶ Timer system based on hardware high-resolution timers
- ▶ Per-skin time base which may be periodic
- ▶ RTDM skin allowing to write real-time drivers

- ▶ Xenomai supports real-time in user space on 5 architectures, including 32 and 64 bits variants.
- ▶ Two modes are defined for a thread
 - ▶ the primary mode, where the thread is handled by the Xenomai scheduler
 - ▶ the secondary mode, when it is handled by the Linux scheduler.
- ▶ Thanks to the services of the Adeos I-pipe service, Xenomai system calls are defined.
 - ▶ A thread migrates from secondary mode to primary mode when such a system call is issued
 - ▶ It migrates from primary mode to secondary mode when a Linux system call is issued, or to handle gracefully exceptional events such as exceptions or Linux signals.

- ▶ Xenomai applications are started like normal Linux processes, they are initially handled by the Linux scheduler and have access to all Linux services
- ▶ After their initialization, they declare themselves as real-time applications, which migrates them to primary mode. In this mode:
 - ▶ They are scheduled directly by the Xenomai scheduler, so they have the real-time properties offered by Xenomai
 - ▶ They don't have access to any Linux service, otherwise they get migrated back to secondary mode and loose all real-time properties
 - ▶ They can only use device drivers that are implemented in Xenomai, not the ones of the Linux kernel
- ▶ Need to implement device drivers in Xenomai, and to split real-time and non real-time parts of your applications.

- ▶ An approach to unify the interfaces for developing device drivers and associated applications under real-time Linux
 - ▶ An API very similar to the native Linux kernel driver API
- ▶ Allows to develop in kernel space:
 - ▶ Character-style device drivers
 - ▶ Network-style device drivers
- ▶ See the whitepaper on
<http://www.xenomai.org/documentation/xenomai-2.6/pdf/RTDM-and-Applications.pdf>
- ▶ Current notable RTDM based drivers:
 - ▶ Serial port controllers;
 - ▶ RTnet UDP/IP stack;
 - ▶ RT socket CAN, drivers for CAN controllers;
 - ▶ Analogy, fork of the Comedi project, drivers for acquisition cards.

Setting up Xenomai

- ▶ Download Xenomai sources at
<http://download.gna.org/xenomai/stable/>
- ▶ Download one of the Linux versions supported by this release
(see `ksrc/arch/<arch>/patches/`)
- ▶ Since version 2.0, split kernel/user building model.
- ▶ Kernel uses a script called `script/prepare-kernel.sh` which integrates Xenomai kernel-space support in the Linux sources.
- ▶ Run the kernel configuration menu.

The screenshot shows the 'Linux/arm 3.8.13 Kernel Configuration' window with the 'Option' menu selected. The left pane displays a hierarchical list of kernel configuration options. The 'Xenomai (NEW)' option is highlighted in blue. The right pane shows a detailed list of configuration options for Xenomai, each with a 'Name' column.

Name
XENOMAI
XENO_OPT_NUCLEUS
XENO_OPT_PERVASIVE
XENO_OPT_PRIOCLP
XENO_OPT_PIPELINE_HEAD
XENO_OPT_SCHED_CLASSES
XENO_OPT_PIPE_NRDEV
XENO_OPT_REGISTRY_NRSLOTS
XENO_OPT_SYS_HEAPSZ
XENO_OPT_SYS_STACKPOOLSZ
XENO_OPT_SEM_HEAPSZ
XENO_OPT_GLOBAL_SEM_HEAPSZ
XENO_OPT_STATS
XENO_OPT_DEBUG
XENO_OPT_DEBUG_NUCLEUS
XENO_OPT_DEBUG_XNLOCK
XENO_OPT_DEBUG_QUEUES
XENO_OPT_DEBUG_REGISTRY
XENO_OPT_DEBUG_TIMERS
XENO_OPT_DEBUG_SYNCH_RELAX
XENO_OPT_WATCHDOG
XENO_OPT_WATCHDOG_TIMEOUT
XENO_OPT_SHIRQ

Xenomai (XENOMAI)

CONFIG_XENOMAI:

Xenomai is a real-time extension to the Linux kernel. Note that Xenomai relies on Adeos interrupt pipeline (CONFIG_IPIPE) option to be enabled so enabling this option selects the

- ▶ User space libraries are compiled using the traditional autotools
 - ▶ `./configure --host=arm-linux && make && make DESTDIR=/your/rootfs/ install`
- ▶ Xenomai installs *pkg-config* files which helps you to compile your own programs against the Xenomai libraries.
- ▶ See Xenomai's examples directory.
- ▶ Installation details may be found in the README.INSTALL guide.

Developing applications on Xenomai

- ▶ The POSIX skin allows to recompile without changes a traditional POSIX application so that instead of using Linux real-time services, it uses Xenomai services
 - ▶ http://www.xenomai.org/index.php/Porting_POSIX_applications_to_Xenomai
 - ▶ Clocks and timers, condition variables, message queues, mutexes, semaphores, shared memory, signals, thread management
 - ▶ Good for existing code or programmers familiar with the POSIX API
- ▶ Of course, if the application uses any Linux service that isn't available in Xenomai, it will switch back to secondary mode
- ▶ To link an application against the POSIX skin

```
CFL='pkg-config --cflags libxenomai_posix'  
LDF='pkg-config --libs libxenomai_posix'  
ARCH-gcc $CFL -o rttest rttest.c $LDF
```

- ▶ If a Xenomai real-time application using the POSIX skin wishes to communicate with a separate non-real-time application, it must use the rtipc mechanism
- ▶ In the Xenomai application, create an IPCPROTO_XDDP socket

```
socket(AF_RTIPC, SOCK_DGRAM, IPCPROTO_XDDP);
setsockopt(s, SOL_RTIPC, XDDP_SETLOCALPOOL,
            &poolsz, sizeof(poolsz));
memset(&saddr, 0, sizeof(saddr));
saddr.sipc_family = AF_RTIPC;
saddr.sipc_port = PORTX;
ret = bind(s, (struct sockaddr *)&saddr, sizeof(saddr));
```

- ▶ And then the normal socket API sendto() / recvfrom()
- ▶ In the Linux application
 - ▶ Open /dev/rtpPORTX, where PORTX is the XDDP port
 - ▶ Use read() and write()

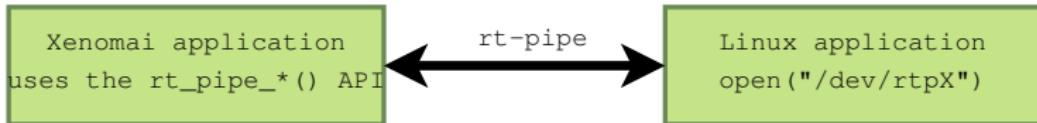
- ▶ A Xenomai specific API for developing real-time tasks
 - ▶ <http://xenomai.org/documentation/branches/v2.4.x/pdf/Native-API-Tour-rev-C.pdf>
 - ▶ Usable both in user space and kernel space. Development of tasks in user space is the preferred way.
 - ▶ More coherent and more flexible API than the POSIX API. Easier to learn and understand. Certainly the way to go for new applications.
- ▶ Applications should include <native/service.h>, where service can be alarm, buffer, cond, event, heap, intr, misc, mutex, pipe, queue, sem, task, timer
- ▶ To compile applications:

```
CFL='pkg-config --cflags libxenomai_native'  
LDF='pkg-config --libs libxenomai_native'  
ARCH-gcc $CFL -o rttest rttest.c $LDF
```

- ▶ Task management services
 - ▶ `rt_task_create()`, `rt_task_start()`, `rt_task_suspend()`,
`rt_task_resume()`, `rt_task_delete()`, `rt_task_join()`, etc.
- ▶ Counting semaphore services
 - ▶ `rt_sem_create()`, `rt_sem_delete()`, `rt_sem_p()`,
`rt_sem_v()`, etc.
- ▶ Message queue services
 - ▶ `rt_queue_create()`, `rt_queue_delete()`,
`rt_queue_alloc()`, `rt_queue_free()`, `rt_queue_send()`,
`rt_queue_receive()`, etc.
- ▶ Mutex services
 - ▶ `rt_mutex_create()`, `rt_mutex_delete()`,
`rt_mutex_acquire()`, `rt_mutex_release()`, etc.

- ▶ Alarm services
 - ▶ `rt_alarm_create()`, `rt_alarm_delete()`,
`rt_alarm_start()`, `rt_alarm_stop()`, `rt_alarm_wait()`, etc.
- ▶ Memory heap services
 - ▶ Allows to share memory between processes and/or to pre-allocate a pool of memory
 - ▶ `rt_heap_create()`, `rt_heap_delete()`, `rt_heap_alloc()`,
`rt_heap_bind()`
- ▶ Condition variable services
 - ▶ `rt_cond_create()`, `rt_cond_delete()`, `rt_cond_signal()`,
`rt_cond_broadcast()`, `rt_cond_wait()`, etc.

- ▶ Using *rt_pipes*
- ▶ In the native Xenomai application, use the Pipe API
 - ▶ `rt_pipe_create()`, `rt_pipe_delete()`, `rt_pipe_receive()`,
`rt_pipe_send()`, `rt_pipe_alloc()`, `rt_pipe_free()`
- ▶ In the normal Linux application
 - ▶ Open the corresponding `/dev/rtpX` file, the minor is specified at `rt_pipe_create()` time
 - ▶ Then, just `read()` and `write()` to the opened file

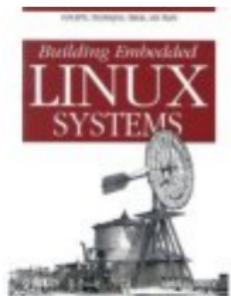


- ▶ ARM OMAP5432 1.1 GHz: 24 us
- ▶ ARM OMAP4430 1 GHz: 23 us
- ▶ ARM OMAP3530 720 MHz: 44 us
- ▶ ARM SAMA5D3 528 MHz: 51 us
- ▶ ARM AT91RM9200 180 MHz: 181 us
- ▶ x86 Atom 1.6 GHz: 35 us
- ▶ Geode LX800 processor at 500 MHz: 55 us

See results at <http://xenomai.org/~gch/core-3.14-latencies/>

Building Embedded Linux Systems, O'Reilly

By Karim Yaghmour, Jon Masters,
Gilad Ben-Yossef, Philippe Gerum and others
(including Michael Opdenacker), August 2008



A nice coverage of Xenomai (Philippe Gerum)
and the RT patch (Steven Rostedt)

<http://oreilly.com/catalog/9780596529680/>

- ▶ <http://www.osadl.org>

Open Source Automation Development Lab (OSADL)

Targets machine and plant control systems. Most member companies are German (Thomas Gleixner is on board).

Supports the use of PREEMPT_RT and Xenomai and contributes to these projects. Shares useful documentation and resources.

They also organize a yearly Real Time Linux Workshop.



- ▶ Check clock accuracy.
- ▶ Start processes with real-time priority.
- ▶ Build a real-time application against the standard POSIX real-time API, and against Xenomai's POSIX skin
- ▶ Compare scheduling latency on your system, between a standard kernel and a kernel with Xenomai.

Last slides

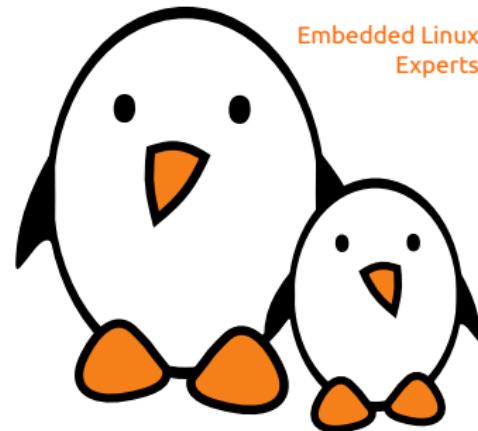
Endocode AG

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Corrections, suggestions, contributions and translations are welcome!



Thank you!