

SoC-FPGA Design Guide

LAP – IC – EPFL

Version 1.08

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4 INTRODUCTION

The development of embedded systems based on chips containing one or more microprocessors and hardcore peripherals, as well as an FPGA part is becoming more and more important. This technology gives the designer a lot of freedom and powerful abilities. Classical design flows with microcontrollers are emphasized with the full power of FPGAs.

Mixed designs are becoming a reality. One can now design specific accelerators to greatly improve algorithms, or create specific programmable interfaces with the external world.

Two main HDL (**H**ardware **D**esign **L**anguage) languages are available for the design of the FPGA part: **VHDL** and Verilog. There also exist other tools that perform automatic translations from C to HDL. New emerging technologies like OpenCL allow compatibility between high-level software design, and low-level hardware implementations such as:

- Compilation for single or multicore processors
- Compilation for GPUs (Graphical Processing Unit)
- Translation and compilation for FPGAs. The latest models use a PCIe interface or some other way of parameters passing between the main processor and the FPGA

*This guide assumes users know how to use **QUARTUS PRIME**, **NIOS II**, **QSYS** and **MODELSIM-ALTERA**.*

*All **HARDWARE AND SOFTWARE EXAMPLES** in this guide were made with Quartus Prime, SoC EDS and Nios II Software Build Tools version **15.1**.*

***SOME FIGURES** in this guide were made with Quartus Prime, SoC EDS and Nios II Software Build Tools version **14.0**.*

We will introduce and use the Terasic [DE1-SoC](#) board, as well as the ARM DS-5 IDE.

5 Terasic DE1-SoC BOARD

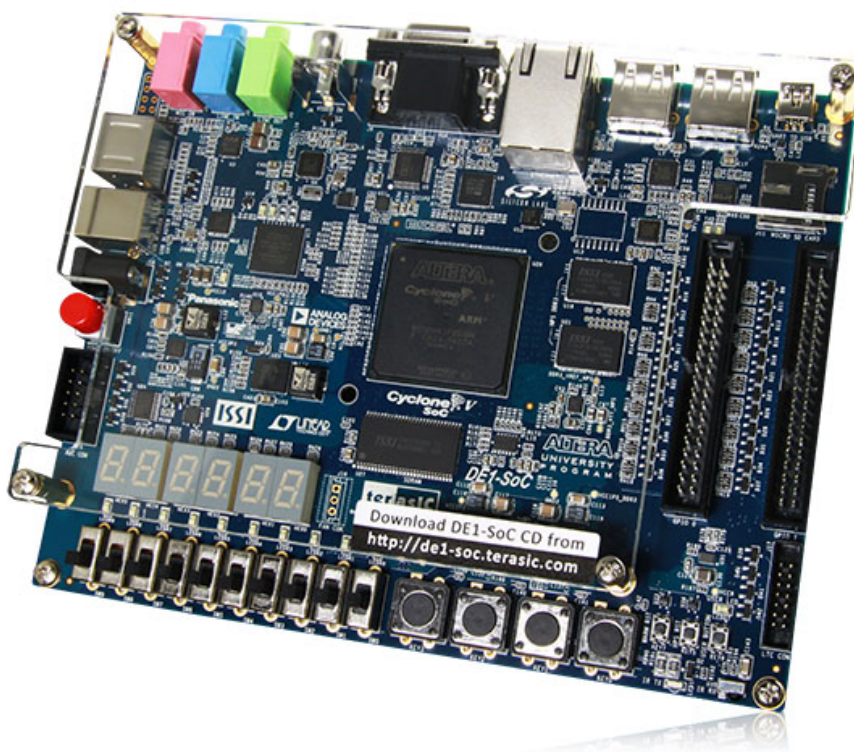


Figure 5-1. Terasic DE1-SoC Board [1]

The DE1-SoC board has many features that allow users to implement a wide range of designed circuits. We will discuss some noteworthy features in this guide.

5.1 SPECIFICATIONS

5.1.1 FPGA Device

- Cyclone V SoC **5CSEMA5F31C6** Device
- Dual-core **ARM CORTEX-A9** (HPS)
- **85K** Programmable Logic Elements
- 4'450 Kbits embedded memory
- 6 Fractional PLLs
- 2 Hard Memory Controllers (only seems to be used for the HPS DDR3 SDRAM, not the FPGA SDRAM)

5.1.2 Configuration and Debug

- Quad Serial Configuration device – **EPCQ256** on FPGA
- On-Board **USB BLASTER II** (Normal type B USB connector)

5.1.3 Memory Device

- **64 MB** (32Mx16) SDRAM on FPGA
- **1 GB** (2x256Mx16) DDR3 SDRAM on HPS
- **MICRO SD** Card Socket on HPS

5.1.4 Communication

- Two Port USB 2.0 Host (ULPI interface with USB type A connector)
- USB to UART (micro USB type B connector)
- 10/100/1000 Ethernet
- PS/2 mouse/keyboard
- IR Emitter/Receiver

5.1.5 Connectors

- Two 40-pin Expansion Headers
- One 10-pin ADC Input Header
- One LTC connector (One Serial Peripheral Interface (SPI) Master, one I2C and one GPIO interface)

5.1.6 Display

- 24-bit VGA DAC

5.1.7 Audio

- 24-bit CODEC, line-in, line-out, and microphone-in jacks

5.1.8 Video Input

- TV Decoder (NTSC/PAL/SECAM) and TV-in connector

5.1.9 ADC

- Fast throughput rate: 1 MSPS
- Channel number: 8
- Resolution: 12 bits
- Analog input range : 0 ~ 2.5 V or 0 ~ 5V as selected via the RANGE bit in the control register

5.1.10 Switches, Buttons and Indicators

- 4 User Keys (FPGA x4)
- 10 User switches (FPGA x10)
- 11 User LEDs (FPGA x10; HPS x 1)
- 2 HPS Reset Buttons (HPS_RST_n and HPS_WARM_RST_n)
- Six 7-segment displays

5.1.11 Sensors

- G-Sensor on HPS

5.1.12 Power

- 12V DC input

5.1.13 Block Diagram

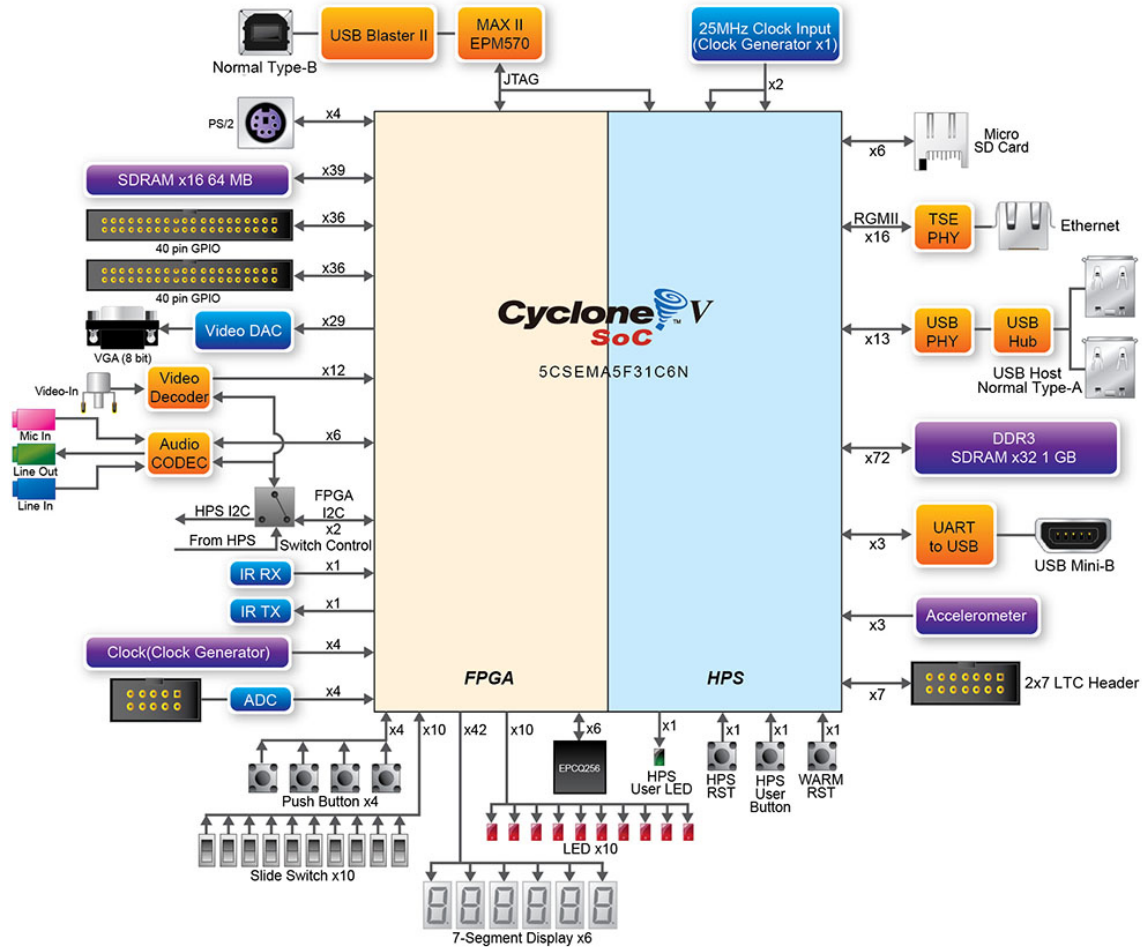


Figure 5-2. Block Diagram of the DE1-SoC Board [1]

5.2 LAYOUT

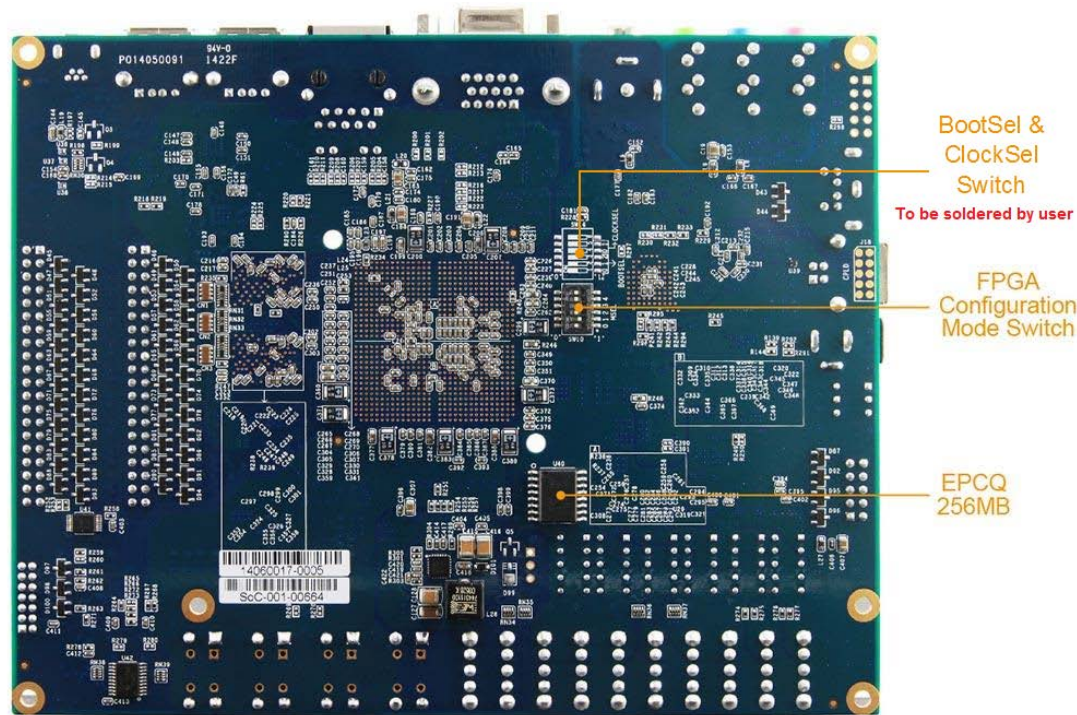


Figure 5-3. Back [1]



Figure 5-4. Front [1]

- Green for peripherals directly connected to the FPGA
- Orange for peripherals directly connected to the HPS
- Blue for board control

6 CYCLONE V OVERVIEW

This section describes some features of the Cyclone V family of devices. We do not list all features, but only the ones most important to us. All information below, along with the most complete documentation regarding this family can be found in the Cyclone V Device Handbook [2].

6.1 INTRODUCTION TO THE CYCLONE V HARD PROCESSOR SYSTEM

The Cyclone V device is a single-die system on a chip (SoC) that consists of two distinct parts – a hard processor system (HPS) portion and an FPGA portion.

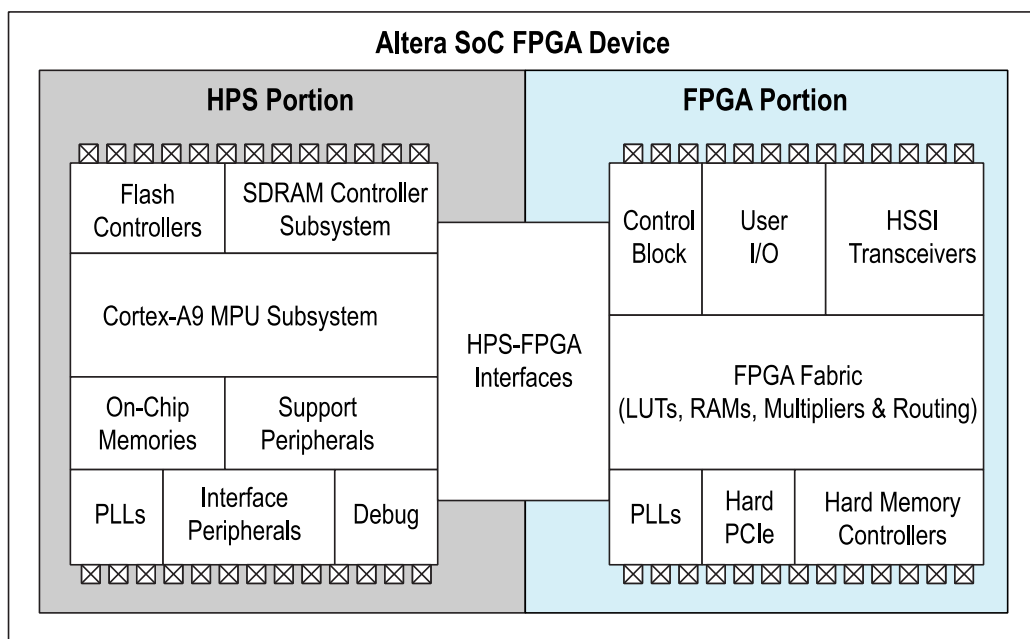


Figure 6-1. Altera SoC FPGA Device Block Diagram [2, pp. 1-1]

The HPS contains a microprocessor unit (MPU) subsystem with single or dual ARM Cortex-A9 MPCore processors, flash memory controllers, SDRAM L3 Interconnect, on-chip memories, support peripherals, interface peripherals, debug capabilities, and phase-locked loops (PLLs). The dual-processor HPS supports symmetric (SMP) and asymmetric (AMP) multiprocessing.

*The DE1-SoC has a **DUAL**-processor HPS.*

The FPGA portion of the device contains the FPGA fabric, a control block (CB), phase-locked loops (PLLs), and depending on the device variant, high-speed serial interface (HSSI) transceivers, hard PCI Express (PCIe) controllers, and hard memory controllers.

The DE1-SoC does not contain any HSSI transceivers, or hard PCIe controllers.

The HPS and FPGA portions of the device are distinctly different. The HPS can boot from

- the FPGA fabric,
- external flash, or
- JTAG

In contrast, the FPGA must be configured either through

- the HPS, or
- an externally supported device such as the *Quartus Prime* programmer.

The MPU subsystem can boot from

- flash devices connected to the HPS pins, or
- from memory available on the FPGA portion of the device (when the FPGA portion is previously configured by an external source).

The HPS and FPGA portions of the device each have their own pins. Pins are not freely shared between the HPS and the FPGA fabric. The **FPGA I/O PINS** are configured by an **FPGA CONFIGURATION IMAGE** through the HPS or any external source supported by the device. The **HPS I/O PINS** are configured by **SOFTWARE** executing in the HPS. Software executing on the HPS accesses control registers in the Cyclone V system manager to assign HPS I/O pins to the available HPS modules.

*The **SOFTWARE** that configures the **HPS I/O PINS** is called the **PRELOADER**.*

The HPS and FPGA portions of the device have separate external power supplies and independently power on. You can power on the HPS without powering on the FPGA portion of the device. However, to power on the FPGA portion, the HPS must already be on or powered on at the same time as the FPGA portion. Table 6-1 summarizes the possible configurations.

HPS Power	FPGA Power
On	On
On	Off
Off	Off

Table 6-1. Possible HPS and FPGA Power Configurations

6.2 FEATURES OF THE HPS

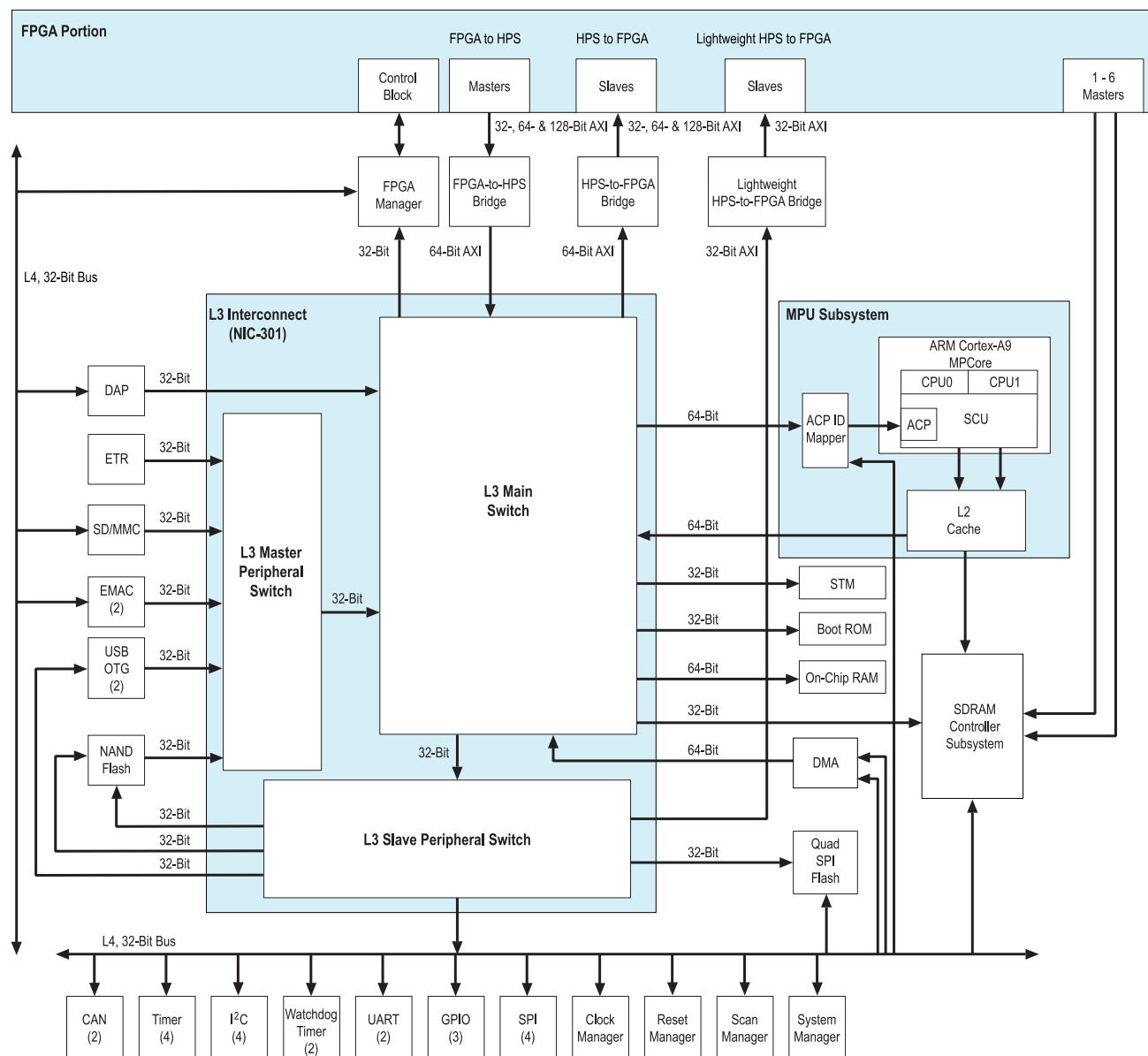


Figure 6-2. HPS Block Diagram [2, pp. 1-3]

The following list contains the main modules of the HPS:

- **Masters**
 - MPU subsystem featuring dual ARM Cortex-A9 MPCore processors
 - General-purpose Direct Memory Access (DMA) controller
 - Two Ethernet media access controllers (EMACs)
 - Two USB 2.0 On-The-Go (OTG) controllers
 - NAND flash controller
 - Secure Digital (SD) / MultiMediaCard (MMC) controller
 - Two serial peripheral interface (SPI) master controllers
 - ARM CoreSight debug components
- **Slaves**
 - Quad SPI flash controller
 - Two SPI slave controllers
 - Four inter-integrated circuit (I²C) controllers
 - 64 KB on-chip RAM

- 64 KB on-chip boot ROM
- Two UARTs
- Four timers
- Two watchdog timers
- Three general-purpose I/O (GPIO) interfaces
- Two controller area network (CAN) controllers
- System manager
- Clock manager
- Reset manager
- Scan manager
- FPGA manager

6.3 SYSTEM INTEGRATION OVERVIEW

In this part, we briefly go through *some* features provided by the most important HPS components.

6.3.1 MPU Subsystem

Here are a few important features of the MPU subsystem:

- Interrupt controller
- One general-purpose timer and one watchdog timer per processor
- One Memory management unit (MMU) per processor

The HPS masters the L3 interconnect and the SDRAM controller subsystem.

6.3.2 SDRAM Controller Subsystem

The SDRAM controller subsystem is **MASTERED** by **HPS MASTERS** and **FPGA FABRIC MASTERS**. It supports DDR2, DDR3, and LPDDR2 devices. It is composed of 2 parts:

- SDRAM controller
- DDR PHY (interfaces the single port memory controller to the HPS I/O)

The DE1-SoC contains DDR3 SDRAM

6.3.3 Support Peripherals

6.3.3.1 System Manager

This is one of the most *essential* HPS components. It offers a few important features:

- **PIN MULTIPLEXING** (term used for the **SOFTWARE** configuration of the **HPS I/O PINS** by the **PRELOADER**)
- Freeze controller that places I/O elements into a safe state for configuration
- Low-level control of peripheral features not accessible through the control and status registers (CSRs)

*The low-level control of some peripheral features that are not accessible through the CSRs is **NOT** externally documented. You will see this type of code when you generate your custom preloader, but must **NOT** use the constructs in your own code.*

6.3.3.2 FPGA Manager

The FPGA manager offers the following features:

- Manages the configuration of the FPGA portion of the device
- Monitors configuration-related signals in the FPGA
- Provides 32 general-purpose inputs and 32 general-purpose outputs to the FPGA fabric

6.3.4 Interface Peripherals

6.3.4.1 GPIO Interfaces

The HPS provides three GPIO interfaces and offer the following features:

- Supports digital de-bounce
- Configurable interrupt mode
- Supports up to 71 I/O pins and 14 input-only pins, based on device variant
- Supports up to 67 I/O pins and 14 input-only pins

The DE1-SoC has 67 I/O pins and 14 input-only pins

6.3.5 On-Chip Memory

*The following on-chip memories are **DIFFERENT** from any on-chip memories located in the FPGA fabric.*

6.3.5.1 On-Chip RAM

The on-chip RAM offers the following features:

- 64 KB size
- High performance for all burst lengths

6.3.5.2 Boot ROM

The boot ROM offers the following features:

- 64 KB size
- Contains the code required to support HPS boot from cold or warm reset
- Used **EXCLUSIVELY** for booting the HPS

*The code in the boot ROM **CANNOT** be changed.*

6.4 HPS-FPGA INTERFACES

The HPS-FPGA interfaces provide a variety of communication channels between the HPS and the FPGA fabric.

The HPS-FPGA interfaces include:

- **FPGA-to-HPS bridge** – a high performance bus with a configurable data width of 32, 64, or 128 bits. It allows the FPGA fabric to master transactions to slaves in the HPS. This interface allows the FPGA fabric to have full visibility into the HPS address space.
- **HPS-to-FPGA bridge** – a high performance bus with a configurable data width of 32, 64, or 128 bits. It allows the HPS to master transactions to slaves in the FPGA fabric. I will sometimes call this the “heavyweight” HPS-to-FPGA bridge to distinguish its “lightweight” counterpart (see below).
- **Lightweight HPS-to-FPGA bridge** – a bus with a 32-bit fixed data width. It allows the HPS to master transactions to slaves in the FPGA fabric.
- **FPGA manager interface** – signals that communicate with FPGA fabric for boot and configuration.
- **Interrupts** – allow soft IP to supply interrupts directly to the MPU interrupt controller.
- **HPS debug interface** – an interface that allows the HPS debug control domain to extend into the FPGA.

6.5 HPS ADDRESS MAP

6.5.1 HPS Address Spaces

The HPS address map specifies the address of slaves, such as memory and peripherals, as viewed by the HPS masters. The HPS has 3 address spaces:

Name	Description	Size
MPU	MPU subsystem	4 GB
L3	L3 interconnect	4 GB
SDRAM	SDRAM controller subsystem	4 GB

Table 6-2. HPS Address Spaces [2, pp. 1-13]

The following figure shows the relationships between the different HPS address spaces. The figure is **NOT** to scale.

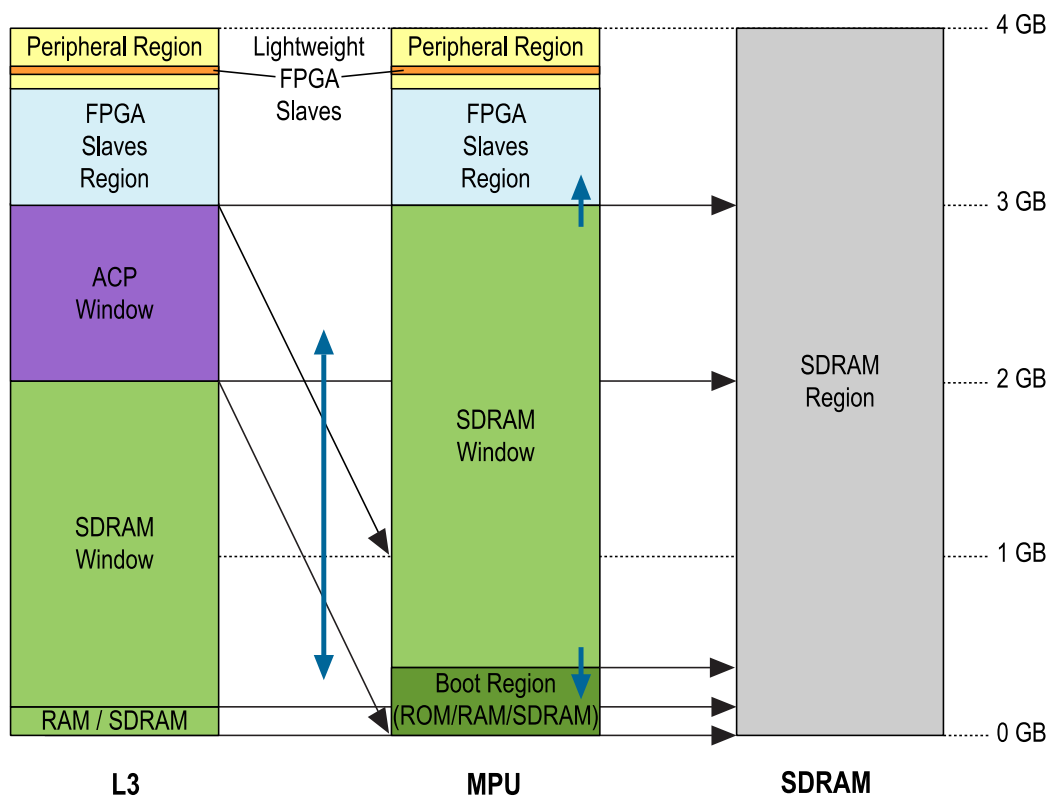


Figure 6-3. HPS Address Space Relations [2, pp. 1-14]

The window regions provide access to other address spaces. The thin black arrows indicate which address space is accessed by a window region (arrows point to accessed address space).

The SDRAM window in the MPU can grow and shrink at the top and bottom (short blue vertical arrows) at the expense of the FPGA slaves and boot regions. The ACP window can be mapped to any 1 GB region in the MPU address space (blue vertical bidirectional arrow), on gigabyte-aligned boundaries.

The following table shows the base address and size of each region that is common to the L3 and MPU address spaces.

Region Name	Description	Base Address	Size
FPGA slaves	FPGA slaves connected to the HPS-to-FPGA bridge	0xC0000000	960 MB
HPS peripherals	Slaves directly connected to the HPS (corresponds to all orange colored elements on Figure 5-4 and Figure 5-3)	0xFC000000	64 MB
Lightweight FPGA slaves	FPGA slaves connected to the lightweight HPS-to-FPGA bridge	0xFF200000	2 MB

Table 6-3. Common Address Space Regions [2, pp. 1-15]

6.5.2 HPS Peripheral Region Address Map

The following table lists the slave identifier, slave title, base address, and size of each slave in the HPS peripheral region. The *Slave Identifier* column lists the names used in the HPS register map file provided by Altera (more on this later).

Slave Identifier	Slave Title	Base Address	Size
STM	STM	0xFC000000	48 MB
DAP	DAP	0xFF000000	2 MB
LWFPGASLAVES	FPGA slaves accessed with lightweight HPS-to-FPGA bridge	0xFF200000	2 MB
LWHP2FPGAREGS	Lightweight HPS-to-FPGA bridge GPV	0xFF400000	1 MB
HPS2FPGAREGS	HPS-to-FPGA bridge GPV	0xFF500000	1 MB
FPGA2HPSREGS	FPGA-to-HPS bridge GPV	0xFF600000	1 MB
EMAC0	EMAC0	0xFF700000	8 KB
EMAC1	EMAC1	0xFF702000	8 KB
SDMMC	SD/MMC	0xFF704000	4 KB
QSPIREGS	Quad SPI flash controller registers	0xFF705000	4 KB
FPGAMGRREGS	FPGA manager registers	0xFF706000	4 KB
ACPIDMAP	ACP ID mapper registers	0xFF707000	4 KB
GPIO0	GPIO0	0xFF708000	4 KB
GPIO1	GPIO1	0xFF709000	4 KB
GPIO2	GPIO2	0xFF70A000	4 KB
L3REGS	L3 interconnect GPV	0xFF800000	1 MB
NANDDATA	NAND controller data	0xFF900000	1 MB
QSPIDATA	Quad SPI flash data	0xFFA00000	1 MB
USB0	USB0 OTG controller registers	0xFFB00000	256 KB
USB1	USB1 OTG controller registers	0xFFB40000	256 KB
NANDREGS	NAND controller registers	0xFFB80000	64 KB
FPGAMGRDATA	FPGA manager configuration data	0xFFB90000	4 KB
CAN0	CAN0 controller registers	0xFFC00000	4 KB
CAN1	CAN1 controller registers	0xFFC01000	4 KB
UART0	UART0	0xFFC02000	4 KB
UART1	UART1	0xFFC03000	4 KB
I2C0	I2C0	0xFFC04000	4 KB
I2C1	I2C1	0xFFC05000	4 KB
I2C2	I2C2	0xFFC06000	4 KB
I2C3	I2C3	0xFFC07000	4 KB
SPTIMER0	SP Timer0	0xFFC08000	4 KB
SPTIMER1	SP Timer1	0xFFC09000	4 KB
SDRREGS	SDRAM controller subsystem registers	0xFFC20000	128 KB
OSC1TIMER0	OSC1 Timer0	0xFFD00000	4 KB
OSC1TIMER1	OSC1 Timer1	0xFFD01000	4 KB
L4WD0	Watchdog0	0xFFD02000	4 KB
L4WD1	Watchdog1	0xFFD03000	4 KB
CLKMGR	Clock manager	0xFFD04000	4 KB
RSTMGR	Reset manager	0xFFD05000	4 KB
SYSMGR	System manager	0xFFD08000	16 KB
DMANONSECURE	DMA nonsecure registers	0xFFE00000	4 KB
DMASECURE	DMA secure registers	0xFFE01000	4 KB
SPI0	SPI slave0	0xFFE02000	4 KB
SPI1	SPI slave1	0xFFE03000	4 KB
SPIM0	SPI master0	0xFFFF0000	4 KB
SPIM1	SPI master1	0xFFFF01000	4 KB

SCANMGR	Scan manager registers	0xFFFF02000	4 KB
ROM	Boot ROM	0xFFFFD0000	64 KB
MPUSCU	MPU SCU registers	0xFFFFEC000	8 KB
MPUL2	MPU L2 cache controller registers	0xFFFFEF000	4 KB
OCRAM	On-chip RAM	0xFFFFF0000	64 KB

Table 6-4. HPS Peripheral Region Address Map [2, pp. 1-16]

The programming model for accessing the HPS peripherals in Table 6-4 is the same as for peripherals created on the FPGA fabric. That is, every peripheral has a base address at which a certain number of registers can be found. You can then read and write to a certain set of these registers in order to modify the peripheral's behavior.

When using a HPS peripheral in

Table 6-4, you do not need to hard-code any base address or peripheral register map in your programs, as Altera provides a header file for each one.

Three directories contain all **HPS**-related **HEADER FILES**:

1. “<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/include”
Contains **HIGH-LEVEL** header files that typically contain a few **FUNCTIONS** which facilitate control over the HPS components. These functions are all part of Altera's **HWLIB**, which was created to make programming the HPS easier. This directory contains code that is common to the Cyclone V, Arria V, and Arria 10 devices.
2. “<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/include/soc_cv_av”
Same as above, but more specifically for the Cyclone V and Arria V FPGA families.
3. “<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/include/soc_cv_av/socal”
Contains **LOW-LEVEL** header files that provide a peripheral's **BIT-LEVEL REGISTER DETAILS**. For example, any bits in a peripheral's register that correspond to undefined behavior will be specified in these header files.

To illustrate the differences among the high and low-level header files, we can compare the ones related to the FPGA manager peripheral:

1. “../hwlib/include/soc_cv_av/alt_fpga_manager.h”

```
ALT_STATUS_CODE alt_fpga_reset_assert(void);
ALT_STATUS_CODE alt_fpga_configure(const void* cfg_buf, size_t cfg_buf_len);
```

2. “../hwlib/include/soc_cv_av/socal/alt_fpgamgr.h”

```
/* The width in bits of the ALT_FPGAMGR_CTL_EN register field. */
#define ALT_FPGAMGR_CTL_EN_WIDTH      1
/* The mask used to set the ALT_FPGAMGR_CTL_EN register field value. */
#define ALT_FPGAMGR_CTL_EN_SET_MSK    0x00000001
/* The mask used to clear the ALT_FPGAMGR_CTL_EN register field value. */
#define ALT_FPGAMGR_CTL_EN_CLR_MSK    0xfffffffffe
```

An **important** header file is “../hwlib/include/soc_cv_av/socal/hps.h”. It contains the HPS component's full **REGISTER MAP**, as provided in Table 6-4.

Note however, that there exists **NO HEADER FILE** for the “*heavyweight*” HPS-to-FPGA bridge, as it is not located in the “HPS peripherals” region in Figure 6-3. Indeed, the “*heavyweight*” HPS-to-FPGA bridge is not

considered a HPS peripheral, whereas the “*lightweight*” HPS-to-FPGA bridge is. Therefore, in order to use the “*heavyweight*” HPS-to-FPGA bridge, you will have to define a macro in your code, as follows:

```
#define ALT_HWFGASLVS_OFST 0xc0000000
```

*Note that HWLIB can only be directly used in a **BARE-METAL APPLICATION**, as it directly references physical addresses. The library can unfortunately **NOT** be used directly in a **LINUX DEVICE DRIVER**, because it uses standard header files that are not available in the kernel. Needless to say that a userspace linux program cannot use the library either, as the linux kernel would terminate a user process that tries to access any of these physical addresses directly.*

6.6 HPS BOOTING AND FPGA CONFIGURATION

Before being able to use the Cyclone V SoC, one needs to understand how the HPS boots and how the FPGA is configured. We'll first take a look at the ordering between the HPS and FPGA.

6.6.1 HPS Boot and FPGA Configuration Ordering

The **HPS BOOT** starts when the processor is released from reset (for example, on power up) and executes code in the internal *boot ROM* at the reset exception address. The boot process ends when the code in the boot ROM jumps to the next stage of the boot software. This next stage of the boot software is referred to as the *preloader*. Figure 6-4 illustrates this *initial* incomplete HPS boot flow.



Figure 6-4. Simplified HPS Boot Flow [2, pp. A-3]

The processor can boot from the following sources:

- NAND flash memory through the NAND flash controller
- SD/MMC flash memory through the SD/MMC flash controller
- SPI and QSPI flash memory through the QSPI flash controller using *Slave Select 0*
- FPGA fabric on-chip memory

The choice of the boot source is done by modifying the *BOOTSEL* and *CLKSEL* values **BEFORE THE DEVICE IS POWERED UP**. Therefore, the Cyclone V device normally uses a **PHYSICAL DIP SWITCH** to configure the *BOOTSEL* and *CLKSEL*.

*The DE1-SoC can **ONLY BOOT** from **SD/MMC** flash memory, as its *BOOTSEL* and *CLKSEL* values are hard-wired on the board. Although its HPS contains all necessary controllers, the board doesn't have a physical DIP switch to modify the *BOOTSEL* and *CLKSEL* values. The actual location of the DIP switch is present underneath the board, as can be seen in Figure 5-3, but a switch isn't soldered.*

CONFIGURATION OF THE FPGA portion of the device starts when the FPGA portion is released from reset state (for example, on power up). The control block (CB) in the FPGA portion of the device is responsible for obtaining an FPGA configuration image and configuring the FPGA. The FPGA configuration ends when the configuration image has been fully loaded and the FPGA enters user mode. The FPGA configuration image is provided by users and is typically stored in non-volatile flash-based memory. The FPGA CB can obtain a configuration image from the HPS through the FPGA manager, or from another external source, such as the *Quartus Prime Programmer*.

The following three figures illustrate the possible HPS boot and FPGA configuration schemes. Note that Cyclone V devices can also be fully configured through a JTAG connection.

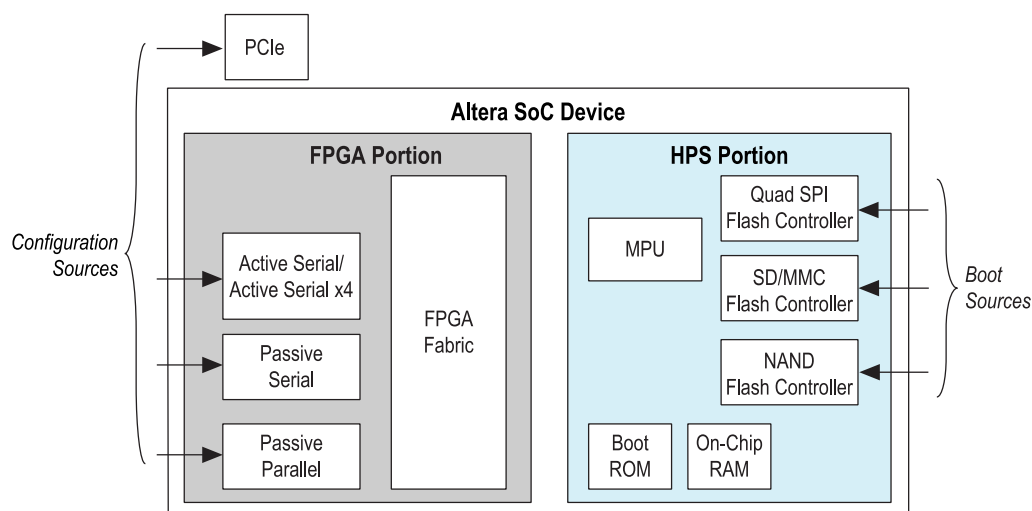


Figure 6-5. Independent FPGA Configuration and HPS Booting [2, pp. A-2]

Figure 6-5 shows the scheme where the FPGA configuration and the HPS boot occur independently. The FPGA configuration obtains its image from a non-HPS source (*Quartus Prime Programmer*), while the HPS boot obtains its configuration image from a non-FPGA fabric source.

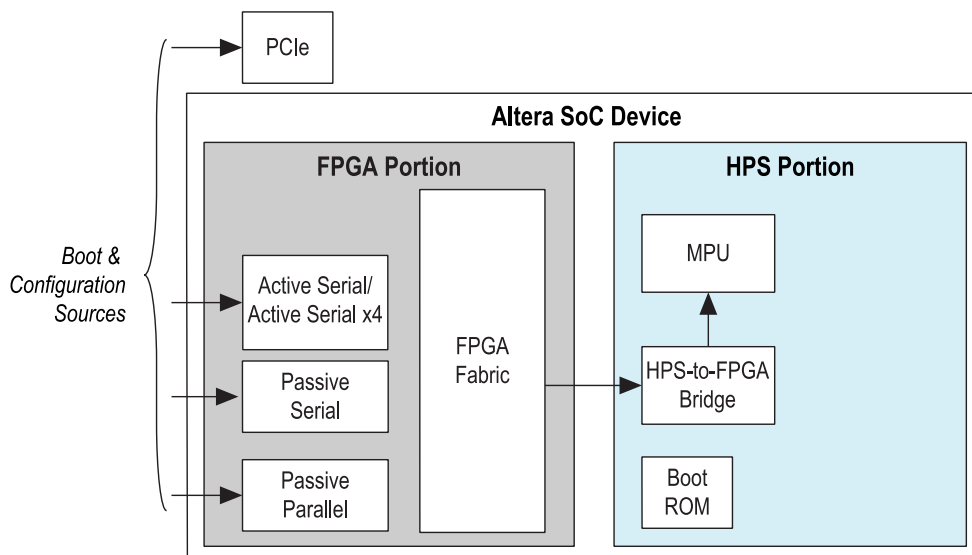


Figure 6-6. FPGA Configuration before HPS Booting (HPS boots from FPGA) [2, pp. A-2]

Figure 6-6 shows the scheme where the FPGA is first configured through the *Quartus Prime Programmer*, then the HPS boots from the FPGA fabric. The HPS boot waits for the FPGA fabric to be powered on and in user mode before executing. The HPS boot ROM code executes the preloader from the FPGA fabric over the HPS-to-FPGA bridge. The preloader can be obtained from the FPGA on-chip memory, or by accessing an external interface (such as a larger external SDRAM).

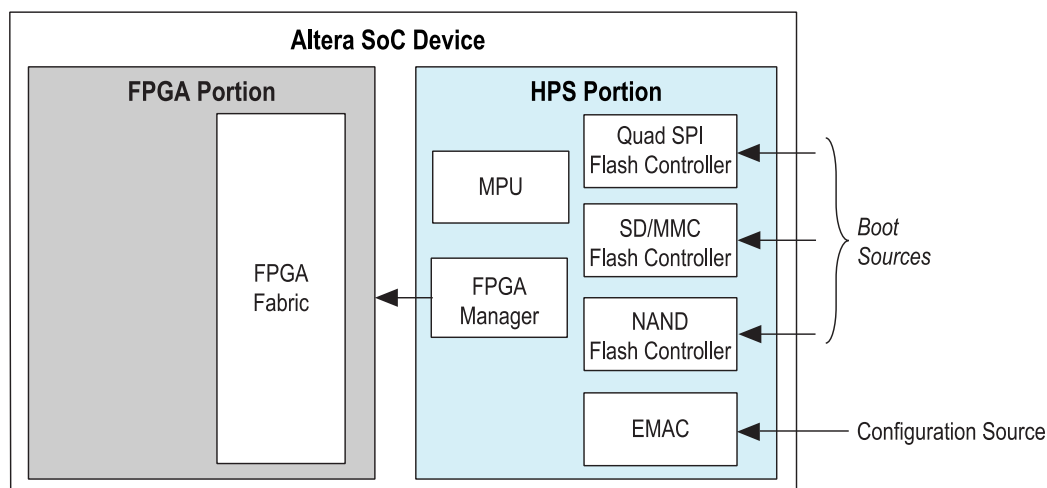


Figure 6-7. HPS Boots and Performs FPGA Configuration [2, pp. A-3]

Figure 6-7 shows the scheme under which the HPS first boots from one of its non-FPGA fabric boot sources, then software running on the HPS configures the FPGA fabric through the FPGA manager. The software on the HPS obtains the FPGA configuration image from any of its flash memory devices or communication interfaces, such as the SD/MMC memory, or the Ethernet port. The software is provided by users and the boot ROM is not involved in configuring the FPGA fabric.

6.6.2 Zooming In On the HPS Boot Process

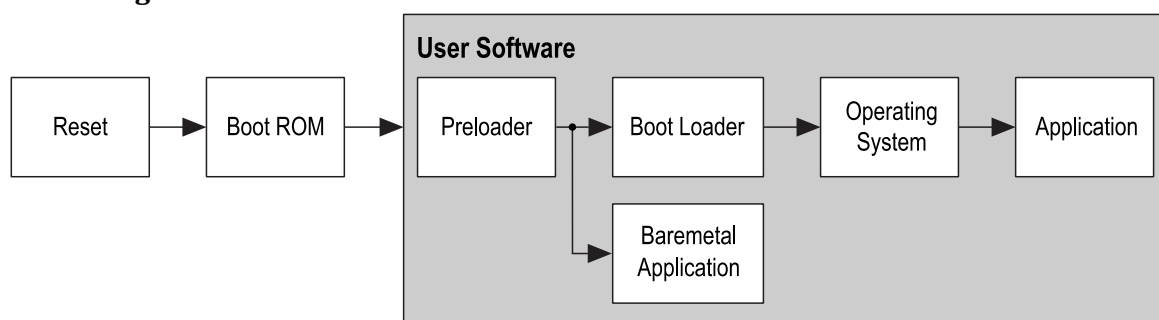


Figure 6-8. HPS Boot Flows [2, pp. A-3]

Booting software on the HPS is a multi-stage process. Each stage is responsible for loading the next stage. The first software stage is the *boot ROM*. The boot ROM code locates and executes the second software stage, called the *preloader*. The preloader locates, and **IF PRESENT**, executes the next software stage. The preloader and subsequent software stages are collectively referred to as *user software*.

The *reset*, *boot ROM*, and *preloader* stages are always present in the HPS boot flow. What comes after the preloader then depends on the type of application you want to run. The HPS can execute 2 types of applications:

- Bare-metal applications (no operating system)
- Applications on top of an operating system (Linux)

Figure 6-8 shows the HPS' available boot flows. The *Reset* and *Boot ROM* stages are the only *fixed* parts of the boot process. Everything in the *user software* stages can be *customized*.

*Although the DE1-SoC has a **DUAL**-processor HPS (CPU0 and CPU1), the boot flow only executes on CPU0 and CPU1 is under reset. If you want to use both processors of the DE1-SoC, then **USER SOFTWARE** executing on CPU0 is responsible for releasing CPU1 from reset.*

6.6.2.1 *Preloader*

The preloader is one of the most important boot stages. It is actually what one would call the boot “*source*”, as all stages before it are unmodifiable. The preloader can be stored on external flash-based memory, or in the FPGA fabric.

The preloader typically performs the following actions:

- Initialize the SDRAM interface
- Configure the HPS I/O through the scan manager
- Configure pin multiplexing through the system manager
- Configure HPS clocks through the clock manager
- Initialize the flash controller (NAND, SD/MMC, QSPI) that contains the next stage boot software
- Load the next boot software into the SDRAM and pass control to it

The preloader does **NOT** release CPU1 from reset. The subsequent stages of the boot process are responsible for it if they want to use the extra processor.

7 USING THE CYCLONE V – POSSIBLE CONFIGURATIONS

7.1 INTRODUCTION

The HPS component is a **SOFT** component, but it does **NOT** mean that the HPS is a softcore processor. In fact, the HPS exclusively contains **HARD LOGIC**. The reason it is considered a softcore component originates from the fact that it enables other soft components to interface with the HPS hard logic. As such, the HPS component has a *small footprint* in the FPGA fabric, as its only purpose is to connect the soft and hard logic together.

Therefore, it is possible to use the Cyclone V SoC in 3 different configurations:

- FPGA-only
- HPS-only
- HPS & FPGA

We will look at the *FPGA-only* and *HPS & FPGA* configurations below. We will not cover the *HPS-only* configuration as it is identical to the *HPS & FPGA* one where you simply don't load any design on the FPGA fabric. The configurations using the HPS are more difficult to set up than the *FPGA-only* one.

7.2 FPGA-ONLY

Exclusively using the FPGA part of the Cyclone V is easy, as the design process is identical to any other Altera FPGA. You can build a complete design in *Quartus Prime* & *Qsys*, simulate it in *ModelSim-Altera*, then program the FPGA through the *Quartus Prime Programmer*. If you instantiated a Nios II processor in *Qsys*, you can use the *Nios II SBT IDE* to develop software for the processor.

The DE1-SoC has a lot of pins, which makes it tedious to start an FPGA design. It is recommended to use the **ENTITY** in Figure 10-1 for your **TOP-LEVEL VHDL FILE**, as it contains all the board's FPGA and HPS pins.

After having defined a top-level module, it is necessary to map your design's pins to the ones available on the DE1-SoC. The **TCL SCRIPT** in Figure 10-2 can be executed in *Quartus Prime* to specify the board's device ID and all its **PIN ASSIGNMENTS**. In order to execute the TCL script, place it in your quartus working directory, then run it through the "Tools > Tcl Scripts..." menu item in *Quartus Prime*.

7.3 HPS & FPGA

7.3.1 Choosing the Type of Application

7.3.1.1 Bare-metal Application

On one hand, bare-metal software enjoys the advantage of having no OS overhead. This has many consequences, the most visible of which are that code executes at native speed as no context switching is ever performed, and additionally, that code can directly address the HPS peripherals using their **PHYSICAL** memory-mapped addresses, as no virtual memory system is being used. This is very useful when trying to use the HPS as a high-speed microcontroller. Such a programming environment is very similar to the one used by other microcontrollers, like the TI MSP430.

On the other hand, bare-metal code has one great disadvantage, as the programmer must continue to configure the Cyclone V to use all its resources. For example, we saw in 6.6.2.1 that the preloader does not release CPU1 from reset, and that it is up to the *user software* to perform this, which is the bare-metal application itself in this case. Furthermore, supposing CPU1 is available for use, it is still difficult to run multi-threaded code, as an OS generally handles program scheduling and CPU affinity for the programmer. The programmer must now manually assign code fragments to each CPU.

7.3.1.2 *Application Over an Operating System (Linux)*

Running code over a Linux operating system has several advantages. First of all, the kernel releases CPU1 from reset upon boot, so all processors are available. Furthermore, the kernel initializes and makes most, if not all HPS peripherals available for use by the programmer. This is possible since the Linux kernel has access to a huge amount of device drivers. Multi-threaded code is also much easier to write, as the programmer has access to the familiar **Pthreads system calls**. Finally, the Linux kernel is not restricted to running compiled C programs. Indeed, you can always run code written in another programming language providing you first install the runtime environment required (that must be available for ARM processors).

However, running an **“EMBEDDED”** application on top of an operating system also has disadvantages. Due to the virtual memory system put in place by the OS, a program cannot directly access the HPS peripherals through their physical memory-mapped addresses. Instead, one first needs to map the physical addresses of interest into the running program’s virtual address space. Only then will it be possible to access a peripheral’s registers. Ideally, the programmer should write a device driver for each specific component that is designed to have a clean interface between user code, and device accesses.

At the end of the day, bare-metal applications and applications running code on top of Linux can do the same things. Generally speaking, programming on top of Linux is superior and much easier compared to bare-metal code, as its advantages greatly outweigh its drawbacks.

8 USING THE CYCLONE V - HANDS-ON DEVELOPMENT TUTORIAL

The complete design for this tutorial can be found in `DE1_SoC_demo.zip` [3].

8.1 GOALS

Let's start by defining what we want to achieve. We want to create a system in which both the HPS and FPGA can do some computation simultaneously. More specifically, we want the following capabilities:

1. A Nios II processor on the **FPGA** must be able to use the 10 LEDs and 10 switches connected to the **FPGA PORTION** of the device. The Nios II processor will create a strobing light effect on the 10 LEDs, with the 10 switches acting as enable signals for the corresponding LEDs.
2. The Nios II processor will use its SDRAM instead of any form of on-chip memory.
3. The **HPS** must be able to use the LED and button that are directly connected to the **HPS PORTION** of the device. Pressing the button should toggle the LED.
4. The **HPS** must be able to use 2 buttons and the six 7-segment displays connected to the **FPGA PORTION** of the device. The HPS will increment and decrement a counter that will be shown on the 7-segment displays. Pressing the first button should invert the counting direction, and pushing the second button should reset the counter to 0.

8.2 PROJECT STRUCTURE

The development process creates a lot more files compared to an FPGA-only design. We will use the folder structure shown in Figure 8-1 to organize our project. In this demo, we will use "DE1_SoC_demo" as the project name.

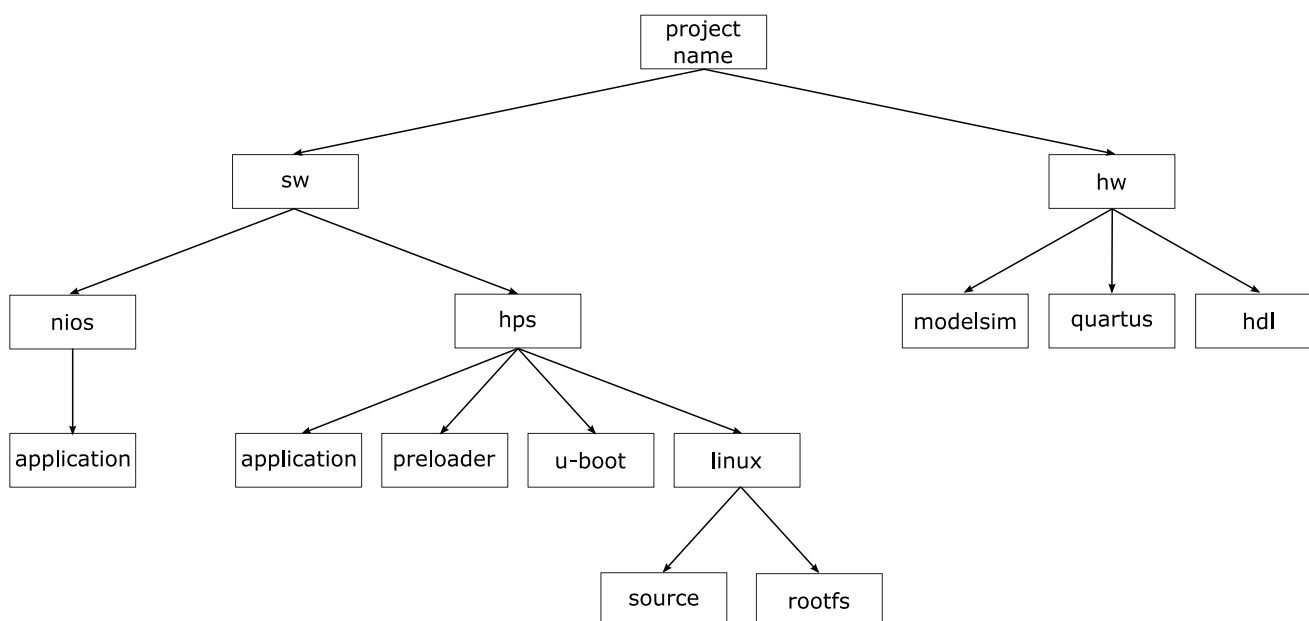


Figure 8-1. Project Folder Structure

A few steps have to be taken in order to configure the Cyclone V before you can use the HPS. The **HARDWARE** design steps are **IDENTICAL** whether you want to write bare-metal applications, or Linux HPS applications. Only the **SOFTWARE** steps **DIFFER** for the **HPS (FPGA SOFTWARE is IDENTICAL)**.

8.3 HARDWARE

The details below give step-by-step instructions to create a full system from scratch.

8.3.1 General Quartus Prime Setup

1. Create a new *Quartus Prime* project. You only need to specify the project name and destination, as all other settings will be set at a later stage by a TCL script. For this demo, we will call our project “DE1_SoC_demo” and will store it in “DE1_SoC_demo/hw/quartus”.
2. Download DE1_SoC_top_level.vhd [4] and save it in “DE1_SoC_demo/hw/hd1”. We will use this file as the project’s top-level VHDL file, as it contains a complete list of pin names available on the DE1-SoC for use in your designs. Add the file to the *Quartus Prime* project by using “Project > Add/Remove Files in Project...” and set it as your design’s top-level entity.
3. Download pin_assignment_DE1_SoC.tcl [5] and save it in “DE1_SoC_demo/hw/quartus”. This script assigns pin locations and I/O standards to all pins names in “DE1_SoC_top_level.vhd”. Execute the TCL script by using “Tools > Tcl Scripts...” in *Quartus Prime*.

At this stage, all general *Quartus Prime* settings have been performed, and we can start creating our design. We want to use the HPS, as well as a Nios II processor in our design, so we will use the Qsys tool to create the system.

4. Launch the Qsys tool and create a new system. Save it under the name “soc_system.qsys”.

8.3.2 System Design with Qsys – Nios II

In this section, we assemble all system components needed to allow the Nios II processor to create a strobing light effect on the 10 LEDs with the 10 switches acting as enable signals for the corresponding LEDs.

We want to use a Nios II processor with an SDRAM. To use an SDRAM, we need 2 things:

- An SDRAM controller.
 - A PLL to generate a clock for the softcore SDRAM controller and a phase-shifted clock for the off-chip SDRAM component. The reference clocks and timings needed for the SDRAM can be found on its datasheet: IS42R16320D.pdf [6].
5. Add an “Altera PLL” to the system.
 - Reference Clock Frequency: 50 MHz
 - Operation Mode: normal
 - Uncheck “Enable locked output port”

We need to generate 3 clocks:

- 50 MHz clock for the Nios II processor and all its peripherals.
- 100 MHz clock for the SDRAM controller.
- 100 MHz, -3758 ps phase-shifted clock for the off-chip SDRAM component.

In Qsys’ “System Contents” tab:

- Export “pll_0.outclk2” under the name “pll_0_sdram”, as shown in Figure 8-2. Exporting the pll_0.outclk2 Signal. This clock will be used for the off-chip SDRAM component.

pll_0	Altera PLL	
refclk	Clock Input	Double-click to
reset	Reset Input	Double-click to
outclk0	Clock Output	Double-click to
outclk1	Clock Output	Double-click to
outclk2	Clock Output	pll_0_sdram

pll_0.outclk2
Clock Output [clock_source 14.1]
Associated clock: None (asynchronous)

Figure 8-2. Exporting the pll_0.outclk2 Signal

6. Add an softcore SDRAM controller to the system. Use the following settings (taken from the SDRAM's datasheet):

- Memory Profile
 - Data Width
 - Bits: 16
 - Architecture
 - Chip select: 1
 - Banks: 4
 - Address Width
 - Row: 13
 - Column: 10
- Timing
 - CAS latency cycles: 3
 - Initialization refresh cycles: 2
 - Issue one refresh command every: 7.8125 us
 - Delay after powerup, before initialization: 100.0 us
 - Duration of refresh command (t_{rfc}): 70.0 ns
 - Duration of precharge command (t_{rp}): 15.0 ns
 - ACTIVE to READ or WRITE delay (t_{rcd}): 15.0 ns
 - Access time (t_{ac}): 5.4 ns
 - Write recovery time (t_{wr}, no auto precharge): 14.0 ns

In Qsys' "System Contents" tab:

- Rename "new_sdram_controller_0" to "sdram_controller_0".
 - Export "sdram_controller_0.wire" under the name "sdram_controller_0_wire".
7. Add a Nios II processor to the system. You can choose any variant. In this demo, we use the "Nios II (classic)" processor, with configuration "Nios II/f".
8. Add a System ID Peripheral to the system. In Qsys' "System Contents" tab:
- Rename the component to "sysid"
9. Add a JTAG UART to the system. This serial console will be used to be able to see the output generated by the printf() function when programming the Nios II processor.
10. Connect the system as shown in Figure 8-3 below:

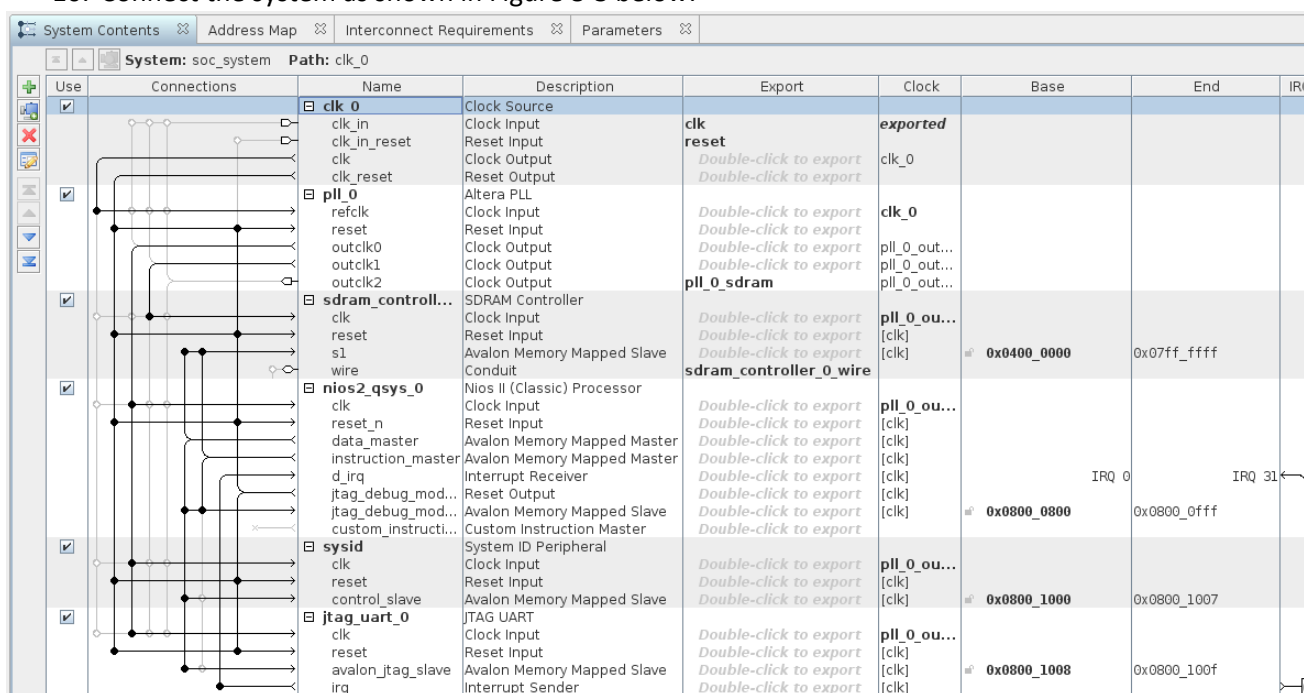


Figure 8-3. Basic Nios II System with SDRAM and JTAG UART

11. Edit the Nios II processor and set “sdram_controller_0.s1” as its Reset and Exception vectors.
12. Add a PIO component to the system for the LEDs. The DE1-SoC has 10 LEDs, so we will use a 10-bit PIO component.

- Width: 10 bits
- Direction: Output
- Output Port Reset Value: 0x00

In Qsys’ “System Contents” tab:

- Rename the component to “leds_0”
- Export “leds_0.external_connection”

13. Add a PIO component to the system for the switches. The DE1-SoC has 10 Switches, so we will again use a 10-bit PIO component.

- Width: 10 bits
- Direction: Input

In Qsys’ “System Contents” tab:

- Rename the component to “switches_0”
- Export “switches_0.external_connection”

14. Connect the system as shown in Figure 8-4 below (we don’t show the full system to make figures hold on one page):



Figure 8-4. Adding LEDs and Switches to the System

At this stage, we have created a system that satisfies goals 1 and 2 defined in 8.1.

8.3.3 System Design with Qsys – HPS

In this section, we assemble all system components needed to allow the HPS to access a button and LED connected directly to itself, as well as a button and the 7-segment displays connected to the FPGA portion of the device.

Note: When using Qsys to manipulate any signal or menu item related to the HPS, the GUI will seem as though it is not responding. However, it is not the case and it is just checking all parameters in the background, which makes the GUI hang momentarily. It is working correctly behind the scenes.

8.3.3.1 Instantiating the HPS Component

15. To use the HPS, add an “Arria V/Cyclone V Hard Processor System” to the system.
16. Open the HPS’ parameters and have a look around. There are 4 tabs that control various aspects of the HPS’ behaviour, as shown on Figure 8-5.

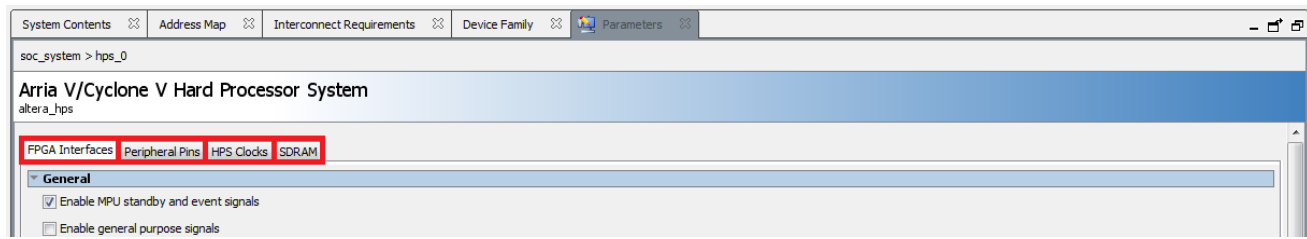


Figure 8-5. HPS Component Parameters

8.3.3.1.1 FPGA Interfaces Tab

This tab configures everything related to the interfaces between the HPS and the FPGA. You can configure which bridges to use, interrupts, ...

17. We want to use the HPS to access FPGA peripherals, so we need to enable one of the following buses:

- HPS-to-FPGA AXI bridge
- Lightweight HPS-to-FPGA AXI bridge

Since we are not going to be using any high performance FPGA peripherals in this demo, we'll choose to enable the Lightweight HPS-to-FPGA AXI bridge.

- Set the FPGA-to-HPS interface width to "Unused".
- Set the HPS-to-FPGA interface width to "Unused".

By default, Qsys checks "Enable MPU standby and event signals", but we are not going to use this feature, so

- Uncheck "Enable MPU standby and event signals".

Qsys also adds an FPGA-to-HPS SDRAM port by default, which we are not going to use either, so

- Remove the port listed under "FPGA-to-HPS SDRAM Interface".

8.3.3.1.2 Peripheral Pins Tab

This tab configures the physical pins that are available on the device. Most device pins have various sources, and are *multiplexed*. The pins can be configured to be sourced by the FPGA, or by various HPS peripherals.

8.3.3.1.2.1 Theory

We want to use the HPS to access the button and LED that are directly connected to it. These HPS peripherals correspond to pins "HPS_KEY" and "HPS_LED" on the device's top-level entity. We need to know how these 2 pins are connected to the HPS to access them. To find out this information, we have to look at the board's schematics. You can find the schematics in DE1-SoC.pdf [7].

The right side of Figure 8-6 shows the area of interest on the DE1-SoC's schematics. We see that "HPS_KEY" and "HPS_LED" are respectively connected to pins G21 and A24.



Figure 8-6. HPS_KEY & HPS_LED on DE1-SoC Schematic

Figure 8-6 allows us to explain what Qsys' Peripheral Pins tab does. The Qsys GUI doesn't make any reference to pins G21 and A24, as they depend on the device being used, and cannot be generalized to other Cyclone V devices. However, the GUI does have references to what is displayed on the left side of Figure 8-6. We will

examine the details of pin G21, to which “HPS_KEY” is connected. The schematic shows that pin G21 is connected to 4 sources:

- TRACE_D5
- SPIS1_MOSI
- CAN1_TX
- HPS_GPIO54

This can be seen in Qsys, as shown in Figure 8-7.

TRACE_D4	CAN1_RX (Set0)	SPI1.CLK (Set0)	TRACE.D4 (Set0)	GPI053	LOANIO53
TRACE_D5	CAN1_TX (Set0)	SPI1.MOSI (Set0)	TRACE.D5 (Set0)	GPI054	LOANIO54

Figure 8-7. HPS_KEY & HPS_LED on Qsys Peripheral Pins Tab

Depending on how you configure the Peripheral Pins tab, you can configure pin G21 to use any of the sources above. For example, if you want to use this pin as an SPI slave control signal, you would use the configuration shown in Figure 8-8.

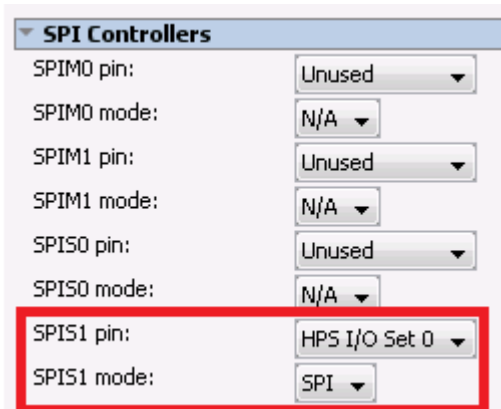


Figure 8-8. Using Pin G21 for SPI

However, if you don’t want to use any of the peripherals available at the top of the *Peripheral Pins* tab, then you can always use one of the 2 buttons on the right side of Figure 8-7:

- **GPIOXY**: Configures the pin to be connected to the **HPS’ GPIO** peripheral.
- **LOANIOXY**: Configures the pin to be connected to the **FPGA** fabric. This pin can be exported from Qsys to be used by the FPGA.

8.3.3.1.2.2 Configuration

- We want the HPS to directly control the “HPS_KEY” and “HPS_LED” pins. To do this, we will connect pins G21 and A24 to the HPS’ GPIO peripheral.
 - Click on the “GPIO53” button. This corresponds to pin A24, which is connected to “HPS_LED”.
 - Click on the “GPIO54” button. This corresponds to pin G21, which is connected to “HPS_KEY”.
- We want to connect to our DE1-SoC with an SSH connection later in the tutorial, so we need to enable the Ethernet MAC controller.
 - Configure “EMAC1 pin” to “HPS I/O Set 0” and the “EMAC 1 mode” to “RGMII”, as shown in Figure 8-9.
 - Click on the “GPIO35” button. This corresponds to pin C19, which is connected to “HPS_ENET_INT_N”.

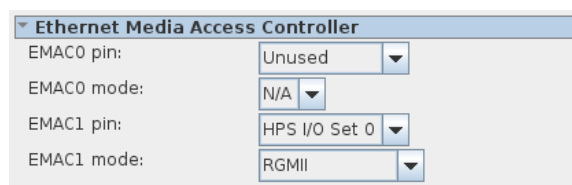


Figure 8-9. Ethernet MAC configuration 1

20. Our system will boot from the microSD card slot, so we need to enable the SD/MMC controller.

- Configure “SDIO pin” to “HPS I/O Set 0” and “SDIO mode” to “4-bit Data”, as shown in Figure 8-10.

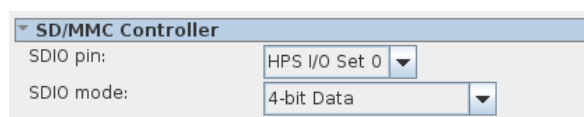


Figure 8-10. SD/MMC configuration

21. When initially configuring our system, we will need to connect a keyboard to our system. We will do this through a UART serial connection, so we need to enable the UART controller.

- Configure “UART0 pin” to “HPS I/O Set 0” and “UART0 mode” to “No Flow Control”, as shown in Figure 8-11.

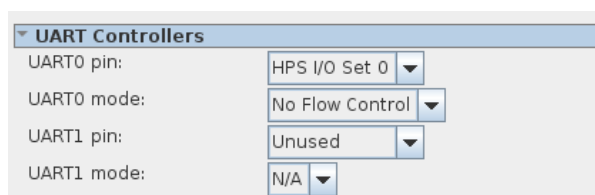


Figure 8-11. UART configuration

At this stage, you should have the same configuration shown in Figure 8-12.

QSPI_CLK	QSPI_CLK (Set0)	QSPI_CLK (Set0)	QSPI_CLK (Set0)	QSPI_CLK (Set0)	QSPI_CLK (Set0)
QSPI_SS1	QSPI_SS1 (Set0)	QSPI_SS1 (Set0)	QSPI_SS1 (Set0)	QSPI_SS1 (Set0)	QSPI_SS1 (Set0)
SDMMC_CMD	SDMMC_CMD (Set0)	SDMMC_CMD (Set0)	SDMMC_CMD (Set0)	SDMMC_CMD (Set0)	SDMMC_CMD (Set0)
SDMMC_DATA0	SDMMC_DATA0 (Set0)	SDMMC_DATA0 (Set0)	SDMMC_DATA0 (Set0)	SDMMC_DATA0 (Set0)	SDMMC_DATA0 (Set0)
SDMMC_DATA1	SDMMC_DATA1 (Set0)	SDMMC_DATA1 (Set0)	SDMMC_DATA1 (Set0)	SDMMC_DATA1 (Set0)	SDMMC_DATA1 (Set0)
SDMMC_DATA2	SDMMC_DATA2 (Set0)	SDMMC_DATA2 (Set0)	SDMMC_DATA2 (Set0)	SDMMC_DATA2 (Set0)	SDMMC_DATA2 (Set0)
SDMMC_DATA3	SDMMC_DATA3 (Set0)	SDMMC_DATA3 (Set0)	SDMMC_DATA3 (Set0)	SDMMC_DATA3 (Set0)	SDMMC_DATA3 (Set0)
SDMMC_DATA4	SDMMC_DATA4 (Set0)	SDMMC_DATA4 (Set0)	SDMMC_DATA4 (Set0)	SDMMC_DATA4 (Set0)	SDMMC_DATA4 (Set0)
SDMMC_DATA5	SDMMC_DATA5 (Set0)	SDMMC_DATA5 (Set0)	SDMMC_DATA5 (Set0)	SDMMC_DATA5 (Set0)	SDMMC_DATA5 (Set0)
SDMMC_DATA6	SDMMC_DATA6 (Set0)	SDMMC_DATA6 (Set0)	SDMMC_DATA6 (Set0)	SDMMC_DATA6 (Set0)	SDMMC_DATA6 (Set0)
SDMMC_DATA7	SDMMC_DATA7 (Set0)	SDMMC_DATA7 (Set0)	SDMMC_DATA7 (Set0)	SDMMC_DATA7 (Set0)	SDMMC_DATA7 (Set0)
SDMMC_FB_CLK_IN	SDMMC_FB_CLK_IN (Set0)	SDMMC_FB_CLK_IN (Set0)	SDMMC_FB_CLK_IN (Set0)	SDMMC_FB_CLK_IN (Set0)	SDMMC_FB_CLK_IN (Set0)
SDMMC_CCLK_OUT	SDMMC_CCLK_OUT (Set0)	SDMMC_CCLK_OUT (Set0)	SDMMC_CCLK_OUT (Set0)	SDMMC_CCLK_OUT (Set0)	SDMMC_CCLK_OUT (Set0)
SDMMC_D0	SDMMC_D0 (Set0)	SDMMC_D0 (Set0)	SDMMC_D0 (Set0)	SDMMC_D0 (Set0)	SDMMC_D0 (Set0)
SDMMC_D1	SDMMC_D1 (Set0)	SDMMC_D1 (Set0)	SDMMC_D1 (Set0)	SDMMC_D1 (Set0)	SDMMC_D1 (Set0)
SDMMC_D2	SDMMC_D2 (Set0)	SDMMC_D2 (Set0)	SDMMC_D2 (Set0)	SDMMC_D2 (Set0)	SDMMC_D2 (Set0)
SDMMC_D3	SDMMC_D3 (Set0)	SDMMC_D3 (Set0)	SDMMC_D3 (Set0)	SDMMC_D3 (Set0)	SDMMC_D3 (Set0)
TRACE_CLK	TRACE_CLK (Set0)	TRACE_CLK (Set0)	TRACE_CLK (Set0)	TRACE_CLK (Set0)	TRACE_CLK (Set0)
TRACE_D0	TRACE_D0 (Set0)	TRACE_D0 (Set0)	TRACE_D0 (Set0)	TRACE_D0 (Set0)	TRACE_D0 (Set0)
TRACE_D1	TRACE_D1 (Set0)	TRACE_D1 (Set0)	TRACE_D1 (Set0)	TRACE_D1 (Set0)	TRACE_D1 (Set0)
TRACE_D2	TRACE_D2 (Set0)	TRACE_D2 (Set0)	TRACE_D2 (Set0)	TRACE_D2 (Set0)	TRACE_D2 (Set0)
TRACE_D3	TRACE_D3 (Set0)	TRACE_D3 (Set0)	TRACE_D3 (Set0)	TRACE_D3 (Set0)	TRACE_D3 (Set0)
TRACE_D4	TRACE_D4 (Set0)	TRACE_D4 (Set0)	TRACE_D4 (Set0)	TRACE_D4 (Set0)	TRACE_D4 (Set0)
TRACE_D5	TRACE_D5 (Set0)	TRACE_D5 (Set0)	TRACE_D5 (Set0)	TRACE_D5 (Set0)	TRACE_D5 (Set0)
TRACE_D6	TRACE_D6 (Set0)	TRACE_D6 (Set0)	TRACE_D6 (Set0)	TRACE_D6 (Set0)	TRACE_D6 (Set0)

Figure 8-12. Exported peripheral pins

22. In Qsys’ “System Contents” tab:

- Export “hps_0.hps_io” under the name “hps_0_io”. This is a conduit that contains all the pins configured in the *Peripheral Pins* tab. We will connect these to our top-level entity later.

8.3.3.1.3 HPS Clocks Tab

This tab configures the clocking system of the HPS. We will generally use the default settings here, so no need to change anything.

8.3.3.1.4 SDRAM Tab

This tab configures the memory subsystem of the HPS.

23. We need to configure all clocks and timings related to the memory used on our system. The DE1-SoC uses DDR3 memory, so we need to consult its datasheet to find all the settings. The datasheet is available at [43TR16256A-85120AL \(ISSI\).pdf \[8\]](#). Based on the memory’s datasheet, we can fill in the following memory settings (you will soon see that it is quite tedious to enter these values):

- SDRAM Protocol: DDR3
- PHY Settings:
 - Clocks:
 - Memory clock frequency: 400.0 MHz
 - PLL reference clock frequency: 25.0 MHz
 - Advanced PHY Settings:
 - Supply Voltage: 1.5V DDR3
- Memory Parameters:
 - Memory vendor: Other
 - Memory device speed grade: 800.0 MHz
 - Total interface width: 32
 - Number of chip select/depth expansion: 1
 - Number of clocks: 1
 - Row address width: 15
 - Column address width: 10
 - Bank-address width: 3
 - Enable DM pins
 - DQS# Enable
 - Memory Initialization Options:
 - Mirror Addressing: 1 per chip select: 0
 - Mode Register 0:
 - Burst Length: Burst chop 4 or 8 (on the fly)
 - Read Burst Type: Sequential
 - DLL precharge power down: DLL off
 - Memory CAS latency setting: 11
 - Mode Register 1:
 - Output drive strength setting: RZQ/7
 - ODT Rtt nominal value: RZQ/4
 - Mode Register 2:
 - Auto selfrefresh method: Manual
 - Selfrefresh temperature: Normal
 - Memory write CAS latency setting: 8
 - Dynamic ODT (Rtt_WR) value: RZQ/4
- Memory Timing:
 - tIS (base): 180 ps
 - tIH (base): 140 ps
 - tDS (base): 30 ps
 - tDH (base): 65 ps
 - tDQSQ: 125 ps
 - tQH: 0.38 cycles
 - tDQSCK: 255 ps
 - tDQSS: 0.25 cycles
 - tQSH: 0.4 cycles
 - tDSH: 0.2 cycles
 - tDSS: 0.2 cycles
 - tINIT: 500 us
 - tMRD: 4 cycles
 - tRAS: 35.0 ns
 - tRCD: 13.75 ns
 - tRP: 13.75 ns

- tREFI: 7.8 us
- tRFC: 260.0 ns
- tWR: 15.0 ns
- tWTR: 4 cycles
- tFAW: 30.0 ns
- tRRD: 7.5 ns
- tRTP: 7.5 ns
- Board Settings:
 - Setup and Hold Derating:
 - Use Altera's default settings
 - Channel Signal Integrity:
 - Use Altera's default settings
 - Board Skews:
 - Maximum CK delay to DIMM/device: 0.03 ns
 - Maximum DQS delay to DIMM/device: 0.02 ns
 - Minimum delay difference between CK and DQS: 0.06 ns
 - Maximum delay difference between CK and DQS: 0.12 ns
 - Maximum skew within DQS group: 0.01 ns
 - Maximum skew between DQS groups: 0.06 ns
 - Average delay difference between DQ and DQS: 0.05 ns
 - Maximum skew within address and command bus: 0.02 ns
 - Average delay difference between address and command and CK: 0.01 ns

24. In Qsys' "System Contents" tab:

- Export "hps_0.memory" under the name "hps_0_ddr".

25. Connect the system as shown in Figure 8-13 below:



Figure 8-13. Adding the "Standalone" HPS to the System

At this stage, we have a functional HPS unit that can be programmed and that satisfies goals 1, 2, and 3 defined in 8.1. In our current system however, the HPS can only be used "standalone" and cannot access any FPGA peripherals.

8.3.3.2 Interfacing with FPGA Peripherals

The next step is to connect the HPS to FPGA peripherals through one of its interface bridges. The setup we have uses the Lightweight HPS-to-FPGA bridge to communicate with the FPGA.

26. Add a PIO component to the system for the buttons. The DE1-SoC has 4 buttons, so we will use a 4-bit PIO component.

- Width: 4 bits
- Direction: Input

In Qsys' "System Contents" tab:

- Rename the component to "buttons_0"
- Export "buttons_0.external_connection"

27. Add a PIO component for one of the 7-segment displays. We will use a 7-bit PIO component.

- Width: 7 bits
- Direction: Output
- Output Port Reset Value: 0x7f

In Qsys' "System Contents" tab:

- Rename the component to "hex_0"
- Export "hex_0.external_connection"

28. Repeat step 27 five more times to obtain a total of six 7-segment displays "hex_0", "hex_1", "hex_2", "hex_3", "hex_4", and "hex_5".

29. Connect the system as shown in Figure 8-14 below. Notice that we use "hps_0.h2f_reset" as the reset signal for the components connected to the HPS. This is a design choice so we can separately reset FPGA-only peripherals, and FPGA peripherals connected to the HPS.

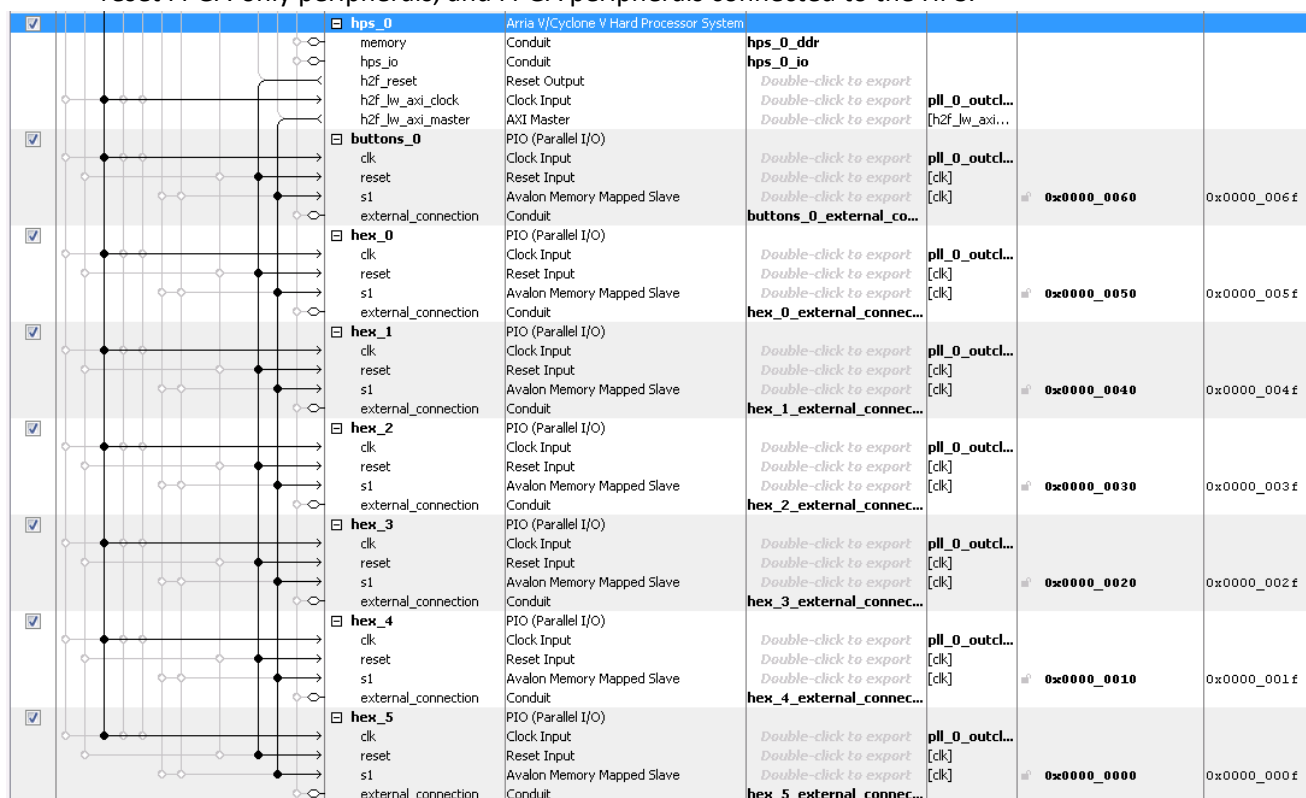


Figure 8-14. Adding Buttons and 7-segment Displays to the Lightweight HPS-to-FPGA Bridge

30. In the main Qsys window, select "System > Assign Base Addresses" to get rid of any error messages regarding memory space overlaps among the different components in the system.

At this stage, we finally have a system that satisfies goals 1, 2, 3, and 4 defined in 8.1. Our design work with Qsys is now done.

8.3.4 Instantiating the Qsys System

31. Save the design and exit Qsys. When asked if you want to generate the design, select "No".

You now have a complete *Qsys* system. The system will be available as an instantiable component in your design files. However, in order for *Quartus Prime* to see the *Qsys* system, you will have to add the system's files to your *Quartus Prime* project.

32. Add "DE1_SoC_demo/hw/quartus/soc_system.qsys" to the *Quartus Prime* project by using "Project > Add/Remove Files in Project...".
33. To use the *Qsys* system in your design, you have to declare its component, and then instantiate it. *Qsys* already provides you with a component declaration. You can find it among the numerous files that were generated. The one we are looking for is "DE1_SoC_demo/hw/quartus/soc_system/soc_system.cmp".
34. Copy the component declaration code in "DE1_SoC_demo/hw/hdl/DE1_SoC_top_level.vhd". Be sure to instantiate the component and assign all the correct pins of the DE1-SoC board. For our demo project, we would use the instantiation shown in Figure 8-15.

```

soc_system_inst : component soc_system
  port map(
    clk_clk           => CLOCK_50,
    reset_reset_n     => '1',
    buttons_0_external_connection_export => KEY_N,
    hex_0_external_connection_export    => HEX0_N,
    hex_1_external_connection_export    => HEX1_N,
    hex_2_external_connection_export    => HEX2_N,
    hex_3_external_connection_export    => HEX3_N,
    hex_4_external_connection_export    => HEX4_N,
    hex_5_external_connection_export    => HEX5_N,
    leds_0_external_connection_export   => LEDR,
    switches_0_external_connection_export => SW,
    pll_0_sdram_clk      => DRAM_CLK,
    sdram_controller_0_wire_addr        => DRAM_ADDR,
    sdram_controller_0_wire_ba          => DRAM_BA,
    sdram_controller_0_wire_cas_n       => DRAM_CAS_N,
    sdram_controller_0_wire_cke         => DRAM_CKE,
    sdram_controller_0_wire_cs_n        => DRAM_CS_N,
    sdram_controller_0_wire_dq          => DRAM_DQ,
    sdram_controller_0_wire_dqm(1)      => DRAM_UDQM,
    sdram_controller_0_wire_dqm(0)      => DRAM_LDQM,
    sdram_controller_0_wire_ras_n       => DRAM_RAS_N,
    sdram_controller_0_wire_we_n        => DRAM_WE_N,
    hps_0_ddr_mem_a                    => HPS_DDR3_ADDR,
    hps_0_ddr_mem_ba                    => HPS_DDR3_BA,
    hps_0_ddr_mem_ck                    => HPS_DDR3_CK_P,
    hps_0_ddr_mem_ck_n                  => HPS_DDR3_CK_N,
    hps_0_ddr_mem_cke                    => HPS_DDR3_CKE,
    hps_0_ddr_mem_cs_n                  => HPS_DDR3_CS_N,
    hps_0_ddr_mem_ras_n                  => HPS_DDR3_RAS_N,
    hps_0_ddr_mem_cas_n                  => HPS_DDR3_CAS_N,
    hps_0_ddr_mem_we_n                  => HPS_DDR3_WE_N,
    hps_0_ddr_mem_reset_n                => HPS_DDR3_RESET_N,
    hps_0_ddr_mem_dq                     => HPS_DDR3_DQ,
    hps_0_ddr_mem_dqs                     => HPS_DDR3_DQS_P,
    hps_0_ddr_mem_dqs_n                   => HPS_DDR3_DQS_N,
    hps_0_ddr_mem_odt                     => HPS_DDR3_ODT,
    hps_0_ddr_mem_dm                      => HPS_DDR3_DM,
    hps_0_ddr_oct_rzqin                   => HPS_DDR3_RZQ,
    hps_0_io_hps_io_emac1_inst_TX_CLK    => HPS_ENET_GTX_CLK,
    hps_0_io_hps_io_emac1_inst_TX_CTL    => HPS_ENET_TX_EN,
    hps_0_io_hps_io_emac1_inst_TXD0      => HPS_ENET_TX_DATA(0),
    hps_0_io_hps_io_emac1_inst_TXD1      => HPS_ENET_TX_DATA(1),
  
```

```

hps_0_io_hps_io_emac1_inst_TXD2    => HPS_ENET_TX_DATA(2),
hps_0_io_hps_io_emac1_inst_TXD3    => HPS_ENET_TX_DATA(3),
hps_0_io_hps_io_emac1_inst_RX_CLK  => HPS_ENET_RX_CLK,
hps_0_io_hps_io_emac1_inst_RX_CTL  => HPS_ENET_RX_DV,
hps_0_io_hps_io_emac1_inst_RXD0    => HPS_ENET_RX_DATA(0),
hps_0_io_hps_io_emac1_inst_RXD1    => HPS_ENET_RX_DATA(1),
hps_0_io_hps_io_emac1_inst_RXD2    => HPS_ENET_RX_DATA(2),
hps_0_io_hps_io_emac1_inst_RXD3    => HPS_ENET_RX_DATA(3),
hps_0_io_hps_io_emac1_inst_MDIO    => HPS_ENET_MDIO,
hps_0_io_hps_io_emac1_inst_MDC     => HPS_ENET_MDC,
hps_0_io_hps_io_sdio_inst_CLK      => HPS_SD_CLK,
hps_0_io_hps_io_sdio_inst_CMD      => HPS_SD_CMD,
hps_0_io_hps_io_sdio_inst_D0       => HPS_SD_DATA(0),
hps_0_io_hps_io_sdio_inst_D1       => HPS_SD_DATA(1),
hps_0_io_hps_io_sdio_inst_D2       => HPS_SD_DATA(2),
hps_0_io_hps_io_sdio_inst_D3       => HPS_SD_DATA(3),
hps_0_io_hps_io_uart0_inst_RX      => HPS_UART_RX,
hps_0_io_hps_io_uart0_inst_TX      => HPS_UART_TX,
hps_0_io_hps_io_gpio_inst_GPIO35   => HPS_ENET_INT_N,
hps_0_io_hps_io_gpio_inst_GPIO53   => HPS_LED,
hps_0_io_hps_io_gpio_inst_GPIO54   => HPS_KEY_N
);

```

Figure 8-15. Qsys Component Instantiation

35. After finishing the design, **REMOVE** all unused pins from the top-level VHDL file. Your top-level entity should look like the one shown in Figure 8-16.

```

entity DE1_SoC_top_level is
  port(
    -- CLOCK
    CLOCK_50      : in    std_logic;

    -- SDRAM
    DRAM_ADDR     : out   std_logic_vector(12 downto 0);
    DRAM_BA       : out   std_logic_vector(1 downto 0);
    DRAM_CAS_N    : out   std_logic;
    DRAM_CKE      : out   std_logic;
    DRAM_CLK      : out   std_logic;
    DRAM_CS_N     : out   std_logic;
    DRAM_DQ       : inout  std_logic_vector(15 downto 0);
    DRAM_LDQM     : out   std_logic;
    DRAM_RAS_N    : out   std_logic;
    DRAM_UDQM     : out   std_logic;
    DRAM_WE_N     : out   std_logic;

    -- SEG7
    HEX0_N        : out   std_logic_vector(6 downto 0);
    HEX1_N        : out   std_logic_vector(6 downto 0);
    HEX2_N        : out   std_logic_vector(6 downto 0);
    HEX3_N        : out   std_logic_vector(6 downto 0);
    HEX4_N        : out   std_logic_vector(6 downto 0);
    HEX5_N        : out   std_logic_vector(6 downto 0);

    -- KEY_N
    KEY_N         : in    std_logic_vector(3 downto 0);

    -- LED
    LEDR          : out   std_logic_vector(9 downto 0);
  );

```

```

-- SW
SW          : in      std_logic_vector(9 downto 0);

-- HPS
HPS_DDR3_ADDR : out    std_logic_vector(14 downto 0);
HPS_DDR3_BA   : out    std_logic_vector(2  downto 0);
HPS_DDR3_CAS_N : out    std_logic;
HPS_DDR3_CK_N : out    std_logic;
HPS_DDR3_CK_P : out    std_logic;
HPS_DDR3_CKE   : out    std_logic;
HPS_DDR3_CS_N  : out    std_logic;
HPS_DDR3_DM    : out    std_logic_vector(3 downto 0);
HPS_DDR3_DQ    : inout  std_logic_vector(31 downto 0);
HPS_DDR3_DQS_N : inout  std_logic_vector(3  downto 0);
HPS_DDR3_DQS_P : inout  std_logic_vector(3  downto 0);
HPS_DDR3_ODT   : out    std_logic;
HPS_DDR3_RAS_N : out    std_logic;
HPS_DDR3_RESET_N : out    std_logic;
HPS_DDR3_RZQ   : in     std_logic;
HPS_DDR3_WE_N  : out    std_logic;
HPS_ENET_GTX_CLK : out    std_logic;
HPS_ENET_INT_N  : inout  std_logic;
HPS_ENET_MDC    : out    std_logic;
HPS_ENET_MDIO   : inout  std_logic;
HPS_ENET_RX_CLK : in     std_logic;
HPS_ENET_RX_DATA : in     std_logic_vector(3  downto 0);
HPS_ENET_RX_DV  : in     std_logic;
HPS_ENET_TX_DATA : out    std_logic_vector(3  downto 0);
HPS_ENET_TX_EN  : out    std_logic;
HPS_KEY_N       : inout  std_logic;
HPS_LED         : inout  std_logic;
HPS_SD_CLK      : out    std_logic;
HPS_SD_CMD      : inout  std_logic;
HPS_SD_DATA     : inout  std_logic_vector(3  downto 0);
HPS_UART_RX     : in     std_logic;
HPS_UART_TX     : out    std_logic

);
end entity DE1_SoC_top_level;

```

Figure 8-16. Final Top-level Entity

8.3.5 HPS DDR3 Pin Assignments

In a normal FPGA design flow, you would be able to compile your design at this stage. However, this isn't possible at the moment in our design. The reason is that the HPS' DDR3 pins assignments have not been performed yet.

How is this possible? We said earlier that our TCL script assigns pin locations and I/O standards to all pins names in "DE1_SoC_top_level.vhd". The truth is that it assigns values for all pin names, except those related to the HPS' DDR3 memory. The reason is that the DDR3 pin assignments depend on how you parameterize the HPS memory timings in Qsys. Our TCL script could not have known what timings you were going to use, so it doesn't set those pin locations and I/O standards.

However, Qsys knows what the parameters are (since you provided it with all the necessary information), and it has generated a custom TCL script for the HPS DDR3 pin assignments.

36. Start the "Analysis and Synthesis" flow to perform a preliminary analysis of the system.
37. Go to "Tools > Tcl Scripts..." in *Quartus Prime*.

IF AT THIS POINT YOU DO NOT SEE THE SAME THING AS ON Figure 8-17, THEN CLOSE AND RELAUNCH QUARTUS PRIME AGAIN. SOME VERSIONS OF QUARTUS PRIME SUFFER FROM A BUG, WHERE THE PROGRAM DOESN'T CORRECTLY DETECT TCL FILES GENERATED BY QSYS. YOU SHOULD SEE THE SAME THING AS ON Figure 8-17.

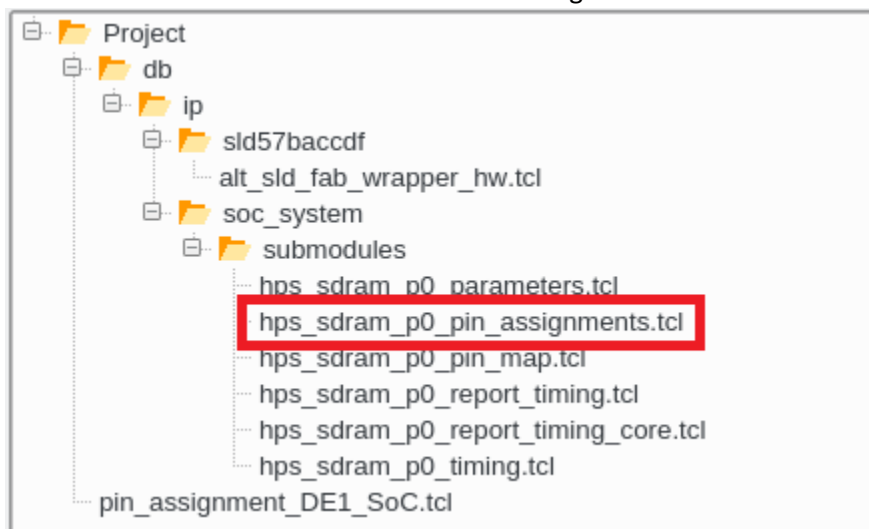


Figure 8-17. Correct HPS DDR3 Pin Assignment TCL Script Selection

38. Execute “hps_sdrn_p0_pin_assignments.tcl”.

39. You can now start the full compilation of your design with the “Start Compilation” flow.

At this point, we have finished the hardware design process and can proceed to programming the FPGA.

8.3.6 Programming the FPGA

40. Open the *Quartus Prime Programmer*.

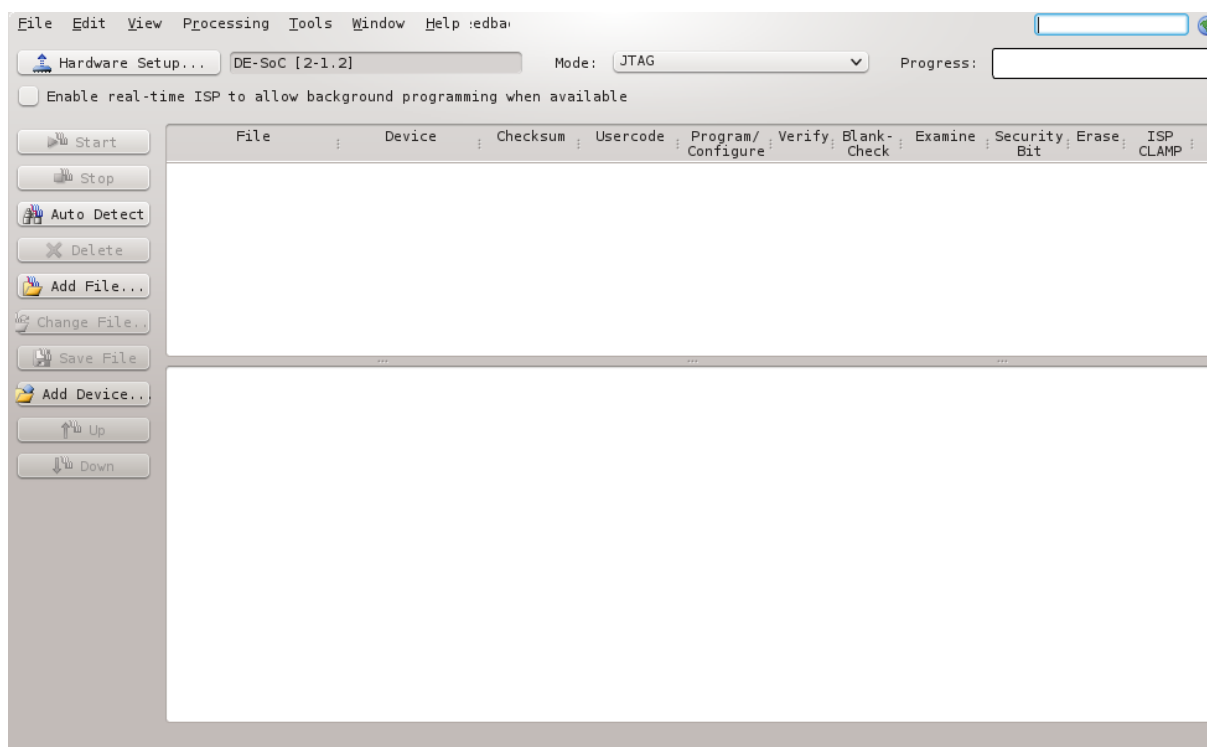


Figure 8-18. Quartus Prime Programmer

41. Choose the “Auto Detect” button on the left of Figure 8-18, then choose “5CSEMA5”, as shown in Figure 8-19.



Figure 8-19. FPGA Selection

You should now see 2 devices on the JTAG scan chain, as shown in Figure 8-20.

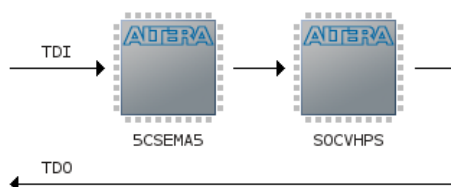


Figure 8-20. JTAG Scan Chain

42. Right-click on the “5CSEMA5” device shown in Figure 8-20 and choose “Edit > Change File”. Then, select “DE1_SoC_demo/hw/quartus/output_files/DE1_SoC_demo.sof” through the file browser.
43. Enable the “Program/Configure” checkbox for device “5CSEMA5F31”, then press the “Start” button, as shown in Figure 8-21.

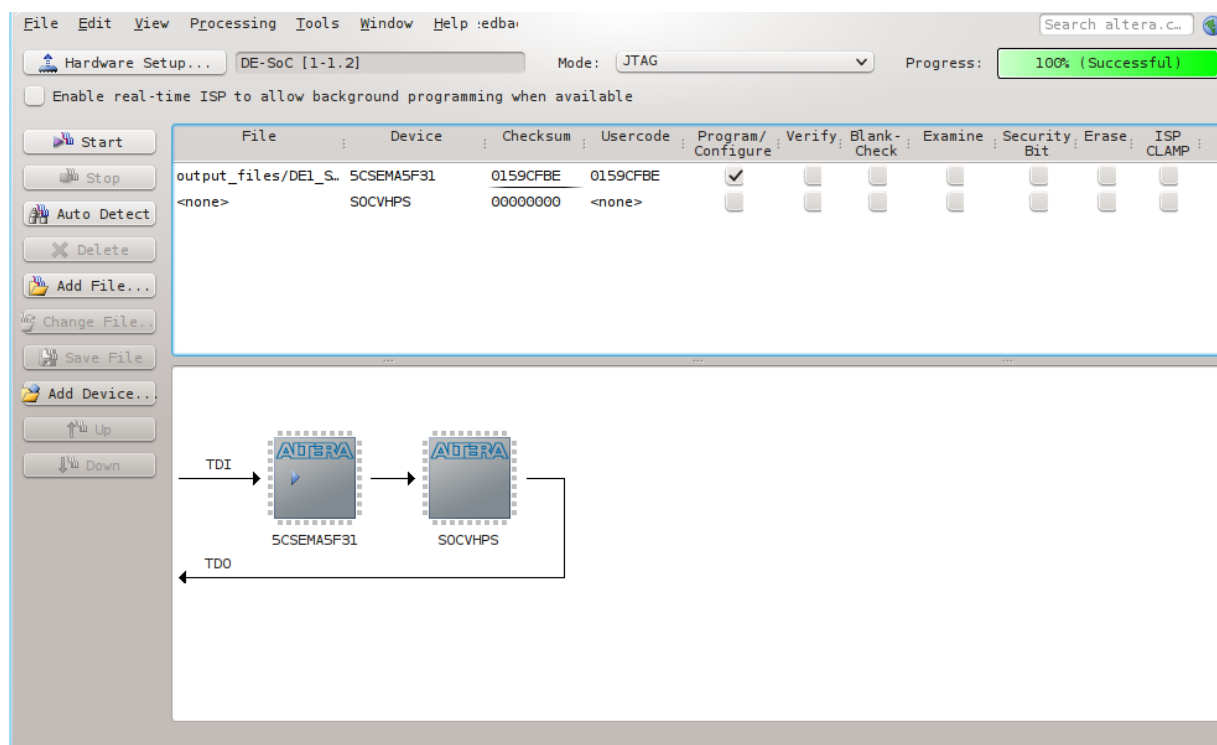


Figure 8-21. Programming the FPGA

We are now done with the *Quartus Prime* program, and will no longer need it for the rest of this tutorial.

8.4 SOFTWARE

Now that all the hardware has been designed, we need to get to the software aspects of the development process.

8.4.1 FPGA – Nios II

8.4.1.1 Project Setup

1. Launch the *Nios II SBT IDE*. You must first launch a *Nios II Command Shell*.
 - a. On Windows machines, you can find a shortcut to the executable in the Windows Start Menu: “Altera [version] Web Edition > Nios II EDS [version] > Nios II [version] Command Shell”.
 - b. On Linux machines, first launch a *Nios II Command Shell*. You can find the executable at “<altera_install_directory>/<version>/nios2eds/nios2_command_shell.sh”.
2. Type “eclipse-nios2” in the *Nios II Command Shell*, then press enter.
3. Choose “File > New > Nios II Application and BSP from Template”.
 - a. All the information needed to program a Nios II processor are contained within the “sopcinfo” file created by Qsys. For the “SOPC Information File name” use “DE1_SoC_demo/hw/quartus/soc_system.sopcinfo”.
 - b. Use “DE1_SoC_demo_nios” as the project name.
 - c. Disable the “Use default location” checkbox
 - d. Use “DE1_SoC_demo/sw/nios/application/DE1_SoC_demo_nios” as the project location.
 - e. Choose the “Blank Project” template.
 - f. Click on the “Finish” button to create the project.
4. Right-click on the “DE1_SoC_demo_nios” project folder and select “New > Source file”. Use the default C source template, and set “nios.c” as the file name.
5. Right-click on the “DE1_SoC_demo_nios_bsp” project, and select “Build Project”. Once the build is completed, a number of files will be generated, the most useful of which is the “system.h” file. This file contains all the details related to the Nios II processor’s various peripherals, as defined in Qsys in 8.3.2.

8.4.1.2 Nios II Programming Theory – Accessing Peripherals

The Nios II processor can be programmed in C similarly to any other microcontroller. However, care must be taken when accessing any of the processor’s peripherals. Depending on which version of the Nios II you instantiated in Qsys, you may not be able to correctly read data at a peripheral’s address space using pointers. The issue arises when your Nios II processor has a *data cache*.

Suppose we use the code in Figure 8-22 to read data from the switches of our Qsys design.

```
int main() {
    alt_u32 *p_switches = SWITCHES_0_BASE;
    while (1) {
        alt_u32 switches_value = *p_switches;
        printf("switches_value = %x\n", (unsigned int) switches_value);
    }
    return 0;
}
```

Figure 8-22. Incorrect Nios II Peripheral Access in C

When this code is run, the initial value of the “switches_value” variable, as obtained from the first iteration of the while loop, will be the correct representation of the switches’ state. However, at each iteration of the while loop, the “switches_value” variable will **NEVER** change again, even if the switches are flipped between each iteration. The issue is that each successive access is being served by the data cache, which doesn’t see that the switches have been modified.

The solution to this issue is to use special instructions that bypass the data cache when reading or writing to peripherals. These instructions are part of the IO family of load and store instructions and bypass all caches. The available instructions are listed below, and an example of how to correctly access Nios II peripherals is shown in Figure 8-23.

- Reading
 - IORD_8DIRECT(BASE, OFFSET)
 - IORD_16DIRECT(BASE, OFFSET)
 - IORD_32DIRECT(BASE, OFFSET)
- Writing
 - IOWR_8DIRECT(BASE, OFFSET, DATA)
 - IOWR_16DIRECT(BASE, OFFSET, DATA)
 - IOWR_32DIRECT(BASE, OFFSET, DATA)

```
#include "io.h"

int main() {
    while (1) {
        alt_u32 switches_value = IORD_32DIRECT(SWITCHES_0_BASE, 0);
        printf("switches_value = %x\n", (unsigned int) switches_value);
    }
    return 0;
}
```

Figure 8-23. Correct Nios II Peripheral Access in C

8.4.1.3 Nios II Programming Practice

6. Write the code provided in Figure 8-24 in "nios.c". The code instructs the Nios II processor to create a strobing light effect on its 10 peripheral LEDs. The processor's 10 peripheral switches are used as enable signals for each corresponding LED. This corresponds to specification 1 in 8.1.

```
#include <stdio.h>
#include <unistd.h>
#include "io.h"
#include "altera_avalon_pio_regs.h"
#include "system.h"

#define LEDS_MAX_ITERATION (1000)
#define SLEEP_DELAY_US (100 * 1000)

void rotate_leds() {
    int loop_count = 0;
    int leds_mask = 0x01;

    // 0/1 = left/right direction
    int led_direction = 0;

    while (loop_count < LEDS_MAX_ITERATION) {
        alt_u32 switches_value = IORD_ALTERA_AVALON_PIO_DATA(SWITCHES_0_BASE);
        alt_u32 leds_value = ~leds_mask;

        // only turn on leds which have their corresponding switch enabled
        IOWR_ALTERA_AVALON_PIO_DATA(LEDS_0_BASE, leds_value & switches_value);

        usleep(SLEEP_DELAY_US);

        if (led_direction == 0) {
            leds_mask <<= 1;
        }
    }
}
```

```

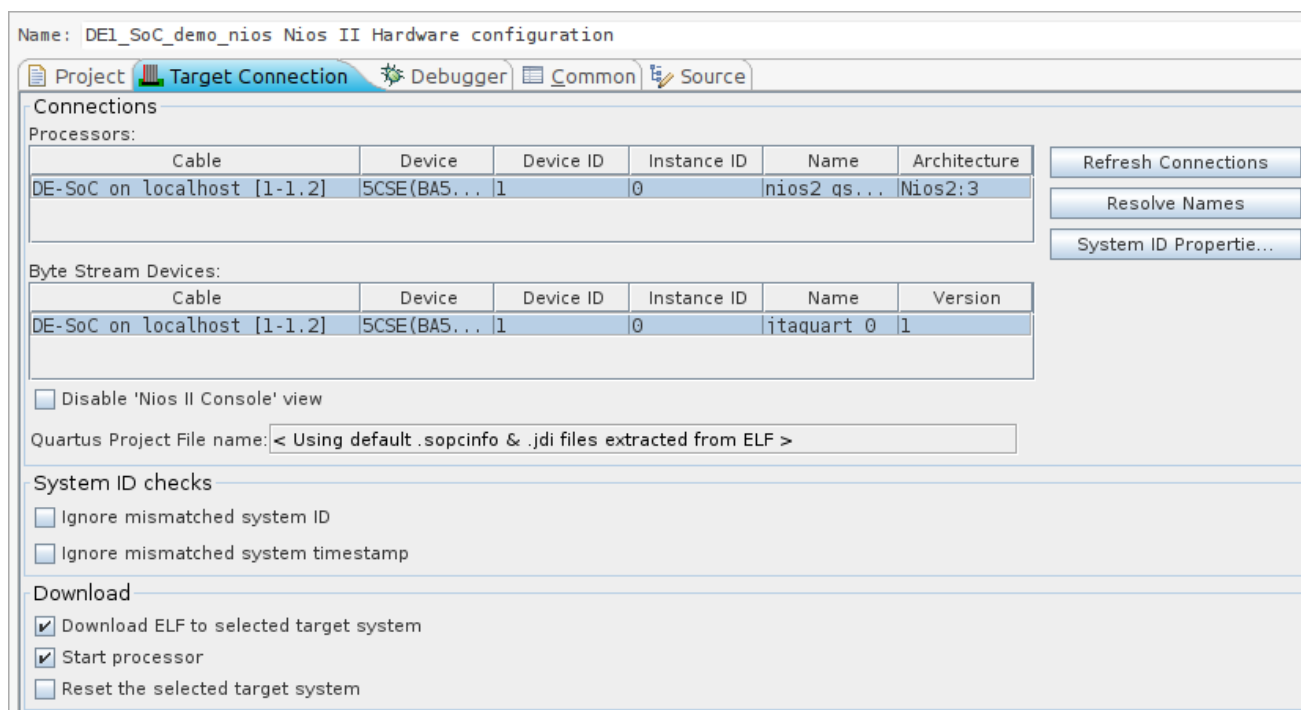
        if (leds_mask == (0x01 << (LEDS_0_DATA_WIDTH - 1))) {
            led_direction = 1;
        }
    } else {
        leds_mask >>= 1;
        if (leds_mask == 0x01) {
            led_direction = 0;
            loop_count++;
        }
    }
}

int main() {
    rotate_leds();
    return 0;
}

```

Figure 8-24. *nios.c*

7. Right-click on “DE1_SoC_demo_nios” project, and select “Build Project”.
8. The code is now ready to be run on the FPGA. Right-click on “DE1_SoC_demo_nios” project, and select “Run As > Nios II Hardware”. You should be able to see a strobing light effect on the 10 FPGA LEDs. You can use the 10 FPGA switches as enable signals for the corresponding LED.
9. In some cases, it is possible that the program will not immediately run on the Nios II processor, and you will be prompted with a “Target Connection” dialog, as shown in Figure 8-25. If your Nios II CPU doesn’t appear in the list of available processors, then
 - a. Click on the “Refresh Connections” button on the right of Figure 8-25.
 - b. Click on the “Run” button to finish.

Figure 8-25. *Nios II Target Connection Dialog*

We now have a programmed Nios II processor on the FPGA. Of course, the design we had specified didn’t require the power of a Nios II processor, and could have easily been done in pure VHDL. Nevertheless, the idea was to show that one can have a secondary programmable processor functioning on the FPGA parallelly to the HPS. We are now done with the *Nios II SBT* IDE, and will no longer need it for the rest of this tutorial.

8.4.2 HPS – ARM

1. Launch a *SoC EDS Embedded Command Shell*.
 - a. On Windows machines, you can find a shortcut to the executable in the Windows Start Menu: “Altera [version] Web Edition > SoC Embedded Design Suite (EDS) [version] > SoC EDS [version] Command Shell”.
 - b. On Linux machines, you can find the executable at “<altera_install_directory>/<version>/embedded/embedded_command_shell.sh”.

8.4.2.1 Generating a Header File for HPS Peripherals

We need the HPS to be able to programmatically access peripherals that are part of the FPGA fabric. In order to do this, we must generate a header file.

2. Create a new file “DE1_SoC_demo/generate_hps_qsys_header.sh”, and populate it with the code shown in Figure 8-26. This code parses the “DE1_SoC_demo/hw/quartus/soc_system.sopcinfo” file looking for a module called “hps_0”, and outputs a header file “hps_soc_system.h”. The generated header file is then moved to the “DE1_SoC_demo/sw/hps/application” directory.

```
#!/bin/bash

# make sure script is run from its current directory
DIR=$( cd "$( dirname "${BASH_SOURCE[0]}" )" && pwd )
cd "$DIR"

sopc-create-header-files \
"hw/quartus/soc_system.sopcinfo" \
--single "hps_soc_system.h" \
--module "hps_0"

if [ ! -d "sw/hps/application/" ]; then
    mkdir "sw/hps/application/"
fi

mv "hps_soc_system.h" "sw/hps/application/"
```

Figure 8-26. generate_hps_qsys_header.sh

3. Execute the “generate_hps_qsys_header.sh” script in the *SoC EDS Embedded Command Shell*. Figure 8-27 shows a short extract of the generated “hps_soc_system.h” header file. At the top of the file, it says that macros for devices connected to master port “h2f_lw_axi_master” of module “hps_0” have been generated.

```
/*
 * This file was automatically generated by the swinfo2header utility.
 *
 * Created from SOPC Builder system 'soc_system' in
 * file hw/quartus/soc_system.sopcinfo'.
 */

/*
 * This file contains macros for module 'hps_0' and devices
 * connected to the following master:
 *   h2f_lw_axi_master
 *
 * Do not include this header file and another header file created for a
 * different module or master group at the same time.
 * Doing so may result in duplicate macro names.
 * Instead, use the system header file which has macros with unique names.
 */
```

```

/*
 * Macros for device 'hex_5', class 'altera_avalon_pio'
 * The macros are prefixed with 'HEX_5_'.
 * The prefix is the slave descriptor.
 */
#define HEX_5_COMPONENT_TYPE altera_avalon_pio
#define HEX_5_COMPONENT_NAME hex_5
#define HEX_5_BASE 0x0
#define HEX_5_SPAN 16
#define HEX_5_END 0xf

```

Figure 8-27. hps_soc_system.h

8.4.2.2 HPS Programming Theory

The HPS works just like any other microcontroller.

- If you want to access a peripheral, you have to read/write at its address.
- If a peripheral is connected to a bus, its address is obtained by adding its offset in the bus to the bus' address.

Altera provides useful utility functions in

“<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/include/soc al/socal.h”, a few of which are listed below. Most functions exist for multiple sizes. These sizes are summarized in Table 8-1. Note that “socal” means “SoC Abstraction Layer”.

- alt_write_byte(dest_addr, byte_data)
- alt_read_byte(src_addr)
- alt_setbits_byte(dest_addr, byte_data)
- alt_clrbits_byte(dest_addr, byte_data)
- alt_xorbits_byte(dest_addr, byte_data)
- alt_replbits_byte(dest_addr, msk, byte_data)

Name	Size (bits)
byte	8
hword	16
word	32
dword	64

Table 8-1. Predefined Data Sizes in socal.h

Up until this point, the hardware and software design process has been **IDENTICAL** for both **BARE-METAL** and **LINUX HPS** applications. This is where the design process **DIVERGES** between bare-metal and Linux HPS applications. If you want to write a bare-metal application for the HPS, then read section 8.4.2.3. If instead you want to write a linux application for the HPS, then read section 8.4.2.4.

Note: In addition to the example used in this tutorial, you can find many more in [9].

8.4.2.3 Bare-metal Applications

The first thing that needs to be done for bare-metal applications is to generate and compile a preloader for the HPS.

8.4.2.3.1 Preloader Generation

4. Type “bsp-editor” in a SoC EDS Embedded Command Shell and press enter.
5. Choose “File > New BSP...”.
 - a. The preloader will need to know which of the HPS’ peripherals were enabled so it can appropriately initialize them in the boot process. Under “Preloader settings directory”, select the “DE1_SoC_demo/hw/quartus/hps_isw_handoff/soc_system_hps_0” directory.

This directory contains settings relative to the HPS' **HARD** peripherals, as configured in the “Arria V/Cyclone V Hard Processor System” component in Qsys.

- b. Disable the “Use default locations” checkbox and under the “BSP target directory”, select the “DE1_SoC_demo/sw/hps/preloader” directory. You should have something similar to Figure 8-28.

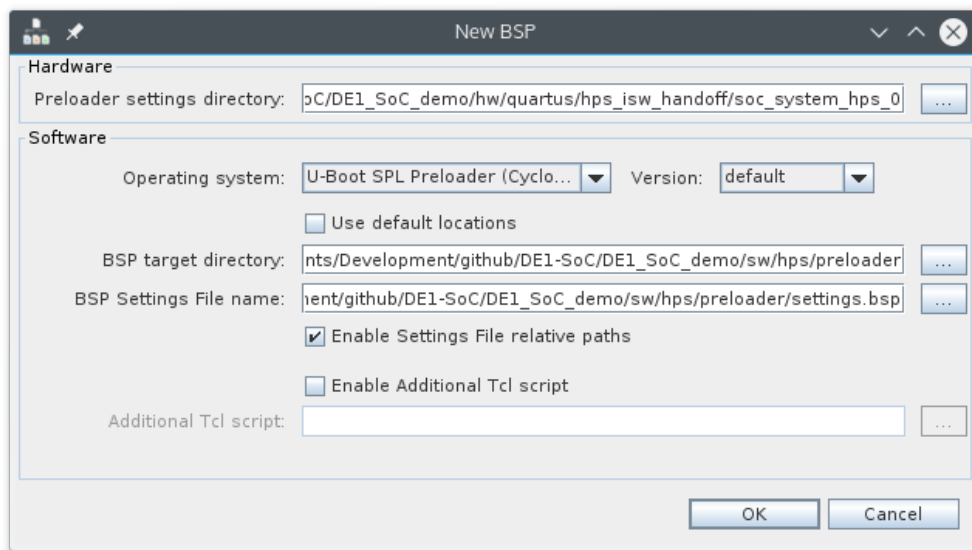


Figure 8-28. New BSP Dialog

- c. Press the “OK” button. You should then arrive on a page with many settings, as shown on Figure 8-29. Take some time to read through them to see what the preloader has the ability to do.

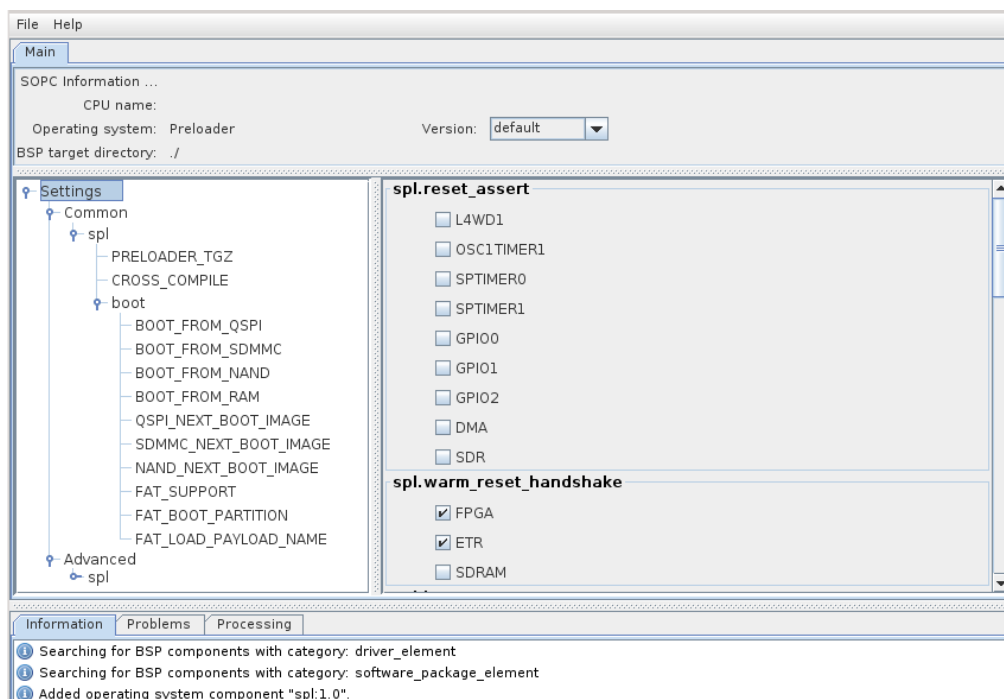


Figure 8-29. Preloader Settings Dialog

6. On the main settings page of Figure 8-29, we will only need to modify 3 parameters for our design.
 - a. Under “spl.boot”, disable the “WATCHDOG_ENABLE” checkbox. This is necessary to prevent the system from being automatically reset after a certain time has elapsed.

- b. Under “spl.performance”, disable the “SERIAL_SUPPORT” checkbox. This greatly speeds up the time spent in the preloader. The “serial support” implied by this checkbox only concerns serial support while the preloader is running. Once we run our bare-metal application, we will still be able to call the `printf()` function.
 - c. Press the “Generate” button to finish. You can then exit the bsp-editor.
- 7. In the *SoC EDS Embedded Command Shell*, navigate to the “DE1_SoC_demo/sw/hps/preloader” directory, and execute “make” to build the preloader.

IF YOU EVER DECIDE TO MOVE THE “DE1_SoC_demo” PROJECT DIRECTORY DEFINED IN FIGURE 8-1, YOU WILL HAVE TO REGENERATE THE PRELOADER. UNFORTUNATELY, THE SCRIPT PROVIDED BY ALTERA WHICH GENERATES THE PRELOADER HARD-CODES MULTIPLE ABSOLUTE PATHS DIRECTLY IN THE RESULTING FILES, RENDERING THEM USELESS ONCE MOVED.

8.4.2.3.2 ARM DS-5

- 8. Launch the ARM DS-5 IDE. Type “eclipse” in a *SoC EDS Embedded Command Shell* and press enter.

BE SURE YOU LAUNCH ARM DS-5 WITH ADMIN RIGHTS, OTHERWISE YOU WON'T BE ABLE TO ACCESS CERTAIN PERIPHERALS ON YOUR MACHINE IN ORDER TO CONNECT TO THE DE1-SOC.

8.4.2.3.2.1 Setting Up a New C Project

- 9. Create a new C project by going to “File > New > Project > C/C++ > C Project”.
 - a. Use “DE1_SoC_demo_hps_baremetal” as the project name.
 - b. Disable the “Use default location” checkbox.
 - c. Set “DE1_SoC_demo/sw/hps/application/DE1_SoC_demo_hps_baremetal” as the target location for the project.
 - d. We want to create a single output executable for our project, so choose “Executable > Empty Project” as the project type.
 - e. Choose “Altera Baremetal GCC” as the Toolchain.
 - f. You should have something similar to Figure 8-30. Then, press the “Finish” button to create the project.

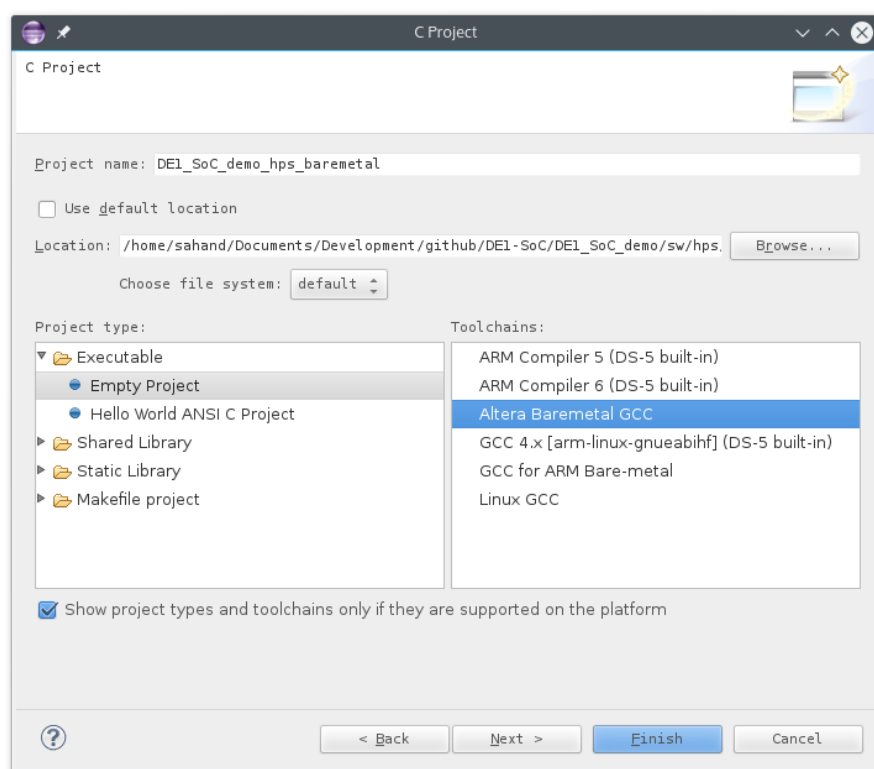


Figure 8-30. New C Project Dialog

10. When programming the HPS, we will need access to a few standard header and linker files provided by Altera. We need to add these files to the *ARM DS-5* project.
 - a. Right-click on the “DE1_SoC_demo_hps_baremetal” project, and go to “Properties”.
 - b. Under “C/C++ Build > Settings > GCC C Compiler > Includes”, add “<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/include” to the “Include paths (-I)” list.
 - c. Since we are not going to be running any operating system, we will need to use a linker script in order to correctly layout our bare-metal program in memory. Altera provides linker scripts for the HPS’ on-chip memory, as well as for its DDR3 memory. We want our code to be loaded in the HPS’ DDR3 memory and will not use any on-chip memory in our design, so we will use the DDR3 linker script.
Under “C/C++ Build > Settings > GCC C Linker > Image”, set the linker script to “<altera_install_directory>/<version>/embedded/host_tools/mentor/gnu/arm/baremetal/arm-altera-eabi/lib/cycloneV-dk-ram-**HOSTED**.ld”. The “hosted” script allows the bare-metal application to use some of the host’s functionality. In this case, we use the “hosted” script to be able to see the output of the `printf()` function on the host’s console.
 - d. Click on the “Apply” button, then on the “Ok” button to close the project properties dialog.

8.4.2.3.2.2 Writing a DS-5 Debug Script

In Figure 6-8, we saw that a bare-metal application cannot run immediately upon boot, and that the HPS must first go through the preloader. As such, we cannot instruct the *DS-5* debugger to *directly* load our bare-metal application’s compiled binary into the HPS’ memory.

Instead, we will use a **DS-5 DEBUG SCRIPT** to instruct the debugger exactly how to load our application.

11. Create a new file for our *DS-5* debug script and save it under “DE1_SoC_demo/sw/hps/application/DE1_SoC_demo_hps_baremetal/debug_setup.ds”.

12. Populate the file with the code shown in Figure 8-31. This script tells the debugger to load the preloader, then to load our bare-metal application.

This is performed by placing a breakpoint at the very last function executed by the preloader prior to handing control of the cpu to the next boot stage. This function is “spl_boot_device()”, which is responsible for choosing the next boot medium on the DE1-SoC and jumping to it’s address. For bare-metal applications, we don’t want the boot process to continue on towards another device. Instead, we want to load our bare-metal code and jump to it’s address. This is exactly what the debug script in Figure 8-31 does.

```
# Reset and stop the system.
stop
wait 5s
reset system
wait 5s

# Delete all breakpoints.
delete breakpoints

# Disable semihosting
set semihosting enabled false

# Load the preloader.
loadfile "$sdir/../../preloader/uboot-socfpga/spl/u-boot-spl" 0x0

# Enable semihosting to allow printing even if you don't have a uart module
# available.
set semihosting enabled true

# Set a breakpoint at the "spl_boot_device()" function. This function is the
# last step of the preloader. It looks for a boot device (qspi flash, sdcard,
# fpga), and jumps to that address. For our bare-metal programs, we don't want
# to use any boot device, but want to run our own program, so we want the
# processor to stop here. Then, we will modify its execution to make it run our
# program.
tbreak spl_boot_device

# Set the PC register to the entry point address previously recorded by the
# "load" or "loadfile" command and start running the target.
run

# Instruct the debugger to wait until either the application completes or a
# breakpoint is hit. In our case, it will hit the breakpoint.
wait

# Load our bare-metal program.
loadfile "$sdir/Debug/DE1_SoC_demo_hps_baremetal.axf"

# Set a breakpoint at our program's "main()" function.
tbreak main

# Start running the target.
run

# wait at main().
Wait
```

Figure 8-31. *debug_setup.ds*

For a comprehensive list of commands supported by the DS-5 debugger, please refer to [10].

Note that it is possible for the HPS to directly execute a Bare-metal application without going through the preloader. However, the application would be forced to fit in the HPS' on-chip memory (which is quite small), and wouldn't be able to use any of the HPS' peripherals, as they haven't been initialized yet.

8.4.2.3.2.3 Setting Up the Debug Configuration

13. Right-click on the “DE1_SoC_demo_hps_baremetal” project, and go to “Debug As > Debug Configurations...”.
14. Choose to create a new debugger configuration by right-clicking on “DS-5 Debugger” on the left and selecting “New”. Use “DE1_SoC_demo_hps_baremetal” as the name of the new debug configuration.
15. Under the “Connection” tab:
 - a. Use “Altera > Cyclone V SoC (Dual Core) > Bare Metal Debug > Debug Cortex-A9_0” as the target platform.
 - b. Set the “Target Connection” to “USB-Blaster”.
 - c. Use the “Browse” button to select the DE1-SoC that is connected to your machine.
 - d. You should have something similar to Figure 8-32.

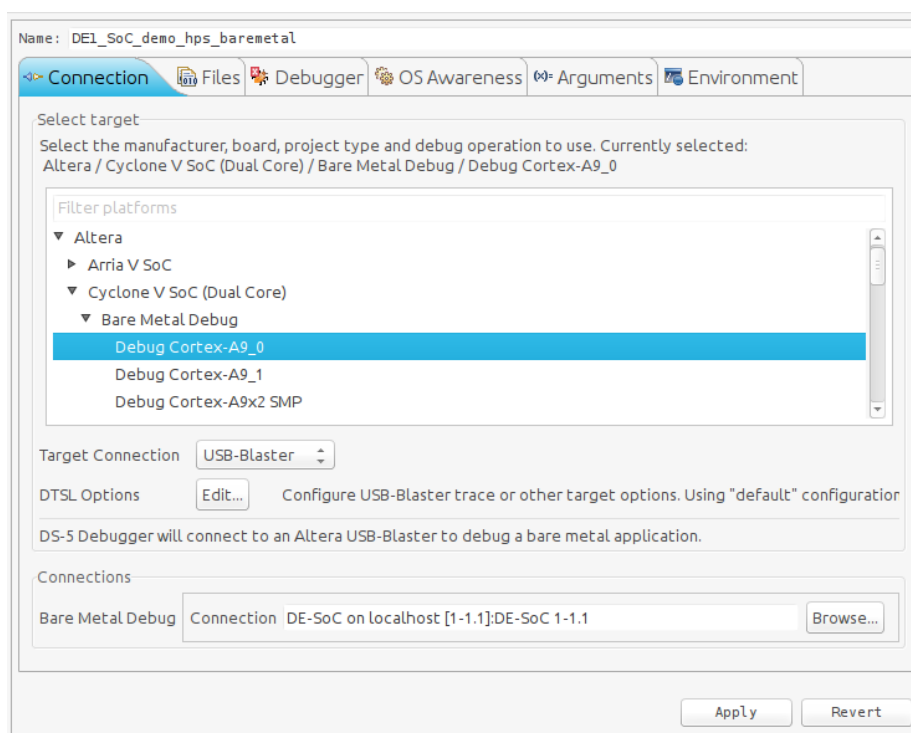


Figure 8-32. Debug Configuraton “Connection” Tab

16. Under the “Files” tab:
 - a. Leave the “Application on host to download” empty. We do this since we are using a debug script to instruct the debugger how to load our application.
 - b. In 8.3.3.2, we configured our HPS to use some FPGA peripherals. We can instruct the debugger about this so it can show more detailed information when debugging. To do this, set the combobox to “Add peripheral description files from directory” and set it to the “DE1_SoC_demo/hw/quartus/soc_system/synthesis” directory, as shown in Figure 8-33. This directory contains a file called “soc_system_hps_0_hps.svd” which has information on all of the HPS' peripherals which are in the FPGA fabric.

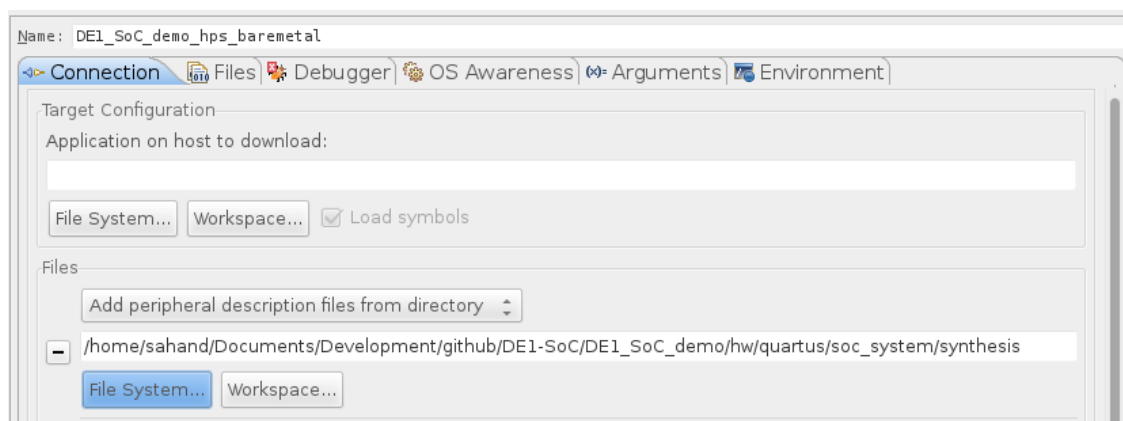


Figure 8-33. Debug Configuration "Files" Tab

17. Under the “Debugger” tab:
 - a. Since we are going to use a debug script to launch the application, we don’t need to specify any function to be loaded by the debugger. So, choose “Connect only” under “Run control”.
 - b. Enable the “Run **DEBUG** initialization debugger script (.ds / .py)” checkbox. Set the debug script to the one we defined for the project in 8.4.2.3.2.2. You should have something similar to Figure 8-34.
18. Click on the “Apply” button, then on the “Close” button to save the debug configuration.

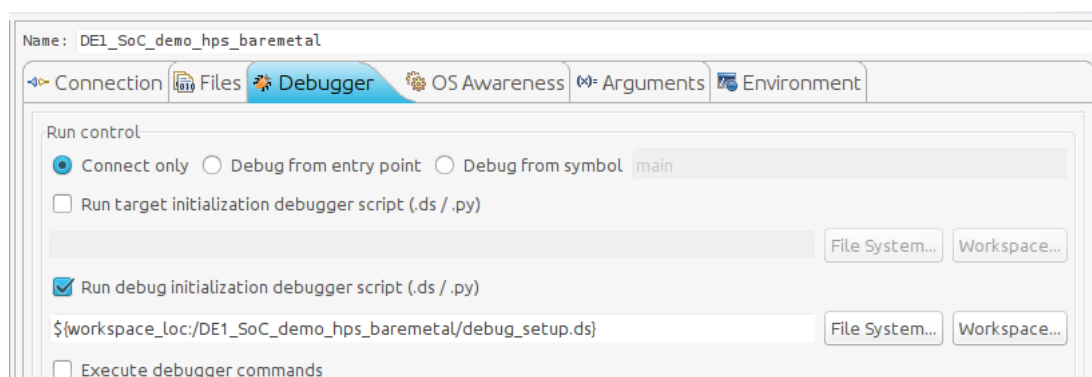


Figure 8-34. Debug Configuration "Debugger" Tab

8.4.2.3.2.4 Bare-metal Programming

We can now start writing bare-metal code for the HPS.

19. Right-click on the “DE1_SoC_demo_hps_baremetal” project, and go to “New > Source File”. Use “hps_baremetal.c” as the file name, and click on the “Finish” button to create the new source file.
20. Right-click on the “DE1_SoC_demo_hps_baremetal” project, and go to “New > Header File”. Use “hps_baremetal.h” as the file name, and click on the “Finish” button to create the new header file.

The code for this part of the application is quite large to be inserted in this document. Therefore, we will just go over a few practical aspects of the code which are worth paying attention to. The full source can be found in DE1_SoC_demo.zip [3].

We are not going to implement any interrupts for the various buttons on the board at this time. Therefore, in order to satisfy the HPS-related goals specified in 8.1, we will need to use an infinite loop and do some polling.

This can be seen in our application’s “main()” function, which is shown in Figure 8-35.

```
int main() {
    printf("DE1-SoC bare-metal demo\n");
```

```

    setup_peripherals();

    uint32_t hex_counter = 0;
    while (true) {
        handle_hex_displays(&hex_counter);
        handle_hps_led();
        delay_us(ALT_MICROSECS_IN_A_SEC / 10);
    }

    return 0;
}

```

Figure 8-35. *hps_baremetal.c main() function*

8.4.2.3.2.4.1 Accessing FPGA Peripherals

Accessing the FPGA peripherals connected to the HPS' *lightweight* HPS-to-FPGA bridge is quite simple, as no libraries are needed. One can simply use the low-level functions listed in 8.4.2.2 to address the peripherals at an offset from the *lightweight* HPS-to-FPGA bridge's base address.

Figure 8-36 shows an example where the HPS accesses the buttons on the FPGA.

```

// fpga buttons can be found at an offset from the base of the lightweight HPS-to-FPGA bridge
void *fpga_buttons = ALT_LWFPGASLVS_ADDR + BUTTONS_0_BASE;

bool is_fpga_button_pressed(uint32_t button_number) {
    // buttons are active-low
    return ((~alt_read_word(fpga_buttons)) & (1 << button_number));
}

```

Figure 8-36. *Accessing FPGA Buttons from the HPS*

A more sophisticated example can be found in Figure 8-37, where the HPS sets the value to be displayed on the FPGA's 7-segment displays.

```

// The 7-segment display is active low
#define HEX_DISPLAY_CLEAR (0x7F)
#define HEX_DISPLAY_ZERO (0x40)
#define HEX_DISPLAY_ONE (0x79)
#define HEX_DISPLAY_TWO (0x24)
#define HEX_DISPLAY_THREE (0x30)
#define HEX_DISPLAY_FOUR (0x19)
#define HEX_DISPLAY_FIVE (0x12)
#define HEX_DISPLAY_SIX (0x02)
#define HEX_DISPLAY_SEVEN (0x78)
#define HEX_DISPLAY_EIGHT (0x00)
#define HEX_DISPLAY_NINE (0x18)
#define HEX_DISPLAY_A (0x08)
#define HEX_DISPLAY_B (0x03)
#define HEX_DISPLAY_C (0x46)
#define HEX_DISPLAY_D (0x21)
#define HEX_DISPLAY_E (0x06)
#define HEX_DISPLAY_F (0x0E)

// The HPS will only use HEX_DISPLAY_COUNT of the 6 7-segment displays
#define HEX_DISPLAY_COUNT (6)
#define HEX_COUNTER_MASK ((1 << (4 * HEX_DISPLAY_COUNT)) - 1)

void *fpga_hex_displays[HEX_DISPLAY_COUNT] = {ALT_LWFPGASLVS_ADDR + HEX_0_BASE,
                                                ALT_LWFPGASLVS_ADDR + HEX_1_BASE,
                                                ALT_LWFPGASLVS_ADDR + HEX_2_BASE,
                                                ALT_LWFPGASLVS_ADDR + HEX_3_BASE,
                                                ALT_LWFPGASLVS_ADDR + HEX_4_BASE,

```

```

                                ALT_LWFGASLVS_ADDR + HEX_5_BASE});

uint32_t hex_display_table[16] = {HEX_DISPLAY_ZERO , HEX_DISPLAY_ONE,
                                HEX_DISPLAY_TWO   , HEX_DISPLAY_THREE,
                                HEX_DISPLAY_FOUR   , HEX_DISPLAY_FIVE,
                                HEX_DISPLAY_SIX    , HEX_DISPLAY_SEVEN,
                                HEX_DISPLAY_EIGHT  , HEX_DISPLAY_NINE,
                                HEX_DISPLAY_A      , HEX_DISPLAY_B,
                                HEX_DISPLAY_C      , HEX_DISPLAY_D,
                                HEX_DISPLAY_E      , HEX_DISPLAY_F};

void set_hex_displays(uint32_t value) {
    char current_char[2] = " \0";
    char hex_counter_hex_string[HEX_DISPLAY_COUNT + 1];

    // get hex string representation of input value on HEX_DISPLAY_COUNT 7-segment displays
    snprintf(hex_counter_hex_string, HEX_DISPLAY_COUNT + 1, "%0*x", HEX_DISPLAY_COUNT, (unsigned int) value);

    uint32_t hex_display_index = 0;
    for (hex_display_index = 0; hex_display_index < HEX_DISPLAY_COUNT; hex_display_index++) {
        current_char[0] = hex_counter_hex_string[HEX_DISPLAY_COUNT - hex_display_index - 1];

        // get decimal representation for this 7-segment display
        uint32_t number = (uint32_t) strtoul(current_char, NULL, 16);

        // use lookup table to find active-low value to represent number on the 7-segment display
        uint32_t hex_value_to_write = hex_display_table[number];

        alt_write_word(fpga_hex_displays[hex_display_index], hex_value_to_write);
    }
}

```

Figure 8-37. Setting the 7-Segment Displays from the HPS

8.4.2.3.2.4.2 Accessing HPS Peripherals

It is possible to do everything with the low-level functions listed in 8.4.2.2. However, a better way would be to use Altera's **HWLIB**, as discussed in 6.5.2. You can easily use **HWLIB** to access all the HPS' **HARD** peripherals.

Note that some things may not be available in **HWLIB**, and you will then have to resort to using the low-level functions. One example of this scenario which we have already seen is when accessing any FPGA peripherals through the *lightweight* or *heavyweight* HPS-to-FPGA bus (as there is no standard header file for any FPGA peripherals).

Since we already demonstrated how to use low-level functions to access peripherals in 8.4.2.3.2.4.1, we will instead use Altera's **HWLIB** to access the HPS' hard peripherals.

8.4.2.3.2.4.2.1 Using Altera's HWLIB - Prerequisites

In order to be able to use **HWLIB** to configure a peripheral, 2 steps need to be performed:

- You need to **ADD** the HPS peripheral's **HWLIB HEADER FILE** to your code.
- You must **COPY** the HPS peripheral's **HWLIB SOURCE FILE** in your *DS-5* project directory. The **HWLIB** source files can be found in directory
 “<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/src”,
 and must be copied to “DE1_SoC_demo/sw/hps/application/DE1_SoC_demo_hps_baremetal”.

8.4.2.3.2.4.2.2 Global Timer & Clock Manager

If you look closely at the code in Figure 8-35, you'll see that we used a “delay_us()” function to slow the counter down. It turns out that among all the code available for the HPS, Altera does not provide any

“sleep()” function (unlike for the Nios II processor). Therefore, we will have to write the “delay_us()” function ourselves.

The easiest way to create a delay in the HPS is to use one of its timers. There are numerous timers on Cyclone V SoCs:

- One such timer is the **GLOBAL TIMER**. This timer is actually shared by both HPS cores, as well as by the FPGA.
- In addition to the unique global timer, each HPS core also has 7 other timers which it can use exclusively, if needed.

For simplicity, we will use the global timer to implement the “delay_us()” function.

As described in 8.4.2.3.2.4.2.1, we need to add the required *HWLIB* sources to our project, and their headers to our code. To program the global timer, we will need information regarding the clock frequency, as well as any timer-specific functions. We can access this information by using the following source and header files:

- alt_clock_manager.c
- alt_clock_manager.h
- alt_globaltmr.c
- alt_globaltmr.h

Figure 8-38 shows how we implement the “delay_us()” function using the global timer.

```
#include "alt_clock_manager.h"
#include "alt_globaltmr.h"

void setup_hps_timer() {
    assert(ALT_E_SUCCESS == alt_globaltmr_init());
}

/* The HPS doesn't have a sleep() function like the Nios II, so we can make one
 * by using the global timer.
 */
void delay_us(uint32_t us) {
    uint64_t start_time = alt_globaltmr_get64();
    uint32_t timer_prescaler = alt_globaltmr_prescaler_get() + 1;
    uint64_t end_time;
    alt_freq_t timer_clock;

    assert(ALT_E_SUCCESS == alt_clk_freq_get(ALT_CLK_MPU_PERIPH, &timer_clock));
    end_time = start_time + us * ((timer_clock / timer_prescaler) / ALT_MICROSECS_IN_A_SEC);

    while(alt_globaltmr_get64() < end_time) {
        // polling wait
    }
}
```

Figure 8-38. Programming the HPS Global Timer

8.4.2.3.2.4.2.3 GPIO

Figure 8-39 shows how we implement the “handle_hps_led()” function. This function uses the HPS_KEY button to toggle HPS_LED.

Once again, we need to add the *HWLIB* source file for the GPIO peripheral to our *DS-5* project directory. The files we will use are listed below:

- alt_generalpurpose_io.c
- alt_generalpurpose_io.h

As stated in 8.4.2.3.2.4.2 previously, *HWLIB* is quite a broad library, but it sometimes lacks certain “obvious” things. In such cases, you have to fall back on using lower-level functions to implement whatever you are missing.

In our case, we see that *HWLIB* has functions that allow us to write to the GPIO peripheral’s “data” register, but it doesn’t have any function to read the it back. We get around this issue by directly reading the register with “alt_read_word(ALT_GPIO1_SWPORTA_DR_ADDR)”.

Note that we also need to include the “socal/alt_gpio.h” header file to have access to the lower-level ALT_GPIO1_SWPORTA_DR_ADDR macro.

```
#include "alt_generalpurpose_io.h"
#include "socal/alt_gpio.h"

// |=====|=====|=====|=====|
// | Signal Name | HPS GPIO | Register/bit | Function |
// |=====|=====|=====|=====|
// |   HPS_LED   |   GPIO53   |   GPIO1[24]   |   I/O   |
// |   HPS_KEY   |   GPIO54   |   GPIO1[25]   |   I/O   |
// |=====|=====|=====|=====|
#define HPS_LED_IDX      (ALT_GPIO1BIT_53)           // GPIO53
#define HPS_LED_PORT     (alt_gpio_bit_to_pid(HPS_LED_IDX)) // ALT_GPIO_PORTB
#define HPS_LED_PORT_BIT (alt_gpio_bit_to_port_pin(HPS_LED_IDX)) // 24 (from GPIO1[24])
#define HPS_LED_MASK     (1 << HPS_LED_PORT_BIT)
#define HPS_KEY_IDX      (ALT_GPIO1BIT_54)           // GPIO54
#define HPS_KEY_PORT     (alt_gpio_bit_to_pid(HPS_KEY_IDX)) // ALT_GPIO_PORTB
#define HPS_KEY_PORT_BIT (alt_gpio_bit_to_port_pin(HPS_KEY_IDX)) // 25 (from GPIO1[25])
#define HPS_KEY_MASK     (1 << HPS_KEY_PORT_BIT)

void setup_hps_gpio() {
    uint32_t hps_gpio_config_len = 2;
    ALT_GPIO_CONFIG_RECORD_t hps_gpio_config[] = {
        {HPS_LED_IDX, ALT_GPIO_PIN_OUTPUT, 0, 0, ALT_GPIO_PIN_DEBOUNCE, ALT_GPIO_PIN_DATAZERO},
        {HPS_KEY_IDX, ALT_GPIO_PIN_INPUT, 0, 0, ALT_GPIO_PIN_DEBOUNCE, ALT_GPIO_PIN_DATAZERO}
    };

    assert(ALT_E_SUCCESS == alt_gpio_init());
    assert(ALT_E_SUCCESS == alt_gpio_group_config(hps_gpio_config, hps_gpio_config_len));
}

void handle_hps_led() {
    uint32_t hps_gpio_input = alt_gpio_port_data_read(HPS_KEY_PORT, HPS_KEY_MASK);

    // HPS_KEY is active-low
    bool toggle_hps_led = (~hps_gpio_input & HPS_KEY_MASK);

    if (toggle_hps_led) {
        uint32_t hps_led_value = alt_read_word(ALT_GPIO1_SWPORTA_DR_ADDR);
        hps_led_value >>= HPS_LED_PORT_BIT;
        hps_led_value = !hps_led_value;
        hps_led_value <<= HPS_LED_PORT_BIT;
        assert(ALT_E_SUCCESS == alt_gpio_port_data_write(HPS_LED_PORT, HPS_LED_MASK, hps_led_value));
    }
}
```

Figure 8-39. Programming the HPS GPIO Peripheral

8.4.2.3.2.4.3 Launching the Bare-metal Code in the Debugger

21. Once you have finished writing all the application's code, right-click on the "DE1_SoC_demo_hps_baremetal" project, and select "Build Project".
22. Switch to the *DS-5 Debug* perspective, as shown in Figure 8-40.

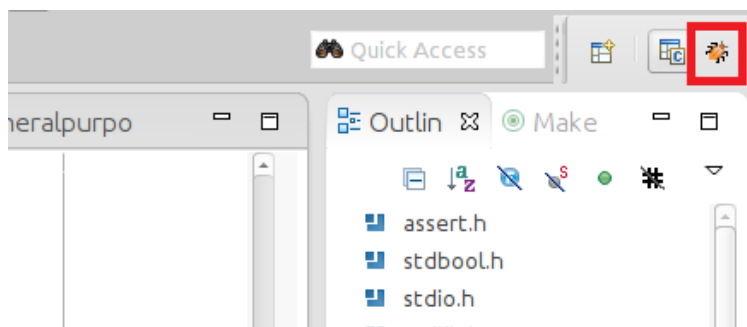


Figure 8-40. Switching to the DS-5 Debug Perspective

23. In the "Debug Control" view, click on the "DE1_SoC_demo_hps_baremetal" entry, then click on the "Connect to Target" button, as shown on Figure 8-41. Our debug script will load and execute the preloader, then it will load and wait at our application's "main()" function.

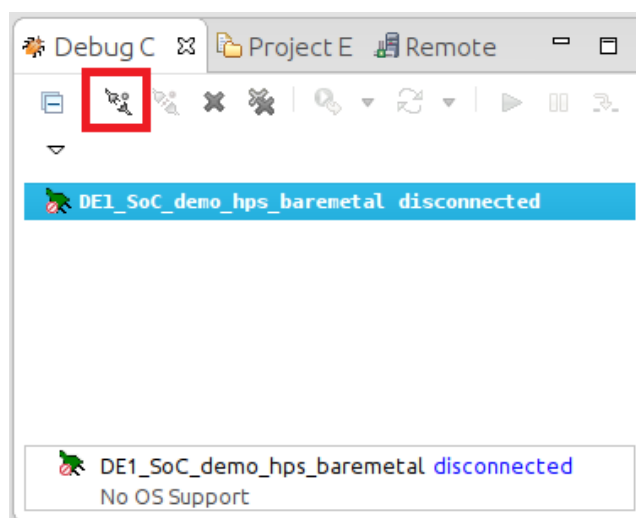


Figure 8-41. Debug Control View

24. You can use the buttons in the "Debug Control" view to control the application's execution.

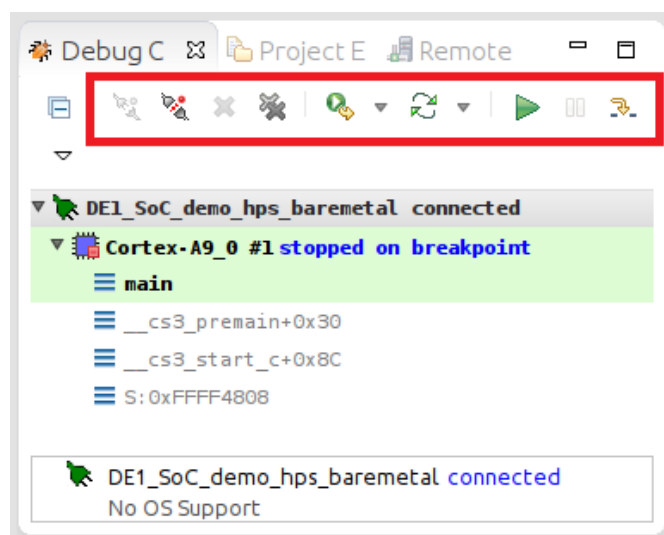


Figure 8-42. DS-5 Debugger Controls

8.4.2.3.2.4.4 DS-5 Bare-metal Debugger Tour

8.4.2.3.2.4.4.1 “Registers” View

DS-5’s **GREATEST** feature is its “Registers” view.

Recall that we provided the debugger with a **PERIPHERAL DESCRIPTION FILE** in 8.4.2.3.2.3. This file allows the debugger’s “Registers” view to display information about all the HPS’ internal and FPGA peripherals, as shown in Figure 8-43.

The screenshot shows the DS-5 Debugger interface with the 'Registers' view selected. On the left, a tree view lists various peripherals under the 'Peripherals' category. The 'gpio1' peripheral is selected. On the right, two detailed views of registers are shown.

Peripherals List (Left Panel):

- Core
- CP15
- VFP
- NEON
- Peripherals**
 - acpidmap
 - can0
 - can1
 - clkmgr
 - dap
 - dmanonsecure
 - dmasecure
 - emac0
 - emac1
 - fpga2hpsregs
 - fpgamgrdata
 - fpgamgrregs
 - gpio0
 - gpio1
 - gpio2
 - hps2fpgaregs
 - i2c0
 - i2c1
 - i2c2
 - i2c3
 - l3regs
 - l4wd0
 - l4wd1
 - lwhps2fpgaregs
 - mpul2
 - mpuscu
 - nandregs
 - oscltimer0
 - oscltimer1
 - qspi0
 - rstmgr
 - scanmgr
 - sdmmc
 - sdr
 - spim0
 - spim1
 - spis0
 - spis1
 - sptimer0
 - sptimer1
 - stm
 - sysmgr
 - uart0
 - uart1
 - usb0
 - usb1
 - altera_avalon_pio_buttons_0_s1
 - altera_avalon_pio_hex_0_s1
 - altera_avalon_pio_hex_1_s1
 - altera_avalon_pio_hex_2_s1
 - altera_avalon_pio_hex_3_s1
 - altera_avalon_pio_hex_4_s1
 - altera_avalon_pio_hex_5_s1

Register Details (Right Panel):

gpio1

Name	Value	Size	Access
gpio1_gpio_swporta_dr	0x00000000	32	R/W
gpio1_gpio_swporta_ddr	0x00000000	32	R/W
gpio1_gpio_inten	0x00000000	32	R/W
gpio1_gpio_intmask	0x00000000	32	R/W
gpio1_gpio_inttype_level	0x00000000	32	R/W
gpio1_gpio_int_polarity	0x00000000	32	R/W
gpio1_gpio_intstatus	0x00000000	32	R/W
gpio1_gpio_raw_intstatus	0x00000000	32	R/W
gpio1_gpio_debounce	0x00000000	32	R/W
gpio1_gpio_porta_eoi	write only	32	WO
gpio1_gpio_ext_porta	0x1FF7FFCF	32	RO
gpio1_gpio_ls_sync	0x00000000	32	R/W
gpio1_gpio_id_code	0x00000000	32	RO
gpio1_gpio_ver_id_code	0x3230382A	32	RO
gpio1_gpio_config_reg2	0x00039CFC	32	RO
gpio1_gpio_config_reg1	0x001FF0F2	32	RO

altera_avalon_pio_hex_0_s1

Name	Value	Size	Access
altera_avalon_pio_hex_0_s1_DATA	0x0000007F	32	R/W
altera_avalon_pio_hex_0_s1_DIRECTION	0x00000000	32	R/W
altera_avalon_pio_hex_0_s1_IRQ_MASK	0x00000000	32	R/W
altera_avalon_pio_hex_0_s1_EDGE_CAP	0x00000000	32	R/W
altera_avalon_pio_hex_0_s1_SET_BIT	write only	32	WO
altera_avalon_pio_hex_0_s1_CLEAR_BITS	write only	32	WO

gpio1 (Detailed View)

Name	Value	Size	Access
gpio1_gpio_swporta_dr	0x00000000	32	R/W
gpio1_gpio_swporta_ddr	0x01000000	32	R/W
gpio1_gpio_inten	0x00000000	32	R/W
gpio1_gpio_intmask	0x00000000	32	R/W
gpio1_gpio_inttype_level	0x00000000	32	R/W
gpio1_gpio_int_polarity	0x00000000	32	R/W
gpio1_gpio_intstatus	0x00000000	32	R/W
gpio1_gpio_raw_intstatus	0x00000000	32	R/W
gpio1_gpio_debounce	0x03000000	32	R/W
gpio1_gpio_porta_eoi	write only	32	WO
gpio1_gpio_ext_porta	0x1EF7FFCF	32	RO
gpio1_gpio_ls_sync	0x00000000	32	R/W
gpio1_gpio_id_code	0x00000000	32	RO
gpio1_gpio_ver_id_code	0x3230382A	32	RO
gpio1_gpio_config_reg2	0x00039CFC	32	RO
gpio1_gpio_config_reg1	0x001FF0F2	32	RO

Figure 8-43. DS-5 Debugger Registers View

You can **MODIFY** any value in this view, and they will automatically be applied to the corresponding peripheral. For example, you can manually switch on one of the 7-segment displays, or manually trigger a button press of HPS_KEY (assuming you write the correct bit in the correct place).

The view also highlights the values that changed when stepping through the code while debugging, which helps you track down invalid peripheral writes, side-effects, ...

However, there is one downside with the “Registers” view. With so many details in this view, one would normally start browsing through each peripheral’s registers (much easier than reading the Cyclone V manual, isn’t it?).

The problem occurs when you expand a peripheral that *has not been enabled* in the preloader, or that has *side-effects* when some of its registers are accessed.

Indeed, *DS-5* will try to access an invalid address, and it will crash the debugging session, therefore leaving the software on the board in an unrecoverable state. You will have to **SWITCH OFF THE BOARD** and reprogram it to relaunch the application. Don’t forget to **REPROGRAM THE FPGA FABRIC** with your design as well.

8.4.2.3.2.4.4.2 App Console

Data sent to standard output is shown in the “App Console” view. Figure 8-44 shows the result of a “printf()” call in our demo code shown in Figure 8-35.

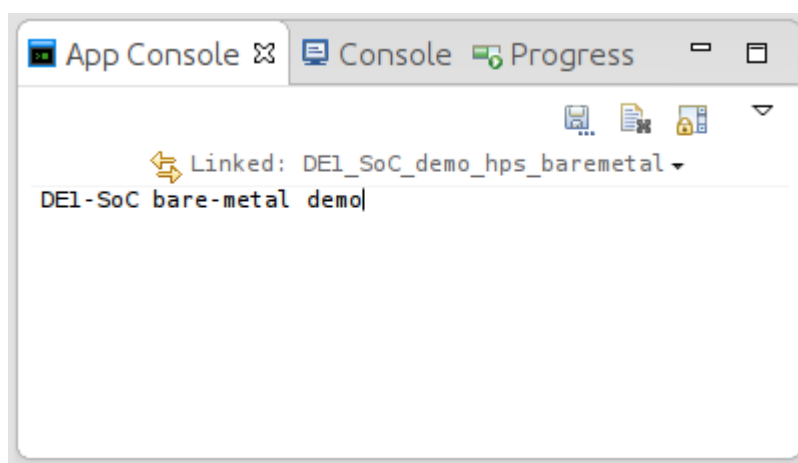


Figure 8-44. DS-5 App Console View

8.4.2.4 Linux Applications

8.4.2.4.1 Getting a linux distribution

The first thing that you will need when writing a linux application for the HPS is to get your hands on a linux distribution. Terasic provides 4 linux distributions which you can use as your base installation:

- “Linux Console” [11]: this is a standard command-line linux distribution. It is *only* accessible through the DE1-SoC’s serial port, or through the ethernet port with SSH.
- “Linux Console with framebuffer” [12]: this linux distribution is identical to the standard linux console, but in addition outputs everything on the DE1-SoC’s VGA connector. Therefore, it is possible to connect a USB or PS-2 keyboard to the DE1-SoC and directly input commands on the device without using a serial port.
- “Linux LXDE Desktop” [13]: this linux distribution proposes a complete GUI to the user. It is based on the lightweight LXDE desktop environment and runs quite smoothly on the DE1-SoC. You can plug in a mouse and a keyboard to the board to use the device just as a standard linux computer.
- “Linux Ubuntu Desktop” [14]: this linux distribution is identical to the LXDE alternative, but uses the Ubuntu GUI instead. The Ubuntu GUI is unfortunately much slower than the LXDE alternative and mouse movements are quite slow on the screen, but otherwise all proposed functionalities are the same between both versions.

In this demo, we will use the standard “Linux Console” distribution.

8.4.2.4.2 Creating a linux microSD card

As we saw in 6.6.1, the DE1-SoC can only boot from SD/MMC flash memory, so we need to write our linux distribution to a microSD card in order to boot from it.

1. Download and extract the distribution available in `Linux Console.zip` [11] to the “DE1_SoC_demo/sw/hps/linux” directory. You should have a single file inside called “DE1_SoC_SD.img” which contains the linux disk image to be written to the microSD card.
2. Write “DE1_SoC_SD.img” to an *empty* microSD card.
 - a. On Windows machines, you can use a tool called “[Win32 Disk Imager](#)” to write the image to the microSD card.
 - b. On Linux machines, you can write the image to a microSD card by using the “dd” command in a terminal.
Change your terminal’s current working directory to “DE1_SoC_demo/sw/hps/linux”, then execute the following command: “dd if=DE1_SoC_SD.img of=/dev/sdb”.
BE SURE TO MODIFY /DEV/SDB to the actual name of the microSD card when it is plugged into your system or else you will end up erasing data on one of your drives!
3. Insert the microSD card into the DE1-SoC’s microSD card slot.
4. Connect an ethernet and serial cable to the DE1-SoC, then power on the board.

Note that we do not need to create any preloader, as each linux distribution already contains one.

8.4.2.4.3 ARM DS-5

5. Launch the ARM DS-5 IDE. Type “eclipse” in a *SoC Embedded Command Shell* and press enter.

BE SURE YOU LAUNCH ARM DS-5 WITH ADMIN RIGHTS, OTHERWISE YOU WON’T BE ABLE TO ACCESS CERTAIN PERIPHERALS ON YOUR MACHINE IN ORDER TO CONNECT TO THE DE1-SOC.

8.4.2.4.3.1 Setting Up a New C Project

6. Create a new C project by going to “File > New > C Project”.
 - a. Use “DE1_SoC_demo_hps_linux” as the project name.
 - b. Disable the “Use default location” checkbox.
 - c. Set “DE1_SoC_demo/sw/hps/application/DE1_SoC_demo_hps_linux” as the target location for the project.
 - d. We want to create a single output executable for our project, so choose “Executable > Empty Project” as the project type.
 - e. Choose “GCC 4.x [arm-linux-gnueabi] (DS-5 built-in)” as the Toolchain.
 - f. You should have something similar to Figure 8-45. Then, press the “Finish” button to create the project.

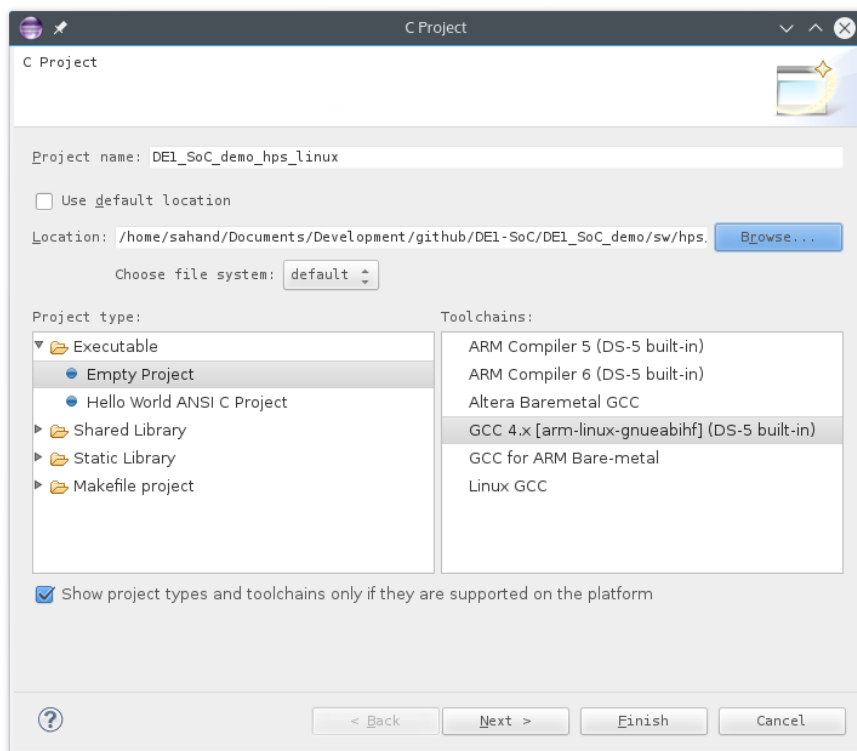


Figure 8-45. New C Project Dialog

7. When programming the HPS, we will need access to a few standard header and linker files provided by Altera. We need to add these files to the *ARM DS-5* project.
 - a. Right-click on the “DE1_SoC_demo_hps_linux” project, and go to “Properties”.
 - b. Under “C/C++ Build > Settings > GCC C Compiler > Includes”, add “<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/include” to the “Include paths (-I)” list.
 - c. Click on the “Apply” button, then on the “Ok” button to close the project properties dialog.
8. In order to unlock a few settings later in this tutorial, we will create a C file that simply contains an empty “main()” function for the moment.
 - a. Right-click on the “DE1_SoC_demo_linux” project, and go to “New > Source File”. Use “hps_linux.c” as the file name, and click on the “Finish” button to create the new source file.
 - b. Right-click on the “DE1_SoC_demo_linux” project, and go to “New > Header File”. Use “hps_linux.h” as the file name, and click on the “Finish” button to create the new header file.
 - c. Fill “hps_linux.c” with the code shown in Figure 8-46.

```
int main(void) {
    return 0;
}
```

Figure 8-46. hps_linux.c with an empty main() function.

- d. Right-click on the “DE1_SoC_demo_linux” project and select “Build Project”.

8.4.2.4.3.2 Creating a Remote Debug Connection to the Linux Distribution

8.4.2.4.3.2.1 Find the Linux Distribution’s IP Address

Later in this tutorial, we will need to know the IP address assigned to the DE1-SoC so *ARM DS-5* can automatically use an SSH connection to transfer Linux binaries and launch gdb debug sessions for us. In this step, we will use a serial terminal to manually connect to the Linux distribution running on the board and find out its IP address.

9. We will use the built-in serial terminal available in *ARM DS-5*. Go to “Window > Show View > Other... > Terminal > Terminal” to open *ARM DS-5*’s the built-in serial terminal. You should see the terminal shown in Figure 8-47.

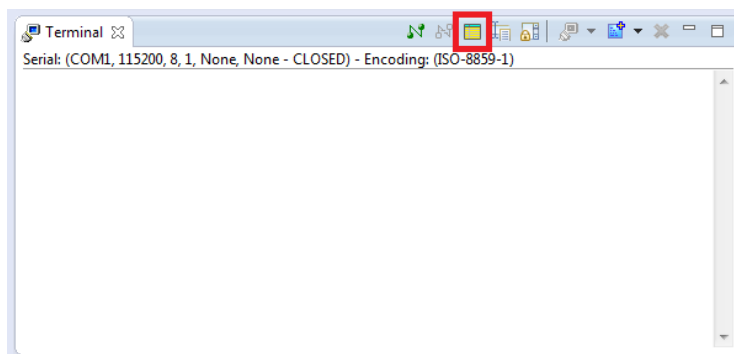


Figure 8-47. ARM DS-5 Serial Terminal

10. Modify the serial terminal’s settings to match those shown in Figure 8-48, then press “OK” to start the connection.

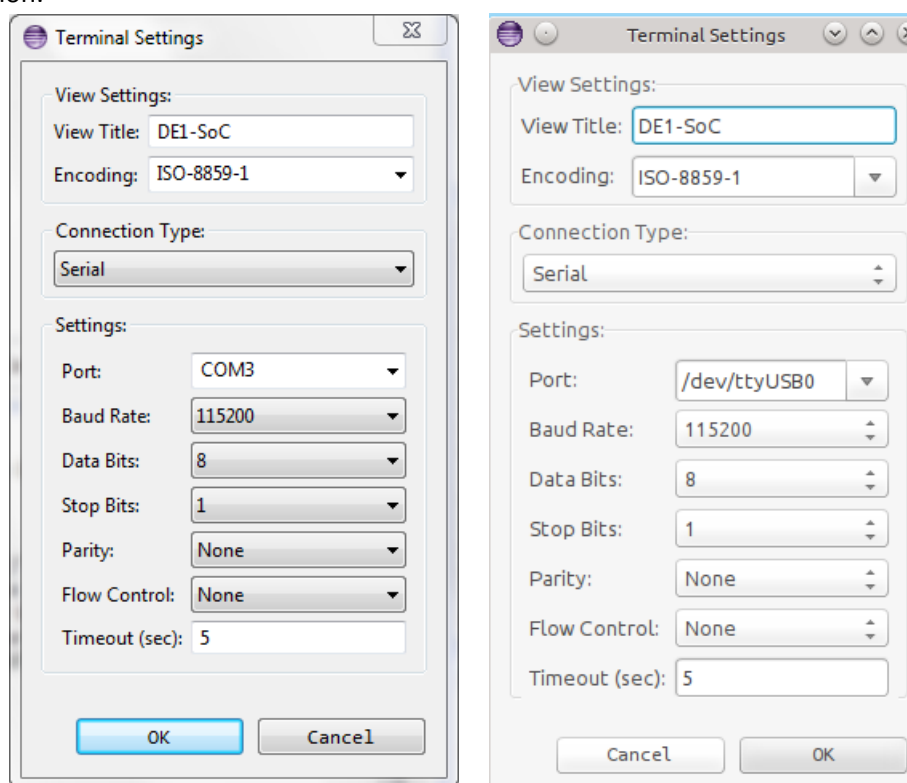


Figure 8-48. ARM DS-5 Serial Terminal Settings (Windows settings on the left, Linux settings on the right)

11. You should see the Linux login prompt. Log in as user “root”, and use “terasic” as password if asked. You should see something similar as Figure 8-49.

```

Serial: (COM3, 115200, 8, 1, None, None - CONNECTED) - Encoding: (ISO-8859-1)
Starting portmap daemon...
Sat Sep 28 04:37:00 UTC 2013
INIT: Entering runlevel: 5
Starting OpenBSD Secure Shell server: sshd
done.
Starting syslogd/klogd: done
Starting Lighttpd Web Server: lighttpd.
Starting blinking LED server
Stopping Bootlog daemon: bootlogd.

Poky 8.0 (Yocto Project 1.3 Reference Distro) 1.3
ttyS0

socfpga login: root
root@socfpga:~#

```

Figure 8-49. ARM DS-5 Serial Terminal Linux Prompt

12. Type “`ifconfig eth0 | grep inet`” to obtain the IP address attributed to the device. You should get something similar to Figure 8-50. If you don’t see an IP address listed, then run “`udhcpc`” to try to automatically obtain one.

```

Serial: (COM3, 115200, 8, 1, None, None - CONNECTED) - Encoding: (ISO-8859-1)

root@socfpga:~# ifconfig eth0 | grep inet
inet addr:10.42.0.58 Bcast:10.42.0.255 Mask:255.255.255.0
root@socfpga:~#

```

Figure 8-50. Obtaining the DE1-SoC's IP Address through ARM DS-5's Serial Terminal

8.4.2.4.3.2 Create an SSH Remote Connection

13. Go to “File > New > Other... > Remote System Explorer > Connection”.
14. Choose to create an “SSH Only” connection.
15. Enter the IP address you found in 8.4.2.4.3.2.1 as the “Host name”.
16. Enter “DE1-SoC” as the “Connection name”. You should have something similar to Figure 8-51.
17. Click on “Finish” to create the connection.

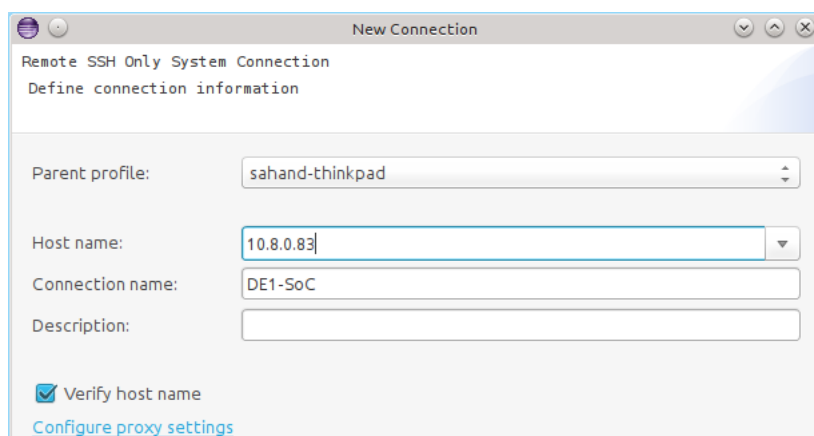


Figure 8-51. New SSH Only Connection

18. You should be able to see the remote system in *ARM DS-5*'s "Remote Systems" view, as shown in Figure 8-52.

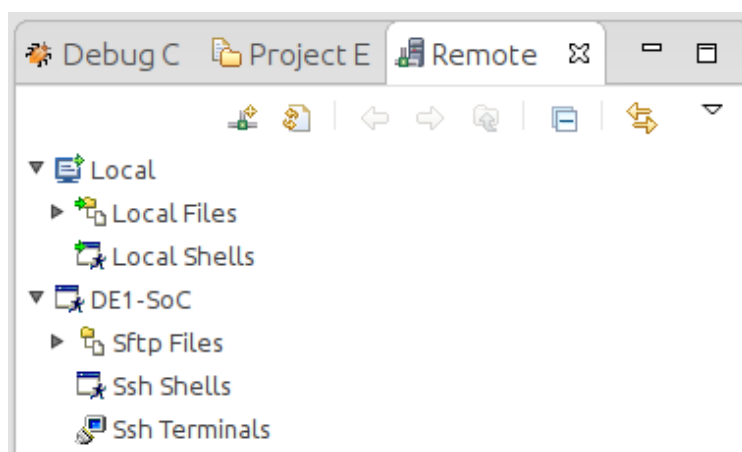


Figure 8-52. New SSH Connection In "Remote Systems" View

8.4.2.4.3.2.3 Setting Up the Debug Configuration

19. Right-click on the "DE1_SoC_demo_linux" project, and go to "Debug As > Debug Configurations...".
20. Choose to create a new debugger configuration by right-clicking on "DS-5 Debugger" on the left and selecting "New". Use "DE1_SoC_demo_hps_linux" as the name of the new debug configuration.
21. Under the "Connection" tab:
 - a. Use "Altera > Cyclone V SoC (Dual Core) > Linux Application Debug > Download and debug application" as the target platform.
 - b. Set the "RSE connection" to "DE1-SoC". This is the remote system connection we created earlier. You should have something similar to Figure 8-53.

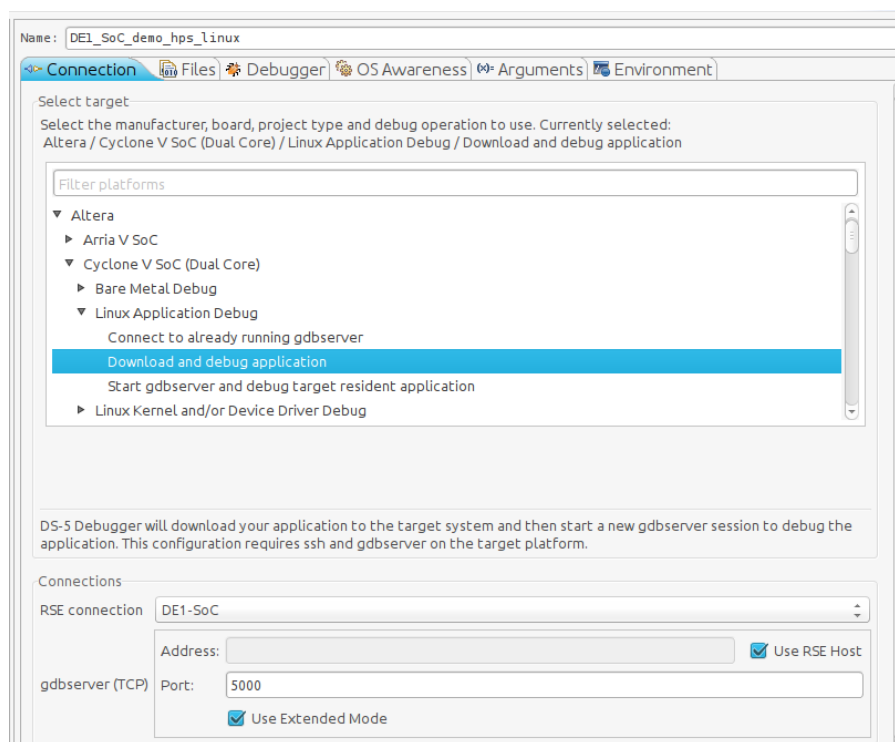


Figure 8-53. Debug Configuraton “Connection” Tab

22. Under the “Files” tab:

- a. Set “Application on host to download” to the built binary of our project. Use the “Workspace” button to choose the binary. You should have something similar to “\${workspace_loc:/DE1_SoC_demo_hps_linux/Debug/DE1_SoC_demo_hps_linux}”.
- b. Set the “Target download directory” to “/root”.
- c. Set the “Target working directory” to “/root”. You should have something similar to Figure 8-54.

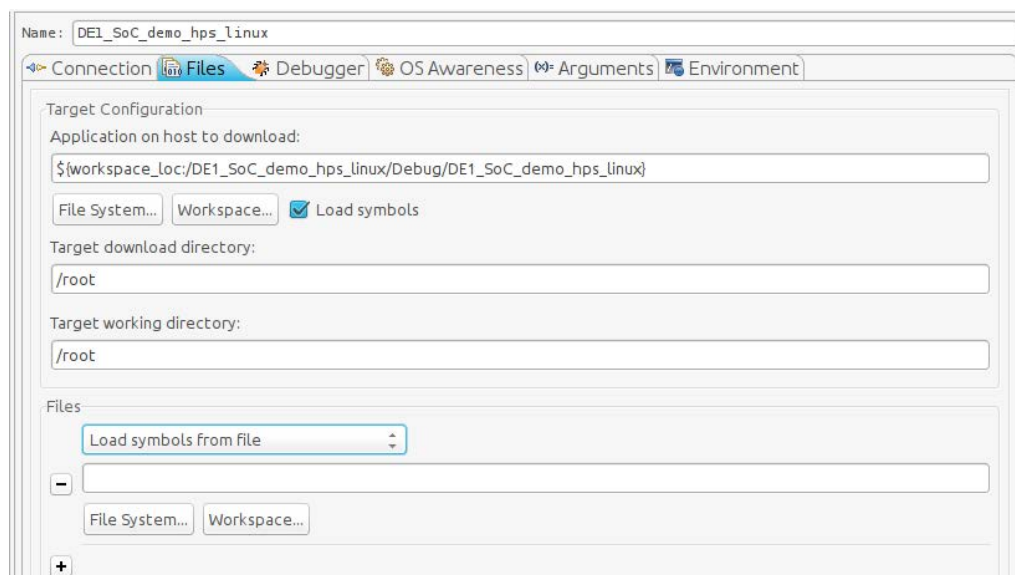


Figure 8-54. Debug Configuration “Files” Tab

23. Under the “Debugger” tab, make sure that “Debug from symbol” is selected and that “main” is the name of the symbol, as shown in Figure 8-55.
24. Click on the “Apply” button, then on the “Close” button to save the debug configuration.

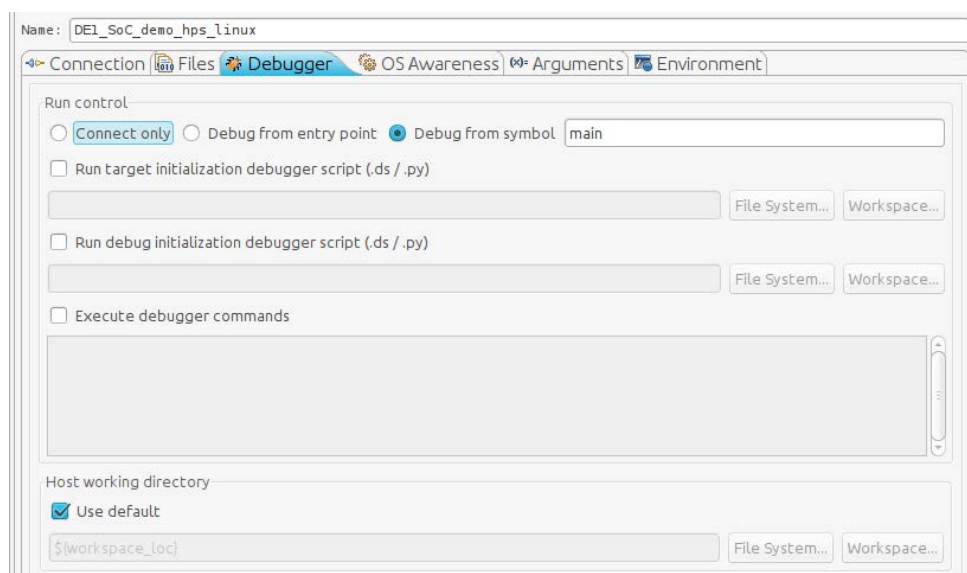


Figure 8-55. Debug Configuration "Debugger" Tab

8.4.2.4.3.3 Linux Programming

The interrupt-driven nature of operating systems requires that error-prone processes be unable to harm the correct operation of the computer. Modern processors provide a hardware solution to this issue by means of a **DUAL-MODE** operating state. CPUs define two *modes* which operating systems can then use to implement protection mechanisms among processes they are handling.

The Linux operating system calls these modes **USER MODE** and **KERNEL MODE**. Processors remain in user mode when executing *harmless* code in user applications, whereas they transition to kernel mode when executing potentially *dangerous* code in the system kernel. Examples of dangerous code are handling an interrupt from a peripheral, copying data from a peripheral's registers to main memory, ...

User code cannot be executed in kernel mode. When a user process needs to perform an action that is only allowed in kernel mode, it performs a system call and asks the operating system to take care of the task in its place. What this boils down to is that **USER CODE CANNOT ACCESS THE HARDWARE DIRECTLY**, as there is too much of a risk for the code to have an error and cause the system to crash. User code must always ask the operating system to perform dangerous operations in its place.

The main advantage of Cyclone V SoCs is the ability to have the HPS and FPGA communicate with each other easily. This is simple to accomplish in a standard bare-metal application as there are absolutely no protection mechanisms implemented. However, this is not possible while the HPS is running Linux, as user code doesn't have the right to access hardware directly.

There are 2 solutions to this problem:

- If developers are knowledgeable enough, they can write a device driver for the target peripheral they want to access in their user code, and package this in a loadable Linux kernel module. This is the correct way to access hardware in Linux, but it requires that the developer know how to write a device driver. The system's *root* user can load the kernel module, then any *standard* user code can interact with the peripheral.
- A simpler technique often used in embedded Linux environments is to leverage the virtual memory system in order to access any **MEMORY-MAPPED** peripherals (peripherals and operations that are only accessible through privileged machine instructions cannot be accessed with this method). Unfortunately, this method requires code to be run with *root* privileges. However, it does not require any kernel code to be written.

Writing a Linux device driver is outside the scope of this tutorial, so we will use the memory mapping technique here.

The code for this part of the application is quite large to be inserted in this document. Therefore, we will just go over a few practical aspects of the code which are worth paying attention to. The full source can be found in `DE1_SoC_demo.zip` [3].

Recall that we cannot handle interrupts in Linux user mode. Therefore, in order to satisfy the HPS-related goals specified in 8.1, we will need to use an infinite loop and do some polling. This can be seen in our application's "main()" function, which is shown in Figure 8-56.

```
int main() {
    printf("DE1-SoC linux demo\n");

    open_physical_memory_device();
    mmap_peripherals();

    setup_hps_gpio();
    setup_hex_displays();

    uint32_t hex_counter = 0;
    while (true) {
        handle_hex_displays(&hex_counter);
        handle_hps_led();
        usleep(ALT_MICROSECS_IN_A_SEC / 10);
    }

    munmap_peripherals();
    close_physical_memory_device();

    return 0;
}
```

Figure 8-56. `hps_linux.c` main() Function

8.4.2.4.3.3.1 Using Altera's HWLIB - Prerequisites

We will use a **SUBSET** of Altera's *HWLIB* in this tutorial. In order to be able to use *HWLIB* to configure a peripheral, 2 steps need to be performed:

- You need to add the HPS peripheral's **HWLIB HEADER FILE** to your code.
- You must **COPY** the HPS peripheral's **HWLIB SOURCE FILE** in your *DS-5* project directory. The *HWLIB* source files can be found in directory "`<altera_install_directory>/<version>/embedded/ip/altera/hps/altera_hps/hwlib/src`", and must be copied to "`DE1_SoC_demo/sw/hps/application/DE1_SoC_demo_hps_linux`".

In the example used in this Linux programming tutorial, we use some *HWLIB* functions related to the HPS' GPIO peripheral, so you must copy "`alt_generalpurpose_io.c`" to your *DS-5* project directory.

8.4.2.4.3.3.2 Accessing Hardware Peripherals from User Space

8.4.2.4.3.3.2.1 Opening the Physical Memory File Descriptor

In Figure 6-3 we saw that the FPGA slaves and HPS peripherals are visible to the MPU unit and are therefore subject to memory-mapped IO. We need to be able to access these peripherals' addresses in order to interact with them.

Unfortunately, a process can only interact with the *virtual address space* it is assigned by the Linux kernel. Any attempt to access memory outside this region will cause the process to be terminated. Nevertheless, it is possible for a process to gain access to another virtual memory region by using the "`mmap()`" function. The

`mmap()` function maps another memory region into the running process' virtual address space. Therefore, all we need to do is to `mmap()` the FPGA slaves and HPS peripherals' memory regions into our address space.

The `mmap()` function's prototype is shown in Figure 8-57. Note that it memory maps a **FILE** into the running process' address space, so we need to find a file that "represents" our peripherals.

```
void *mmap(void *addr, size_t length, int prot, int flags, int fd, off_t offset)
```

Figure 8-57. Prototype of the `mmap()` Function

By design, Linux represents everything as a file, including all devices. In particular, the special `"/dev/mem"` file represents the content of the system's physical memory. This is the file we will `mmap()` in order to access the memory regions we are interested in.

Since we are memory-mapping a file, the first step is to open this file. Figure 8-58 shows how to open the `/dev/mem` file. Remember that `/dev/mem` grants access to physical memory, so a user requires elevated rights in order to open it. Therefore, don't forget to launch this code as the `root` user in order to have enough privileges.

```
// physical memory file descriptor
int fd_dev_mem = 0;

void open_physical_memory_device() {
    fd_dev_mem = open("/dev/mem", O_RDWR | O_SYNC);
    if(fd_dev_mem == -1) {
        printf("ERROR: could not open \"/dev/mem\"...\n");
        printf("    errno = %s\n", strerror(errno));
        exit(EXIT_FAILURE);
    }
}
```

Figure 8-58. `open_physical_memory_device()` Function

8.4.2.4.3.3.2.2 Accessing HPS Peripherals

Now that we have opened the physical memory file, we can memory-map a subset of it into our process' virtual address space. Figure 8-59 shows how this is done for memory-mapping the HPS' GPIO peripheral. Note that you must know the offset of your peripheral within the physical memory file, as well as the amount of memory you want to be memory-mapped from that offset. In our case, we will start memory-mapping from the GPIO1 peripheral's offset, and we choose to map the size of the full peripheral.

```
void *hps_gpio = NULL;
size_t hps_gpio_span = ALT_GPIO1_UB_ADDR - ALT_GPIO1_LB_ADDR + 1;
size_t hps_gpio_ofst = ALT_GPIO1_OFST;

void mmap_hps_peripherals() {
    hps_gpio = mmap(NULL, hps_gpio_span, PROT_READ | PROT_WRITE, MAP_SHARED, fd_dev_mem, hps_gpio_ofst);
    if (hps_gpio == MAP_FAILED) {
        printf("Error: hps_gpio mmap() failed.\n");
        printf("    errno = %s\n", strerror(errno));
        close(fd_dev_mem);
        exit(EXIT_FAILURE);
    }
}
```

Figure 8-59. `mmap_hps_peripherals()` Function

Finally, after having memory-mapped the HPS' GPIO peripheral, we can access any of its internal registers with the low-level functions we saw in 8.4.2.2. Figure 8-60 shows how we configure the HPS' GPIO peripheral, and Figure 8-61 shows how we can toggle HPS_LED on the DE1-SoC by using the HPS_KEY button.

```
void setup_hps_gpio() {
    // Initialize the HPS PIO controller:
```

```
//      Set the direction of the HPS_LED GPIO bit to "output"
//      Set the direction of the HPS_KEY GPIO bit to "input"
void *hps_gpio_direction = ALT_GPIO_SWPORTA_DDR_ADDR(hps_gpio);
alt_setbits_word(hps_gpio_direction, ALT_GPIO_PIN_OUTPUT << HPS_LED_PORT_BIT);
alt_setbits_word(hps_gpio_direction, ALT_GPIO_PIN_INPUT << HPS_KEY_PORT_BIT);
```

Figure 8-60. setup_hps_gpio() Function

```
void handle_hps_led() {
    void *hps_gpio_data = ALT_GPIO_SWPORTA_DR_ADDR(hps_gpio);
    void *hps_gpio_port = ALT_GPIO_EXT_PORTA_ADDR(hps_gpio);

    uint32_t hps_gpio_input = alt_read_word(hps_gpio_port) & HPS_KEY_MASK;

    // HPS_KEY is active-low
    bool toggle_hps_led = (~hps_gpio_input & HPS_KEY_MASK);

    if (toggle_hps_led) {
        uint32_t hps_led_value = alt_read_word(hps_gpio_data);
        hps_led_value >>= HPS_LED_PORT_BIT;
        hps_led_value = !hps_led_value;
        hps_led_value <<= HPS_LED_PORT_BIT;
        alt_replbits_word(hps_gpio_data, HPS_LED_MASK, hps_led_value);
    }
}
```

Figure 8-61. handle_hps_led() Function

The key to doing memory-mapped IO in Linux is to use *HWLIB*'s **OFFSET**-based macros with the virtual address returned by `mmap()` as the base address. Note that *HWLIB* also has macros with **ABSOLUTE** addresses for every device, but those can only be used in bare-metal or Linux device driver code as they directly access certain physical addresses.

In Figure 8-60 and Figure 8-61, we used three such offset-based macros to access the HPS GPIO peripheral's "Port A Data Register", "Port A Data Direction Register", and "External Port A Register". These macros were the following:

- `ALT_GPIO_SWPORTA_DR_ADDR(base)`
- `ALT_GPIO_SWPORTA_DDR_ADDR(base)`
- `ALT_GPIO_EXT_PORTA_ADDR(base)`

8.4.2.4.3.2.3 Accessing FPGA Peripherals

Memory-mapping FPGA peripherals is identical to the process used for HPS peripherals. However, there is one subtlety that must be taken care of. When using `mmap()` you must specify an offset within the file that is to be mapped, as well as the amount of memory to be mapped. The `mmap()` manual page states that the offset provided **MUST BE A MULTIPLE OF THE SYSTEM'S PAGE SIZE**, which is 0x1000 bytes in our case.

If you look closely at the addresses in

Table 6-4, you will realize that this requirement always holds for the HPS' peripherals. However, this is not always true for the FPGA peripherals. For example, the design we used in this tutorial puts the FPGA buttons at address 0xFF200060 (offset 0x60 from the base address of the Lightweight HPS-to-FPGA bridge), which is not a multiple of the system's page size.

This implies that it isn't possible to memory-map the FPGA buttons alone, but we must instead use some offset which is a multiple of the system's page size. To get around this issue, we will memory-map FPGA peripherals from the HPS peripheral to which they are connected, as we are sure that the particular HPS peripheral's base address is a multiple of the page size.

Figure 8-62 shows how we memory-map the FPGA peripherals in our design from the Lightweight HPS-to-FPGA bridge, and Figure 8-63 shows how we can check if one of the FPGA buttons are being pressed.

```
void *h2f_lw_axi_master      = NULL;
size_t h2f_lw_axi_master_span = ALT_LWFGASLVS_UB_ADDR - ALT_LWFGASLVS_LB_ADDR + 1;
size_t h2f_lw_axi_master_ofst = ALT_LWFGASLVS_OFST;

void *fpga_buttons          = NULL;
void *fpga_hex_displays[HEX_DISPLAY_COUNT] = {NULL, NULL, NULL, NULL, NULL, NULL};

void mmap_fpga_peripherals() {
    h2f_lw_axi_master = mmap(NULL, h2f_lw_axi_master_span, PROT_READ | PROT_WRITE, MAP_SHARED, fd_dev_mem,
                             h2f_lw_axi_master_ofst);

    if (h2f_lw_axi_master == MAP_FAILED) {
        printf("Error: h2f_lw_axi_master mmap() failed.\n");
        printf("    errno = %s\n", strerror(errno));
        close(fd_dev_mem);
        exit(EXIT_FAILURE);
    }

    fpga_buttons      = h2f_lw_axi_master + BUTTONS_0_BASE;
    fpga_hex_displays[0] = h2f_lw_axi_master + HEX_0_BASE;
    fpga_hex_displays[1] = h2f_lw_axi_master + HEX_1_BASE;
    fpga_hex_displays[2] = h2f_lw_axi_master + HEX_2_BASE;
    fpga_hex_displays[3] = h2f_lw_axi_master + HEX_3_BASE;
    fpga_hex_displays[4] = h2f_lw_axi_master + HEX_4_BASE;
    fpga_hex_displays[5] = h2f_lw_axi_master + HEX_5_BASE;
}
```

Figure 8-62. *mmap_fpga_peripherals()* Function.

```
bool is_fpga_button_pressed(uint32_t button_number) {
    // buttons are active-low
    return ((~alt_read_word(fpga_buttons)) & (1 << button_number));
}
```

Figure 8-63. *is_fpga_button_pressed()* Function

8.4.2.4.3.2.4 Cleaning Up Before Application Exit

Although the operating system should take care of this for you, it is always a good practice to remove any unneeded memory mappings and to close the physical memory file descriptor before your application terminates.

Figure 8-64 shows how to unmap the GPIO peripheral's memory-mapping, and Figure 8-65 shows how to close the physical memory file descriptor.

```
void munmap_hps_peripherals() {
    if (munmap(hps_gpio, hps_gpio_span) != 0) {
        printf("Error: hps_gpio munmap() failed\n");
        printf("    errno = %s\n", strerror(errno));
        close(fd_dev_mem);
        exit(EXIT_FAILURE);
    }

    hps_gpio = NULL;
}
```

Figure 8-64. *munmap_hps_peripherals()* Function

```
void close_physical_memory_device() {
    close(fd_dev_mem);
}
```

Figure 8-65. *close_physical_memory_device()* Function**8.4.2.4.3.3 Launching the Linux code in the Debugger**

25. Once you have finished writing all the application's code, right-click on the "DE1_SoC_demo_hps_linux" project, and select "Build Project".
26. Switch to the *DS-5 Debug* perspective, as shown in Figure 8-40.

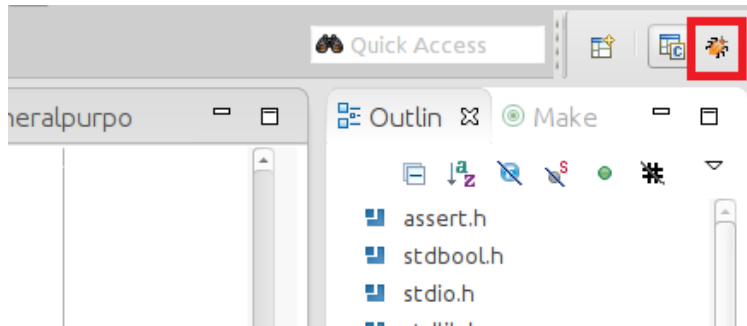


Figure 8-66. Switching to the DS-5 Debug Perspective

27. In the "Debug Control" view, click on the "DE1_SoC_demo_hps_linux" entry, then click on the "Connect to Target" button, as shown on Figure 8-67. The debugger will start an SSH connection to the Linux distribution running on the DE1-SoC and will automatically transfer our binary file and wait at our application's "main()" function.

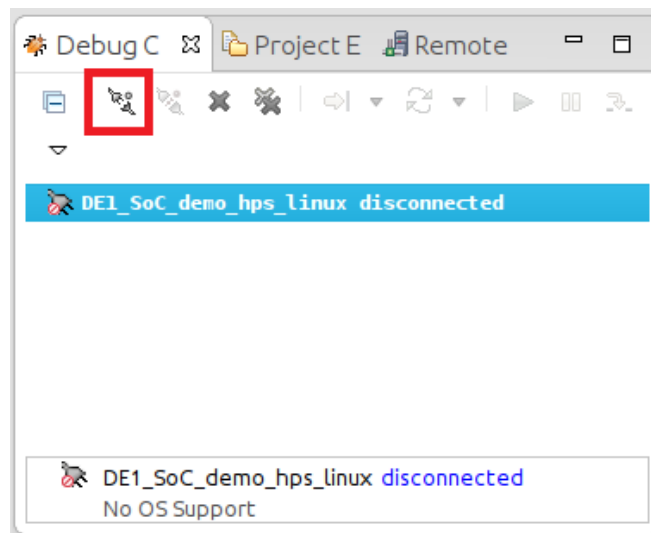


Figure 8-67. Debug Control View

28. You can use the buttons in the "Debug Control" view to control the application's execution.

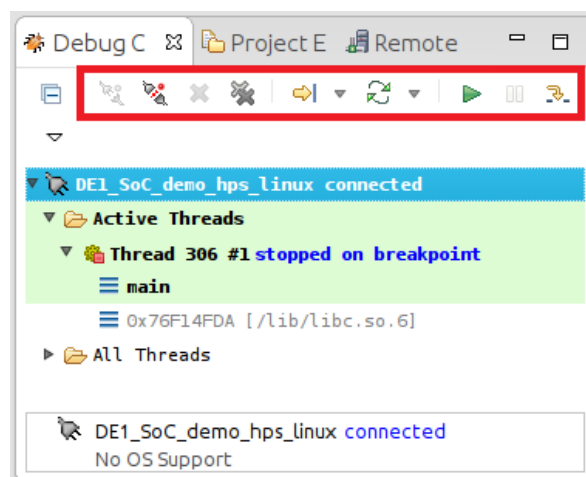


Figure 8-68. DS-5 Debugger Controls

8.4.2.4.3.3.4 App Console

Data sent to standard output is shown in the “App Console” view. Figure 8-69 shows the result of a “printf()” call in our demo code shown in Figure 8-56.



Figure 8-69. DS-5 App Console View

8.4.2.4.3.3.5 DS-5 Linux Debugger Restrictions

In 8.4.2.3.2.4.4.1, we saw that the DS-5 **BARE-METAL** debugger had a “Registers” view which could show the registers of all HPS and FPGA peripherals. This was a very handy tool, as it made it easy to verify if registers were accessed and updated correctly.

Unfortunately, when it comes to debugging **LINUX** binaries, the DS-5 debugger is subject to the same constraints our Linux applications are. Namely, it cannot directly access physical hardware addresses directly. As such, there is no “Registers” view when debugging Linux applications, and you must resort to manually memory-mapping and verifying peripheral accesses yourself.

9 TODO

- Explain MSEL when reprogramming the FPGA from the HPS.
- Talk about what the JTAG to Avalon masters are.
- Why is HPS_KEY active-low ? It isn't written anywhere in the documentation.

10 APPENDIX

10.1 DE1-SoC TOP-LEVEL VHDL ENTITY

The DE1-SoC has a lot of pins, which makes it tedious to start an FPGA design. It is recommended to use the following **ENTITY** for your **TOP-LEVEL VHDL FILE**, as it contains all the board's FPGA and HPS pins. The file can be found at DE1_SoC_top_level.vhd [4].

```
-- #####
-- DE1_SoC_top_level.vhd
--
-- BOARD      : DE1-SoC from Terasic
-- Author     : Sahand Kashani-Akhavan from Terasic documentation
-- Revision   : 1.2
-- Creation date : 04/02/2015
--
-- Syntax Rule : GROUP_NAME_N[bit]
--
-- GROUP  : specify a particular interface (ex: SDR_)
-- NAME   : signal name (ex: CONFIG, D, ...)
-- bit    : signal index
-- _N     : to specify an active-low signal
-- #####

library ieee;
use ieee.std_logic_1164.all;

entity DE1_SoC_top_level is
    port(
        -- ADC
        ADC_CS_n      : out  std_logic;
        ADC_DIN       : out  std_logic;
        ADC_DOUT      : in   std_logic;
        ADC_SCLK      : out  std_logic;

        -- Audio
        AUD_ADCDAT     : in   std_logic;
        AUD_ADCLRCK    : inout std_logic;
        AUD_BCLK       : inout std_logic;
        AUD_DACDAT     : out  std_logic;
        AUD_DACLCK     : inout std_logic;
        AUD_XCK        : out  std_logic;

        -- CLOCK
        CLOCK_50       : in   std_logic;
        CLOCK2_50      : in   std_logic;
        CLOCK3_50      : in   std_logic;
        CLOCK4_50      : in   std_logic;

        -- SDRAM
        DRAM_ADDR      : out  std_logic_vector(12 downto 0);
        DRAM_BA        : out  std_logic_vector(1 downto 0);
        DRAM_CAS_N     : out  std_logic;
        DRAM_CKE       : out  std_logic;
        DRAM_CLK       : out  std_logic;
        DRAM_CS_N      : out  std_logic;
        DRAM_DQ        : inout std_logic_vector(15 downto 0);
        DRAM_LDQM      : out  std_logic;
```

```

DRAM_RAS_N      : out   std_logic;
DRAM_UDQM       : out   std_logic;
DRAM_WE_N       : out   std_logic;

-- I2C for Audio and Video-In
FPGA_I2C_SCLK   : out   std_logic;
FPGA_I2C_SDAT   : inout std_logic;

-- SEG7
HEX0_N          : out   std_logic_vector(6 downto 0);
HEX1_N          : out   std_logic_vector(6 downto 0);
HEX2_N          : out   std_logic_vector(6 downto 0);
HEX3_N          : out   std_logic_vector(6 downto 0);
HEX4_N          : out   std_logic_vector(6 downto 0);
HEX5_N          : out   std_logic_vector(6 downto 0);

-- IR
IRDA_RXD        : in    std_logic;
IRDA_TXD        : out   std_logic;

-- KEY_n
KEY_N           : in    std_logic_vector(3 downto 0);

-- LED
LEDR            : out   std_logic_vector(9 downto 0);

-- PS2
PS2_CLK         : inout std_logic;
PS2_CLK2        : inout std_logic;
PS2_DAT         : inout std_logic;
PS2_DAT2        : inout std_logic;

-- SW
SW              : in    std_logic_vector(9 downto 0);

-- Video-In
TD_CLK27        : inout std_logic;
TD_DATA         : out   std_logic_vector(7 downto 0);
TD_HS           : out   std_logic;
TD_RESET_N      : out   std_logic;
TD_VS           : out   std_logic;

-- VGA
VGA_B           : out   std_logic_vector(7 downto 0);
VGA_BLANK_N     : out   std_logic;
VGA_CLK         : out   std_logic;
VGA_G           : out   std_logic_vector(7 downto 0);
VGA_HS         : out   std_logic;
VGA_R           : out   std_logic_vector(7 downto 0);
VGA_SYNC_N      : out   std_logic;
VGA_VS         : out   std_logic;

-- GPIO_0
GPIO_0          : inout std_logic_vector(35 downto 0);

-- GPIO_1
GPIO_1          : inout std_logic_vector(35 downto 0);

-- HPS

```

```

    HPS_CONV_USB_N    : inout std_logic;
    HPS_DDR3_ADDR     : out   std_logic_vector(14 downto 0);
    HPS_DDR3_BA       : out   std_logic_vector(2 downto 0);
    HPS_DDR3_CAS_N    : out   std_logic;
    HPS_DDR3_CK_N     : out   std_logic;
    HPS_DDR3_CK_P     : out   std_logic;
    HPS_DDR3_CKE      : out   std_logic;
    HPS_DDR3_CS_N     : out   std_logic;
    HPS_DDR3_DM       : out   std_logic_vector(3 downto 0);
    HPS_DDR3_DQ       : inout std_logic_vector(31 downto 0);
    HPS_DDR3_DQS_N    : inout std_logic_vector(3 downto 0);
    HPS_DDR3_DQS_P    : inout std_logic_vector(3 downto 0);
    HPS_DDR3_ODT      : out   std_logic;
    HPS_DDR3_RAS_N    : out   std_logic;
    HPS_DDR3_RESET_N  : out   std_logic;
    HPS_DDR3_RZQ      : in    std_logic;
    HPS_DDR3_WE_N     : out   std_logic;
    HPS_ENET_GTX_CLK  : out   std_logic;
    HPS_ENET_INT_N    : inout std_logic;
    HPS_ENET_MDC      : out   std_logic;
    HPS_ENET_MDIO     : inout std_logic;
    HPS_ENET_RX_CLK   : in    std_logic;
    HPS_ENET_RX_DATA  : in    std_logic_vector(3 downto 0);
    HPS_ENET_RX_DV    : in    std_logic;
    HPS_ENET_TX_DATA  : out   std_logic_vector(3 downto 0);
    HPS_ENET_TX_EN    : out   std_logic;
    HPS_FLASH_DATA    : inout std_logic_vector(3 downto 0);
    HPS_FLASH_DCLK    : out   std_logic;
    HPS_FLASH_NCSO    : out   std_logic;
    HPS_GPIO          : inout std_logic_vector(1 downto 0);
    HPS_GSENSOR_INT   : inout std_logic;
    HPS_I2C_CONTROL   : inout std_logic;
    HPS_I2C1_SCLK     : inout std_logic;
    HPS_I2C1_SDAT     : inout std_logic;
    HPS_I2C2_SCLK     : inout std_logic;
    HPS_I2C2_SDAT     : inout std_logic;
    HPS_KEY           : inout std_logic;
    HPS_LED           : inout std_logic;
    HPS_SD_CLK        : out   std_logic;
    HPS_SD_CMD        : inout std_logic;
    HPS_SD_DATA       : inout std_logic_vector(3 downto 0);
    HPS_SPIM_CLK      : out   std_logic;
    HPS_SPIM_MISO     : in    std_logic;
    HPS_SPIM_MOSI     : out   std_logic;
    HPS_SPIM_SS       : inout std_logic;
    HPS_UART_RX       : in    std_logic;
    HPS_UART_TX       : out   std_logic;
    HPS_USB_CLKOUT    : in    std_logic;
    HPS_USB_DATA      : inout std_logic_vector(7 downto 0);
    HPS_USB_DIR       : in    std_logic;
    HPS_USB_NXT       : in    std_logic;
    HPS_USB_STP       : out   std_logic
);
end entity DE1_SoC_top_level;

architecture rtl of DE1_SoC_top_level is
begin
end;

```

Figure 10-1. DE1-SoC Top-level VHDL Entity

10.2 DE1-SoC PIN ASSIGNMENT TCL SCRIPT

After having defined a top-level module, it is necessary to map your design's pins to the ones available on the DE1-SoC. The following **TCL SCRIPT** can be executed in *Quartus Prime* to specify the board's device ID and all its **PIN ASSIGNMENTS**. The file can be found at `pin_assignment_DE1_SoC.tcl` [5].

```
#####
# pin_assignment_DE1_SoC.tcl
#
# BOARD      : DE1-SoC from Terasic
# Author     : Sahand Kashani-Akhavan from Terasic documentation
# Revision   : 1.1
# Creation date : 04/02/2015
#
# Syntax Rule : GROUP_NAME_N[bit]
#
# GROUP  : specify a particular interface (ex: SDR_)
# NAME   : signal name (ex: CONFIG, D, ...)
# bit    : signal index
# _N     : to specify an active-low signal
#
# You can run this script from Quartus by observing the following steps:
# 1. Place this TCL script in your project directory
# 2. Open your project in Quartus
# 3. Go to the View > Utility Windows -> Tcl Console
# 4. In the Tcl Console type:
#      source pin_assignment_DE1_SoC.tcl
#
# 5. The script will assign pins and return an "assignment made" message.
#####

set_global_assignment -name FAMILY "Cyclone V"
set_global_assignment -name DEVICE 5CSEMA5F31C6
set_global_assignment -name DEVICE_FILTER_PACKAGE FBGA
set_global_assignment -name DEVICE_FILTER_PIN_COUNT 896
set_global_assignment -name DEVICE_FILTER_SPEED_GRADE 6

#=====
# ADC
#=====
set_location_assignment PIN_AJ4 -to ADC_CS_N
set_location_assignment PIN_AK4 -to ADC_DIN
set_location_assignment PIN_AK3 -to ADC_DOUT
set_location_assignment PIN_AK2 -to ADC_SCLK

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to ADC_CS_N
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to ADC_DIN
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to ADC_DOUT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to ADC_SCLK

#=====
# Audio
#=====
set_location_assignment PIN_K7 -to AUD_ADCDAT
set_location_assignment PIN_K8 -to AUD_ADCLRCK
set_location_assignment PIN_H7 -to AUD_BCLK
set_location_assignment PIN_J7 -to AUD_DACDAT
set_location_assignment PIN_H8 -to AUD_DACLCK
set_location_assignment PIN_G7 -to AUD_XCK
```

```

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to AUD_ADCDAT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to AUD_ADCLRCK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to AUD_BCLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to AUD_DACDAT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to AUD_DACLCK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to AUD_XCK

```

```

#=====

```

```

# CLOCK

```

```

#=====

```

```

set_location_assignment PIN_AF14 -to CLOCK_50
set_location_assignment PIN_AA16 -to CLOCK2_50
set_location_assignment PIN_Y26 -to CLOCK3_50
set_location_assignment PIN_K14 -to CLOCK4_50

```

```

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to CLOCK_50
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to CLOCK2_50
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to CLOCK3_50
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to CLOCK4_50

```

```

#=====

```

```

# SDRAM

```

```

#=====

```

```

set_location_assignment PIN_AK14 -to DRAM_ADDR[0]
set_location_assignment PIN_AH14 -to DRAM_ADDR[1]
set_location_assignment PIN_AG15 -to DRAM_ADDR[2]
set_location_assignment PIN_AE14 -to DRAM_ADDR[3]
set_location_assignment PIN_AB15 -to DRAM_ADDR[4]
set_location_assignment PIN_AC14 -to DRAM_ADDR[5]
set_location_assignment PIN_AD14 -to DRAM_ADDR[6]
set_location_assignment PIN_AF15 -to DRAM_ADDR[7]
set_location_assignment PIN_AH15 -to DRAM_ADDR[8]
set_location_assignment PIN_AG13 -to DRAM_ADDR[9]
set_location_assignment PIN_AG12 -to DRAM_ADDR[10]
set_location_assignment PIN_AH13 -to DRAM_ADDR[11]
set_location_assignment PIN_AJ14 -to DRAM_ADDR[12]
set_location_assignment PIN_AF13 -to DRAM_BA[0]
set_location_assignment PIN_AJ12 -to DRAM_BA[1]
set_location_assignment PIN_AF11 -to DRAM_CAS_N
set_location_assignment PIN_AK13 -to DRAM_CKE
set_location_assignment PIN_AG11 -to DRAM_CS_N
set_location_assignment PIN_AH12 -to DRAM_CLK
set_location_assignment PIN_AK6 -to DRAM_DQ[0]
set_location_assignment PIN_AJ7 -to DRAM_DQ[1]
set_location_assignment PIN_AK7 -to DRAM_DQ[2]
set_location_assignment PIN_AK8 -to DRAM_DQ[3]
set_location_assignment PIN_AK9 -to DRAM_DQ[4]
set_location_assignment PIN_AG10 -to DRAM_DQ[5]
set_location_assignment PIN_AK11 -to DRAM_DQ[6]
set_location_assignment PIN_AJ11 -to DRAM_DQ[7]
set_location_assignment PIN_AH10 -to DRAM_DQ[8]
set_location_assignment PIN_AJ10 -to DRAM_DQ[9]
set_location_assignment PIN_AJ9 -to DRAM_DQ[10]
set_location_assignment PIN_AH9 -to DRAM_DQ[11]
set_location_assignment PIN_AH8 -to DRAM_DQ[12]
set_location_assignment PIN_AH7 -to DRAM_DQ[13]
set_location_assignment PIN_AJ6 -to DRAM_DQ[14]
set_location_assignment PIN_AJ5 -to DRAM_DQ[15]

```

```

set_location_assignment PIN_AB13 -to DRAM_LDQM
set_location_assignment PIN_AE13 -to DRAM_RAS_N
set_location_assignment PIN_AK12 -to DRAM_UDQM
set_location_assignment PIN_AA13 -to DRAM_WE_N

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[8]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[9]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[10]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[11]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_ADDR[12]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_BA[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_BA[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_CAS_N
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_CKE
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_CS_N
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_CLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[8]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[9]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[10]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[11]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[12]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[13]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[14]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_DQ[15]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_LDQM
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_RAS_N
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_UDQM
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to DRAM_WE_N

#=====
# I2C for Audio and Video-In
#=====
set_location_assignment PIN_J12 -to FPGA_I2C_SCLK
set_location_assignment PIN_K12 -to FPGA_I2C_SDAT

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to FPGA_I2C_SCLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to FPGA_I2C_SDAT

#=====
# SEG7
#=====
set_location_assignment PIN_AE26 -to HEX0_N[0]
set_location_assignment PIN_AE27 -to HEX0_N[1]

```



```

set_location_assignment PIN_AE28 -to HEX0_N[2]
set_location_assignment PIN_AG27 -to HEX0_N[3]
set_location_assignment PIN_AF28 -to HEX0_N[4]
set_location_assignment PIN_AG28 -to HEX0_N[5]
set_location_assignment PIN_AH28 -to HEX0_N[6]
set_location_assignment PIN_AJ29 -to HEX1_N[0]
set_location_assignment PIN_AH29 -to HEX1_N[1]
set_location_assignment PIN_AH30 -to HEX1_N[2]
set_location_assignment PIN_AG30 -to HEX1_N[3]
set_location_assignment PIN_AF29 -to HEX1_N[4]
set_location_assignment PIN_AF30 -to HEX1_N[5]
set_location_assignment PIN_AD27 -to HEX1_N[6]
set_location_assignment PIN_AB23 -to HEX2_N[0]
set_location_assignment PIN_AE29 -to HEX2_N[1]
set_location_assignment PIN_AD29 -to HEX2_N[2]
set_location_assignment PIN_AC28 -to HEX2_N[3]
set_location_assignment PIN_AD30 -to HEX2_N[4]
set_location_assignment PIN_AC29 -to HEX2_N[5]
set_location_assignment PIN_AC30 -to HEX2_N[6]
set_location_assignment PIN_AD26 -to HEX3_N[0]
set_location_assignment PIN_AC27 -to HEX3_N[1]
set_location_assignment PIN_AD25 -to HEX3_N[2]
set_location_assignment PIN_AC25 -to HEX3_N[3]
set_location_assignment PIN_AB28 -to HEX3_N[4]
set_location_assignment PIN_AB25 -to HEX3_N[5]
set_location_assignment PIN_AB22 -to HEX3_N[6]
set_location_assignment PIN_AA24 -to HEX4_N[0]
set_location_assignment PIN_Y23 -to HEX4_N[1]
set_location_assignment PIN_Y24 -to HEX4_N[2]
set_location_assignment PIN_W22 -to HEX4_N[3]
set_location_assignment PIN_W24 -to HEX4_N[4]
set_location_assignment PIN_V23 -to HEX4_N[5]
set_location_assignment PIN_W25 -to HEX4_N[6]
set_location_assignment PIN_V25 -to HEX5_N[0]
set_location_assignment PIN_AA28 -to HEX5_N[1]
set_location_assignment PIN_Y27 -to HEX5_N[2]
set_location_assignment PIN_AB27 -to HEX5_N[3]
set_location_assignment PIN_AB26 -to HEX5_N[4]
set_location_assignment PIN_AA26 -to HEX5_N[5]
set_location_assignment PIN_AA25 -to HEX5_N[6]

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX0_N[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX0_N[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX0_N[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX0_N[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX0_N[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX0_N[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX0_N[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX1_N[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX1_N[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX1_N[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX1_N[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX1_N[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX1_N[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX1_N[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX2_N[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX2_N[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX2_N[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX2_N[3]

```

```

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX2_N[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX2_N[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX2_N[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX3_N[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX3_N[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX3_N[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX3_N[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX3_N[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX3_N[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX3_N[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX4_N[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX4_N[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX4_N[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX4_N[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX4_N[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX4_N[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX4_N[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX5_N[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX5_N[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX5_N[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX5_N[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX5_N[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX5_N[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HEX5_N[6]

#=====
# IR
#=====
set_location_assignment PIN_AA30 -to IRDA_RXD
set_location_assignment PIN_AB30 -to IRDA_TXD

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to IRDA_RXD
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to IRDA_TXD

#=====
# KEY_N
#=====
set_location_assignment PIN_AA14 -to KEY_N[0]
set_location_assignment PIN_AA15 -to KEY_N[1]
set_location_assignment PIN_W15 -to KEY_N[2]
set_location_assignment PIN_Y16 -to KEY_N[3]

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to KEY_N[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to KEY_N[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to KEY_N[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to KEY_N[3]

#=====
# LED
#=====
set_location_assignment PIN_V16 -to LEDR[0]
set_location_assignment PIN_W16 -to LEDR[1]
set_location_assignment PIN_V17 -to LEDR[2]
set_location_assignment PIN_V18 -to LEDR[3]
set_location_assignment PIN_W17 -to LEDR[4]
set_location_assignment PIN_W19 -to LEDR[5]
set_location_assignment PIN_Y19 -to LEDR[6]
set_location_assignment PIN_W20 -to LEDR[7]
set_location_assignment PIN_W21 -to LEDR[8]

```

```

set_location_assignment PIN_Y21 -to LEDR[9]

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[8]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to LEDR[9]

#=====
# PS2
#=====
set_location_assignment PIN_AD7 -to PS2_CLK
set_location_assignment PIN_AD9 -to PS2_CLK2
set_location_assignment PIN_AE7 -to PS2_DAT
set_location_assignment PIN_AE9 -to PS2_DAT2

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to PS2_CLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to PS2_CLK2
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to PS2_DAT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to PS2_DAT2

#=====
# SW
#=====
set_location_assignment PIN_AB12 -to SW[0]
set_location_assignment PIN_AC12 -to SW[1]
set_location_assignment PIN_AF9 -to SW[2]
set_location_assignment PIN_AF10 -to SW[3]
set_location_assignment PIN_AD11 -to SW[4]
set_location_assignment PIN_AD12 -to SW[5]
set_location_assignment PIN_AE11 -to SW[6]
set_location_assignment PIN_AC9 -to SW[7]
set_location_assignment PIN_AD10 -to SW[8]
set_location_assignment PIN_AE12 -to SW[9]

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[8]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to SW[9]

#=====
# Video-In
#=====
set_location_assignment PIN_H15 -to TD_CLK27
set_location_assignment PIN_D2 -to TD_DATA[0]
set_location_assignment PIN_B1 -to TD_DATA[1]
set_location_assignment PIN_E2 -to TD_DATA[2]
set_location_assignment PIN_B2 -to TD_DATA[3]

```

```

set_location_assignment PIN_D1 -to TD_DATA[4]
set_location_assignment PIN_E1 -to TD_DATA[5]
set_location_assignment PIN_C2 -to TD_DATA[6]
set_location_assignment PIN_B3 -to TD_DATA[7]
set_location_assignment PIN_A5 -to TD_HS
set_location_assignment PIN_F6 -to TD_RESET_N
set_location_assignment PIN_A3 -to TD_VS

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_CLK27
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_DATA[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_HS
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_RESET_N
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to TD_VS

#=====
# VGA
#=====
set_location_assignment PIN_B13 -to VGA_B[0]
set_location_assignment PIN_G13 -to VGA_B[1]
set_location_assignment PIN_H13 -to VGA_B[2]
set_location_assignment PIN_F14 -to VGA_B[3]
set_location_assignment PIN_H14 -to VGA_B[4]
set_location_assignment PIN_F15 -to VGA_B[5]
set_location_assignment PIN_G15 -to VGA_B[6]
set_location_assignment PIN_J14 -to VGA_B[7]
set_location_assignment PIN_F10 -to VGA_BLANK_N
set_location_assignment PIN_A11 -to VGA_CLK
set_location_assignment PIN_J9 -to VGA_G[0]
set_location_assignment PIN_J10 -to VGA_G[1]
set_location_assignment PIN_H12 -to VGA_G[2]
set_location_assignment PIN_G10 -to VGA_G[3]
set_location_assignment PIN_G11 -to VGA_G[4]
set_location_assignment PIN_G12 -to VGA_G[5]
set_location_assignment PIN_F11 -to VGA_G[6]
set_location_assignment PIN_E11 -to VGA_G[7]
set_location_assignment PIN_B11 -to VGA_HS
set_location_assignment PIN_A13 -to VGA_R[0]
set_location_assignment PIN_C13 -to VGA_R[1]
set_location_assignment PIN_E13 -to VGA_R[2]
set_location_assignment PIN_B12 -to VGA_R[3]
set_location_assignment PIN_C12 -to VGA_R[4]
set_location_assignment PIN_D12 -to VGA_R[5]
set_location_assignment PIN_E12 -to VGA_R[6]
set_location_assignment PIN_F13 -to VGA_R[7]
set_location_assignment PIN_C10 -to VGA_SYNC_N
set_location_assignment PIN_D11 -to VGA_VS

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to VGA_B[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to VGA_B[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to VGA_B[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to VGA_B[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to VGA_B[4]

```

[illegible]

[illegible]

```

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_FLASH_DATA[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_FLASH_DCLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_FLASH_NCS0
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_GPIO[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_GPIO[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_GSENSOR_INT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_I2C1_SCLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_I2C1_SDAT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_I2C2_SCLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_I2C2_SDAT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_I2C_CONTROL
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_KEY
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_LED
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SD_CLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SD_CMD
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SD_DATA[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SD_DATA[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SD_DATA[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SD_DATA[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SPIM_CLK
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SPIM_MISO
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SPIM_MOSI
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_SPIM_SS
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_UART_RX
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_UART_TX
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_CLKOUT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DATA[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_DIR
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_NXT
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_USB_STP
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to HPS_CONV_USB_N

#=====
# GPIO_0, GPIO_0 connect to GPIO Default
#=====
set_location_assignment PIN_AC18 -to GPIO_0[0]
set_location_assignment PIN_Y17 -to GPIO_0[1]
set_location_assignment PIN_AD17 -to GPIO_0[2]
set_location_assignment PIN_Y18 -to GPIO_0[3]
set_location_assignment PIN_AK16 -to GPIO_0[4]
set_location_assignment PIN_AK18 -to GPIO_0[5]
set_location_assignment PIN_AK19 -to GPIO_0[6]
set_location_assignment PIN_AJ19 -to GPIO_0[7]
set_location_assignment PIN_AJ17 -to GPIO_0[8]
set_location_assignment PIN_AJ16 -to GPIO_0[9]
set_location_assignment PIN_AH18 -to GPIO_0[10]
set_location_assignment PIN_AH17 -to GPIO_0[11]
set_location_assignment PIN_AG16 -to GPIO_0[12]
set_location_assignment PIN_AE16 -to GPIO_0[13]
set_location_assignment PIN_AF16 -to GPIO_0[14]
set_location_assignment PIN_AG17 -to GPIO_0[15]
set_location_assignment PIN_AA18 -to GPIO_0[16]

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```

set_location_assignment PIN_AA19 -to GPIO_0[17]
set_location_assignment PIN_AE17 -to GPIO_0[18]
set_location_assignment PIN_AC20 -to GPIO_0[19]
set_location_assignment PIN_AH19 -to GPIO_0[20]
set_location_assignment PIN_AJ20 -to GPIO_0[21]
set_location_assignment PIN_AH20 -to GPIO_0[22]
set_location_assignment PIN_AK21 -to GPIO_0[23]
set_location_assignment PIN_AD19 -to GPIO_0[24]
set_location_assignment PIN_AD20 -to GPIO_0[25]
set_location_assignment PIN_AE18 -to GPIO_0[26]
set_location_assignment PIN_AE19 -to GPIO_0[27]
set_location_assignment PIN_AF20 -to GPIO_0[28]
set_location_assignment PIN_AF21 -to GPIO_0[29]
set_location_assignment PIN_AF19 -to GPIO_0[30]
set_location_assignment PIN_AG21 -to GPIO_0[31]
set_location_assignment PIN_AF18 -to GPIO_0[32]
set_location_assignment PIN_AG20 -to GPIO_0[33]
set_location_assignment PIN_AG18 -to GPIO_0[34]
set_location_assignment PIN_AJ21 -to GPIO_0[35]

set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[8]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[9]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[10]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[11]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[12]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[13]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[14]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[15]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[16]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[17]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[18]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[19]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[20]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[21]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[22]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[23]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[24]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[25]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[26]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[27]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[28]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[29]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[30]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[31]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[32]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[33]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[34]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_0[35]

```

```

#=====
# GPIO_1, GPIO_1 connect to GPIO Default

```



```
#=====
set_location_assignment PIN_AB17 -to GPIO_1[0]
set_location_assignment PIN_AA21 -to GPIO_1[1]
set_location_assignment PIN_AB21 -to GPIO_1[2]
set_location_assignment PIN_AC23 -to GPIO_1[3]
set_location_assignment PIN_AD24 -to GPIO_1[4]
set_location_assignment PIN_AE23 -to GPIO_1[5]
set_location_assignment PIN_AE24 -to GPIO_1[6]
set_location_assignment PIN_AF25 -to GPIO_1[7]
set_location_assignment PIN_AF26 -to GPIO_1[8]
set_location_assignment PIN_AG25 -to GPIO_1[9]
set_location_assignment PIN_AG26 -to GPIO_1[10]
set_location_assignment PIN_AH24 -to GPIO_1[11]
set_location_assignment PIN_AH27 -to GPIO_1[12]
set_location_assignment PIN_AJ27 -to GPIO_1[13]
set_location_assignment PIN_AK29 -to GPIO_1[14]
set_location_assignment PIN_AK28 -to GPIO_1[15]
set_location_assignment PIN_AK27 -to GPIO_1[16]
set_location_assignment PIN_AJ26 -to GPIO_1[17]
set_location_assignment PIN_AK26 -to GPIO_1[18]
set_location_assignment PIN_AH25 -to GPIO_1[19]
set_location_assignment PIN_AJ25 -to GPIO_1[20]
set_location_assignment PIN_AJ24 -to GPIO_1[21]
set_location_assignment PIN_AK24 -to GPIO_1[22]
set_location_assignment PIN_AG23 -to GPIO_1[23]
set_location_assignment PIN_AK23 -to GPIO_1[24]
set_location_assignment PIN_AH23 -to GPIO_1[25]
set_location_assignment PIN_AK22 -to GPIO_1[26]
set_location_assignment PIN_AJ22 -to GPIO_1[27]
set_location_assignment PIN_AH22 -to GPIO_1[28]
set_location_assignment PIN_AG22 -to GPIO_1[29]
set_location_assignment PIN_AF24 -to GPIO_1[30]
set_location_assignment PIN_AF23 -to GPIO_1[31]
set_location_assignment PIN_AE22 -to GPIO_1[32]
set_location_assignment PIN_AD21 -to GPIO_1[33]
set_location_assignment PIN_AA20 -to GPIO_1[34]
set_location_assignment PIN_AC22 -to GPIO_1[35]

set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[0]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[1]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[2]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[3]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[4]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[5]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[6]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[7]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[8]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[9]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[10]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[11]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[12]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[13]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[14]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[15]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[16]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[17]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[18]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[19]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTTL" -to GPIO_1[20]
```

```
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[21]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[22]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[23]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[24]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[25]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[26]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[27]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[28]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[29]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[30]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[31]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[32]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[33]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[34]
set_instance_assignment -name IO_STANDARD "3.3-V LVTTL" -to GPIO_1[35]
```

Figure 10-2. DE1-SoC Pin Assignment TCL Script

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