

BERI

Bluespec Extensible RISC Implementation

Software Reference

Version 1.7

This interim document is not released for public consumption

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Abstract

This document is the *Software Reference* for the research prototype implementation of the Bluespec Extensible RISC Implementation (BERI) developed by SRI International and the University of Cambridge. The reference is targeted at software programmers who will work on BERI or BERI-derived systems, describing bare-metal and FreeBSD-based software development on the platform. It complements the *BERI Hardware Reference* by providing information required by hardware and software developers working with the prototype.

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Chapter 1

Introduction

This is the *Software Reference* for the Bluespec Extensible RISC Implementation (BERI) prototype. The *Software Reference* describes the software development environment on the BERI processor – especially, as relates using the FreeBSD operating system on FPGA-synthesized BERI systems. The reference is intended to address the needs of hardware and software developers who are prototyping new hardware features, bringing up operating systems, language runtimes, and compilers on BERI, rather than literal end users. It complements the *BERI Hardware Reference*, which describes the BERI physical platform, the *CHERI Architecture Document*, which describes our CHERI ISA extensions, and the *CHERI User’s Guide*, which describes our software extensions for CHERI.

1.1 Bluespec Extensible RISC Implementation (BERI)

The Bluespec Extensible RISC Implementation (BERI) is a platform for performing research into the hardware-software interface that has been developed as part of the CTSRD project at SRI International and the University of Cambridge. It consists of a 64-bit FPGA soft-core processor implemented in Bluespec System Verilog and a complete software stack based on FreeBSD, Clang/LLVM, and a range of popular open-source software products. BERI implements a roughly 1994-vintage version of the 64-bit MIPS ISA with FPU and system co-processor sufficient to support a full operating-system implementation. It also implements research extensions such as the CHERI ISA, which supports fine-grained memory protection and scalable compartmentalization within conventional address spaces. Wherever possible, BERI makes use of BSD- and Apache-licensed software to maximize opportunities for technology transition.

1.2 FreeBSD

FreeBSD is an open-source UNIX operating system originating from the Berkeley Software Distribution in the 1980s. Released under the liberal BSD open-source license, FreeBSD is widely used in service provider environments (e.g., Yahoo!, Verio, ISC, Netflix) and as a foundation for

commercial appliance and embedded products (e.g., NetApp, Juniper, Cisco, EMC, Apple). We have adapted FreeBSD to run on BERI, which includes a platform support package and a set of device drivers for common Altera and Terasic peripherals. As part of the BERI effort, we have invested significant effort in improving upstream components such as LLVM and LLDB to work well with the 64-bit MIPS ISA.

FreeBSD can be cross-compiled from 32-bit and 64-bit x86 workstations and servers running FreeBSD (or from a VM running FreeBSD). We have also adapted the FreeBSD third-party package build system (‘ports’) to support cross-compilation, making tens of thousands of open-source applications (e.g., Apache) available on BERI. FreeBSD is of particular interest to teaching and research in the hardware-software interface due to tight integration with the clang/LLVM compiler suite.

1.3 Version history

This is the eighth version of the *BERI Software Reference*; the document was previously part of the *CHERI User’s Guide*.

- 1.0 An initial version of the *CHERI User’s Guide* documented the implementation status of the CHERI prototype, including the CHERI ISA and processor implementation, as well as user information on how to build, simulate, debug, test, and synthesize the prototype.
- 1.1 Minor refinements were made to the text and presentation of the document, with incremental updates to its descriptions of the SRI/Cambridge development and testing environments.
- 1.2 This version of the *CHERI User’s Guide* followed an initial demonstration of CHERI synthesized for the Terasic tPad FPGA platform. The Guide contained significant updates on the usability of CHERI features, the build process, and debugging features such as CHERI’s debug unit. A chapter was added on Deimos, a demonstration microkernel for the CHERI architecture.
- 1.3 The document was restructured into hardware prototype and software reference material. Information on the status of MIPS ISA implementation was updated and expanded, especially with respect to the MMU. Build dependencies were updated, as was information on the CHERI simulation environment. The distinction between BERI and CHERI was discussed in detail. The Altera development environment is now described in its own chapter. A new chapter was added that detailed bus and device configuration and use of the Terasic tPad and DE4 boards, including the Terasic/Cambridge MTL touch screen display. New chapters were added on building and using CheriBSD, as well as a chapter on FreeBSD device drivers on BERI/CHERI. A new chapter was added on cross-building and using the CHERI-modified Clang/LLVM suite, including C-language extensions for capabilities.
- 1.4 This version introduced improved Altera build and Bluespec simulation instructions. A number of additional C-language extensions that can be mapped into capability protections were

introduced. FreeBSD build instructions were updated for changes to the FreeBSD cross-build system. Information on the CHERI2 prototype was added.

- 1.5** In this version of the *CHERI User's Guide*, several chapters describe the CHERI hardware prototype have been moved into a separate document, the *CHERI Platform Reference Manual*, leaving the User's Guide focused on software-facing activities.
- 1.6** This version updated the *CHERI User's Guide* for changes in the CheriBSD build including support for the CFI driver, incorporation of Subversion into the FreeBSD base tree, and non-root cross builds. It also added information on the `quartus_pgm` command, and made a number of minor clarifications and corrections throughout the document.
- 1.7** In this revision, the *BERI Software Reference* has become an independent document from the *CHERI User's Guide*. This version is updated for the complete merge of FreeBSD/BERI to the FreeBSD Subversion repository, and migration of CheriBSD to GitHub. Reflect the change from `cherictl` to `berictl` and a number of enhancements to `berictl` that avoid the need to manually invoke Altera's underlying tools for FPGA programming or console access. The `isf` driver has been replaced with use of the stock FreeBSD `cfi` driver. We no longer recommend explicitly building the cross-toolchain; instead, rely on `world`.

1.4 Licensing

CheriBSD and the CHERI-enhanced version of the Clang/LLVM have been released under BSD licenses. Modifications to the `gas` assembler have been released under GPLv2. BERI itself will shortly become available under the BERI hardware-software license, a lightly modified version of the Apache open-source license.

1.5 Document Structure

This document is an introduction and user manual for Version 1 of the Bluespec Extensible RISC Implementation (BERI) CPU prototype:

Chapter 2 describes how to build the FreeBSD/BERI port.

Chapter 3 describes how to use FreeBSD/BERI.

Chapter 4 provides additional reference material for device driver configuration and use under FreeBSD/BERI.

Chapter 2

Building FreeBSD/BERI

FreeBSD/BERI is an adaptation of the open-source FreeBSD operating system to run on the Bluespec Extensible RISC Implementation (BERI). This support has been ‘upstreamed’ to the mainstream FreeBSD distribution, and appears from version FreeBSD 10.0 onwards. As we are actively continuing development of FreeBSD/BERI, extending it to support evolving features in BERI itself, including device drivers for new hardware peripherals, and kernel support for new CPU features. FreeBSD/BERI can be cross-compiled from 32-bit or 64-bit FreeBSD/x86 running FreeBSD 10.0. CheriBSD, a set of extensions to FreeBSD/BERI to support the CHERI capability coprocessor, are described in a separate document, the *CHERI User’s Guide*.

2.1 Obtaining FreeBSD/BERI source code

FreeBSD/BERI has been merged to the FreeBSD source tree as released in FreeBSD 10.0. However, due to post-FreeBSD 10.0 enhancements, we recommend using FreeBSD 10-STABLE, which can be tracked in the following Subversion branch:

<http://svn.freebsd.org/base/stable/10>

For closer (and likely faster) access to the repository see the list of mirrors found at:

http://www.freebsd.org/doc/en_US.ISO8859-1/books/handbook/svn-mirrors.html

With some caution, the FreeBSD development head (11-CURRENT) might also be used in order to get the very latest BERI features – e.g., at the time of writing, BERI boot-loader support is only present in that branch. However, as it includes many other experimental in-development OS features, this is not recommended unless you are able to closely track FreeBSD development mailing lists to be aware of evolving sources of instability:

<http://svn.freebsd.org/base/head>

2.2 About FreeBSD/BERI

The FreeBSD/BERI port is adapted from the FreeBSD/MALTA 64-bit MIPS port, which offers the closest match in terms of ISA. BERI-related kernel files may be found in directories listed in Table 2.1. Wherever

Filename	Description
<code>sys/mips/beri/</code>	BERI-specific processor/platform code.
<code>sys/boot/fdt/dts/</code>	Home of BERI flattened device tree (FDT) description files.
<code>sys/dev/altera/atse</code>	Altera Triple-Speed Ethernet MAC.
<code>sys/dev/altera/avgen</code>	Avalon “generic” driver to export I/O address ranges to userspace.
<code>sys/dev/altera/jtag_uart</code>	Altera JTAG UART device driver.
<code>sys/dev/altera/sdcard</code>	Altera University Program SD Card IP core device driver.
<code>sys/dev/terasic/de4led</code>	Terasic DE4 LED array device driver.
<code>sys/dev/terasic/mtl</code>	Terasic Multitouch LCD device driver.

Table 2.1: FreeBSD/BERI directories in `src/sys/`

possible, FreeBSD/BERI reuses generic MIPS platform code, and is successful in almost all cases. BERI uses flattened device tree (FDT); currently, DTS files describing BERI hardware are stored in the FreeBSD source tree, but we hope to embed them in ROMs in BERI bitfiles in the future. Table 2.2 lists BERI-specific files in the common MIPS configuration directory.

2.3 Building FreeBSD/BERI

The following sections describe how to build a FreeBSD/BERI system. Examples assume the Cambridge *zenith* development environment, a FreeBSD 10.0 x86/64 server. With appropriate pathname and user-name substitutions, they should work on other FreeBSD 10 build hosts. The FreeBSD userspace build will automatically build suitable cross-compilers and tools. Once userspace has been built, it must be installed to a suitable directory tree from which disk images can be created. If you wish to build a kernel that includes a memory root file system, userspace must be built, installed to a temporary location, and a memory file system image created, before the kernel can be built.

Where appropriate, `cheribsd` may be substituted for `freebsd`, and kernel configuration file names changed, to build CheriBSD instead of FreeBSD/BERI. Please consult the *CHERI User’s Guide* for instructions on checking out CheriBSD source code.

Note well: The details of the build process are likely to change over time as we merge changes from the upstream FreeBSD tree due to the rapid evolution of MIPS support. Users should take care to ensure that they are using a *BERI Software reference* that is contemporary with their source tree.

2.3.1 Configuring the build environment

By default, the FreeBSD build system will use `/usr/obj` as its scratch area. Instead, create and configure your own per-user scratch space:

```
$ mkdir -p /pool/users/${USER}/obj
$ export MAKEOBJDIRPREFIX=/pool/users/${USER}/obj
```

Filename	Description
BERI_DE4.hints	Terasic DE4 hardware configuration hints
BERI_SIM.hints	Bluespec simulation hardware configuration hints
BERI_TPAD.hints	Terasic tPad hardware configuration hints
BERI_TEMPLATE	FreeBSD/BERI template configuration entries, included by more specific kernel configuration files
BERI_DE4_BASE	FreeBSD/BERI template configuration entries for DE4 configurations, included by DE4 kernel configuration files
BERI_DE4_MDROOT	FreeBSD/BERI kernel configuration to use a memory root file system on the Terasic DE4
BERI_DE4_SDROOT	FreeBSD/BERI kernel configuration to use an SD Card root file system on the Terasic DE4
BERI_SIM_BASE	FreeBSD/BERI template configuration entries for DE4 configurations, included by DE4 kernel configuration files
BERI_SIM_MDROOT	FreeBSD/BERI kernel configuration to use a memory root file system while in simulation
BERI_SIM_SDROOT	FreeBSD/BERI kernel configuration to use a simulated SD Card root file system

Table 2.2: FreeBSD/BERI files in `src/sys/mips/conf`; note that `hints` files have been deprecated in favour of FDT DTS files for board configuration.

You may wish to modify your `.cshrc` or `.bashrc` to automatically configure the `MAKEOBJDIRPREFIX` variable every time you log in.

2.3.2 Cross-building world

In FreeBSD parlance, “world” refers to all elements of the base operating system other than the kernel – i.e., userspace. This includes system libraries, the toolchain (including the compiler), userland utilities, daemons, and generated configuration files. It excludes third-party software such as Apache, X11, and Chrome. Cross-build a big-endian, 64-bit MIPS world with the following commands:

```
$ cd /pool/users/${USER}/freebsd
$ make -j 16 TARGET=mips TARGET_ARCH=mips64 DEBUG_FLAGS=-g \
  -DMALLOC_PRODUCTION buildworld
```

Note: the `DEBUG_FLAGS=-g` requests that debugging symbols be generated for all userland components.

Some utility software and software used for demos is stored in the `tools/tools/atsect1` directory. It can be built with the world by adding the following to the `make` command line:

```
LOCAL_DIRS="tools/tools/atsect1"
```

2.3.3 Cross-building a kernel

FreeBSD kernels are compiled in the context of a configuration file. For BERI, we have provided several reference configuration files as described earlier in this chapter. In this section we describe only how to build a kernel without a memory root file system. Information on memory root file systems may be found in Section 2.4.3. The following commands cross-build a BERI kernel:

```
$ cd /pool/users/${USER}/freebsd
$ make -j 16 TARGET=mips TARGET_ARCH=mips64 buildkernel \
  KERNCONF=BERI_DE4_SDROOT
```

Notice that the kernel configuration used here is `BERI_DE4_SDROOT`; replace this with other configuration file names as required.

BERI uses FDT to describe most aspects of hardware configuration (including bus topology and peripheral attachments). The only significant exception is physical memory configuration, which is passed directly to the kernel by the boot loader; we anticipate that physical memory will also be configured using FDT in the future. For the time being, DTS files describing hardware are embedded in the FreeBSD source tree in a manner similar to `hints` files used in earlier iterations of BERI. In the future, these will be embedded in hardware and a pointer to the configuration will be passed to the FreeBSD kernel on boot by the loader.

2.4 Cross-installing FreeBSD

The install phase of the FreeBSD build process takes generated userspace and kernel binaries from the `MAKEOBJDIRPREFIX` and installs them into a directory tree that can then be converted into a file system image. Most `make` targets in this phase make use of the `DESTDIR` variable to determine where

files should be installed to. Typically, `DESTDIR` will be set to a dedicated scratch directory such as `/pool/users/${USER}/freebsd-root`. We advise you to remove the directory between runs to ensure that no artifacts slip from one instance into a later one:

```
# rm -Rf /pool/users/${USER}/freebsd-root
# mkdir -p /pool/users/${USER}/freebsd-root
```

2.4.1 Cross-installing world

This phase consists of two steps: first, `installworld`, which installs libraries, daemons, command line utilities, and so on; second, `distribution`, which creates additional files and directories used in the installed configuration, such as `/etc` and `/var`. The following commands cross-install to `/pool/users/${USER}/freebsd-root`:

```
# cd /pool/users/${USER}/freebsd
# make DESTDIR=/pool/users/${USER}/freebsd-root \
    TARGET=mips TARGET_ARCH=mips64 -DDB_FROM_SRC -DNO_ROOT \
    installworld distribution
```

To install the software in the `tools/tools/atsect1` directory, the following should be added to the make command line:

```
LOCAL_DIRS="tools/tools/atsect1"
```

2.4.2 Cross-installing kernels

As with `world`, kernels can be installed to a target directory tree along with any associated modules. The following commands install the `BERI_DE4_SDR00T` kernel into `/pool/users/${USER}/freebsd-root`:

```
# cd /pool/users/${USER}/freebsd
# make DESTDIR=/pool/users/${USER}/freebsd-root \
    TARGET=mips TARGET_ARCH=mips64 -DDB_FROM_SRC -DNO_ROOT \
    KERNCONF=BERI_DE4_SDR00T installkernel
```

2.4.3 Preparing a memory root file system

To build the `BERI_DE4_MDROOT` kernel, a memory file system image must first be made available. A demonstration script, `makeroot.sh`, is available via the CTSRD Subversion repository; most users will wish to customize the script arguments based on their specific environment. The following command generates an 26 megabyte root file system image in `/pool/users/${USER}/mdroot.img`, and requires that previous steps to install `world` have been completed:

```
# cd /pool/users/${USER}/freebsd/tools/tools/makeroot
# sh makeroot.sh -B big -e extras/sdroot.mtree -s 26112k -f net.files \
    /pool/users/${USER}/mdroot.img /pool/users/${USER}/freebsd-root
```

You must also customize `BERI_DE4_MDROOT` in order to notify it of the memory location of the root file system image. Modify the following section of its configuration file to reflect actual image location and size:

```
options MD_ROOT # MD is a potential root device
options MD_ROOT_SIZE="26112"
makeoptions MFS_IMAGE=/pool/users/${USER}/mdroot.img
options ROOTDEVNAME=\"ufs:md0\"
```

Once the root file system image is generated, and the kernel configuration file generated, you can build the kernel:

```
$ cd /pool/users/${USER}/freebsd
$ make -j 16 TARGET=mips TARGET_ARCH=mips64 buildkernel \
  KERNCONF=BERI_DE4_MDROOT
```

The resulting kernel can be found in your MAKEOBJDIRPREFIX tree.

2.5 Preparing a FreeBSD SD Card image

Build and install world and distribution as described in earlier sections. Then build and install a kernel using the configuration file BERI_DE4_SDRROOT. Apply a few tweaks to configuration files, then use the `makefs` command to generate a UFS image file:

```
# echo "/dev/altera_sdcard0 / ufs rw 1 1" > \
  /pool/users/${USER}/freebsd-root/etc/fstab
# RCCONF=/pool/users/${USER}/freebsd-root/etc/rc.conf
# cat > ${RCCONF} <<EOF
hostname="beril"
sendmail_submit_enable="NO"
sendmail_outbound_enable="NO"
cron_enable="NO"
tmpmfs="YES"
EOF
# METALOG=/pool/users/${USER}/freebsd-root/METALOG
# echo "./etc/fstab type=file uname=root gname=wheel mode=0644" >> \
  ${METALOG}
# echo "./etc/rc.conf type=file uname=root gname=wheel mode=0644" >> \
  ${METALOG}
# cd /pool/users/${USER}/freebsd-root && makefs -B big -s 1886m -D \
  -N /pool/users/${USER}/freebsd-root/etc \
  /pool/users/${USER}/beribsd-sdcard.img METALOG
```

This command creates a big-endian file system of size 1,977,614,336 bytes – the size of the Terasic 2 GB SD Cards shipped with the tPad and DE4 boards. The resulting `beribsd-rootfs.img` can then be installed on an SD Card using `dd` as described in later sections.

If a smaller file system is desired (e.g. quicker to prepare and write to the SD card) then size 1,977,614,336 bytes (2GiB) can be replaced by `512m` or the `-s` argument can be omitted entirely to create a minimally sized root image.

2.6 Automated builds

The set of files described in Chapter 3 can be built with the help of the Makefile in `ctsrd/cheribsd/trunk/bsdtools`. The template config file in `Makefile.conf.template` can be copied to `Makefile.conf` and customized to your environment. The `worlds` target runs the `buildworld`, `installworld`, and `distribution` for each source tree. The `images` target builds file system images from the installed root directories. The `kernels` target builds kernels, including MDROOT kernels with images build by `images` target. The `flash` target build flash preparation images for each kernel. Finally, the `dated` target makes dated stamped files of each compressed kernel and image.

All these targets support the make flag `-j`. We strongly encourage passing an appropriate value to `-j`. In addition to standard FreeBSD tools, the Makefile requires installation of the `archives/pxz` port.

Chapter 3

Using FreeBSD/BERI

This chapter describes the installation and use of FreeBSD/BERI on the Terasic DE4 FPGA board. We have structured our modifications to FreeBSD into two development branches:

- FreeBSD/BERI is a version of FreeBSD that can run on the BERI hardware-software research platform as a general-purpose OS.
- CheriBSD is a version of FreeBSD/BERI that has been enhanced to make use of CHERI's experimental capability coprocessor features.

At the time of writing, FreeBSD has been modified to support a number of BERI features, such as peripheral devices present on the Terasic DE4 board. CheriBSD extends FreeBSD/BERI to initialize and maintain CHERI coprocessor registers; more information on CheriBSD can be found in the *CHERI User's Guide*.

3.1 Getting started with FreeBSD

To get started with FreeBSD/BERI, you need the following:

- Ubuntu development PC
- Altera Quartus 12 tools
- Terasic DE4 board with 1GB DRAM
- 2GB SD card¹
- BERI bitfile targeted for the Terasic DE4
- Pre-built or custom-compiled FreeBSD kernel
- Pre-built or custom-compiled FreeBSD root file system image

¹Note: Altera's SD Card IP Core does not support SD cards larger than 2GB.

Synchronized versions of BERI bitfiles and FreeBSD must be used together: as the prototype evolves, hardware-software interfaces change, as do board configurations, and mismatched combinations will almost certainly function incorrectly. The installed Quartus toolchain should also match the one used to generate the bitfile being programmed, in order to avoid documented incompatibility.

The remainder of the chapter describes how to obtain FreeBSD kernels and root file system images, write the FreeBSD root file system image onto the SD card, program the Terasic DE4 FPGA with a BERI bitfile, set up the JTAG debugging tunnel so that the `berictl` tool can manipulate BERI via its debug unit, connect to the BERI console using `nios2-terminal` over JTAG, and optionally re-flash the DE4's on-board CFI flash with a bitfile and kernel to avoid the need to program them via JTAG on every boot.

3.1.1 Obtaining FreeBSD/BERI

Early adopter pre-generated images of FreeBSD/BERI and CheriBSD may currently be obtained from the password protected early adopters page <https://www.cl.cam.ac.uk/research/security/ctsrds/cheri-early/>. If you require access, please contact Robert Watson.

Additionally, FreeBSD/BERI and CheriBSD may be built from source code using the instructions found in Chapter 2. Finally, pre-compiled snapshots of key files and images may be found, for the time being, in `/usr/groups/ctsrds/cheri` in the Cambridge environment. Each file is named based on the date it was generated, consisting of `YYYYMMDDv` where `v` is an optional letter indicating further builds that occurred on the same day.

Table 3.1 describes file types that may be found in on the early adopters page and in the above mentioned directory; all bitfiles and kernels are compressed using `bzip2` and all file system images are compressed with `xz`. File systems images must be decompressed before they can be used. Files passed to `berictl` may be uncompressed; alternatively, the `-z` flag may be used to decompress them on the fly.

3.1.2 Writing out the SD Card disk image

To use FreeBSD/BERI with an SD Card root file system, write out the file system image on an existing Mac, FreeBSD, Linux, or Windows workstation. The following command is typical for a UNIX system; ensure that the disk device name here is actually your SD Card and not another drive!

```
$ dd if=annabella-beribsd-sdcard.img of=/dev/disk1 bs=512
```

On Mac OS X, `diskutil list` may be used to list possible devices to write to. You may need to use `diskutil unmountDisk` (or `DiskUtility.app`) to first unmount an auto-mounted FAT file system if one existed when the card was inserted. Note that SD cards should not be initialized with FAT or other file systems, and such file systems may need to be unmounted before the first image is written to an SD Card; disk images include a complete UFS file system intended to be written directly to the SD card starting at the first block.

3.1.3 Setting up the DE4 development environment

Many commands in the chapter depend on Altera Quartus 12 tools. Specifically, the `nios2-terminal` must be in the user's `PATH`, and the `system-console` command must be available.

In the Cambridge environment, setup can be accomplished by configuring the CHERI build environment:

Filename	Description
<code>beribsd-de4-kernel-demo-mdroot</code>	DE4 kernel with built-in memory root file system of CTSRD demos
<code>beribsd-de4-kernel-net-mdroot</code>	DE4 kernel with built-in memory root file system with basic network tools
<code>beribsd-de4-kernel-singleuser-mdroot</code>	DE4 kernel with built-in memory root file system that drops to single user mode with limited tools
<code>beribsd-de4-kernel-sdroot</code>	DE4 kernel using an SD Card as a root file system
<code>beribsd-sim-kernel-mdroot</code>	Simulation kernel with build-in memory root file system
<code>beribsd-sim-kernel-mdroot</code>	Simulation kernel a simulated SD Card as a root file system
<code>beribsd-sdcard.img</code>	SD Card root file system image
<code>cheribsd-*</code>	Same as similarly named <code>beribsd-*</code> files
<code>cheri-bitfile.bin</code>	Altera bitfile for CHERI processor in binary format (suitable for writing to flash)
<code>cheri-bitfile.sof</code>	Altera bitfile for CHERI processor in SOF format (for use with Altera tools)
<code>cfi0-de4-terasic</code>	Vanilla CFI flash <code>cfi0</code> image for the DE4

Table 3.1: Binary files available for FreeBSD/BERI. `-dump` files will sometimes also be present, which contain `objdump -dS` output for kernels and other binaries. Releases will have the release name (e.g. `ambrunes-`) prepended and snapshots a date string.

```
$ source ctsrd/cheri/trunk/setup.sh
```

A default user install of the Quartus 12 toolkit will also accomplish setup, so long as the `~/bin` directory is in the user's path.

The `berictl` command controls various aspects of CPU and board behavior. For example, it can be used to inspect register state, modify control flow, and load data into memory. `berictl` works with BERI in both simulation and in FPGA. Build `berictl` using the following commands:

```
$ cd ctsrd/cherilibs/trunk/tools/debug
$ make
```

For users without access to the Subversion repository, statically linked versions of `berictl` are distributed along with each BERI release.

3.1.4 JTAG

Many hardware debugging functions rely on JTAG, which allows a host Linux workstation to program the FPGA board, read and write DRAM on the board, and also interact with the CHERI debug unit for the purposes of low-level system software debugging. Use of JTAG requires that a USB cable be connected from your Linux workstation to the Terasic DE4 board. In the remaining sections, JTAG will be used to access four different debugging functions:

- programming the FPGA (via `berictl loadsof`);
- BERI's JTAG UART console (via `berictl console`);
- direct DRAM manipulation (via `berictl loadbin` or `berictl loadram`);
- and to use BERI's debug unit (most other `berictl` commands).

3.1.5 berictl

`berictl` is a front-end to a variety of development and debugging features associated with the BERI processor, both in simulation and when synthesized to FPGA. `berictl` will generally communicate with the BERI debug unit over JTAG or a socket.

3.2 Programming the DE4 FPGA

FPGA designs are encapsulated in a *bitfile*, which can be programmed dynamically using JTAG, or from the on-board CFI flash on the DE4 when the board is powered on. The former configuration will be used most frequently during development of processor or other hardware features; the latter will be used most frequently when developing software to run on BERI, as it effectively treats the board as a stand-alone computer whose firmware (and hence CPU!) may occasionally be upgraded. The DE4's FPGA may be programmed as follows:

```
$ cd ctsrd/cherilibs/trunk/tools/debug
$ ./berictl loadsof -z annabella-cheri-bitfile.sof.bz2
```

Note well: you must terminate all `berictl` and `nios2-terminal` sessions connected to the DE4 before using `berictl`'s `loadsof` command. If you do not the board may not be reprogrammed or instances of `system-console` may crash.

3.2.1 Writing an FPGA bitfile to DE4 flash from FreeBSD

When powered on, the Terasic DE4 board will attempt to automatically load a bitfile from the on-board CFI flash. New FPGA bitfiles in binary format may be written to the flash from FreeBSD; they take effect during the board's next power-cycle. This write operation can be done using `dd` (note the skipping of the first 128k):

```
# dd if=annabella-cheri-de4-bitfile.bin of=/dev/cfid0s.fpga0 isseek=256 \
    conv=oseek
```

Bitfiles in SOF format can be converted to binary format using the `sof2flash.sh` script found in the CTSRD Subversion repository at `cherilibs/trunk/tools/sof2bin.sh`.

To simplify the process and add reliability, a script called `/usr/sbin/flashit` performs these actions after verifying the MD5 checksum of the files and optionally decompressing `bzip2` compressed images. Note that if `flashit` is writing a file `foo` a corresponding `foo.md5` file must exist. In addition to FPGA images, `flashit` can be used to write kernel images by replacing the `fpga` argument with `kernel`.

```
# flashit fpga Design.bin
```

Power to the board must not be lost during reflash, as this may corrupt the bitfile and prevent programming of the board on power-on. Therefore, battery-backed DE4 boards should be programmed only while fully charged.

3.3 Start a console

Connect to the BERI JTAG UART using:

```
$ berictl console
```

The console may be terminated by typing `~.` (tilde followed by period) after a newline. If connecting to the console via `ssh` or other network terminal programs an appropriate number of `~` characters must be used as most use the same escape sequence. *Note: `berictl` starts an instance of `nios2-terminal` to connect to the console so it must be terminated before a kernel image or bitfile can be loaded.*

3.4 Models for booting a FreeBSD/BERI kernel

FreeBSD kernels may be booted via two different means: installation on the on-board CFI flash device on the Terasic DE4, or direct insertion of the kernel into DRAM using `berictl` via JTAG. The micro-boot loader embedded in ROM in CHERI on the DE4, `miniboot`, uses the `USER_DIP1` switch to control

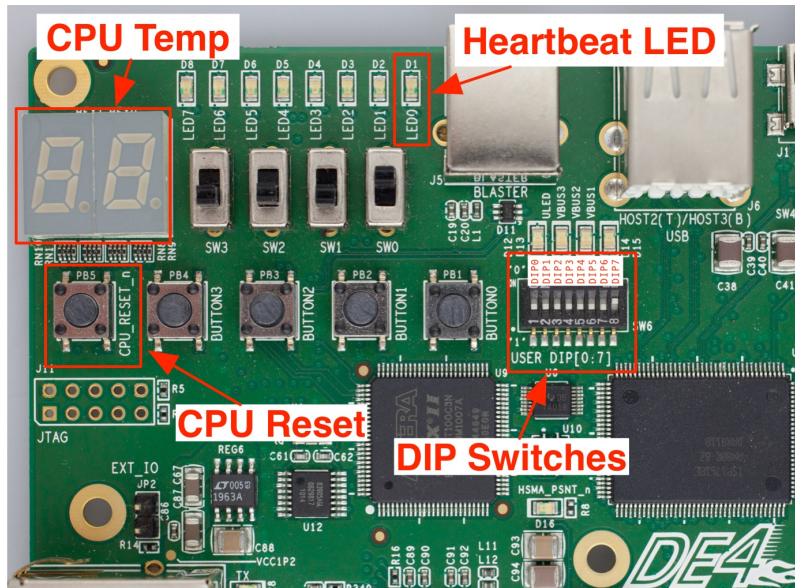


Figure 3.1: Buttons and switches on the DE4

whether a kernel is relocated from flash or started directly. Note that DIP switches are numbered 0-7, but the physical package has labels 1-8. The proper labels can be seen in Figure 3.1.

USER_DIP0 controls whether `miniboot` runs immediately or whether it spins while waiting for register 13 to become 0 before booting the kernel, leaving time for the kernel to be injected into DRAM following programming of the FPGA. Register 13 would normally be set to 0 using the debug unit.

3.4.1 Load a kernel into DRAM over JTAG

To load the kernel into DDR2 memory, load it at the physical address `0x100000` where `miniboot` boot loader expects to find it. `miniboot` reads the ELF header in order to determine the kernel start address. You can then use `berictl loadbin2` to load the kernel to DDR2 memory starting at address `0x100000` (also see note below about USER_DIP0 and USER_DIP1):

```
$ cd ctsrd/cherilibs/trunk/tools/debug
$ ./berictl loadbin -z cheribsd-de4-kernel-sdroot.bz2 0x100000
```

To boot a kernel thus loaded, you must ensure that both USER_DIP0 and USER_DIP1 are on (toward the top of the board where the USB blaster is connected). USER_DIP0 will cause the processor to spin in very early boot, waiting for register 13 to become 0. This boot operation can be accomplished through the debug command:

```
$ ./berictl boot
```

USER_DIP1 will skip the relocation from flash routine that would overwrite your freshly inserted kernel.

²Some users may be able to use the faster `berictl loadram` command, but it is broken for most configuration at this time as it relies on undocumented Altera internals that have changed in recent releases.

3.4.2 Load a kernel into flash from FreeBSD

From FreeBSD you can use `dd` or the `flashit` script to load a kernel to flash:

```
# dd if=kernel of=/dev/map/kernel conv=osync
```

The safer option using `flashit` allows compresses the kernel with `bzip2` or `gzip`, and requires a `.md5` file to exist containing the md5 output for the file:

```
# ls kernel.bz2*
kernel.bz2  kernel.bz2.md5
# flashit kernel kernel.bz2
```

At boot, a kernel written to flash will be relocated to DRAM and executed if `USER_DIP1` is set to off. This relocation will occur at power on if `USER_DIP0` is off, or when `berictl boot` is run if it is on.

3.5 Start kernel execution

If `USER_DIP0` is set to on, then resume the processor after power on/reset:

```
$ ./berictl boot
```

If the DIP switch is unset, then boot will proceed as soon as the FPGA is programmed, either using JTAG or from flash. If all has gone well, you should see kernel boot messages in output from the console. If you are using the `BERI_DE4_MDROOT` or `CHERI_DE4_MDROOT` kernel configuration, a memory root file system will be used; single or multi-user mode should be reached, depending on the image. If you are using the `BERI_DE4_SDROOT` or `CHERI_DE4_SDROOT` kernel configuration, the SD Card should be used for the root file system, and multi-user mode should be reached. Be warned that the SD-card IP core provided by Altera is extremely slow (100KB/s), and so multi-user boots can take several minutes.

3.6 Post boot issues

After boot, FreeBSD/BERI is much like any FreeBSD system with a similar set of components. There are a few issues to keep in mind

- The MDROOT kernels are space limited and have minimal set of tools available.
- Since the root file systems of MDROOT kernels are stored in memory, all configuration including ssh keys will be lost at reboot time.
- The SD Card images are kept relatively small to accelerate writes to the (often very slow) cards, to support multiple card sizes.
- The Ethernet controllers have no default source of unique MAC addresses and thus default to a random address that changes each boot.
- The MIPS soft reset in instruction is not currently implemented, so rebooting consists of a clean shutdown followed by booting as per the instructions above. The easiest software reboot mechanism is reprogramming the FPGA.

3.6.1 Increasing the size of an SD Card root file system

After boot, you can extend the file system to the size of the SD Card using FreeBSD's `growfs` command:

```
$ growfs -y /dev/altera_sdcard0
```

Before running this command, make sure your file system is backed up or easily replaceable.

3.6.2 Setting a MAC address

The Altera Triple-Speed Ethernet (ATSE) devices obtain a unique MAC address from the configuration area at the beginning of the CFI flash. Unfortunately, all DE4 boards come from the factory with the same MAC address, so that address has been blacklisted by the driver; instead, a random address is generated at boot for each interface.

An address can be written to the DE4 using the `atsectl` command. An address derived from the factory PPR on the Intel StrataFlash on the DE4 can be written with the command:

```
$ atsectl -u
```

The default address has the locally administered bit set and uses the Altera prefix dedicated to this purpose.

In the Cambridge environment, the decision was made to not set the locally administered bit. This can be accomplished with the command:

```
$ atsectl -gu
```

If the board was configured following the *DE4 Factory Install Guide v1.0*, then an Altera prefixed MAC without the locally administered bit will have been installed on the DE4.

Chapter 4

FreeBSD/BERI Device-Driver Reference

This chapter provides reference information for BERI- and CHERI-specific device drivers and features. Most device drivers are also documented in `man` pages in the FreeBSD/BERI distribution.

4.1 Device drivers for Altera IP cores

FreeBSD/BERI provides device drivers for a number of useful IP cores and peripheral devices on the Terasic tPad and Terasic DE4 teaching boards. The drivers are statically linked into the reference BERI kernels; because the Avalon bus does not support auto-configuration and device enumeration, these drivers are also statically configured into the kernel using FDT DTS files. `device.hints` may also be used to configure these devices; examples of each are included in this chapter.

4.1.1 Altera JTAG UART

The Altera JTAG device driver implements FreeBSD low-level console and TTY interfaces for the Altera JTAG UART, which can be connected to using `nios2-terminal` to provide a system console for FreeBSD/BERI. This driver assumes that the low-level console JTAG UART will always be configured at a fixed physical address, and so cannot be configured using FDT or `device.hints` files. However, high-level console support is entirely configurable. The device name for the first Altera JTAG UART is `/dev/ttyu0`.

Note: the Altera JTAG UART is not the same IP core as the Altera UART intended to be used with the RS232 serial port on the Terasic DE4, which is currently unsupported in FreeBSD/BERI, and not configured in our reference DE4 design.

Kernel Configuration

```
device          altera_jtag_uart
```

FDT

```
serial@7f000000 {
    compatible = "altera,jtag_uart-11_0";
    reg = <0x7f000000 0x40>;
    interrupts = <0>;
```

```
};

serial@7f001000 {
    compatible = "altera,jtag_uart-11_0";
    reg = <0x7f001000 0x40>;
};

serial@7f002000 {
    compatible = "altera,jtag_uart-11_0";
    reg = <0x7f002000 0x40>;
};
```

device.hints

```
#
# Altera JTAG UARTs configured for console, debugging, and
# data putput on the DE4.
#
hint.altera_jtag_uart.0.at="nexus0"
hint.altera_jtag_uart.0.maddr=0x7f000000
hint.altera_jtag_uart.0.msize=0x40
hint.altera_jtag_uart.0.irq=0

hint.altera_jtag_uart.1.at="nexus0"
hint.altera_jtag_uart.1.maddr=0x7f001000
hint.altera_jtag_uart.1.msize=0x40

hint.altera_jtag_uart.2.at="nexus0"
hint.altera_jtag_uart.2.maddr=0x7f002000
hint.altera_jtag_uart.2.msize=0x40
```

/etc/ttys

```
# Altera JTAG UART
ttyj0    "/usr/libexec/getty std.115200" xterm    on    secure
ttyj1    "/usr/libexec/getty std.115200" xterm    on    secure
ttyj2    "/usr/libexec/getty std.115200" xterm    on    secure
```

4.1.2 Generic Avalon device driver

The Generic Avalon device driver exports a region of physical memory, typically representing a memory-mapped device on the Avalon bus, to userspace processes via a device node. User processes can perform I/O on the device using the POSIX `read` and `write` system call APIs, but can also map the device into virtual memory using the `mmap` API. Device instances are configured using `BERI.hints` entries, which specify the base, length, and mapping properties of the memory region, as well as any I/O alignment requirements and restrictions (e.g., a read-only, 32-bit access only).

The following example instantiates a `berirom` device node representing physical memory starting at `0x7f00a000` and continuing for 20 bytes on the Avalon bus. I/O must be performed with 32-bit alignment; data may be both read and written using the POSIX file APIs, and may not be memory-mapped.

Currently, the `avgen` device does not support direction of interrupts to userspace components, but we hope to add this function in the future, in which case it will likely be exposed using the `kqueue` and `poll` APIs.

Kernel Configuration

```
device            altera_avgen
```

FDT

```
avgen@0x7f00a000 {
    compatible = "sri-cambridge,avgen";
    reg = <0x7f00a000 0x14>;
    sri-cambridge,width = <4>;
    sri-cambridge,fileio = "rw";
    sri-cambridge,devname = "berirom";
};
```

device.hints

```
hint.altera_avgen.0.at="nexus0"
hint.altera_avgen.0.maddr=0x7f00a000
hint.altera_avgen.0.msize=20
hint.altera_avgen.0.width=4
hint.altera_avgen.0.fileio="rw"
hint.altera_avgen.0.devname="berirom"
```

4.1.3 Altera University Program SD Card IP core

This device driver implements FreeBSD block storage device interfaces for the Altera University Program SD Card IP core. Currently, the driver supports only CSD structure 0 SD Cards, limited to 2 GB in size. This limitation may also apply to the Altera SD Card IP Core. SD Card devices appear in `/dev` as they are inserted, and will typically be named `/dev/altera_sdcard0`; FreeBSD's GEOM framework will automatically discover partitions on the disk, causing additional device nodes for those partitions to appear as well – for example, `/dev/altera_sdcard0s1` for the first MBR partition.

Kernel Configuration

```
device            altera_sdcard
```

FDT

```
sdcard@7f008000 {
```

```

        compatible = "altera,sdcard_11_2011";
        reg = <0x7f008000 0x400>;
};

```

device.hints

```

hint.altera_sdcardc.0.at="nexus0"
hint.altera_sdcardc.0.maddr=0x7f008000
hint.altera_sdcardc.0.msize=0x400

```

4.1.4 Altera Triple-Speed Ethernet

The `atse(4)` driver implements a FreeBSD Ethernet interface for the Altera Triple-Speed Ethernet IP core. The driver currently supports *only gigabit Ethernet* (no 10/100). Interfaces must be configured in polling mode. In FreeBSD this may be accomplished with a line like this in `/etc/rc.conf`. (This example also causes the interface to be configured using DHCP.)

```
ifconfig_atse0="polling DHCP"
```

`atse(4)` devices are discovered by FDT, but `device.hints` entries are currently required to properly configure the PHYs for each device.

Kernel Configuration

```

device            altera_atse

device            ether
device            miibus
options            DEVICE_POLLING

```

FDT

```

ethernet@7f007000 {
    compatible = "altera,atse";
    /* MAC, RX+RXC, TX+TXC. */
    reg = <0x7f007000 0x400
          0x7f007500 0x8
          0x7f007520 0x20
          0x7f007400 0x8
          0x7f007420 0x20>;
    /* RX, TX */
    interrupts = <1 2>;
};

ethernet@7f005000 {
    compatible = "altera,atse";

```

```

/* MAC, RX+RXC, TX+TXC. */
reg = <0x7f005000 0x400
      0x7f005500 0x8
      0x7f005520 0x20
      0x7f005400 0x8
      0x7f005420 0x20>;
};

```

device.hints

```

#
# Altera Triple-Speed Ethernet Mac, present in tPad and DE4
# configurations
#
hint.atse.0.at="nexus0"
hint.atse.0.maddr=0x7f007000
hint.atse.0.msize=0x400
hint.atse.0.tx_maddr=0x7f007400
hint.atse.0.tx_msize=0x8
hint.atse.0.txc_maddr=0x7f007420
hint.atse.0.txc_msize=0x20
hint.atse.0.tx_irq=2
hint.atse.0.rx_maddr=0x7f007500
hint.atse.0.rx_msize=0x8
hint.atse.0.rxc_maddr=0x7f007520
hint.atse.0.rxc_msize=0x20
hint.atse.0.rx_irq=1

#
# Altera Triple-Speed Ethernet Mac, present in tPad and DE4
# configurations
# configured from fdt(4) but PHYs are still described in here.
# Currently configured for individual tse_mac cores.
#
hint.e1000phy.0.at="miibus0"
hint.e1000phy.0.phyno=0
hint.e1000phy.1.at="miibus0"
hint.e1000phy.1.phyno=0
hint.e1000phy.2.at="miibus0"
hint.e1000phy.2.phyno=0
hint.e1000phy.3.at="miibus0"
hint.e1000phy.3.phyno=0

```

4.2 Device drivers for Terasic components

FreeBSD/BERI provides device drivers for several devices on the Terasic DE4 and Terasic tPad teaching boards. As with Altera device drivers, Terasic device drivers are statically linked into the FreeBSD kernel, and configured using `BERI.hints`.

4.2.1 Terasic DE4 8-element LED

The Terasic DE4 device driver implements FreeBSD LED interfaces for the Terasic DE4 8-element LED, which may be written to as described in the FreeBSD `led(4)` man page. Device nodes appear in `/dev/led`, with names using the scheme `de4led_0`, `de4led_1`, and so on.

The following command at the FreeBSD/BERI shell will cause DE4 LED 1 to blink roughly once a second:

```
$ echo f9 > /dev/led/de4led_1
```

Kernel Configuration

```
device          terasic_de4led
```

FDT

```
led@7f006000 {
    compatible = "sri-cambridge,de4led";
    reg = <0x7f006000 0x1>;
};
```

device.hints

```
hint.terasic_de4led.0.at="nexus0"
hint.terasic_de4led.0.maddr=0x7f006000
hint.terasic_de4led.0.msize=1
```

4.2.2 Common Flash memory interface

FreeBSD/BERI includes an improved version of the `cfi(4)` driver that supports Intel, Sharp, and AMD NOR flash with respect to the *Common Flash memory Interface* (CFI) standard. The `cfi(4)` is used to support to the Intel StrataFlash found on the DE4. The flash is both configured and partitioned using FDT via the `geom_flashmap(4)` driver. Partitions are accessible at `/dev/<device>s.<label>` for example `/dev/cfid0s.os`.

Kernel Configuration

```
device          cfi
device          cfid
options          CFI_SUPPORT_STRATAFLASH
```


FDT

```
flash@74000000 {
    #address-cells = <1>;
    #size-cells = <1>;
    compatible = "cfi-flash";
    reg = <0x74000000 0x4000000>;

    /* Board configuration */
    partition@0 {
        reg = <0x0 0x20000>;
        label = "config";
    };

    /* Power up FPGA image */
    partition@20000 {
        reg = <0x20000 0xc00000>;
        label = "fpga0";
    };

    /* Secondary FPGA image (on RE_CONFIGn button) */
    partition@C20000 {
        reg = <0xc20000 0xc00000>;
        label = "fpga1";
    };

    /* Space for operating system use */
    partition@1820000 {
        reg = <0x1820000 0x027c0000>;
        label = "os";
    };

    /* Second stage bootloader */
    partition@3fe0000 {
        reg = <0x3fe0000 0x20000>;
        label = "boot";
    };
};
```

4.2.3 Flash partitioning

This section documents use of `device.hints` to configure regions of the flash as separate `/dev/map` partitions via the `geom_map(4)` driver. We use `/dev/map` partitions for backwards compatibility and to provide easy access to regions not defined by the hardware.

Kernel Configuration

```
device                geom_map
```

device.hints

```
# Hardwired location of bitfile
hint.map.0.at="cfid0s.fpga0"
hint.map.0.start=0x00000000
hint.map.0.end=0x00c00000
hint.map.0.name="fpga"

# Kernel in the middle of the operating system partition
hint.map.1.at="cfid0s.os"
hint.map.1.start=0x007e0000
hint.map.1.end=0x01fe0000
hint.map.1.name="kernel"
```

4.2.4 Cambridge/Terasic Multi-Touch LCD Display (MTL)

The `terasic_mtl` device driver implements a set of device nodes representing various aspects of the Terasic MTL as interfaced with using the Cambridge IP core. These device nodes implement POSIX I/O and memory-mapped interfaces to the register interface, text frame buffer, and pixel frame buffer, respectively.

Kernel Configuration

```
device                terasic_mtl
```

FDT

```
touchscreen@70400000 {
    compatible = "sri-cambridge,mtl";
    reg = <0x70400000 0x1000
           0x70000000 0x177000
           0x70177000 0x2000>;
};
```

device.hints

```
hint.terasic_mtl.0.at="nexus0"
hint.terasic_mtl.0.reg_maddr=0x70400000
hint.terasic_mtl.0.reg_msize=0x1000
hint.terasic_mtl.0.pixel_maddr=0x70000000
hint.terasic_mtl.0.pixel_msize=0x177000
hint.terasic_mtl.0.text_maddr=0x70177000
hint.terasic_mtl.0.text_msize=0x2000
```