Buildroot: a nice, simple and efficient embedded Linux build system

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  - Embedded Linux development: kernel and driver development, system integration, boot time and power consumption optimization, consulting, etc.
  - Embedded Linux training, Linux driver development training and Android system development training, with materials freely available under a Creative Commons license.
  - `http://www.free-electrons.com`
- Major contributor to Buildroot, an open-source, simple and fast embedded Linux build system
- Living in Toulouse, south west of France

What is Buildroot?

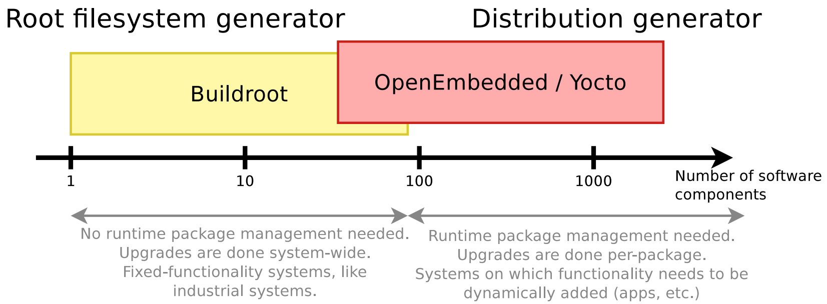
Buildroot is an **embedded Linux build system**.

Its purpose is to **simplify** and **automate** the process of building an embedded Linux system.

Buildroot main characteristics

- Based on **well-known technologies**: *kconfig* for the configuration interface and language, *make* for the build logic. These technologies are familiar to all embedded Linux developers.
- Very **simple to use**, and **easily hackable** code base. The core infrastructure is a few hundred lines of *make* code.
- **Fast**. It does really build only what's necessary. The base system, composed only of BusyBox, takes less than 3 minutes to build with an external toolchain.
- **Designed for small to medium sized embedded systems**. There is no runtime package management system (dpkg, rpm). Complete rebuilds are often required. Well-suited for systems with a limited number of components.

Buildroot vs. OpenEmbedded/Yocto


Root filesystem generator
Distribution generator
Buildroot
OpenEmbedded / Yocto
1
10
100
1000
Number of software components
No runtime package management needed.
Upgrades are done system-wide.
Fixed-functionality systems, like industrial systems.
Runtime package management needed.
Upgrades are done per-package.
Systems on which functionality needs to be dynamically added (apps, etc.)

Context: quick Buildroot history

December 2001

Buildroot is created by *uClibc* developers as a way of building small embedded Linux systems to test *uClibc*

Context: quick Buildroot history

Starting around 2005

Buildroot really starts to be used as an embedded Linux build system for production devices.

The number of developers increases with everybody having write-access to the repository, and the maintainer is no longer active. No stable releases, no design.

The code slowly gets crappier over the years.

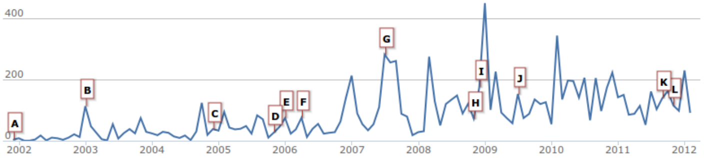
Context: quick Buildroot history

January 2009

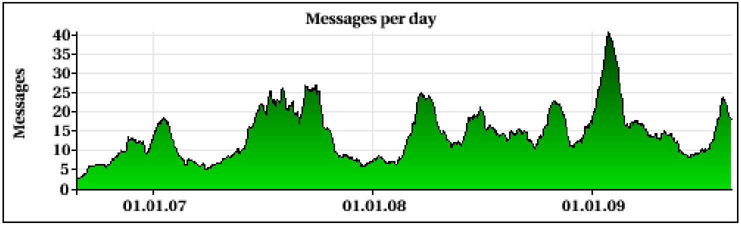
Peter Korsgaard becomes the new maintainer. Start of a new period for the project:

- Stable releases every three months. First release 2009.02, 2012.02 due at the end of the month.
- Huge cleanup effort: code base reduction from 5.2 MB to 2.2 MB, while many packages are added, updated and many new features are added.
- Increase in the number of contributors and users. Regular *Buildroot Developer Days*.
- Linux model: only the maintainer has write-access. Allows to keep a very good consistency in the design decisions.

Context: quick Buildroot history



Number of commits per month

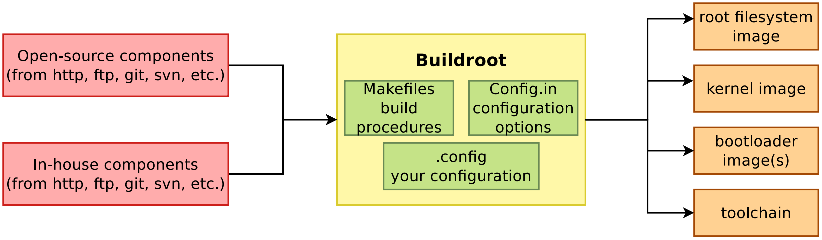


Number of e-mails per day

Three years of change

After three years of major changes in *Buildroot*, it's a good time to have a fresh look at it.

Buildroot: general principle



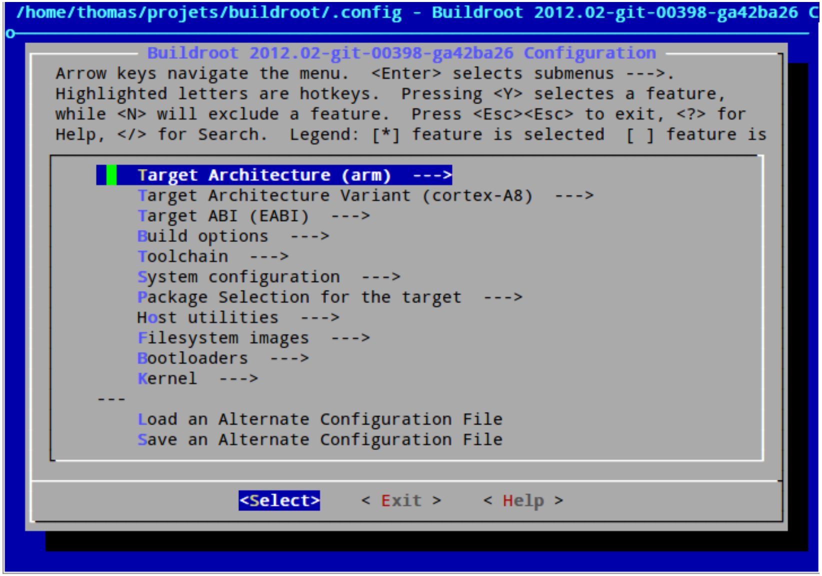
Using Buildroot

```
$ wget http://buildroot.org/downloads/buildroot-2011.11.tar.bz2
$ tar xjf buildroot-2011.11.tar.bz2
$ cd buildroot-2011.11

$ make [menu|x|n|g]config
```

- No need to run as root. Ever.
- No need to symlink `/bin/sh` to `bash`
- Very limited set of dependencies: a native compiler, and basic utilities like *awk*, *bison*, *patch*, *gzip*, *tar*, *wget*, etc.
- Out-of-tree build is possible using `O=`, exactly like the Linux kernel.

Buildroot *menuconfig*



```
/home/thomas/projets/buildroot/.config - Buildroot 2012.02-git-00398-ga42ba26 C

      Buildroot 2012.02-git-00398-ga42ba26 Configuration
  Arrow keys navigate the menu.  <Enter> selects submenus --->.
  Highlighted letters are hotkeys.  Pressing <Y> selectes a feature,
  while <N> will exclude a feature.  Press <Esc><Esc> to exit, <?> for
  Help, </> for Search.  Legend: [*] feature is selected  [ ] feature is

            Target Architecture (arm)  --->
            Target Architecture Variant (cortex-A8)  --->
            Target ABI (EABI)  --->
            Build options  --->
            Toolchain  --->
            System configuration  --->
            Package Selection for the target  --->
            Host utilities  --->
            Filesystem images  --->
            Bootloaders  --->
            Kernel  --->
        ---
            Load an Alternate Configuration File
            Save an Alternate Configuration File

                  <Select>    < Exit >    < Help >
```

Target architecture

Allows you to define:

- The **target architecture**, i.e ARM, x86, PowerPC, MIPS. Buildroot supports non-MMU architectures such as Blackfin or soon Microblaze, thanks to its uClibc support.
- The **target architecture variant**, such as ARM926 or Cortex-A8 on ARM. Allows to automatically add the appropriate `-mcpu`, `-march`, `-mtune` arguments to *gcc*.
- **Target architecture ABI**

Build options

- The **download directory**, where tarballs are saved for future builds. Defaults to `$(TOPDIR)/dl`. Can also be overridden using the `BUILDROOT_DL_DIR` environment variable.
- The **host directory**, where all host utilities are installed, including the *toolchain* and its *sysroot*. Defaults to `$(O)/host`, but can be changed to generate an SDK in a different directory.
- The **number of jobs**. Buildroot runs the build of the different components sequentially, but uses `make -j` for the compilation of the individual components.
- Use of **ccache**
- Other build options: build with debugging symbols, install documentation on target, install development files on target, etc.

Toolchain

Buildroot provides three toolchain *back-ends*:

- An **internal Buildroot toolchain back-end**, which has been available since Buildroot creation. Buildroot will directly build a *uClibc* toolchain and use it for cross-compiling all packages.
- An **external toolchain back-end**, which allows use existing pre-built uClibc, glibc or eglibc toolchains, such as Sourcery CodeBench toolchains, Linaro toolchains, or toolchains that have previously been built using Crosstool-NG or Buildroot. Using an external toolchain removes the toolchain build time.
- A **Crosstool-NG back-end**, which tells Buildroot to build a cross-compiling toolchain with Crosstool-NG. This allows to benefit from all Crosstool-NG advantages, such as the support for *glibc* or *eglibc*.

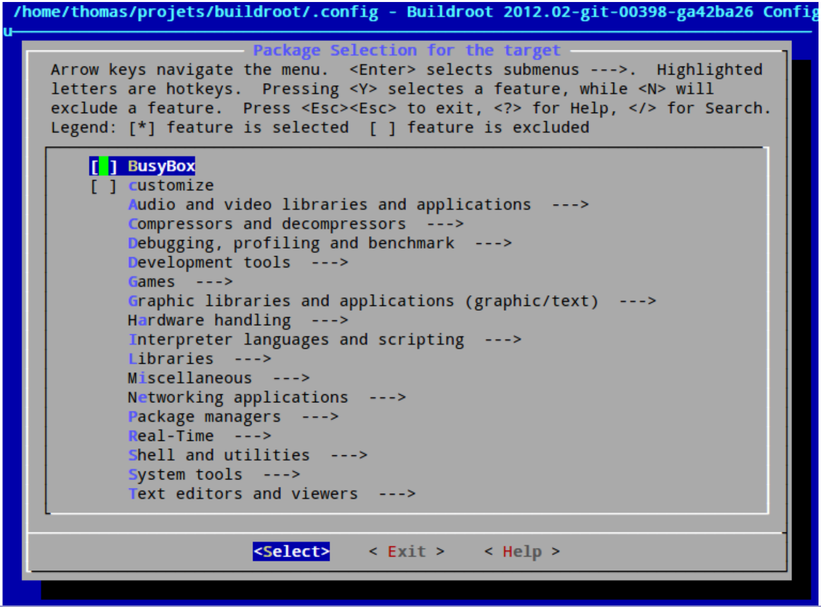
→ Buildroot often had the reputation of being limited to uClibc, but it is no longer the case since several years.

System configuration

Allows the definition of various system-wide parameters:

- The `/dev` **management solution**:
  - *static*, where device nodes are created statically at build time according to a device table
  - *devtmpfs*
  - *devtmpfs* + *BusyBox' mdev*
  - *devtmpfs* + *udev*
- The serial port for the console
- Location of a *post-build script* that gets run after all packages have been built, but before the filesystem images are created.
- Some misc. other parameters (hostname, etc.)

Packages



```
/home/thomas/projets/buildroot/.config - Buildroot 2012.02-git-00398-ga42ba26 Config
u
                        Package Selection for the target
  Arrow keys navigate the menu.  <Enter> selects submenus --->.  Highlighted
  letters are hotkeys.  Pressing <Y> selectes a feature, while <N> will
  exclude a feature.  Press <Esc><Esc> to exit, <?> for Help, </> for Search.
  Legend: [*] feature is selected  [ ] feature is excluded

      [ ] BusyBox
      [ ] customize
          Audio and video libraries and applications  --->
          Compressors and decompressors  --->
          Debugging, profiling and benchmark  --->
          Development tools  --->
          Games  --->
          Graphic libraries and applications (graphic/text)  --->
          Hardware handling  --->
          Interpreter languages and scripting  --->
          Libraries  --->
          Miscellaneous  --->
          Networking applications  --->
          Package managers  --->
          Real-Time  --->
          Shell and utilities  --->
          System tools  --->
          Text editors and viewers  --->

                     <Select>    < Exit >    < Help >
```

Packages

A selection of more than 750 open-source components typically used in embedded systems:

- Audio and multimedia: gstreamer, mplayer, pulseaudio, many codec libraries, alsa, etc.
- Graphics: full X.org stack, Gtk, Qt, EFL, DirectFB, SDL, etc.
- System tools, filesystem utilities, hardware utilities and libraries
- Networking applications: dropbear, avahi, bluez, samba, pppd, connman, etc.
- Development, debugging: oprofile, lttng, etc.
- Interpreters: Python, PHP, Ruby, Perl

Filesystem images

Buildroot can generate filesystem images in multiple formats:

- tar
- cpio
- ext2
- jffs2
- ubi/ubifs
- cramfs
- cloop
- iso9660
- squashfs
- initramfs built into the kernel

Kernel and bootloader

- Automates the **Linux kernel build process**. Builds the kernel using a *defconfig* or a specified configuration file. Takes care of installing the kernel modules into the root filesystem. It is also capable of patching the kernel for real-time extensions like Xenomai or RTAI.
- Includes support for the **most popular bootloaders**: U-Boot, Barebox, Grub, syslinux, but also architecture-specific bootloaders: AT91Bootstrap, X-Loader, lpc32xxcdl, etc.

Building

Once the configuration is defined and saved in `.config`, the compilation is triggered using:

```
$ make
...
$ ls output/images/
dataflash_at91sam9m10g45ek.bin  rootfs.tar
rootfs.ubi                      rootfs.ubifs
u-boot.bin                      u-boot-env.bin
uImage
```

Buildroot will automatically download, extract, patch, configure, compile and install the selected components, taking care of following the necessary dependencies.

Build output (1/2)

In the output directory (by default, `output/`, but can be changed using out-of-tree build), Buildroot generates:

- **build**, with one sub-directory per component built. This is where Buildroot extracts and builds the various components of the system.
- **host**, with a typical Unix organization, in which Buildroot installs all utilities compiled for the host, including the cross-compiler. It also contains, in `host/usr/<tuple>/sysroot` the toolchain *sysroot*, with all the headers and libraries built for the target.
- **images**, with the final images (root filesystem, kernel, bootloaders)
- ...

Build output (2/2)

- ...
- **stamps**, a few stamp files used internally by Buildroot to keep track of what has been built
- **target**, the target root filesystem (but with an empty `/dev` and invalid permissions, those are fixed using *fakeroot* in the final image)
- **toolchain**, where the different toolchain components are built in the case of the internal back-end. Otherwise unused.

Build-time: basic examples

- Building a simple ARM system with simply Busybox, using an already extracted CodeSourcery glibc toolchain, and generating a .tar filesystem image takes **39 seconds**. The target system size is **4.2 MB**.
- Building a simple ARM system with simply Busybox, using a tarball CodeSourcery glibc toolchain, and generating an UBIFS filesystem image takes **2 minutes 57 seconds**. Identical system size.
- Building the same simple ARM system, using an internal Buildroot toolchain (with largefile, locales, C++ support), takes **9 minutes 59 seconds**. The target system size is **2.2 MB**.

Note: durations measured with the *real* output of the `time` command. Download times are excluded.

Build time: real-world example 1

- The device is an ARM AT91-based platform with GPS, RFID readers, GSM modem, Ethernet and USB.
- The Buildroot configuration:
  - CodeSourcery ARM glibc toolchain
  - *Linux kernel*
  - *BusyBox* for the basic system
  - *Dropbear* for SSH access (debugging)
  - *Qt* with only *QtCore*, *QtNetwork* and *QtXml*, no GUI
  - *QExtSerialPort*
  - *zlib*, *libxml2*, *logrotate*, *pppd*, *strace*, a special RFID library, *popt* library
  - The *Qt* application
  - JFFS2 root filesystem
- Filesystem size: 11 MB. Could be reduced by using *uClibc*.
- Build time: 10 minutes on a fast build server (quad-core i7, 12 GB of RAM)

Build time: real-world example 2

- An x86-based system, with an OpenGL application for vehicle navigation system.
  - External *glibc* toolchain generated with *crosstool-NG*
  - The Grub bootloader
  - *Linux kernel*, of course
  - *BusyBox*
  - A large part of the *X.org* stack (the server, a few drivers, and some client libraries), including *libdrm*, *Mesa*
  - The *fglrx* ATI proprietary OpenGL driver
  - *ALSA utils*, *ALSA library*, *V4L library*, *Flashrom*, *LM Sensors*, *Lua*, *Dropbear*, *Ethtool*
  - The OpenGL application and its data
- Filesystem size: 95 MB, with 10 MB of application (binary + data) and 45 MB (!) of *fglrx* driver.
- Build time: 27 minutes on a fast build server (quad-core i7, 12 GB of RAM)

Overall logic: preparation

Buildroot starts by:

- Creating all output directories
- Copying the *target root filesystem skeleton*, located in `fs/skeleton` in the source tree, into the `target/` output directory. This *skeleton* contains the basic directories and configuration files for the target system.
  One can specify, through a configuration option, a different skeleton.

Overall logic: toolchain

Buildroot continues by building the toolchain:

- For **internal** toolchains, it extracts and builds the different elements (binutils, gcc, uClibc, etc.) in the `toolchain` directory, with *stamp* files to keep track of what has already been done. It installs the results in the `host/usr/` directory (for binaries) and `host/usr/<tuple>/sysroot` directory (for libraries and headers)
- For **external** toolchains, Buildroot copies the original toolchain sysroot to the `host/usr/<tuple>/sysroot` directory and creates wrappers for the toolchain binaries in `host/usr/bin`
- For **Crosstool-NG toolchains**, Buildroot installs *Crosstool-NG* in `host/`, and then uses it to generate a toolchain with binaries in `host/usr/bin` and sysroot in `host/usr/<tuple>/sysroot`.

Overall logic: packages (1/2)

- Buildroot continues by building the packages. Packages encapsulate the build procedure of userspace libraries and programs but also the Linux kernel or bootloaders build procedures.
- The build method of each package is described using an infrastructure: **AUTOTARGETS** for autotools-based packages, **CMAKETARGETS** for CMake-based packages and **GENTARGETS** for other packages.
- Buildroot follows the dependencies expressed in the package recipes, and triggers the configuration, compilation and installation steps as described in the recipes.
- ...

Overall logic: packages (2/2)

- ...
- The package source code is extracted in `build/<pkg>-<version>/`, and *stamp* files are created after each step to let Buildroot know of what has already been done. Commands like `make <foo>-reconfigure` and `make <foo>-rebuild` allow to restart the build of a package if needed.
- Host packages are installed in `host/`, while target packages are installed in `target/` (usually stripped, no headers). Target libraries are also installed in `host/usr/<tuple>/sysroot` so that they are found by the cross-compiler (unstripped, with headers and static libraries)

Packages: an overview of the internals

```
$(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_downloaded:
      # downloads the package
      touch $@

$(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_extracted:
      # extracts the package
      touch $@

$(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_built:
      # builds the package
      touch $@

$(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_installed:
      # installs the package
      touch $@

<pkgname>-download:
           $(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_downloaded

<pkgname>-extract: <pkgname>-download
           $(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_extracted

<pkgname>-build: <pkgname>-extract
           $(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_built

<pkgname>-install: <pkgname>-build
           $(BUILD_DIR)/<pkgname>-<pkgversion>/.stamp_installed

<pkgname>: <pkgname>-install

TARGETS += <pkgname>
```

Overall logic: root filesystem image

Finally, Buildroot generates the *root filesystem image(s)*:

- It uses *fakeroot* to generate this root filesystem image without having to be root
- A *makedevs* utility is used to adjust the file permissions and ownership, and to create device files if a static `/dev` was chosen.

Source code organization

- **board**, board-specific patches and configuration files
- **boot**, bootloaders recipes
- **configs**, default configuration files for various platforms. Same concept as kernel *defconfigs*
- **docs**
- **fs**, recipes for generating root filesystem images in various formats, and also root filesystem skeleton in **fs/skeleton**
- **package**, all user-space packages (for the host and the target)
- **support**, misc scripts and tools
- **target**, legacy, almost empty directory
- **toolchain**, toolchain handling code (build recipes for internal and Crosstool-NG back-ends, integration recipes for external toolchains)

Important files

- **Makefile**, the entry point of the build system. Handles the *kconfig* part, and the overall build logic. About 700 lines.
- **package/Makefile.package.in**, the *GENTARGETS* infrastructure. The core logic for building packages. About 700 lines as well.
- **package/Makefile.autotools.in** and **package/Makefile.cmake.in** for the *AUTOTARGETS* and *CMAKETARGETS* infrastructures. Both inherit from *GENTARGETS*. Respectively 300 and 200 lines.
- **fs/common.mk**, the common logic for building the root filesystem images.

Adding packages: configuration

- Each package has its own directory in `package/`. Let's say `package/foo` for our package.
- A `package/foo/Config.in` file needs to be created to declare at least one configuration option for the package. The syntax is identical to the *kconfig* syntax:

```
config BR2_PACKAGE_FOO
        bool "foo"
        select BR2_PACKAGE_ZLIB
        help
          This is package foo

          http://foo-project.org
```

- This `package/foo/Config.in` file must be included from `package/Config.in`:

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

Adding packages: writing the recipe

- The recipe must be written in the `package/foo/foo.mk` file
- It consists of
  - Variable declarations to define the package location, version, and the steps to be done to build the package.
  - A call to one of the `AUTOTARGETS`, `GENTARGETS` or `CMAKETARGETS` macro to expand the package recipe

Adding packages: minimal recipe

Basic recipe for *autotools* based package

```
FOO_VERSION = 1.3
FOO_SOURCE = foo-$(FOO_VERSION).tar.bz2
FOO_SITE = http://foo-project.org/downloads
FOO_DEPENDENCIES = zlib host-pkg-config

$(eval $(call AUTOTARGETS))
```

The **AUTOTARGETS** infrastructure:

- knows how to configure, build and install the package
- handles the common cross-compilation issues with *autotools* based packages (libtool problems, passing the right arguments and environment variables to `./configure`, etc.).

Adding packages: various source methods

From Git

```
FOO_VERSION = this-branch
FOO_SITE = git://git.foo-project.org/foo.git
```

From Subversion

```
FOO_VERSION = 12345
FOO_SITE = http://foo-project.org/svn/foo/trunk/
FOO_SITE_METHOD = svn
```

From a local directory

```
FOO_SITE = /home/thomas/projects/foo/
FOO_SITE_METHOD = local
```

And also from Mercurial, from Bazaar, etc.

Packages: adding a sub-configuration option

In Config.in

```
config BR2_PACKAGE_FOO
...

config BR2_PACKAGE_FOO_BZIP2_SUPPORT
        bool "enable bzip2 support"
        depends on BR2_PACKAGE_FOO
        select BR2_PACKAGE_BZIP2
        help
          Adds support for bzip2
```

In `foo.mk`

```
...
ifeq ($(BR2_PACKAGE_FOO_BZIP2_SUPPORT),y)
FOO_CONF_OPT     += --enable-bzip2
FOO_DEPENDENCIES += bzip2
else
FOO_CONF_OPT     += --disable-bzip2
endif
...
```

Packages: GENTARGETS

For packages that use a special build system (not autotools, not CMake).

```
FOO_VERSION = 1.3
FOO_SOURCE = foo-$(FOO_VERSION).tar.bz2
FOO_SITE = http://foo-project.org/downloads
FOO_DEPENDENCIES = zlib

define FOO_CONFIGURE_CMDS
        echo "HAS_ZLIB=YES" >> $(@D)/config
endef

define FOO_BUILD_CMDS
        $(MAKE) -C $(@D) \
                CC="$(TARGET_CC)" CFLAGS="$(TARGET_CFLAGS)" \
                all
endef

define FOO_INSTALL_TARGET_CMDS
        $(INSTALL) -D -m 0755 $(@D)/foo $(TARGET_DIR)/usr/bin
endef

$(eval $(call GENTARGETS))
```

Packages: other important mechanisms

- **Patches** in the `package/foo` directory are automatically applied if they are named `<number>-<something>.patch` or `<version>/<number>-<something>.patch`
- Need to set `FOO_INSTALL_STAGING = YES` for **packages that install libraries**, so that headers and static library are installed in the toolchain *sysroot*
- Can add *hooks* to **execute custom actions** before/after the different steps, especially for *AUTOTARGETS* packages
- Can set `FOO_AUTORECONF = YES` for autotools-based package to **autoreconfigure** them, useful when the `configure.ac` or `Makefile.am` files are patched.
- The **documentation** contains tutorials and a reference with all details about the package infrastructure `docs/manual/manual.pdf`

Buildroot simplicity

- After a configuration modification, Buildroot **does not even try to apply the configuration changes** during the next `make` invocation.
- Tracking the consequences of configuration modifications is very complicated (when a toolchain setting is changed everything need to be rebuilt; when a library is removed, all reverse dependencies needs to be rebuilt)
- Buildroot remains simple: it **simply executes the build procedure of the selected packages, and does not try to track the files installed by each package**.
- Relies on the **user's knowledge** about the configuration change to know what needs to be done. Since building is very fast, full rebuilds are not problematic.
- This focus on simplicity is a **very strong design decision** of Buildroot. Some features, such as binary packages generation, are not implemented in order to keep the build system simple.

Customizing for a project

Buildroot offers multiple mechanisms to handle all the particularities of a given project:

- A `board/<company>/<project>` directory to store all **project-specific files**: kernel and bootloaders patches, scripts and configuration files, etc.
- Storage of the **project configuration** as a minimal *defconfig* file in the `configs/` directory.
- A **hookable post-build** script that gets called after all packages are installed but before the root filesystem image is created.
- The possibility of **easily adding packages for custom software**, including software coming from local repositories or directories.

See the slides of the *Using Buildroot for real projects* talk given at the Embedded Linux Conference Europe 2011.

Testing effort

Buildroot provides more than 2000 config options, which creates a huge number of possible configurations.

- Peter Korsgaard the maintainer, has a random configuration builder running 24/24 since more than a year, with an ARM toolchain, and we have 100% successful builds, except when regression are introduced.
- I run from time to time random configuration builds on a random set of 30 toolchains for various architectures (ARM, AVR32, PowerPC, x86, x86-64, MIPS, Blackfin). The results are not as good, but mostly due to architecture-specific issues.

Future directions

- Implement a mechanism for automatic generation of a *licensing* report, detailing all components used in the system and their license
- Add more packages for *SoC*-specific software (hardware codecs, 3D acceleration, special bootloaders)
- Improve the documentation with more tutorials
- Finalize the cleanup effort in the remaining areas
- Further increase the testing effort, and make the testing results publicly available

References

- Website: `http://buildroot.org`
- Mailing-list: `buildroot@uclibc.org`
  `http://buildroot.org/lists.html`
- IRC channel: `#buildroot` on Freenode
- Bug tracker: `https://bugs.uclibc.org`

Conclusion

- **Nice** : uses well-known technologies and languages, *kconfig* and *make*. Active community.
- **Simple** : only a few hundreds lines of code to understand the core infrastructure. Easy to get started, and easy to fully understand the internal mechanisms.
- **Efficient** : very reasonable build times, only what's necessary gets built.

Of course, Buildroot is not suitable for *all* embedded Linux projects, but it is well adapted to industrial-like projects which have a limited number of software components and fixed functionality.

Questions?

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