Anatomy of cross-compilation toolchains

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Drawing from Frank Tizzoni, at Kernel Recipes 2016

Disclaimer

- I am **not a toolchain developer**. Not pretending to know everything about toolchains.
- Experience gained from building simple toolchains in the context of Buildroot
- Purpose of the talk is to give an introduction, not in-depth information.
- Focused on simple gcc-based toolchains, and for a number of examples, on ARM specific details.
  - Will not cover advanced use cases, such as LTO, GRAPHITE optimizations, etc.
  - Will not cover LLVM

What is a cross-compiling toolchain?

- A set of tools that allows to build source code into binary code for a *target platform* different than the one where the build takes place
  - Different CPU architecture
  - Different ABI
  - Different operating system
  - Different C library
- Three *machines* involved in the build process
  - **build** machine, where the build takes place
  - **host** machine, where the execution takes place
  - **target** machine, for which the programs generate code
- Native toolchain: *build* == *host* == *target*
- Cross-compilation toolchain: *build* == *host* != *target*
- Corresponds to the `--build`, `--host` and `--target` *autoconf* `configure` script arguments
  - By default, automatically guessed by *autoconf* to be for the current machine

Toolchain tuple

- autoconf defines the concept of *system definitions*, represented as **tuples**
- A system definition describes a system: CPU architecture, operating system, vendor, ABI, C library
- Different forms:
  - `<arch>-<vendor>-<os>-<libc/abi>`, full form
  - `<arch>-<os>-<libc/abi>`
- Components:
  - `<arch>`, the CPU architecture: arm, mips, powerpc, i386, i686, etc.
  - `<vendor>`, (mostly) free-form string, ignored by *autoconf*
  - `<os>`, the operating system. Either `none` or `linux` for the purpose of this talk.
  - `<libc/abi>`, combination of details on the C library and the ABI in use

Toolchain tuple examples

- `arm-foo-none-eabi`, bare-metal toolchain targeting the ARM architecture, from vendor *foo*
- `arm-unknown-linux-gnueabihf`, Linux toolchain targeting the ARM architecture, using the EABIhf ABI and the glibc C library, from an *unknown* vendor
- `armeb-linux-uclibcgnueabi`, Linux toolchain targeting the ARM big-endian architecture, using the EABI ABI and the uClibc C library
- `mips-img-linux-gnu`, Linux toolchain targeting the MIPS architecture, using the glibc C library, provided by Imagination Technologies.

Bare-metal vs. Linux toolchain

- Two main values for `<os>`
  - `none` for **bare-metal** toolchains
    - Used for development without an operating system
    - C library used is generally **newlib**
    - Provides C library services that do not require an operating system
    - Allows to provide basic *system calls* for specific hardware targets
    - Can be used to build bootloaders or the Linux kernel, cannot build Linux userspace code
  - `linux` for **Linux** toolchains
    - Used for development with a Linux operating system
    - Choice of Linux-specific C libraries: **glibc**, **uclibc**, **musl**
    - Supports Linux system calls
    - Can be used to build Linux userspace code, but also bare-metal code such as bootloaders or the kernel itself

Components

- There are four core components in a Linux cross-compilation toolchain
  1. **binutils**
  2. **gcc**
  3. **Linux kernel headers**
  4. **C library**
- In addition to these, a few dependencies are needed to build *gcc* itself.

binutils

- "*collection of binary tools*"
- Main tools
  - **ld**, the linker. Links multiple object files into a shared library, an executable, or another object file.
  - **as**, the assembler. Takes architecture-specific assembler code in text form, and produces a corresponding object file with binary code.
- Debugging/analysis tools and other tools
  - addr2line, ar, c++filt, gold, gprof, nm, objcopy, objdump, ranlib, readelf, size, strings, strip
- Needs to be configured for each CPU architecture: your native x86 binutils cannot produce ARM code.
- Pretty straightforward to cross-compile, no special dependencies are needed.

```
./configure --target=arm-buildroot-linux-gnueabihf --with-sysroot=PATH
```

gcc

- GNU Compiler Collection
- Front-ends for many source languages: C, C++, Fortran, Go, etc.
- Back-ends for many CPU architectures.
- Provides:
  - The compiler itself, `cc1` for C, `cc1plus` for C++. Only generates assembly code in text format.
  - The compiler driver, `gcc`, `g++`, which drives the compiler itself, but also the binutils assembler and linker.
  - Target libraries: `libgcc` (gcc runtime), `libstdc++` (the C++ library), `libgfortran` (the Fortran runtime)
  - Header files for the standard C++ library.
- Building *gcc* is a bit more involved than building *binutils*: two steps are needed, see later.

Linux Kernel headers

- In order to build a C library, the Linux kernel headers are needed: definitions of system call numbers, various structure types and definitions.
- In the kernel, headers are split between:
  - User-space visible headers, stored in `uapi` directories: `include/uapi/`, `arch/<ARCH>/include/uapi/asm`
  - Internal kernel headers.
- Installation takes place using `make ARCH=.. INSTALL_HDR_PATH=... headers_install`
  - The installation includes a sanitation pass, to remove kernel-specific constructs from the headers.
  - As of Linux 4.8, installs 756 header files.

Linux Kernel headers version

- Which version of the kernel headers should be used in a toolchain?
- The kernel to userspace ABI is backward compatible.
- Therefore, the version of the kernel used for the kernel headers must be the same version or older than the kernel version running on the target system.
- Otherwise the C library might use system calls that are not provided by the kernel.
- Examples:
  - Toolchain using 3.10 kernel headers, running 4.4 kernel on the target → OK
  - Toolchain using 4.8 kernel headers, running 4.4 kernel on the target → NOK

Linux 3.13.0 headers

```
$ cat arm-none-linux-gnueabi/libc/usr/include/linux/version.h
define LINUX_VERSION_CODE 199936
#define KERNEL_VERSION(a,b,c) (((a) << 16) + ((b) << 8) + (c))
```

C library

- Provides the implementation of the POSIX standard functions, plus several other standards and extensions
- Based on the Linux system calls
- Several implementations available:
  - glibc
  - uClibc-ng (formerly uClibc)
  - musl
  - bionic, for Android systems
  - A few other more special-purpose: newlib (for bare-metal), dietlibc, klibc
- After compilation and installation, provides:
  - The dynamic linker, `ld.so`
  - The C library itself `libc.so`, and its companion libraries: `libm`, `librt`, `libpthread`, `libutil`, `libnsl`, `libresolv`, `libcrypt`
  - The C library headers: `stdio.h`, `string.h`, etc.

C library: glibc

- GNU C Library
- **De-facto standard** of Linux C libraries
- Used in virtually all common desktop/server distributions
- **Full-featured**
- Supports for numerous architectures or operating systems
- No support for noMMU platforms
- No support for static linking
- **ABI backward** compatibility
- Almost no configurability
- Used to be “too big” for embedded, but no longer necessarily the case.
- LGPLv2.1 or later
- `https://www.gnu.org/software/libc/`

C library: uClibc/uClibc-ng

- Started in **2000**
- High-level of configurability
- Supports many architectures, include some not supported by glibc
- Supports **only Linux** as operating system
- **No ABI** backward compatibility
- Supports numerous **no-MMU** architectures: ARM noMMU, Blackfin, etc.
- No longer related to *uClinux*
- Support for **static linking**
- Original *uClibc* project dead (last release in May 2012), but the **uClibc-ng** fork is very active and is the de-facto replacement.
- LGPLv2.1
- `http://uclibc-ng.org/`

C library: musl

- Started in 2011
- **MIT licensed**
- Very active development
- Support for ARM, ARM64, i386, Microblaze, MIPS(64), OpenRisc, PowerPC(64), SuperH, x86-4
- Recently, **noMMU support** was added for SuperH2, for the J-core Open Processor
- No configurability
- **Small**, even smaller than uClibc, especially for static linking scenarios
- Strict conformance to standards (stricter than glibc, uClibc), causes a few build issues with a number of packages
- Nice comparison of the three main C libraries: `http://www.etalabs.net/compare_libcs.html`
- `http://www.musl-libc.org/`

C library: size comparison

	glibc	uclibc	musl
`ld`, dynamic linker	121 KB	25 KB	N/A
`libc`	878 KB	286 KB	437 KB
`libcrypt`	30 KB	17 KB	N/A
`libdl`	9.5 KB	9 KB	N/A
`libm`	414 KB	37 KB	N/A
`libnsl`	54 KB	4.7 KB	N/A
`libnss_dns`	14 KB	N/A	N/A
`libnss_files`	30 KB	N/A	N/A
`libpthread`	105 KB	76 KB	N/A
`libresolv`	54 KB	4.7 KB	N/A
`librt`	22 KB	13 KB	N/A
`libutil`	9.5K	4.7 KB	N/A
TOTAL	1741 KB	477 KB	437 KB

ARM Cortex-A9 toolchain built with the Thumb-2 instruction set, using Buildroot. gcc 4.9, binutils 2.26, musl 1.1.15, glibc 2.23, uclibc-ng 1.0.17

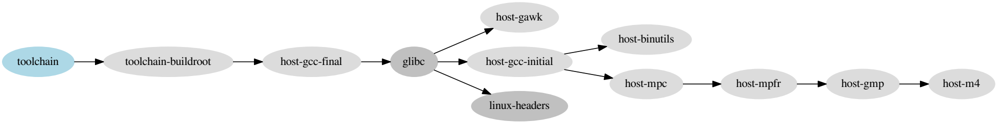
gcc dependencies

- Several math libraries are needed to build *gcc*
- They are compiled for the host machine, i.e they are not needed on the target
  - **mpfr**, multiple-precision floating-point computations. Used since gcc 4.3 to *evaluate and replace at compile-time calls to built-in math functions having constant arguments with their mathematically equivalent results*
  - **gmp**, dependency of *mpfr*
  - **mpc**, for computation of complex numbers. Used since gcc 4.5 to *evaluate calls to complex built-in math functions having constant arguments and replace them at compile time with their mathematically equivalent result*

Overall build process

- The build process for a regular Linux cross-compilation toolchain is in fact fairly easy:
  1. Build *binutils*
  2. Build the dependencies of *gcc*: *mpfr*, *gmp*, *mpc*
  3. Install the Linux kernel headers
  4. Build a first stage *gcc*: no support for a C library, support only for static linking
  5. Build the *C library* using the first stage *gcc*
  6. Build the final *gcc*, with C library and support for dynamic linking

Overall build process: example in Buildroot



Concept of sysroot

- The *sysroot* is the **the logical root directory for headers and libraries**
- Where *gcc* looks for headers, and *ld* looks for libraries
- Both *gcc* and *binutils* are built with `--with-sysroot=<SYSROOT>`
- The kernel headers and the C library are installed in `<SYSROOT>`
- If the toolchain has been moved to a different location, *gcc* will still find its sysroot if it's in a subdir of `--prefix`
  - `--prefix=/home/thomas/buildroot/arm-uclibc/host/usr`
  - `--with-sysroot=/home/thomas/buildroot/arm-uclibc/host/usr/arm-buildroot-linux-uclibcgnueabihf/sysroot`
- Can be overridden at runtime using gcc's `--sysroot` option.
- The current *sysroot* can be printed using the `-print-sysroot` option.

Multilib toolchains (1)

- Most toolchains provide a **single sysroot** with the C library and gcc runtime libraries
- These libraries, built for the target, are optimized for a **specific architecture variant and ABI**
- Need to have one toolchain for each architecture variant or ABI
- **Multilib** toolchains contain multiple *sysroot*, each having a version of the target libraries for different architecture/ABI variants.
- Example of the Sourcery CodeBench ARM toolchain:

```
$ arm-none-linux-gnueabi-gcc -print-multi-lib
.;
armv4t;@march=armv4t
thumb2;@mthumb@march=armv7-a
```

- Three sysroots: ARMv5, ARMv4 and ARMv7 Thumb-2

Multilib toolchains (2)

- The compiler automatically selects the right *sysroot* depending on the gcc flags:

```
$ arm-none-linux-gnueabi-gcc -march=armv5te -print-sysroot
.../bin/../arm-none-linux-gnueabi/libc
$ arm-none-linux-gnueabi-gcc -march=armv4t -print-sysroot
.../bin/../arm-none-linux-gnueabi/libc/armv4t
$ arm-none-linux-gnueabi-gcc -march=armv7-a -mthumb -print-sysroot
.../bin/../arm-none-linux-gnueabi/libc/thumb2
```

- Each *sysroot* has a different library variant:

```
$ readelf -A arm-none-linux-gnueabi/libc/lib/ld-2.18.so
  Tag_CPU_name: "5TE"
  Tag_CPU_arch: v5TE
$ readelf -A arm-none-linux-gnueabi/libc/armv4t/lib/ld-2.18.so
  Tag_CPU_name: "4T"
  Tag_CPU_arch: v4T
$ readelf -A arm-none-linux-gnueabi/libc/thumb2/lib/ld-2.18.so
  Tag_CPU_name: "7-A"
  Tag_CPU_arch: v7
  Tag_THUMB_ISA_use: Thumb-2
```

Toolchain contents

Cross-compilation toolchain generated by Buildroot

- `arm-buildroot-linux-uclibcgnueabihf/`
- `bin/`
- `include/`
- `lib/`
- `libexec/`
- `share/`

Toolchain contents

- `arm-buildroot-linux-uclibcgnueabihf/`
  - `bin/`
    - Limited set of *binutils* programs, without their cross-compilation prefix. Hard links to their counterparts with the prefix. This is where *gcc* finds them.
  - `include/c++/4.9.4/`
    - Headers for the C++ standard library, installed by *gcc*
    - Interestingly, they are not part of the *sysroot* per-se.
  - `lib/`
    - The *gcc* runtime libraries, built for the target
    - `libatomic`, provides a software implementation of `atomic` built-ins, when needed
    - `libgcc`, the main *gcc* runtime (optimized functions, 64-bit division, floating point emulation)
    - `libitm`, transactional memory library
    - `libstdc++`, standard C++ library
    - `libsupc++`, subset of `libstdc++` with only the *language support* functions
  - `sysroot/`
    - `lib/`, `usr/lib/`: C library and gcc runtime libraries (shared and static)
    - `usr/include/`, Linux kernel and C library headers
- `bin/`

Toolchain contents

- `arm-buildroot-linux-uclibcgnueabihf/`
- `bin/`
  - `arm-buildroot-linux-uclibcgnueabihf-` prefixed tools
  - From *binutils*: addr2line, ar, as, elfedit, gcov, gprof, ld, nm, objcopy, objdump, ranlib, readelf, size, strings, strip
  - From *gcc*: c++ (same as g++), cc (same as gcc), cpp, g++, gcc, gcc-ar, gcc-nm, gcc-ranlib
  - The `gcc-{ar,nm,ranlib}` are wrappers for the corresponding binutils program, to support Link Time Optimization (LTO)
- `include/`
- `lib/`
- `libexec/`
- `share/`

Toolchain contents

- `arm-buildroot-linux-uclibcgnueabihf/`
- `bin/`
- `include/`
  - Headers of the host libraries (*gmp*, *mpfr*, *mpc*)
- `lib/`
- `libexec/`
- `share/`

Toolchain contents

- `arm-buildroot-linux-uclibcgnueabihf/`
- `bin/`
- `include/`
- `lib/`
  - `gcc/arm-buildroot-linux-uclibcgnueabihf/4.9.4/`
    - `crtbegin*.o`, `crtend*.o`, object files handling constructors/destructors, linked into executables
    - `include/`, headers provided by the compiler (`stdarg.h`, `stdint.h`, `stdatomic.h`, etc.)
    - `include-fixed/`, system headers that gcc fixed up using *fixincludes*
    - `install-tools/`, also related to the *fixincludes* process
    - `libgcc.a`, `libgcc_eh.a`, `libgcov.a`, static variants of the gcc runtime libraries
  - `ldscripts/`, linker scripts provided by *gcc* to link programs and libraries
  - Host version of *gmp*, *mpfr*, *mpc*, needed for *gcc*
- `libexec/`
- `share/`

Toolchain contents

- `arm-buildroot-linux-uclibcgnueabihf/`
- `bin/`
- `include/`
- `lib/`
- `libexec/`
  - `gcc/arm-buildroot-linux-uclibcgnueabihf/4.9.4/`
    - `cc1`, the actual C compiler
    - `cc1plus`, the actual C++ compiler
    - `collect2`, program from gcc collecting initialization functions, wrapping the linker
    - `install-tools/`, misc *gcc* related tools, not needed for the compilation process
    - `liblto_plugin.so.0.0.0`, `lto-wrapper`, `lto1`, related to LTO support (outside of the scope of this talk)
- `share/`

Toolchain contents

- `arm-buildroot-linux-uclibcgnueabihf/`
- `bin/`
- `include/`
- `lib/`
- `libexec/`
- `share/`
  - documentation (man pages and info pages)
  - translation files for gcc and binutils

Architecture tuning

- *gcc* provides several configure-time options to tune for a specific architecture/CPU variant: `--with-arch`, `--with-cpu`, `--with-abi`, `--with-fpu`
- These define the *default* architecture/CPU variant for which *gcc* will generate code.
- They can be overridden at runtime using the `-march`, `-mcpu`, `-mabi`, `-mfpu` options.
- However, be careful: parts of the toolchain are built for the target!
  - The gcc runtime libraries
  - The C library, dynamic linker, and startup code
- They are built *together* with the rest of the toolchain, so it's important to know with what optimization level they were built!
- Passing `-march=armv5te` is not sufficient to make your binary work on ARMv5 if your toolchain originally targets ARMv7.
- Read the *gcc* documentation, section *Machine-dependent options* to get the complete list of possible values.

ABI: definition

- ABI = *Application Binary Interface*
- From the point of a toolchain, the ABI defines:
  - How function calls are made (so-called *calling convention*)
    - How arguments are passed: in registers (which ones?), on the stack, how 64-bits arguments are handled on 32 bits architectures
    - How the return value is passed
  - Size of basic data types
  - Alignment of members in structures
  - When there is an operating system, how system calls are made
- Object files from different ABIs cannot be linked together (especially important if you have pre-built libraries or executables!)
- For a given CPU architecture, there can potentially be an infinite number of ABIs: ABIs are just specifications on how to use the CPU architecture
- Need to understand the ABIs for each architecture.

ABI: example of ARM 32

- **OABI**: obsolete ABI. Forced the use of hard-float instructions, which required emulation of floating-point operations in the kernel. No longer supported anywhere.
- **EABI**, standardized by ARM. Allows mixing hard-float code with soft-float code. Floating point arguments passed in integer registers.
  - Hard-float code: uses floating point instructions directly.
  - Soft-float code: emulates floating point instructions using a userspace library provided by gcc
- **EABIhf**, also standardized by ARM. Requires a floating point unit: only hard-float code. Floating point arguments passed in floating point registers.
- *gcc* options
  - EABI soft-float: `-mabi=aapcs-linux -mfloat-abi=soft`
  - EABI hard-float: `-mabi=aapcs-linux -mfloat-abi=softfp`
  - EABIhf: `-mabi=aapcs-linux -mfloat-abi=hard`

Difference between toolchain and SDK

- Toolchain: just the compiler, binutils and C library
- SDK: a toolchain, plus a number (potentially large) of libraries built for the target architecture, and additional native tools helpful when building software.
- Build systems such as OpenEmbedded or Yocto can typically:
  - Use an existing toolchain as input, or build their own toolchain
  - In addition to producing a root filesystem, they can also produce a SDK to allow application developers to build applications/libraries for the target.

How to get a cross-compilation toolchain

- Pre-built
  - From your **distribution**. Ubuntu and Debian have numerous cross-compilers readily available.
  - From various **organization**: Linaro provides ARM and AArch64 toolchains, Mentor provides a few free Sourcery CodeBench toolchains, Imagination provides MIPS toolchains, etc.
- Built it yourself
  - **Crosstool-NG**, tool specialized in building cross-compilation toolchain. By far the most configurable/versatile.
  - Embedded Linux **build systems** generally all know how to build a cross-compilation toolchain: Yocto/OpenEmbedded, Buildroot, OpenWRT, etc.

References

- Crosstool-NG documentation, https://github.com/crosstool-ng/crosstool-ng/blob/master/docs/
- GCC documentation, https://gcc.gnu.org/onlinedocs/
- Binutils documentation, https://sourceware.org/binutils/docs/

Thanks for your attention!

Questions?

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http://bootlin.com/pub/conferences/2016/elce/petazzoni-toolchain-anatomy/