Advanced Workshop on FPGA-based Systems-On-Chip for Scientific Instrumentation and Reconfigurable Computing

ICTP

Embedded 'C' for Zynq

Cristian Sisterna

Universidad Nacional San Juan

Argentina

Embedded C

Embedded C

From Wikipedia, the free encyclopedia

Embedded C is a set of language extensions for the C Programming language by the C Standards committee to address commonality issues that exist between C extensions for different embedded systems. Historically, embedded C programming requires nonstandard extensions to the C language in order to support exotic features such as fixed-point arithmetic, multiple distinct memory banks, and basic I/O operations.

In 2008, the C Standards Committee extended the C language to address these issues by providing a common standard for all implementations to adhere to. It includes a number of features not available in normal C, such as, fixed-point arithmetic, named address spaces, and basic I/O hardware addressing.

Difference Between C and *Embedded C*

Embedded systems programming is different from developing applications on a desktop computers. Key characteristics of an embedded system, when compared to PCs, are as follows:

- Embedded devices have resource constraints(limited ROM, limited RAM, limited stack space, less processing power)
- Components used in embedded system and PCs are different; embedded systems typically uses smaller, less power consuming components
- Embedded systems are more tied to the hardware
- Two salient features of Embedded Programming are ***code speed*** and ***code size***. Code speed is governed by the processing power, timing constraints, whereas code size is governed by available program memory and use of programming language.

Difference Between C and Embedded C

Though ***C*** and ***Embedded C*** appear different and are used in different contexts, they have more similarities than the differences. Most of the constructs are same; the difference lies in their applications.

C is used for desktop computers, while ***Embedded C*** is for microcontroller based applications.

Compilers for ***C*** (ANSI C) typically generate OS dependent executables. ***Embedded C*** requires compilers to create files to be downloaded to the microcontrollers/microprocessors where it needs to run. Embedded compilers give access to all resources which is not provided in compilers for desktop computer applications.

Embedded systems often have the real-time constraints, which is usually not there with desktop computer applications.

Embedded systems often do not have a console, which is available in case of desktop applications.

Advantages of Using *Embedded C*

- It is small and reasonably simpler to learn, understand, program and debug
- C Compilers are available for almost all embedded devices in use today, and there is a large pool of experienced C programmers
- Unlike assembly, C has advantage of processor-independence and is not specific to any particular microprocessor/ microcontroller or any system. This makes it convenient for a user to develop programs that can run on most of the systems
- As C combines functionality of assembly language and features of high level languages, C is treated as a ‘middle-level computer language’ or ‘high level assembly language’
- It is fairly efficient
- It supports access to I/O and provides ease of management of large embedded projects
- Objected oriented language, C++ is not apt for developing efficient programs in resource constrained environments like embedded devices.

Reviewing Embedded ‘C’ Basic Concepts

Basic Data Types

Type	Size	Unsigned Range	Signed Range
char	8 bits	0 to 255	–128 to 127
short int	8 bits	0 to 255	–128 to 127
int	16 bits	0 to 65535	–32768 to 32767
long Int	32 bits	0 to 4294967295	–2147483648 to 2147483647

'SDK' Basic Data Types

xbasic_types.h

```
typedef unsigned char   Xuint8;     /**< unsigned 8-bit */
typedef char            Xint8;      /**< signed 8-bit */
typedef unsigned short  Xuint16;    /**< unsigned 16-bit */
typedef short           Xint16;     /**< signed 16-bit */
typedef unsigned long   Xuint32;    /**< unsigned 32-bit */
typedef long            Xint32;     /**< signed 32-bit */
typedef float           Xfloat32;   /**< 32-bit floating point */
typedef double          Xfloat64;   /**< 64-bit double precision FP */
typedef unsigned long   Xboolean;   /**< boolean (XTRUE or XFALSE) */
```

xil_types.h

```
typedef uint8_t  u8;
typedef uint16_t u16;
typedef uint32_t u32;
```

Local vs Global Variables

Variables in C can be classified by their scope

Local Variables

Accesible only by the function within which they are declared and are allocated storage on *the stack*

The '***static***' access modifier causes that the local variable to be permanently allocated storage in memory, like a global variable

Global Variables

Accesible by any part of the program and are allocated permanent storage in RAM

Returning a pointer to a GLOBAL or STATIC variable is quite safe

Local Variables

- The ‘static’ access modifier causes that the local variable to be permanently allocated storage in memory, like a global variable, so the value is preserved between function calls (but still is local)
- Local variables only occupy RAM while the function to which they belong is running
- Usually the stack pointer addressing mode is used (This addressing mode requires one extra byte and one extra cycle to access a variable compared to the same instruction in indexed addressing mode)
  - If the code requires several consecutive accesses to local variables, the compiler will usually transfer the stack pointer to the 16-bit index register and use indexed addressing instead

Global Variables

- *Global variables* are allocated permanent storage in memory at an absolute address determined when the code is linked
- The memory occupied by a *global variable* cannot be reused by any other variable
- *Global variables* are not protected in any way, so any part of the program can access a global variable at any time
  - This means that the variable data could be corrupted if part of the variable is derived from one value and the rest of the variable is derived from another value
- The 'static' access modifier may also be used with *global variables*
  - This gives some degree of protection to the variable as it restricts access to the variable to those functions in the file in which the variable is declared
- The compiler will generally use the extended addressing mode to access *global variables* or indexed addressing mode if they are accessed though a pointer

Other Application for the ‘static’ modifier

By default, all functions and variables declared *in global space* have external linkage and are visible to the entire program. Sometimes you require global variables or functions that have internal linkage: they should be visible within a single compilation unit, but not outside. Use the static keyword to restrict the scope of variables.

```
#include "xparameters.h"
#include "xgpio.h"
#include "xgpiops.h"

static XGpioPs psGpioInstancePtr;
static int iPinNumber = 7; /*Led LD9 is connected to MIO pin 7*/
//=====================================================

int main (void)
{
      XGpio sw, led;
      int i, pshb_check, sw_check;
      static XGpio GPIOInstance_Ptr;
```

Volatile Variable

The value of *volatile variables* may change from outside the program.

For example, you may wish to read an A/D converter or a port whose value is changing.

Often your compiler may eliminate code to read the port as part of the compiler's code optimization process if it does not realize that some outside process is changing the port's value.

You can avoid this by declaring the variable volatile.

Volatile Variable

```
#include <stdio.h>

/* Optimization code snippet 1 */
#include<stdio.h>

int x = 0;

int main()
{
    if (x == 0) // This condition is always
    {
        printf(" x = 0 \n");
    }
    else        // Else part will be optimiz
    {
        printf(" x != 0 \n");
    }
    return 0;
}
```

```
#include<stdio.h>

volatile int = 0;     /* volatile Keyword*/

int main()
{
    x = 0;

    if (x == 0)
    {
    printf(" x = 0 \n");
    }
    else        // Now compiler never optimize else part because the
    {           // variable is declared as volatile
    printf(" x != 0 \n");
    }
    return 0;
}
```

Functions Data Types

A function data type defines the value that a subroutine can return

- A function of type `int` returns a signed integer value
- Without a specific return type, any function returns an `int`
- To avoid confusion, you should always declare `main()` with return type `void`

```
void XGpioPs_IntrEnable(XGpioPs *InstancePtr, u8 Bank, u32 Mask);
void XGpioPs_IntrDisable(XGpioPs *InstancePtr, u8 Bank, u32 Mask);
u32 XGpioPs_IntrGetEnabled(XGpioPs *InstancePtr, u8 Bank);
u32 XGpioPs_IntrGetStatus(XGpioPs *InstancePtr, u8 Bank);
```

Parameters Data Types

Indicate the values to be passed into the function and the memory to be reserved for storing them

```
int XGpio_Initialize(XGpio *InstancePtr, u16 DeviceId);
/**
* Initialize the XGpio instance provided by the caller based on the
* given DeviceID.
*
* Nothing is done except to initialize the InstancePtr.
*
* @param    InstancePtr is a pointer to an XGpio instance. The memory the
*        pointer references must be pre-allocated by the caller. Further
*        calls to manipulate the instance/driver through the XGpio API
*        must be made with this pointer.
* @param    DeviceId is the unique id of the device controlled by this XGpio
*        instance. Passing in a device id associates the generic XGpio
```

Structures

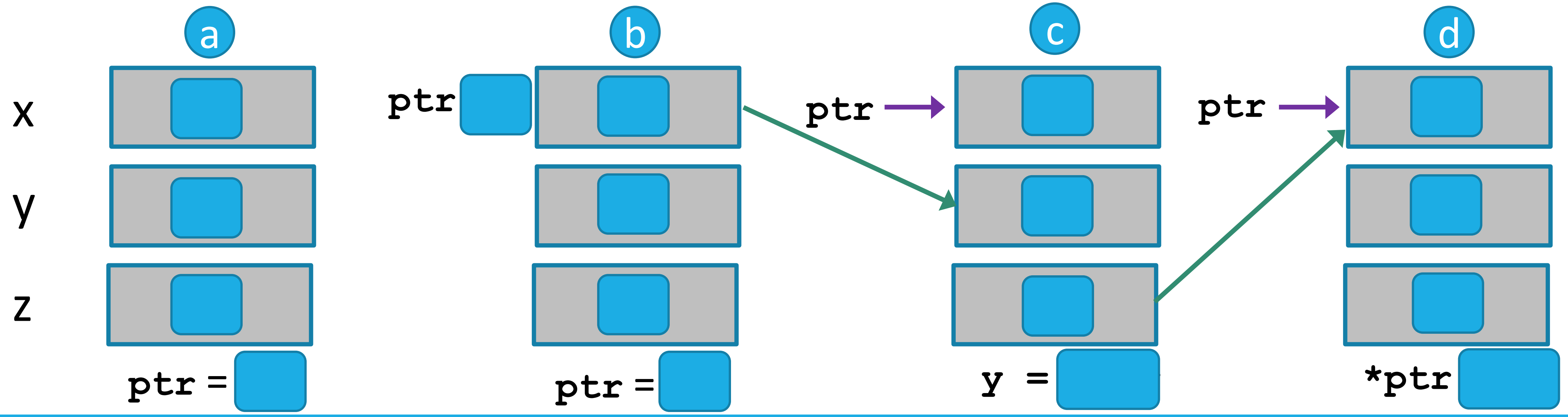
```c
#include "xparameters.h"
#include "xgpio.h"
#include "xgpiops.h"

static XGpioPs psGpioInstancePtr;
static int iPinNumber = 7; /*Led LD9

//=======================

int main (void)
{
    XGpio sw, led;
    int i, psHb_chec
```

```c
/**
 * The XGpio driver instance data. The user is required to allocate a
 * variable of this type for every GPIO device in the system. A pointer
 * to a variable of this type is then passed to the driver API functions.
 */
typedef struct {
    u32 BaseAddress;        /* Device base address */
    u32 IsReady;            /* Device is initialized and ready */
    int InterruptPresent;   /* Are interrupts supported in h/w */
    int IsDual;             /* Are 2 channels supported in h/w */
} XGpio;
```

Review of ‘C’ Pointer

In ‘C’, the pointer data type corresponds to a MEMORY ADDRESS

```
a  int x = 1, y = 5, z = 8, *ptr;
b  ptr  = &x;    // ptr gets (point to) address of x
c  y    = *ptr; // content of y gets content pointed by ptr
d  *ptr = z;    // content pointed by ptr gets content of z
```



‘C’ Techniques for low-level I/O Operations

Bit Manipulation in ‘C’

Bitwise operators in ‘C’: `~ (not)`, `& (and)`, `| (or)`, `^ (xor)`
which operate on one or two operands at bit levels

```
u8 mask = 0x60;    //0110_0000 mask bits 6 and 5
u8 data = 0xb3     //1011_0011 data
u8 d0, d1, d2, d3; //data to work with in the coming example
. . .
```

```
d0 = data & mask;  // 0010_0000; isolate bits 6 and 5 from data
d1 = data & ~mask; // 1001_0011; clear bits 6 and 5 of data
d2 = data | mask;  // 1111_0011; set bits 6 and 5 of data
d3 = data ^ mask;  // 1101_0011; toggle bits 6 and 5 of data
```

Bit Shift Operators

Both operands of a bit shift operator must be integer values

The **right shift operator** shifts the data right by the specified number of positions. Bits shifted out the right side disappear. With unsigned integer values, 0s are shifted in at the high end, as necessary. For signed types, the values shifted in is implementation-dependant. The binary number is shifted right by *number* bits.

```
x >> number;
```

The **left shift operator** shifts the data right by the specified number of positions. Bits shifted out the left side disappear and new bits coming in are 0s. The binary number is shifted left by *number* bits

```
x << number;
```

Bit Shift Example

```
void led_(XGpio *pLED_GPIO, int nNumberOfTimes)
{
        int i=0;        int j=0;
        u8 uchLedStatus=0;
        //
        for(i=0;i<nNumberOfTimes;i++)
        {
                for(j=0;j<8;j++)   //
                {
                        uchLedStatus = 1 << j;
                        XGpio_DiscreteWrite(pLED_GPIO, 1, uchLedStatus);
                        delay(ABOUT_ONE_SECOND / 15);
                }
                for(j=0;j<8;j++)   //
                {
                        uchLedStatus = 8 >> j;
                        XGpio_DiscreteWrite(pLED_GPIO, 1, uchLedStatus);
                        delay(ABOUT_ONE_SECOND / 15);
                }
        }
}
```

Unpacking Data

There are cases that in the same memory address different fields are stored

Example: let's assume that a 32-bit memory address contains a 16-bit field for an integer data and two 8-bit fields for two characters


```
u32 io_rd_data;
int num;
char ch1, ch0;
```

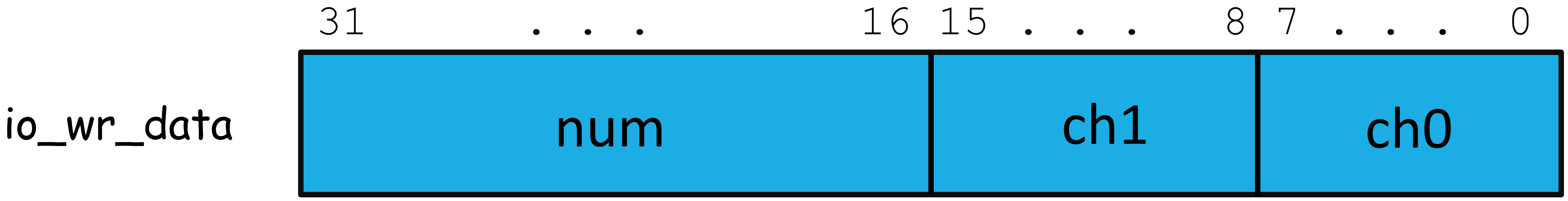
Unpacking:

```
io_rd_data = my_iord(...);
num = (int) ((io_rd_data & 0xffff0000) >> 16);
ch1 = (char)((io_rd_data & 0x0000ff00) >> 8);
ch0 = (char)((io_rd_data & 0x000000ff ));
```

Packing Data

There are cases that in the same memory address different fields are written

Example: let's assume that a 32-bit memory address will be written as a 16-bit field for an integer data and two 8-bit fields for two characters




```c
u32 wr_data;
int num = 5;
char ch1, ch0;
```

Packing

```c
wr_data = (u32) (num);                          //num[15:0]
wr_data = (wr_data << 8) | (u32) ch1; //num[23:8],ch1[7:0]
wr_data = (wr_data << 8) | (u32) ch0; //num[31:16],ch1[15:8]
my_iowr( . . . , wr_data) ;                    //ch0[7:0]
```

I/O Read Macro

Read from an Input

```
int switch_s1;
. . .
switch_s1 = *(volatile int *)(0x00011000);
```

```
#define SWITCH_S1_BASE = 0x00011000;
. .
switch_s1 = *(volatile int *)(SWITCH_S1_BASE);
```

```
#define SWITCH_S1_BASE = 0x00011000;
#define my_iord(addr) (*(volatile int *)(addr))
. . .
switch_s1 = my_iord(SWITCH_S1_BASE);   //
```

Macro

I/O Write Macro

Write to an Output

```
char pattern = 0x01;
. . .
*(0x11000110) = pattern;
```

```
#define LED_L1_BASE = 0x11000110;
. . .
*(LED_L1_BASE) = pattern;
```

```
#define LED_L1_BASE = 0x11000110;
#define my_iowr(addr, data)   (*(int *)(addr) = (data))
. . .
my_iowr(LED_L1_BASE, (int)pattern);   //
```

Macro

Basic ‘C’ Program Template

Basic Embedded Program Architecture

An embedded application consists of a collection tasks, implemented by hardware accelerators, software routines, or both.

```
#include "nnnnn.h"
#include <ppppp.h>
main()
  {
    sys_init();//
    while(1){
      task_1();
      task_2();
      . . .
      task_n();
            }
  }
```

Basic Example

The flashing-LED system turns on and off *two* LEDs alternatively according to the interval specified by the *ten* sliding switches

Tasks ????

1. reading the interval value from the switches
2. toggling the two LEDs after a specific amount of time

Basic Example

```
main()
  {
while(1){
      . . .
      task_1();
      task_2();
      . . .
     }
  }
```

```
#include "nnnnn.h"
#include "aaaaa.h"
```

```
main()
  {
int period;

while(1){
      read_sw(SWITCH_S1_BASE, &period);
      led_flash(LED_L1_BASE, period);
         }
  }
```

Basic Example - Reading

```
/***********************************************************************
* function: read_sw ()
* purpose: get flashing period from switches
* argument:
*      sw-base: base address of switch PIO
*      period: pointer to period
* return:
*      updated period
* note :
***********************************************************************/
void read_sw(u32 switch_base, int *period)
{
  *period = my_iord(switch_base) & 0x000000ff; //read flashing period
                                               // from switch
}
```

Basic Example - Writing

```
/****************************************************************************************
* function: led.flash ()
* purpose: toggle 2 LEDs according to the given period
* argument:
*         led-base: base address of discrete LED PIO
*         period: flashing period in ms
* return :
* note :
* — The delay is done by estimating execution time of a dummy for loop
* — Assumption: 400 ns per loop iteration (2500 iterations per ms)
*  - 2 instruct. per loop iteration /10 clock cycles per instruction /20ns per clock cycle(50-MHz clock)
****************************************************************************************/
void led_flash(u32 addr_led_base, int period)
{
 static u8 led_pattern = 0x01;               // initial pattern
 unsigned long i, itr;
  led_pattern ^= 0x03;                        // toggle 2 LEDs (2 LSBs)
  my_iowr(addr_led_base, led_pattern);        // write LEDs
  itr = period * 2500;
  for (i=0; i<itr; i++) {}                    // dummy loop for delay
}
```

Basic Example – Read / Write

```
main()
   {
int period;

while(1){
  read_sw(SWITCH_S1_BASE, &period);
  led_flash(LED_L1_BASE, period);
        }
   }
```

```
void read_sw(u32 switch_base, int *period)
{
  *period = my_iord(switch_base) & 0x000003ff;
}
```

```
void led_flash(u32 addr_led_base, int period)
{
 static u8 led_pattern = 0x01;
 unsigned long i, itr;
  led_pattern ^= 0x03;
  my_iowr(addr_led_base, led_pattern);
  itr = period * 2500;
  for (i=0; i<itr; i++) {}
}
```

Read/Write From/To GPIO Inputs and Outputs

Steps for Reading from a GPIO

1. Create a GPIO instance
2. Initialize the GPIO
3. Set data direction
4. Read the data

Steps for Reading from a GPIO – Step 1

1. Create a GPIO instance

```
#include "xparameters.h"
#include "xgpio.h"
int main (void)
 {
   XGpio switches;
   XGpio leds;
   . . .
```

```
/**
 * The XGpio driver instance data. The user is required to allocate a
 * variable of this type for every GPIO device in the system. A pointer
 * to a variable of this type is then passed to the driver API functions.
 */
typedef struct {
    u32 BaseAddress;        /* Device base address */
    u32 IsReady;            /* Device is initialized and ready */
    int InterruptPresent;   /* Are interrupts supported in h/w */
    int IsDual;             /* Are 2 channels supported in h/w */
} XGpio;
```

The **XGpio** driver instance data. The user is required to allocate a *variable of this type* for *every GPIO device in the system*. A pointer to a variable of this type is then passed to the driver API functions.

Steps for Reading from a GPIO – Step 2

2. Initialize the GPIO

```
(int) XGpio_Initialize(XGpio *InstancePtr, u16 DeviceID);
```

InstancePtr: is a pointer to an XGpio instance. The memory the pointer references must be pre-allocated by the caller. Further calls to manipulate the component through the XGpio API must be made with this pointer.

DeviceID: is the unique id of the device controlled by this XGpio component. Passing in a device ID associates the generic XGpio instance to a specific device, as chosen by the caller or application developer.

@return

- XST_SUCCESS if the initialization was successfull.
- XST_DEVICE_NOT_FOUND if the device configuration data was not

} xstatus.h

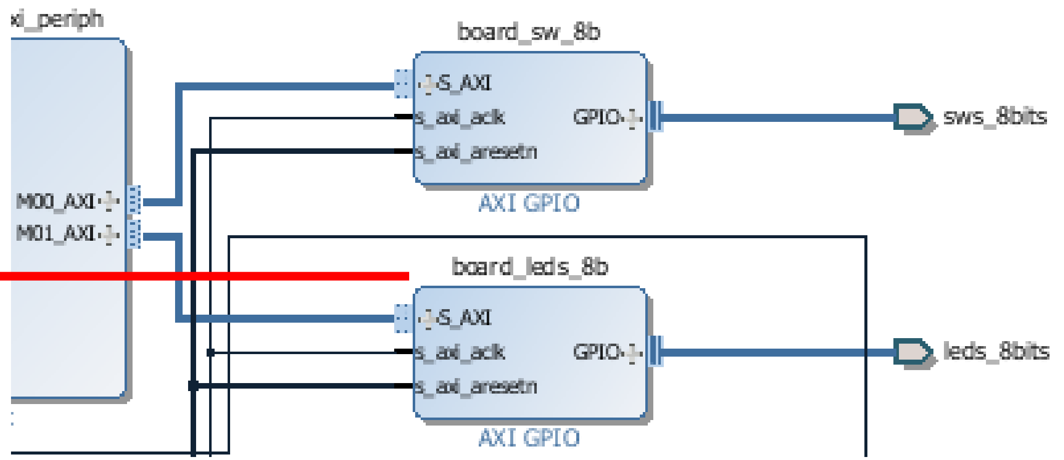
Steps for Reading from a GPIO – Step 2(cont')

```
(int) XGpio_Initialize(XGpio *InstancePtr, u16 DeviceID);
```

```
// AXI GPIO switches initialization
XGpio_Initialize (&switches, XPAR_BOARD_SW_8B_DEVICE_ID);
// AXI GPIO leds initialization
XGpio_Initialize (&led, XPAR_BOARD_LEDS_8B_DEVICE_ID);
```

xparameters.h | lab_gpio_in_... | xgpiops_hw.h

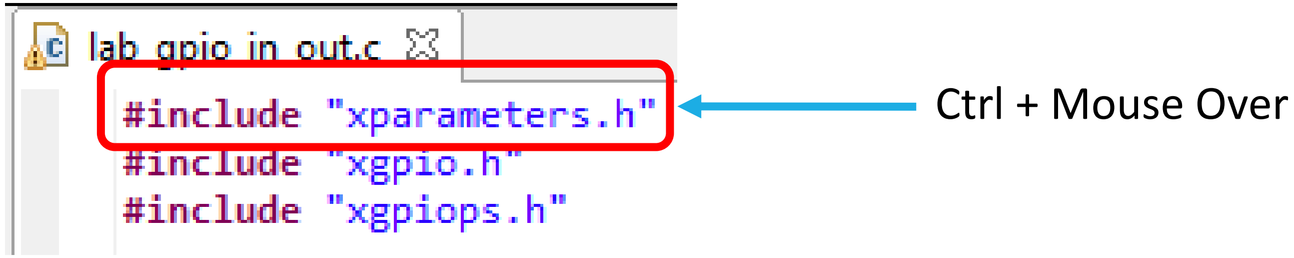
```
/* Definitions for peripheral BOARD_LEDS_8B */
#define XPAR_BOARD_LEDS_8B_BASEADDR 0x41210000
#define XPAR_BOARD_LEDS_8B_HIGHADDR 0x4121FFFF
#define XPAR_BOARD_LEDS_8B_DEVICE_ID 0
#define XPAR_BOARD_LEDS_8B_INTERRUPT_PRESENT 0
#define XPAR_BOARD_LEDS_8B_IS_DUAL 0
```

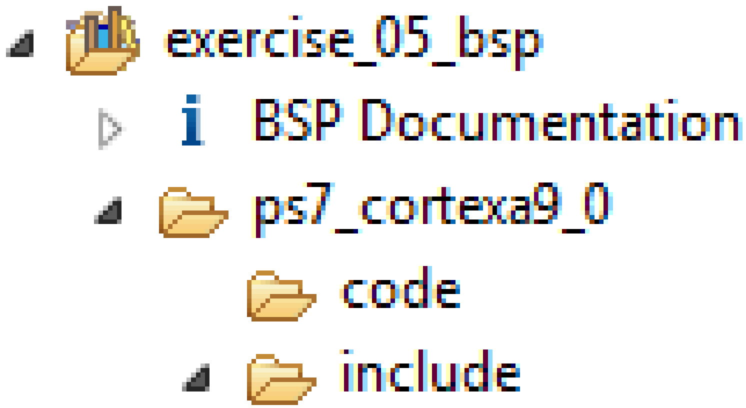


xparameters.h

The *xparameters.h* file contains the address map for peripherals in the created system

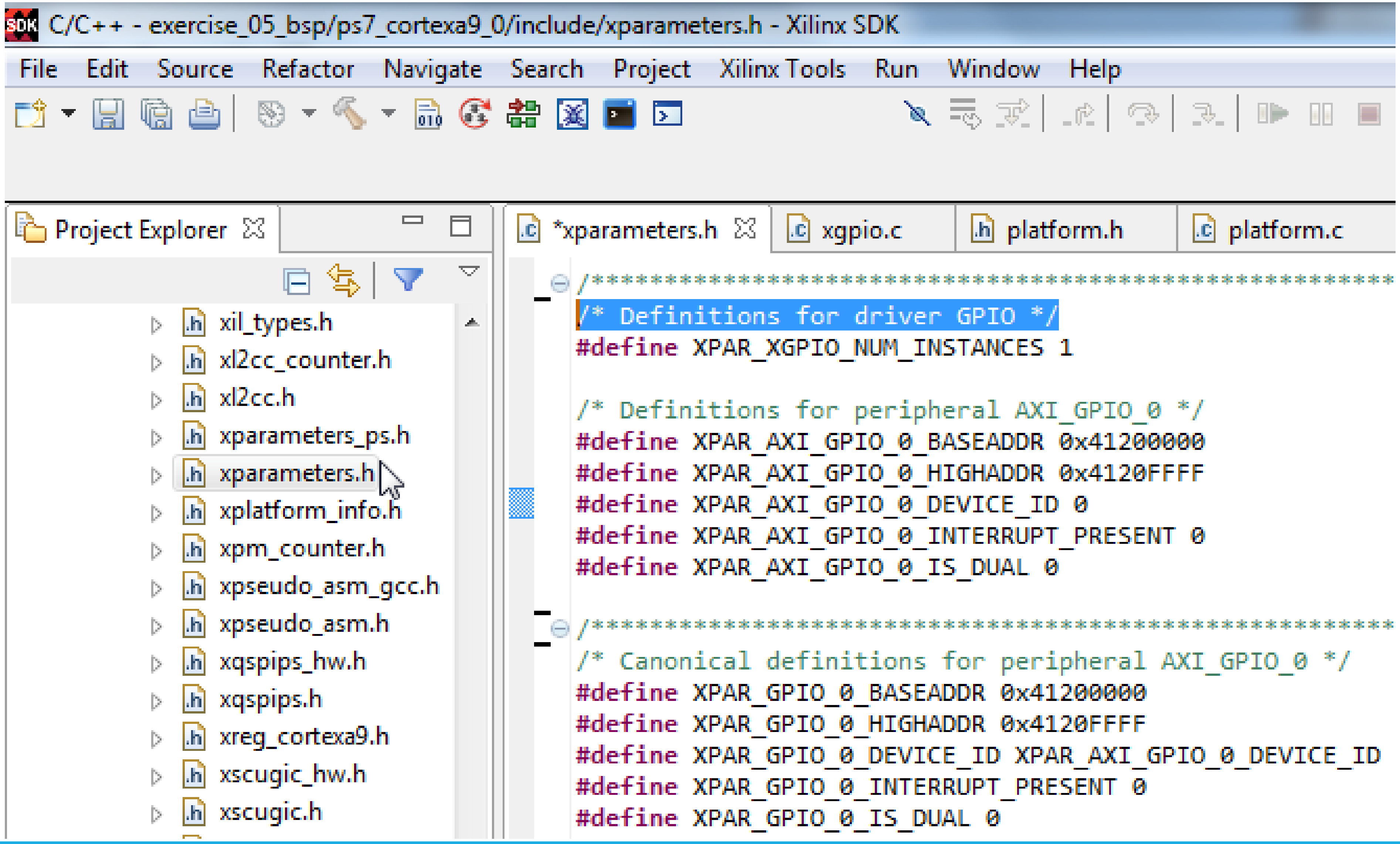
This file is generated from the hardware platform description from Vivado



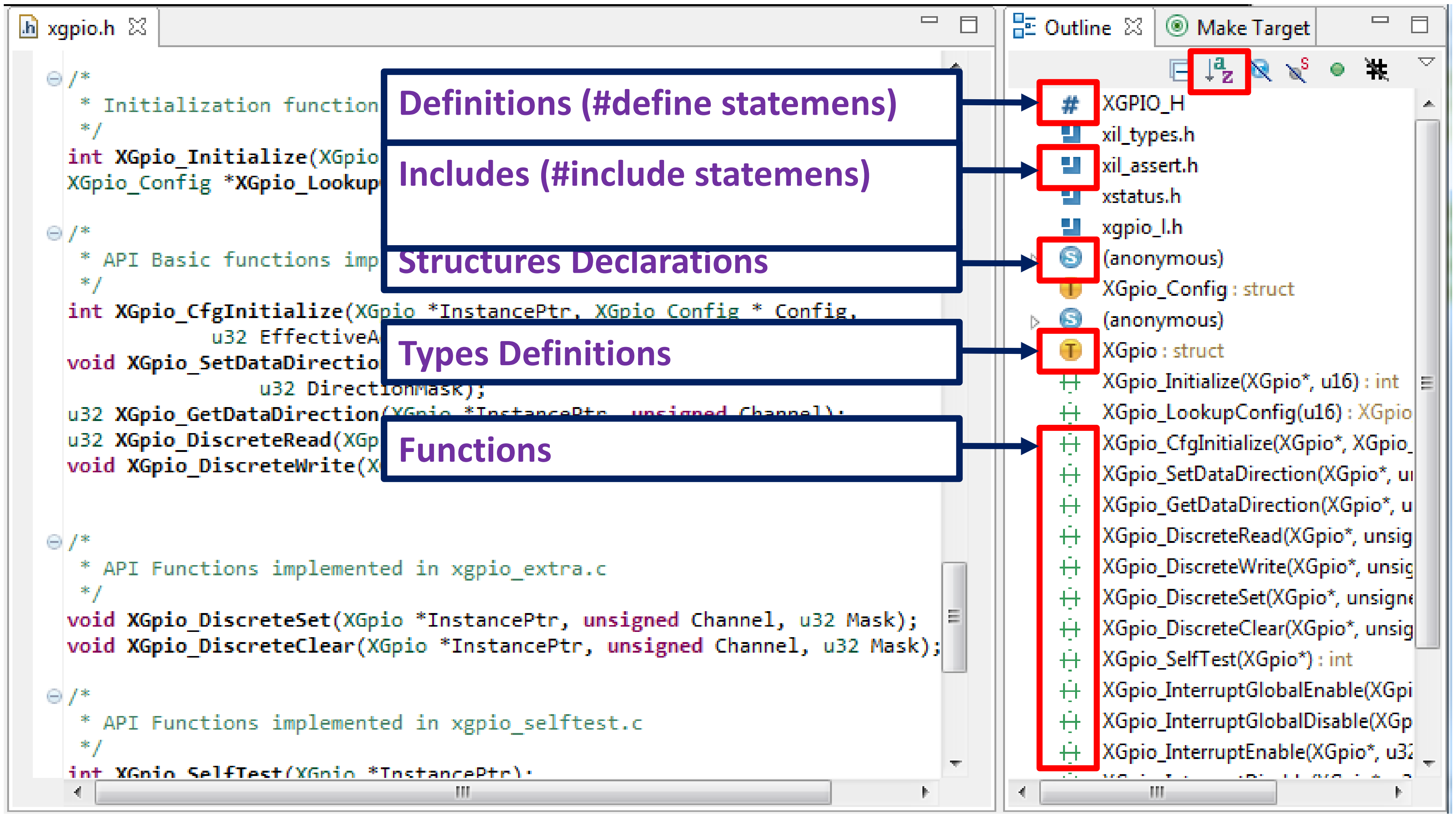


xparameters.h file can be found underneath the include folder in the ps7_cortexa9_0 folder of the BSP main folder

xparameters.h



xgpio.h – Outline Pane



Steps for Reading from a GPIO - Step 3

3. Set data direction

```
void XGpio_SetDataDirection (XGpio *InstancePtr, unsigned Channel, u32 DirectionMask);
```

InstancePtr: is a pointer to an XGpio instance to be worked on.

Channel: contains the channel of the XGpio (1 o 2) to operate with.

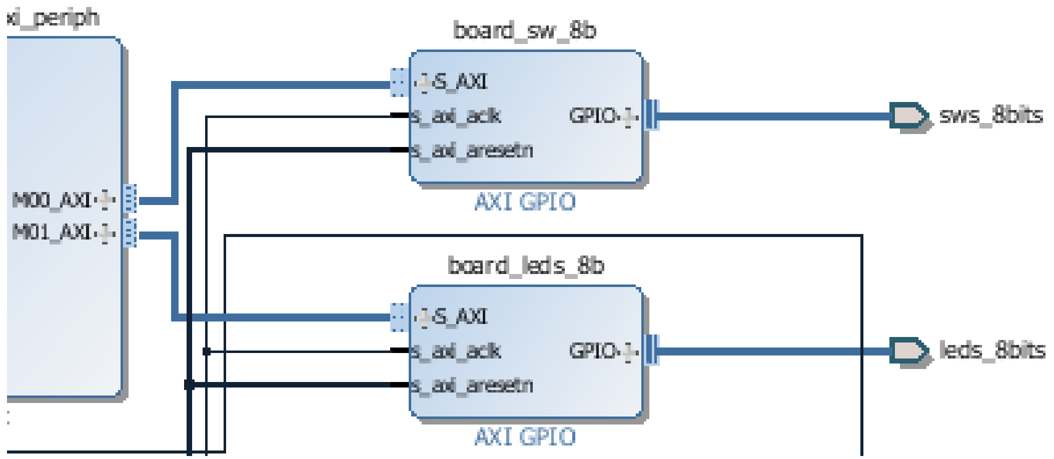
DirectionMask: is a bitmask specifying which bits are inputs and which are outputs. Bits set to ‘0’ are output, bits set to ‘1’ are inputs.

Return: none

Steps for Reading from a GPIO - Step 3 (cont’)

```
void XGpio_SetDataDirection (XGpio *InstancePtr, unsigned Channel, u32 DirectionMask);
```

```
// AXI GPIO switches: bits direction configuration
XGpio_SetDataDirection(&switches, 1, 0xffffffff);
```



Steps for Reading from a GPIO – Step 4

4. Read the data

```
u32 XGpio_DiscreteRead (XGpio *InstancePtr, unsigned Channel);
```

InstancePtr: is a pointer to an XGpio instance to be worked on.

Channel: contains the channel of the XGpio (1 o 2) to operate with.

Return: read data

Steps for Reading from a GPIO – Step 4 (cont')

```
u32 XGpio_DiscreteRead (XGpio *InstancePtr, unsigned Channel);
```

```
// AXI GPIO: read data from the switches
sw_check = XGpio_DiscreteRead(&switches, 1);
```

Steps for Writing to GPIO

1. Create a GPIO instance
2. Initialize the GPIO
3. Read the data

Steps for Writing to a GPIO – Step 1

1. Create a GPIO instance

```
#include "xgpio.h"
int main (void)
 {
   XGpio switches;
   XGpio leds;
   . . .
```

```
/**
 * The XGpio driver instance data. The user is required to allocate a
 * variable of this type for every GPIO device in the system. A pointer
 * to a variable of this type is then passed to the driver API functions.
 */
typedef struct {
    u32 BaseAddress;        /* Device base address */
    u32 IsReady;            /* Device is initialized and ready */
    int InterruptPresent;   /* Are interrupts supported in h/w */
    int IsDual;             /* Are 2 channels supported in h/w */
} XGpio;
```

The **XGpio** driver instance data. The user is required to allocate a variable of this type for *every GPIO device in the system*. A pointer to a variable of this type is then passed to the driver API functions.

Steps for Writing to a GPIO – Step 2

2. Initialize the GPIO

```
(int) XGpio_Initialize(XGpio *InstancePtr, u16 DeviceID);
```

InstancePtr: is a pointer to an XGpio instance. The memory the pointer references must be pre-allocated by the caller. Further calls to manipulate the component through the XGpio API must be made with this pointer.

DeviceID: is the unique id of the device controlled by this XGpio component. Passing in a device ID associates the generic XGpio instance to a specific device, as chosen by the caller or application developer.

@return

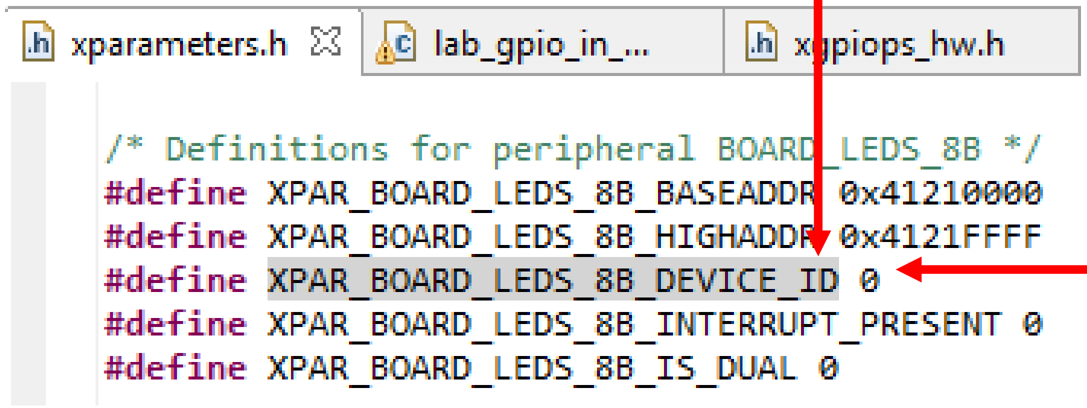
- XST_SUCCESS if the initialization was successfull.
- XST_DEVICE_NOT_FOUND if the device configuration data was not

} xstatus.h

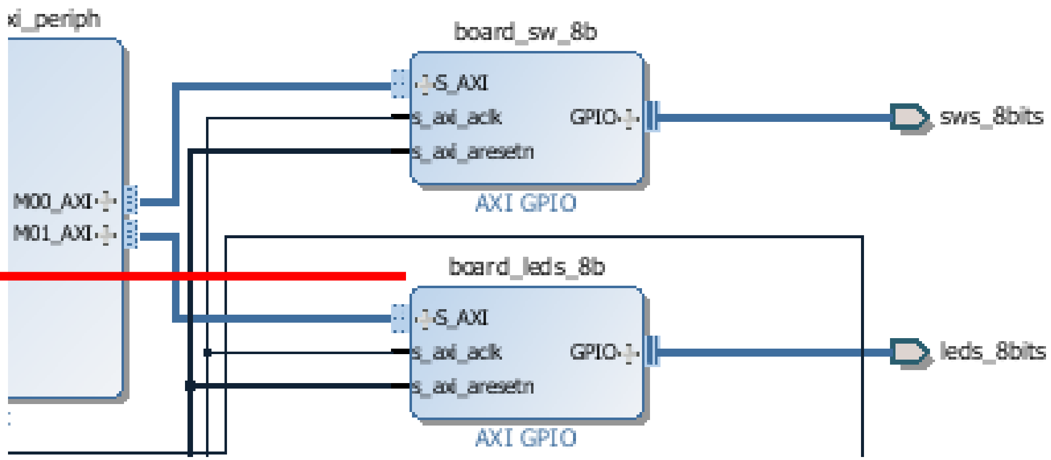
Steps for Writing to a GPIO – Step 2(cont')

```
(int) XGpio_Initialize (XGpio *InstancePtr, u16 DeviceID);
```

```
// AXI GPIO switches initialization
XGpio_Initialize (&switches, XPAR_BOARD_SW_8B_DEVICE_ID);
// AXI GPIO leds initialization
XGpio_Initialize (&led, XPAR_BOARD_LEDS_8B_DEVICE_ID);
```


xparameters.h | lab_gpio_in_... | xgpiops_hw.h

```
/* Definitions for peripheral BOARD_LEDS_8B */
#define XPAR_BOARD_LEDS_8B_BASEADDR 0x41210000
#define XPAR_BOARD_LEDS_8B_HIGHADDR 0x4121FFFF
#define XPAR_BOARD_LEDS_8B_DEVICE_ID 0
#define XPAR_BOARD_LEDS_8B_INTERRUPT_PRESENT 0
#define XPAR_BOARD_LEDS_8B_IS_DUAL 0
```



Steps for Writing to a GPIO – Step 3

3. Write the data

```
void XGpio_DiscreteWrite (XGpio *InstancePtr, unsigned Channel, u32 Data);
```

InstancePtr: is a pointer to an XGpio instance to be worked on.

Channel: contains the channel of the XGpio (1 o 2) to operate with.

Data: Data is the value to be written to the discrete register

Return: none

Steps for Writing to a GPIO – Step 3 (cont')

```
void XGpio_DiscreteWrite (XGpio *InstancePtr, unsigned Channel, u32 Data);
```

```
// AXI GPIO: read data from the switches
 sw_check = XGpio_DiscreteRead(&switches, 1);
// AXI GPIO: write data (sw_check) to the LEDs
XGpio_DiscreteWrite(&led, 1, sw_check);
```

IP Drivers for Custom IP

My VHDL Code for the Future IP

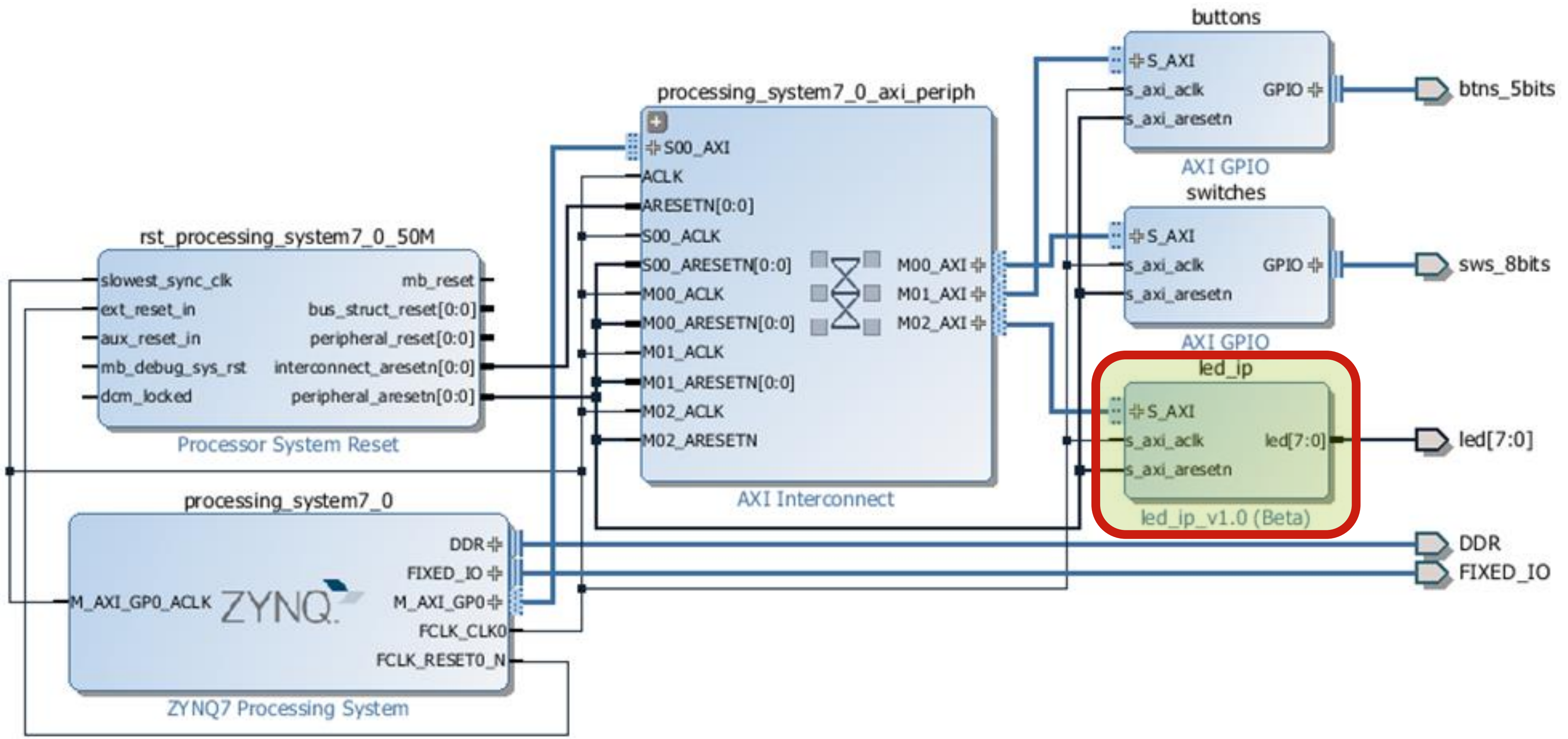
```vhdl
-------------------------------------------------------------------------------
-- lab name: lab_custom_ip
-- component name: my_led_ip
-- author: cas
-- version: 1.0
-- description: simple logic to
-------------------------------------------------------------------------------
library ieee;
use ieee.std_logic_1164.all;

entity lab_led_ip is

  generic (
    led_width : integer := 8);          -- 8 LEDs
  port (
    -- clock and reset
    S_AXI_ACLK    : in std_logic;
    S_AXI_ARESETN : in std_logic;
    -- write data channel
    S_AXI_WDATA   : in std_logic_vector(31 downto 0);
    SLV_REG_WREN  : in std_logic;
    -- address channel
    AXI_AWADDR    : in std_logic_vector(3 downto 0);
    -- my inputs / outputs --
    -- output
    LED           : out std_logic_vector(led_width-1 downto 0)
    );
end entity lab_led_ip;
```

AXI4-Lite IP

```vhdl
architecture beh of lab_led_ip is

begin  -- architecture beh

  process(S_AXI_ACLK, S_AXI_ARESETN)
  begin
    if(S_AXI_ARESETN='0')then
      LED <= (others=>'0');
    elsif(rising_edge(S_AXI_ACLK))then
      if(SLV_REG_WREN='1' and AXI_AWADDR="0000") then
        LED <= S_AXI_WDATA(led_width-1 downto 0);
      end if;
    end if;
  end process;
end architecture beh;
```

Address Decode & Write Enable

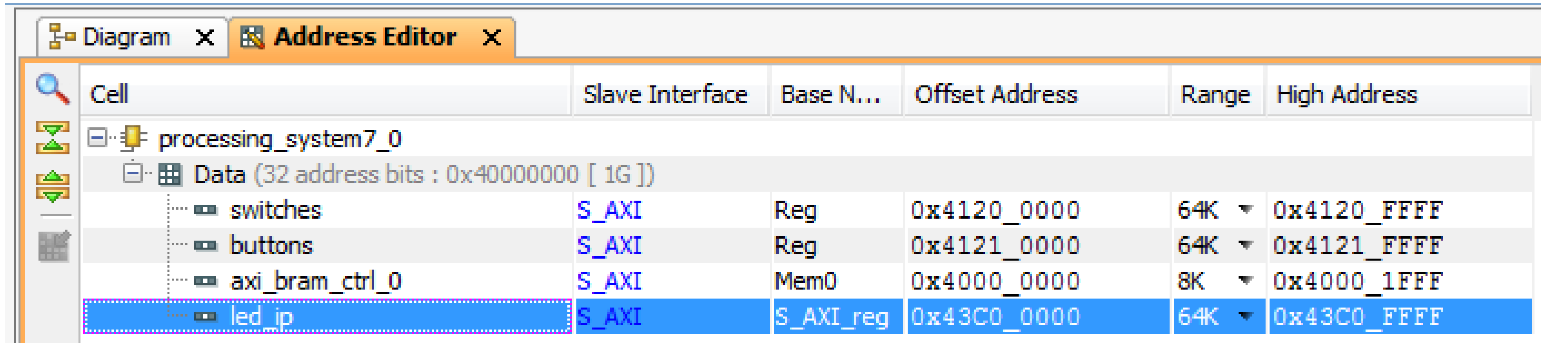
Custom IP


buttons
S_AXI
s_axi_aclk
s_axi_aresetn
GPIO
AXI GPIO
btns_5bits
switches
S_AXI
s_axi_aclk
s_axi_aresetn
GPIO
AXI GPIO
sws_8bits
led_ip
S_AXI
s_axi_aclk
s_axi_aresetn
led[7:0]
led_ip_v1.0 (Beta)
led[7:0]
processing_system7_0_axi_periph
S00_AXI
ACLK
ARESETN[0:0]
S00_ACLK
S00_ARESETN[0:0]
M00_ACLK
M00_ARESETN[0:0]
M01_ACLK
M01_ARESETN[0:0]
M02_ACLK
M02_ARESETN
M00_AXI
M01_AXI
M02_AXI
AXI Interconnect
rst_processing_system7_0_50M
slowest_sync_clk
ext_reset_in
aux_reset_in
mb_debug_sys_rst
dcm_locked
mb_reset
bus_struct_reset[0:0]
peripheral_reset[0:0]
interconnect_aresetn[0:0]
peripheral_aresetn[0:0]
Processor System Reset
processing_system7_0
M_AXI_GP0_ACLK
ZYNQ
DDR
FIXED_IO
M_AXI_GP0
FCLK_CLK0
FCLK_RESET0_N
ZYNQ7 Processing System
DDR
FIXED_IO

System Level Address Map

Address Range	CPUs and ACP	AXI_HP	Other Bus Masters[1]	Notes
0000_0000 to 0003_FFFF[2]	OCM	OCM	OCM	Address not filtered by SCU and OCM is mapped low
	DDR	OCM	OCM	Address filtered by SCU and OCM is mapped low
	DDR			Address filtered by SCU and OCM is not mapped low
				Address not filtered by SCU and OCM is not mapped low
0004_0000 to 0007_FFFF	DDR			Address filtered by SCU
				Address not filtered by SCU
0008_0000 to 000F_FFFF	DDR	DDR	DDR	Address filtered by SCU
		DDR	DDR	Address not filtered by SCU[3]
0010_0000 to 3FFF_FFFF	DDR	DDR	DDR	Accessible to all interconnect masters
4000_0000 to 7FFF_FFFF	PL		PL	General Purpose Port #0 to the PL, M_AXI_GP0
8000_0000 to BFFF_FFFF	PL		PL	General Purpose Port #1 to the PL, M_AXI_GP1
E000_0000 to E02F_FFFF	IOP		IOP	I/O Peripheral registers, see Table 4-6
E100_0000 to E5FF_FFFF	SMC		SMC	SMC Memories, see Table 4-5
F800_0000 to F800_0BFF	SLCR		SLCR	SLCR registers, see Table 4-3
F800_1000 to F880_FFFF	PS		PS	PS System registers, see Table 4-7
F890_0000 to F8F0_2FFF	CPU			CPU Private registers, see Table 4-4
FC00_0000 to FDFF_FFFF[4]	Quad-SPI		Quad-SPI	Quad-SPI linear address for linear mode
FFFC_0000 to FFFF_FFFF[2]	OCM	OCM	OCM	OCM is mapped high
				OCM is not mapped high

My IP – Memory Address Range



Custom IP Drivers

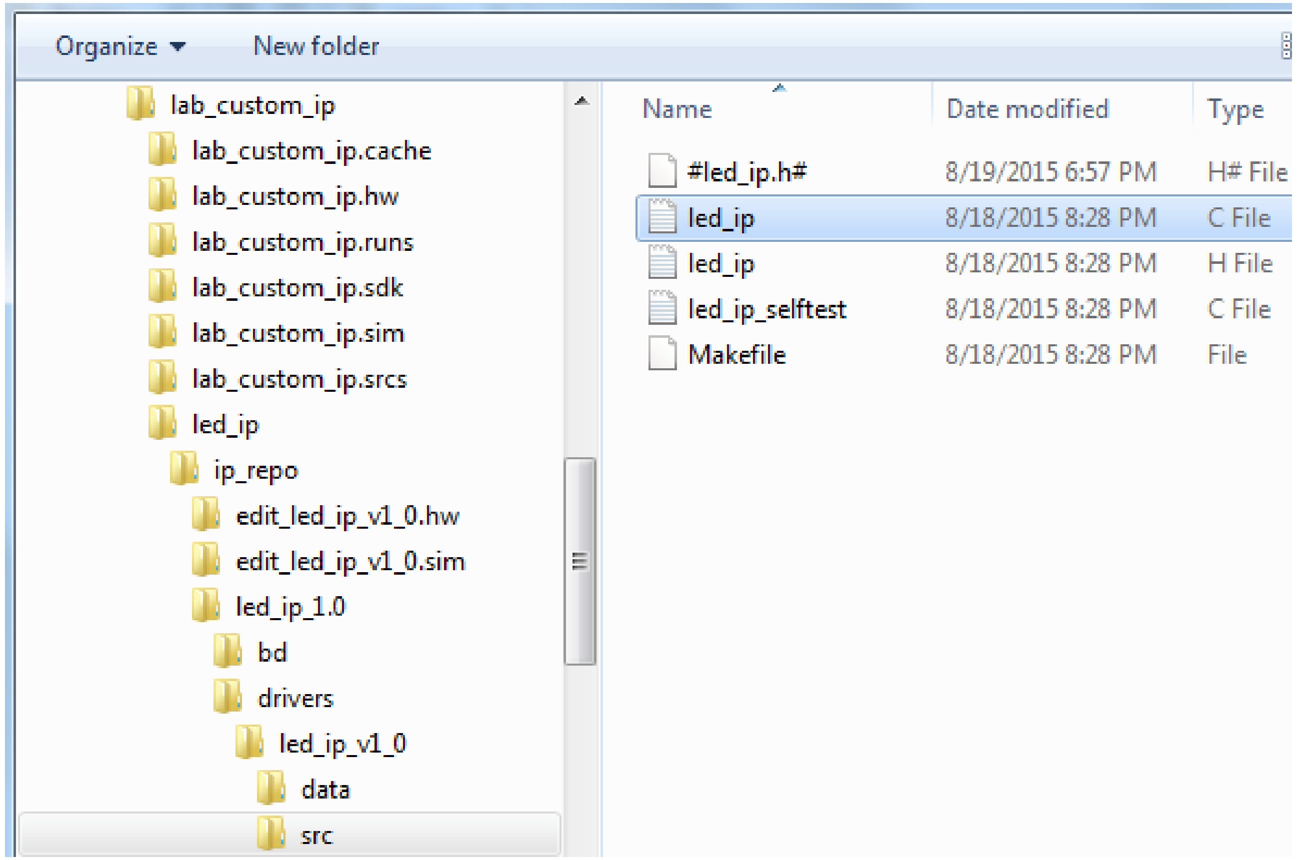
- The *driver code* are generated automatically when the IP template is created.
- The *driver* includes higher level functions which can be called from the user application.
- The *driver* will implement the low level functionality used to control your peripheral.

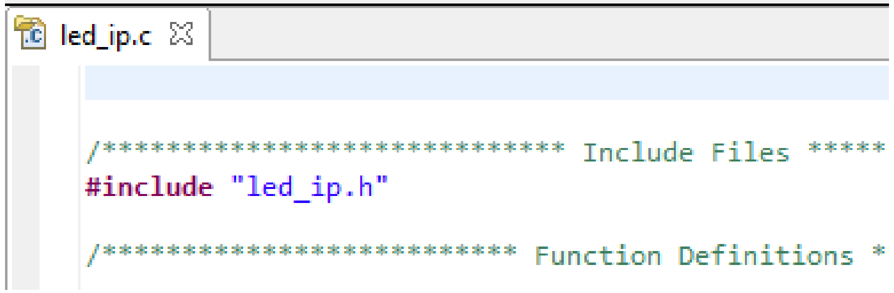
led_ip\ip_repo\led_ip_1.0\drivers\led_ip_v1_0\src

- *led_ip.c*
- *led_ip.h*
  - *LED_IP_mWriteReg(…)*
  - *LED_IP_mReadReg(…)*

Custom IP Drivers: *.c

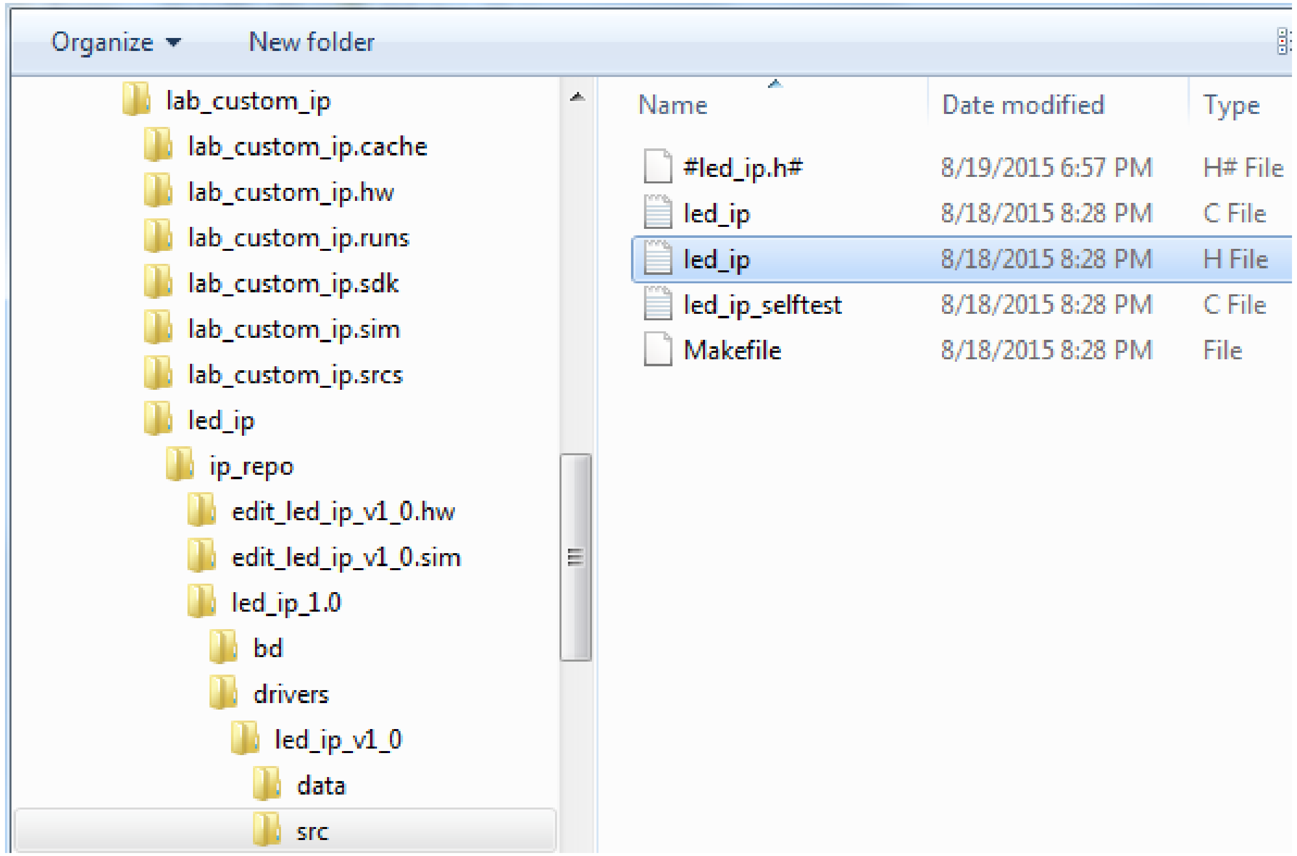
led_ip\ip_repo\led_ip_1.0\drivers\led_ip_v1_0\src\led_ip.c





Custom IP Drivers: *.h

led_ip\ip_repo\led_ip_1.0\drivers\led_ip_v1_0\src\led_ip.h



Custom IP Drivers: *.h (cont' 1)

led_ip\ip_repo\led_ip_1.0\drivers\led_ip_v1_0\src\led_ip.h

led_ip.h

```
/****************** Include Files ********************/
#include "xil_types.h"
#include "xstatus.h"

#define LED_IP_S_AXI_SLV_REG0_OFFSET 0
#define LED_IP_S_AXI_SLV_REG1_OFFSET 4
#define LED_IP_S_AXI_SLV_REG2_OFFSET 8
#define LED_IP_S_AXI_SLV_REG3_OFFSET 12
```

Custom IP Drivers: *.h (cont' 2)

led_ip\ip_repo\led_ip_1.0\drivers\led_ip_v1_0\src\led_ip.h

```
/**
 *
 * Write a value to a LED_IP register. A 32 bit write is performed.
 * If the component is implemented in a smaller width, only the least
 * significant data is written.
 *
 * @param   BaseAddress is the base address of the LED_IPdevice.
 * @param   RegOffset is the register offset from the base to write to.
 * @param   Data is the data written to the register.
 *
 * @return  None.
 *
 * @note
 * C-style signature:
 *  void LED_IP_mWriteReg(u32 BaseAddress, unsigned RegOffset, u32 Data)
 *
 */
#define LED_IP_mWriteReg(BaseAddress, RegOffset, Data) \
    Xil_Out32((BaseAddress) + (RegOffset), (u32)(Data))
```

Custom IP Drivers: *.h (cont' 3)

led_ip\ip_repo\led_ip_1.0\drivers\led_ip_v1_0\src\led_ip.h

```
/**
 *
 * Read a value from a LED_IP register. A 32 bit read is performed.
 * If the component is implemented in a smaller width, only the least
 * significant data is read from the register. The most significant data
 * will be read as 0.
 *
 * @param   BaseAddress is the base address of the LED_IP device.
 * @param   RegOffset is the register offset from the base to write to.
 *
 * @return  Data is the data from the register.
 *
 * @note
 * C-style signature:
 *  u32 LED_IP_mReadReg(u32 BaseAddress, unsigned RegOffset)
 *
 */
#define LED_IP_mReadReg(BaseAddress, RegOffset) \
    Xil_In32((BaseAddress) + (RegOffset))
```

Custom IP Drivers: *.h (cont' 4)

led_ip\ip_repo\led_ip_1.0\drivers\led_ip_v1_0\src\led_ip.h

```
/**
 *
 * Run a self-test on the driver/device. Note this may be a destructive test if
 * resets of the device are performed.
 *
 * If the hardware system is not built correctly, this function may never
 * return to the caller.
 *
 * @param   baseaddr_p is the base address of the LED_IP instance to be worked on
 *
 * @return
 *
 *    - XST_SUCCESS   if all self-test code passed
 *    - XST_FAILURE   if any self-test code failed
 *
 * @note    Caching must be turned off for this function to work.
 * @note    Self test may fail if data memory and device are not on the same bus.
 *
 */
XStatus LED_IP_Reg_SelfTest(void * baseaddr_p);
```

‘C’ Code for Writing to My_IP

```c
#include "xparameters.h"
#include "xgpio.h"
#include "led_ip.h"

//====================================================
int main (void)
{
   XGpio dip, push;
   int i, psb_check, dip_check;

   xil_printf("-- Start of the Program --\r\n");

   XGpio_Initialize(&dip, XPAR_SWITCHES_DEVICE_ID);
   XGpio_SetDataDirection(&dip, 1, 0xffffffff);

   XGpio_Initialize(&push, XPAR_BUTTONS_DEVICE_ID);
   XGpio_SetDataDirection(&push, 1, 0xffffffff);

   while (1)
   {
      psb_check = XGpio_DiscreteRead(&push, 1);
      xil_printf("Push Buttons Status %x\r\n", psb_check);
      dip_check = XGpio_DiscreteRead(&dip, 1);
      xil_printf("DIP Switch Status %x\r\n", dip_check);

      for (i=0; i<9999999; i++);
   }
}
```

IP Drivers – *Xil_Out32/Xil_In32*

```
#define LED_IP_mWriteReg(BaseAddress, RegOffset, Data) Xil_Out32((BaseAddress) + (RegOffset), (Xuint32)(Data))

#define LED_IP_mReadReg(BaseAddress, RegOffset) Xil_In32((BaseAddress) + (RegOffset))
```

- For this driver, you can see the macros are aliases to the lower level functions **Xil_Out32( )** and **Xil_In32( )**
- The macros in this file make up the higher level API of the led_ip driver.
- If you are writing your own driver for your own IP, you will need to use low level functions like these to read and write from your IP as required. The low level hardware access functions are wrapped in your driver making it easier to use your IP in an Application project.

IP Drivers – *Xil_In32 (xil_io.h/xil_io.c)*

```
/******************************************************************************/
/**
* Performs an input operation for a 32-bit memory location by reading from the
* specified address and returning the Value read from that address.
*
* @param	Addr contains the address to perform the input operation at.
*
* @return	The Value read from the specified input address.
*
* @note		None.
*
******************************************************************************/
u32 Xil_In32(INTPTR Addr)
{
		return *(volatile u32 *) Addr;
}
```

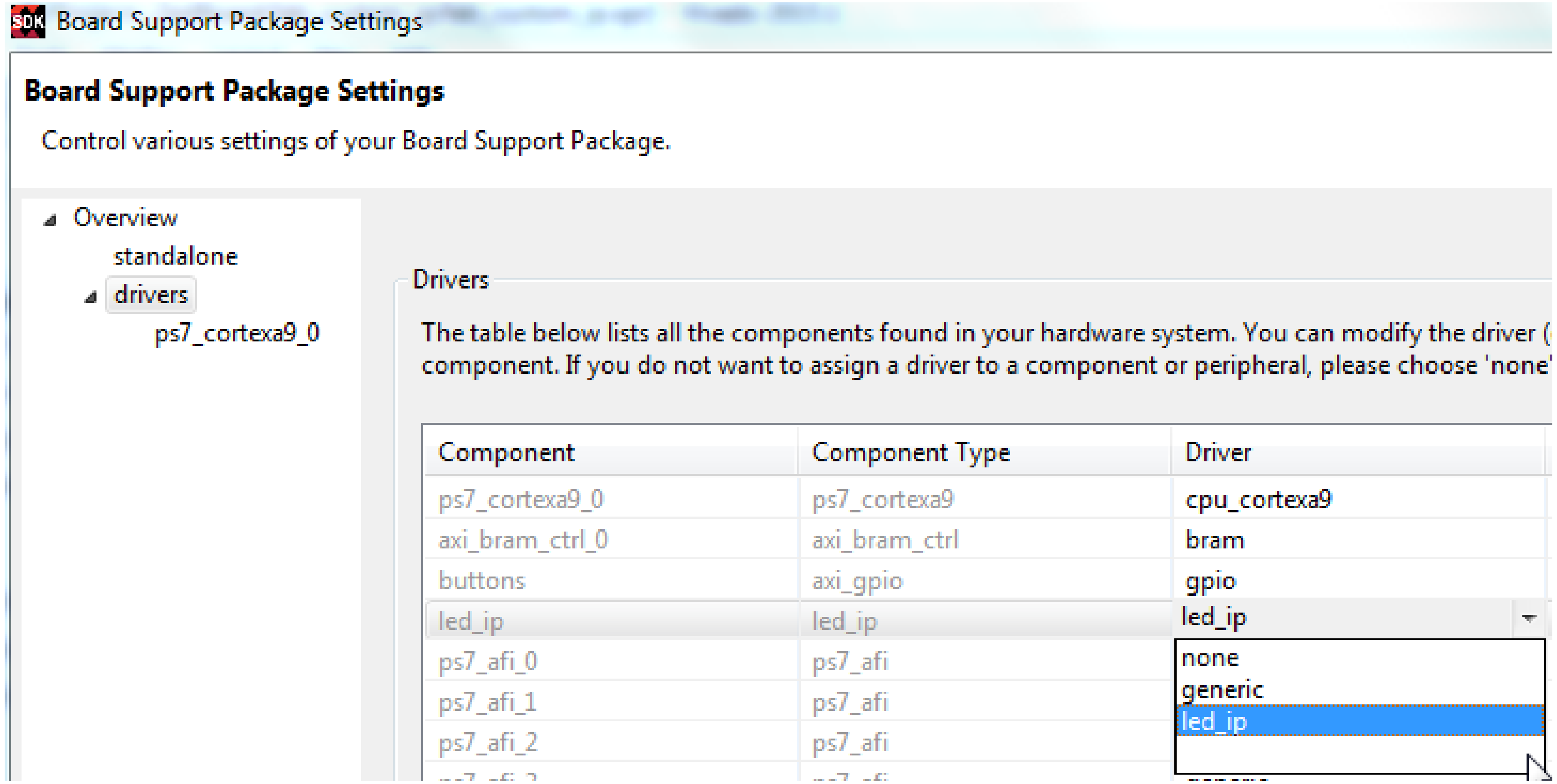
IP Drivers – *Xil_Out32 (xil_io.h/xil_io.c)*

```
/******************************************************************************/
/**
* Performs an output operation for a 32-bit memory location by writing the
* specified Value to the the specified address.
*
* @param     Addr contains the address to perform the output operation at.
* @param     Value contains the Value to be output at the specified address.
*
* @return    None.
*
* @note      None.
******************************************************************************/
void Xil_Out32(INTPTR Addr, u32 Value)
{
        u32 *LocalAddr = (u32 *)Addr;

        *LocalAddr = Value;
}
```

IP Drivers – SDK ‘Activation’

- Select <***project_name>_bsp*** in the project view pane. Right-click
- Select ***Board Support Package Settings***
- Select ***Drivers*** on the ***Overview*** pane
- If the ***led_ip*** driver has not already been selected, select Generic under the Driver Column for ***led_ip*** to access the dropdown menu. From the dropdown menu, select ***led_ip***, and click OK>

IP Drivers – SDK 'Activation' (cont')



Read and Write From/To Memory

Note On Reading from / Writing to Memory

Generally speaking processors work on byte (8bit) address boundaries.

If we wish to write byte-wide data values into the first four consecutive locations in a region of memory starting at "*DDR_BASEADDR*", we must write the first to DDR_BASEADDR + 0, the second to *DDR_BASEADDR + 1*, the third to *DDR_BASEADDR + 2*, and the last to *DDR_BASEADDR + 3*.

However, if we wish to write four half-word wide (16 bit) data values to four memory addresses starting at the same location, we must write the first to DDR_BASEADDR + 0, the second to DDR_BASEADDR + 2, the third to DDR_BASEADDR + 4, and the last to DDR_BASEADDR + 6.

When writing word wide (32 bit) data values, we must do so on 4 byte boundaries; 0x0, 0x4, 0x8, and 0xC.

Reading from / Writing to Memory: *xil_io.h*

Writing Functions

Xil_Out8(memory_address, 8_bit_value);

Xil_Out16(memory_address, 16_bit_value);

Xil_Out32(memory_address, 32_bit_value);

Reading Functions

8_bit_value = ***Xil_In8***(memory_address);

16_bit_value = ***Xil_In16***(memory_address);

32_bit_value = **Xil_In32**(memory_address);

Reading from / Writing to Memory: *xil_io.h*

```
int main(void)
{
  int result1; // integers are 32 bits wide!
  int result2; // integers are 32 bits wide!

  Xil_Out8(XPAR_PS7_RAM_0_S_AXI_BASEADDR + 0, 0x12);
  Xil_Out8(XPAR_PS7_RAM_0_S_AXI_BASEADDR + 1, 0x34);
  Xil_Out8(XPAR_PS7_RAM_0_S_AXI_BASEADDR + 2, 0x56);
  Xil_Out8(XPAR_PS7_RAM_0_S_AXI_BASEADDR + 3, 0x78);
  result1 = Xil_In32(XPAR_PS7_RAM_0_S_AXI_BASEADDR);
  Xil_Out16(XPAR_PS7_RAM_0_S_AXI_BASEADDR + 4, 0x9876);
  Xil_Out16(XPAR_PS7_RAM_0_S_AXI_BASEADDR + 6, 0x5432);
  result2 = Xil_In32(XPAR_PS7_RAM_0_S_AXI_BASEADDR + 4);

return(0);
}
```