Introduction

This document describes a simple computer system that can be implemented on the Altera DE2 development and education board. This system, called the DE2 Basic Computer, is intended to be used as a platform for introductory experiments in computer organization and embedded systems. To support these beginning experiments, the system contains only a few components: a processor, memory, and some simple I/O peripherals. The FPGA programming file that implements this system, as well as its design source files, can be obtained from the University Program section of Altera’s web site.

DE2 Basic Computer Contents

A block diagram of the DE2 Basic Computer is shown in Figure 1. Its main components include the Altera Nios II processor, memory for program and data storage, parallel ports connected to switches and lights, a timer module, and a serial port. As shown in the figure, the processor and its interfaces to I/O devices are implemented inside the Cyclone®II FPGA chip on the DE2 board. Each of the components shown in Figure 1 is described below.

2.1 Nios II Processor

The Altera Nios® II processor is a 32-bit CPU that can be instantiated in an Altera FPGA chip. Three versions of the Nios II processor are available, designated economy (/e), standard (/s), and fast (/f). The DE2 Basic Computer includes the Nios II/e version, which has an appropriate feature set for use in introductory experiments.

An overview of the Nios II processor can be found in the document Introduction to the Altera Nios II Processor, which is provided in the University Program section of Altera’s web site. An easy way to begin working with the DE2 Basic Computer and the Nios II processor is to make use of a utility called the Altera Monitor Program. This utility provides an easy way to assemble and compile Nios II programs on the DE2 Basic Computer that are written in either assembly language or the C programming language. The Monitor Program, which can be downloaded from Altera’s web site, is an application program that runs on the host computer connected to the DE2 board. The Monitor Program can be used to control the execution of code on Nios II, list (and edit) the contents of processor registers, display/edit the contents of memory on the DE2 board, and similar operations. The Monitor Program includes the DE2 Basic Computer as a predesigned system that can be downloaded onto the DE2 board, as well as several sample programs in assembly language and C that show how to use various peripheral devices in the DE2 Basic Computer. Some images that show how the DE2 Basic Computer is integrated with the Monitor Program are described in section 7. An overview of the Monitor Program is available in the document Altera Monitor Program Tutorial, which is provided in Altera’s University Program web site.
As indicated in Figure 1, the Nios II processor can be reset by pressing $KEY_0$ on the DE2 board. The address of the reset vector is given in section 3. All of the I/O peripherals in the DE2 Basic Computer are accessible by the processor as memory mapped devices, using the address ranges that are given in the following subsections.

### 2.2 Memory Components

The DE2 Basic Computer has three types of memory components: SDRAM, SRAM, and on-chip memory inside the FPGA chip. Each type of memory is described below.

#### 2.2.1 SDRAM

An SDRAM Controller provides a 32-bit interface to the synchronous dynamic RAM (SDRAM) chip on the DE2 board. This SDRAM chip is organized as $1\text{M} \times 16 \text{ bits} \times 4 \text{ banks}$, but is accessible by the Nios II processor using word (32-bit), halfword (16-bit), or byte operations. The SDRAM memory is mapped to the address space $0\times00000000$ to $0\times007FFFFF$. 

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**Figure 1. Block diagram of the DE2 Basic Computer.**
2.2.2 SRAM

An SRAM Controller provides a 32-bit interface to the static RAM (SRAM) chip on the DE2 board. This SRAM chip is organized as 256K x 16 bits, but is accessible by the Nios II processor using word (32-bit), halfword (16-bit), or byte operations. The SRAM memory is mapped to the address space 0x08000000 to 0x0807FFFF.

2.2.3 On-Chip Memory

The DE2 Basic Computer includes an 8-Kbyte memory that is implemented in the Cyclone II FPGA chip. This memory is organized as 2K x 32 bits, and can be accessed using either word, halfword, or byte operations. The memory spans addresses in the range 0x09000000 to 0x09001FFF.

2.3 Parallel Ports

The DE2 Basic Computer includes several parallel ports that support input, output, and bidirectional transfers of data between the Nios II processor and I/O peripherals. As illustrated in Figure 2, each parallel port is assigned a Base address and contains up to four 32-bit registers. Ports that have output capability include a writable Data register, and ports with input capability have a readable Data register. Bidirectional parallel ports also include a Direction register that has the same bit-width as the Data register. Each bit in the Data register can be configured as an input by setting the corresponding bit in the Direction register to 0, or as an output by setting this bit position to 1. The Direction register is assigned the address Base + 4.

<table>
<thead>
<tr>
<th>Address</th>
<th>31 30 · · · 4 3 2 1 0</th>
<th>Data register</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>Input or output data bits</td>
<td></td>
</tr>
<tr>
<td>Base + 4</td>
<td>Direction bits</td>
<td></td>
</tr>
<tr>
<td>Base + 8</td>
<td>Mask bits</td>
<td>Interruptmask register</td>
</tr>
<tr>
<td>Base + C</td>
<td>Edge bits</td>
<td>Edgecapture register</td>
</tr>
</tbody>
</table>

Figure 2. Parallel port registers in the DE2 Basic Computer.

Some of the parallel ports in the DE2 Basic Computer have registers at addresses Base + 8 and Base + C, as indicated in Figure 2. These registers are discussed in section 3.

2.3.1 Red and Green LED Parallel Ports

The red lights LEDR_{17-0} and green lights LEDG_{8-0} on the DE2 board are each driven by an output parallel port, as illustrated in Figure 3. The port connected to LEDR contains an 18-bit write-only Data register, which has the address 0x10000000. The port for LEDG has a nine-bit Data register that is mapped to address 0x10000010. These two registers can be written using word accesses, and the upper bits not used in the registers are ignored.
2.3.2 7-Segment Displays Parallel Port

There are two parallel ports connected to the 7-segment displays on the DE2 board, each of which comprises a 32-bit write-only Data register. As indicated in Figure 4, the register at address 0x10000020 drives digits \( \text{HEX3} \) to \( \text{HEX0} \), and the register at address 0x10000030 drives digits \( \text{HEX7} \) to \( \text{HEX4} \). Data can be written into these two registers by using word operations. This data directly controls the segments of each display, according to the bit locations given in Figure 4. The locations of segments 6 to 0 in each seven-segment display on the DE2 board is illustrated on the right side of the figure.

Figure 4. Bit locations for the 7-segment displays parallel ports.
2.3.3 Slider Switch Parallel Port

The SW$_{17-0}$ slider switches on the DE2 board are connected to an input parallel port. As illustrated in Figure 5, this port comprises an 18-bit read-only Data register, which is mapped to address 0x10000040.

<table>
<thead>
<tr>
<th>Address</th>
<th>31</th>
<th>30</th>
<th>. . .</th>
<th>17</th>
<th>. . .</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10000040</td>
<td>Unused</td>
<td>18</td>
<td>. . .</td>
<td>0</td>
<td>. . .</td>
<td>Data register</td>
</tr>
</tbody>
</table>

Figure 5. Data register in the slider switch parallel port.

2.3.4 Pushbutton Parallel Port

The parallel port connected to the KEY$_{3-1}$ pushbutton switches on the DE2 board comprises three 3-bit registers, as shown in Figure 6. These registers have base addresses 0x10000050 to 0x1000005C and can be accessed using word operations. The read-only Data register provides the values of the switches KEY$_3$, KEY$_2$ and KEY$_1$. Bit 0 of the Data register is not used, because, as discussed in section 2.1, the corresponding switch KEY$_0$ is reserved for use as a reset mechanism for the DE2 Basic Computer. The other two registers shown in Figure 6, at addresses 0x10000058 and 0x1000005C, are discussed in section 3.

<table>
<thead>
<tr>
<th>Address</th>
<th>31</th>
<th>30</th>
<th>. . .</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10000050</td>
<td>Unused</td>
<td>. . .</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>1</td>
<td>0</td>
<td>Data register</td>
</tr>
<tr>
<td>Unused</td>
<td>Unused</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0x10000058</td>
<td>Unused</td>
<td>Mask bits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Interruptmask register</td>
<td></td>
</tr>
<tr>
<td>0x1000005C</td>
<td>Unused</td>
<td>Edge bits</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Edgecapture register</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6. Registers used in the pushbutton parallel port.

2.3.5 Expansion Parallel Ports

The DE2 Basic Computer includes two bidirectional parallel ports that are connected to the JP1 and JP2 expansion headers on the DE2 board. Each of these parallel ports includes the four 32-bit registers that were described previously for Figure 2. The base addresses of the ports connected to JP1 and JP2 are 0x10000060 and 0x10000070, respectively. Figure 7 gives a diagram of the JP1 and JP2 expansion connectors on the DE2 board, and shows how
the respective parallel port Data register bits, \(D_{31-0}\), are assigned to the pins on the connector. The figure shows that bit \(D_0\) of the parallel port for JP1 is assigned to the pin at the top right corner of the connector, bit \(D_1\) is assigned below this, and so on. Note that some of the pins on JP1 and JP2 are not usable as input/output connections, and are therefore not used by the parallel ports. Also, only 32 of the 36 data pins that appear on each connector can be used.

![Figure 7. Assignment of parallel port bits to pins on JP1 and JP2.](image)

### 2.3.6 Using the Parallel Ports with Assembly Language Code and C Code

The DE2 Basic Computer provides a convenient platform for experimenting with Nios II assembly language code, or C code. A simple example of such code is provided in Figures 8 and 9. Both programs perform the same operations, and illustrate the use of parallel ports by using either assembly language or C code.

The code in the figures displays the values of the SW switches on the red LEDs, and the pushbutton keys on the green LEDs. It also displays a rotating pattern on 7-segment displays \(HEX3 \ldots HEX0\) and \(HEX7 \ldots HEX4\). This pattern is shifted to the right by using a Nios II \(rotate\) instruction, and a delay loop is used to make the shifting slow enough to observe. The pattern on the HEX displays can be changed to the values of the SW switches by pressing any of pushbuttons \(KEY_3, KEY_2,\) or \(KEY_1\) (recall from section 2.1 that \(KEY_0\) causes a reset of the DE2 Basic Computer). When a pushbutton key is pressed, the program waits in a loop until the key is released.

The source code files shown in Figures 8 and 9 are distributed as part of the Altera Monitor Program. The files can be found under the heading \(sample\ programs\), and are identified by the name \(Getting\ Started\).
This program demonstrates the use of parallel ports in the DE2 Basic Computer:
1. displays the SW switch values on the red LEDR
2. displays the KEY[3..1] pushbutton values on the green LEDG
3. displays a rotating pattern on the HEX displays
4. if KEY[3..1] is pressed, uses the SW switches as the pattern

Figure 8. An example of Nios II assembly language code that uses parallel ports.
/* This program demonstrates the use of parallel ports in the DE2 Basic Computer:
* 1. displays the SW switch values on the red LEDR
* 2. displays the KEY[3..1] pushbutton values on the green LEDG
* 3. displays a rotating pattern on the HEX displays
* 4. if KEY[3..1] is pressed, uses the SW switches as the pattern
********************************************************************************/

int main(void)
{
    /* Declare volatile pointers to I/O registers (volatile means that IO load and store
     instructions (e.g., ldwio, stwio) will be used to access these pointer locations) */
    volatile int * red_LED_ptr = (int *) 0x10000000; // red LED address
    volatile int * green_LED_ptr = (int *) 0x10000010; // green LED address
    volatile int * HEX3_HEX0_ptr = (int *) 0x10000020; // HEX3_HEX0 address
    volatile int * HEX7_HEX4_ptr = (int *) 0x10000030; // HEX7_HEX4 address
    volatile int * SW_switch_ptr = (int *) 0x10000040; // SW slider switch address
    volatile int * KEY_ptr = (int *) 0x10000050; // pushbutton KEY address

    int HEX_bits = 0x0000000F; // pattern for HEX displays
    int SW_value, KEY_value, delay_count;

    while(1)
    {
        SW_value = *(SW_switch_ptr); // read the SW slider switch values
        *(red_LED_ptr) = SW_value; // light up the red LEDs
        KEY_value = *(KEY_ptr); // read the pushbutton KEY values
        *(green_LED_ptr) = KEY_value; // light up the green LEDs
        if (KEY_value != 0) // check if any KEY was pressed
        {
            HEX_bits = SW_value; // set pattern using SW values
            while (*KEY_ptr) // wait for pushbutton KEY release
            {
            }
            *(HEX3_HEX0_ptr) = HEX_bits; // display pattern on HEX3 ... HEX0
            *(HEX7_HEX4_ptr) = HEX_bits; // display pattern on HEX7 ... HEX4
            if (HEX_bits & 0x80000000) /* rotate the pattern shown on the HEX displays */
                HEX_bits = (HEX_bits << 1) | 1;
            else
                HEX_bits = HEX_bits << 1;
        }
        for (delay_count = 100000; delay_count != 0; --delay_count); // delay loop
    } // end while

Figure 9. An example of C code that uses parallel ports.
2.4 JTAG Port

The JTAG port implements a communication link between the DE2 board and its host computer. This link is automatically used by the Quartus II software to transfer FPGA programming files into the DE2 board, and by the Altera Monitor Program. The JTAG port also includes a UART, which can be used to transfer character data between the host computer and programs that are executing on the Nios II processor. If the Altera Monitor Program is used on the host computer, then this character data is sent and received through its Terminal Window. The Nios II programming interface of the JTAG UART consists of two 32-bit registers, as shown in Figure 10. The register mapped to address 0x10001000 is called the Data register and the register mapped to address 0x10001004 is called the Control register.

<table>
<thead>
<tr>
<th>Address</th>
<th>31 . . . 16</th>
<th>15</th>
<th>14 . . . 11</th>
<th>10</th>
<th>9</th>
<th>8</th>
<th>7 . . . 1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10001000</td>
<td>RAVAIL</td>
<td>RVALID</td>
<td>Unused</td>
<td>DATA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0x10001004</td>
<td>WSPACE</td>
<td>Unused</td>
<td>AC</td>
<td>WI</td>
<td>RI</td>
<td>WE</td>
<td>RE</td>
<td></td>
</tr>
</tbody>
</table>

Data register

Control register

Figure 10. JTAG UART registers.

When character data from the host computer is received by the JTAG UART it is stored in a 64-character FIFO. The number of characters currently stored in this FIFO is indicated in the field RAVAIL, which are bits 31−16 of the Data register. If the receive FIFO overflows, then additional data is lost. When data is present in the receive FIFO, then the value of RAVAIL will be greater than 0 and the value of bit 15, RVALID, will be 1. Reading the character at the head of the FIFO, which is provided in bits 7−0, decrements the value of RAVAIL by one and returns this decremented value as part of the read operation. If no data is present in the receive FIFO, then RVALID will be set to 0 and the data in bits 7−0 is undefined.

The JTAG UART also includes a 64-character FIFO that stores data waiting to be transmitted to the host computer. Character data is loaded into this FIFO by performing a write to bits 7−0 of the Data register in Figure 10. Note that writing into this register has no effect on received data. The amount of space, WSPACE, currently available in the transmit FIFO is provided in bits 31−16 of the Control register. If the transmit FIFO is full, then any characters written to the Data register will be lost.

Bit 10 in the Control register, called AC, has the value 1 if the JTAG UART has been accessed by the host computer. This bit can be used to check if a working connection to the host computer has been established. The AC bit can be cleared to 0 by writing a 1 into it.

The Control register bits RE, WE, RI, and WI are described in section 3.

2.4.1 Using the JTAG UART with Assembly Language Code and C Code

Figures 11 and 12 give simple examples of assembly language and C code, respectively, that use the JTAG UART. Both versions of the code perform the same function, which is to first send an ASCII string to the JTAG UART, and then enter an endless loop. In the loop, the code reads character data that has been received by the JTAG UART, and echoes this data back to the UART for transmission. If the program is executed by using the Altera Monitor
Program, then any keyboard character that is typed into the Terminal Window of the Monitor Program will be echoed back, causing the character to appear in the Terminal Window.

The source code files shown in Figures 11 and 12 are made available as part of the Altera Monitor Program. The files can be found under the heading sample programs, and are identified by the name JTAG UART.

```assembly
/* This program demonstrates use of the JTAG UART port in the DE2 Basic Computer */
/* It performs the following: */
/* 1. sends a text string to the JTAG UART */
/* 2. reads character data from the JTAG UART */
/* 3. echos the character data back to the JTAG UART */
.text
.global _start
_start:
/* set up stack pointer */
movia sp, 0x007FFFFC /* stack starts from highest memory address in SDRAM */
movia r6, 0x10001000 /* JTAG UART base address */
/* print a text string */
movia r8, TEXT_STRING
LOOP:

GET_JTAG:

/* read and echo characters */
GET_JTAG:
```

Figure 11. An example of assembly language code that uses the JTAG UART (Part a).
/* Subroutine to send a character to the JTAG UART
 * r5 = character to send
 * r6 = JTAG UART base address
 */

.global PUT_JTAG

PUT_JTAG:
    /* save any modified registers */
    subi sp, sp, 4  /* reserve space on the stack */
    stw r4, 0(sp)  /* save register */
    ldwio r4, 4(r6)  /* read the JTAG UART Control register */
    andhi r4, r4, 0xffff  /* check for write space */
    beq r4, r0, END_PUT  /* if no space, ignore the character */
    stwio r5, 0(r6)  /* send the character */

END_PUT:
    /* restore registers */
    ldw r4, 0(sp)
    addi sp, sp, 4
    ret

.data
    TEXT_STRING:  /* data follows */
    .asciz "\nJTAG UART example code\n> "

.end

Figure 11. An example of assembly language code that uses the JTAG UART (Part b).
**void** put_jtag(volatile int *, char); // function prototype

/*****************************/
* This program demonstrates use of the JTAG UART port in the DE2 Basic Computer  
*
* It performs the following:  
* 1. sends a text string to the JTAG UART  
* 2. reads character data from the JTAG UART  
* 3. echos the character data back to the JTAG UART
/*****************************/

int main(void)
{
    /* Declare volatile pointers to I/O registers (volatile means that IO load and store  
       instructions (e.g., ldwio, stwio) will be used to access these pointer locations) */
    volatile int * JTAG_UART_ptr = (int *) 0x10001000; // JTAG UART address
    int data, i;
    char text_string[] = "\nJTAG UART example code\n> \0";

    for (i = 0; text_string[i] != 0; ++i) // print a text string
        put_jtag (JTAG_UART_ptr, text_string[i]);

    /* read and echo characters */
    while(1)
    {
        data = *(JTAG_UART_ptr); // read the JTAG_UART Data register
        if (data & 0x00008000) // check RVALID to see if there is new data
        {
            data = data & 0x000000FF; // the data is in the least significant byte
            /* echo the character */
            put_jtag (JTAG_UART_ptr, (char) data & 0xFF );
        }
    }
}

/*****************************/
* Subroutine to send a character to the JTAG UART
/*****************************/

void put_jtag( volatile int * JTAG_UART_ptr, char c )
{
    int control;
    control = *(JTAG_UART_ptr + 1); // read the JTAG_UART Control register
    if (control & 0xFFFF0000) // if space, then echo character, else ignore
        *(JTAG_UART_ptr) = c;
}

Figure 12. An example of C code that uses the JTAG UART.
2.5 Serial Port

The serial port in the DE2 Basic Computer implements a UART that is connected to an RS232 chip on the DE2 board. This UART is configured for 8-bit data, one stop bit, odd parity, and operates at a baud rate of 115,200. The serial port’s programming interface consists of two 32-bit registers, as illustrated in Figure 13. The register at address 0x10001010 is referred to as the Data register, and the register at address 0x10001014 is called the Control register.

![Figure 13. Serial port UART registers.](image)

When character data is received from the RS 232 chip it is stored in a 256-character FIFO in the UART. As illustrated in Figure 13, the number of characters RAVAIL currently stored in this FIFO is provided in bits 31−16 of the Data register. If the receive FIFO overflows, then additional data is lost. When the data that is present in the receive FIFO is available for reading, then the value of bit 15, RVALID, will be 1. Reading the character at the head of the FIFO, which is provided in bits 7−0, decrements the value of RAVAIL by one and returns this decremented value as part of the read operation. If no data is available to be read from the receive FIFO, then RVALID will be set to 0 and the data in bits 7−0 is undefined.

The UART also includes a 256-character FIFO that stores data waiting to be sent to the RS 232 chip. Character data is loaded into this register by performing a write to bits 7−0 of the Data register. Writing into this register has no effect on received data. The amount of space WSPACE currently available in the transmit FIFO is provided in bits 31−16 of the Control register, as indicated in Figure 13. If the transmit FIFO is full, then any additional characters written to the Data register will be lost.

The Control register bits RE, WE, RI, and WI are described in section 3.

2.6 Interval Timer

The DE2 Basic Computer includes a timer that can be used to measure various time intervals. The interval timer is loaded with a preset value, and then counts down to zero using the 50-MHz clock signal provided on the DE2 board. The programming interface for the timer includes six 16-bit registers, as illustrated in Figure 14. The 16-bit register at address 0x10002000 provides status information about the timer, and the register at address 0x10002004 allows control settings to be made. The bit fields in these registers are described below:

- **TO** provides a timeout signal which is set to 1 by the timer when it has reached a count value of zero. The TO bit can be reset by writing a 0 into it.
- **RUN** is set to 1 by the timer whenever it is currently counting. Write operations to the status halfword do not affect the value of the RUN bit.
• *ITO* is used for generating Nios II interrupts, which are discussed in section 3.

<table>
<thead>
<tr>
<th>Address</th>
<th>31</th>
<th>17</th>
<th>16</th>
<th>15</th>
<th>...</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10002000</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Status register</td>
</tr>
<tr>
<td>0x10002004</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>RUN</td>
<td></td>
<td></td>
<td>Control register</td>
</tr>
<tr>
<td>0x10002008</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>STOP</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0x1000200C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>START</td>
<td>CONT</td>
<td>ITO</td>
</tr>
<tr>
<td>0x10002010</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0x10002014</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 14. Interval timer registers.

• *CONT* affects the continuous operation of the timer. When the timer reaches a count value of zero it automatically reloads the specified starting count value. If *CONT* is set to 1, then the timer will continue counting down automatically. But if *CONT* = 0, then the timer will stop after it has reached a count value of 0.

• *(START/STOP)* can be used to commence/suspend the operation of the timer by writing a 1 into the respective bit.

The two 16-bit registers at addresses 0x10002008 and 0x1000200C allow the period of the timer to be changed by setting the starting count value. The default setting provided in the DE2 Basic Computer gives a timer period of 125 msec. To achieve this period, the starting value of the count is 50 MHz × 125 msec = 6.25 × 10^6. It is possible to capture a snapshot of the counter value at any time by performing a write to address 0x10002010. This write operation causes the current 32-bit counter value to be stored into the two 16-bit timer registers at addresses 0x10002010 and 0x10002014. These registers can then be read to obtain the count value.

### 2.7 System ID

The system ID module provides a unique value that identifies the DE2 Basic Computer system. The host computer connected to the DE2 board can query the system ID module by performing a read operation through the JTAG port. The host computer can then check the value of the returned identifier to confirm that the DE2 Basic Computer has been properly downloaded onto the DE2 board. This process allows debugging tools on the host computer, such as the Altera Monitor Program, to verify that the DE2 board contains the required computer system before attempting to execute code that has been compiled for this system.
3 Exceptions and Interrupts

The reset address of the Nios II processor in the DE2 Basic Computer is set to 0x00000000. The address used for all other general exceptions, such as divide by zero, and hardware IRQ interrupts is 0x00000020. Since the Nios II processor uses the same address for general exceptions and hardware IRQ interrupts, the Exception Handler software must determine the source of the exception by examining the appropriate processor status register. Table 1 gives the assignment of IRQ numbers to each of the I/O peripherals in the DE2 Basic Computer.

<table>
<thead>
<tr>
<th>I/O Peripheral</th>
<th>IRQ #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval timer</td>
<td>0</td>
</tr>
<tr>
<td>Pushbutton switch parallel port</td>
<td>1</td>
</tr>
<tr>
<td>JTAG port</td>
<td>8</td>
</tr>
<tr>
<td>Serial port</td>
<td>10</td>
</tr>
<tr>
<td>JP1 Expansion parallel port</td>
<td>11</td>
</tr>
<tr>
<td>JP2 Expansion parallel port</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1. Hardware IRQ interrupt assignment for the DE2 Basic Computer.

3.1 Interrupts from Parallel Ports

Parallel port registers in the DE2 Basic Computer were illustrated in Figure 2, which is reproduced as Figure 15. As the figure shows, parallel ports that support interrupts include two related registers at the addresses Base + 8 and Base + C. The Interruptmask register, which has the address Base + 8, specifies whether or not an interrupt signal should be sent to the Nios II processor when the data present at an input port changes value. Setting a bit location in this register to 1 allows interrupts to be generated, while setting the bit to 0 prevents interrupts. Finally, the parallel port may contain an Edgecapture register at address Base + C. Each bit in this register has the value 1 if the corresponding bit location in the parallel port has changed its value from 0 to 1 since it was last read. Performing a write operation to the Edgecapture register sets all bits in the register to 0, and clears any associated Nios II interrupts.
3.1.1 Interrupts from the Pushbutton Switches

Figure 6, reproduced as Figure 16, shows the registers associated with the pushbutton parallel port. The Interrupt-mask register allows processor interrupts to be generated when a key is pressed. Each bit in the Edgecapture register is set to 1 by the parallel port when the corresponding key is pressed. The Nios II processor can read this register to determine which key has been pressed, in addition to receiving an interrupt request if the corresponding bit in the interrupt mask register is set to 1. Writing any value to the Edgecapture register deasserts the Nios II interrupt request and sets all bits of the Edgecapture register to zero.

<table>
<thead>
<tr>
<th>Address</th>
<th>31 30 … 4 3 2 1 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10000050</td>
<td>Unused  KEY₃₋₁</td>
</tr>
<tr>
<td>Unused</td>
<td>Unused</td>
</tr>
<tr>
<td>0x10000058</td>
<td>Unused  Mask bits</td>
</tr>
<tr>
<td>0x1000005C</td>
<td>Unused  Edge bits</td>
</tr>
</tbody>
</table>

Figure 16. Registers used for interrupts from the pushbutton parallel port.

3.2 Interrupts from the JTAG UART

Figure 10, reproduced as Figure 17, shows the data and Control registers of the JTAG UART. As we said in section 2.4, RAVAIL in the Data register gives the number of characters that are stored in the receive FIFO, and WSPACE gives the amount of unused space that is available in the transmit FIFO. The RE and WE bits in Figure 17 are used to enable processor interrupts associated with the receive and transmit FIFOs. When enabled, interrupts are generated when RAVAIL for the receive FIFO, or WSPACE for the transmit FIFO, exceeds 7. Pending interrupts are indicated in the Control register’s RI and WI bits, and can be cleared by writing or reading data to/from the JTAG UART.

<table>
<thead>
<tr>
<th>Address</th>
<th>31 … 16 15 14 … 11 10 9 8 … 1 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x10001000</td>
<td>RAVAIL  RVALID  Unused  DATA</td>
</tr>
<tr>
<td>0x10001004</td>
<td>WSPACE  Unused  AC  WI  RI  WE  RE</td>
</tr>
</tbody>
</table>

Figure 17. Interrupt bits in the JTAG UART registers.

3.3 Interrupts from the Serial Port UART

We introduced the Data and Control registers associated with the serial port UART in Figure 13, in section 2.5. The RE and WE bits in the Control register in Figure 13 are used to enable processor interrupts associated with the receive and transmit FIFOs. When enabled, interrupts are generated when RAVAIL for the receive FIFO, or WSPACE for the transmit FIFO, exceeds 31. Pending interrupts are indicated in the Control register’s RI and WI bits, and can be cleared by writing or reading data to/from the UART.
3.4 Interrupts from the Interval Timer

Figure 14, in section 2.6, shows six registers that are associated with the interval timer. As we said in section 2.6, the bit $b_0$ (TO) is set to 1 when the timer reaches a count value of 0. It is possible to generate an interrupt when this occurs, by using the bit $b_{16}$ (ITO). Setting the bit ITO to 1 allows an interrupt request to be generated whenever TO becomes 1. After an interrupt occurs, it can be cleared by writing any value to the register that contains the bit TO.

3.5 Using Interrupts with Assembly Language Code

An example of assembly language code for the DE2 Basic Computer that uses interrupts is shown in Figure 18. When this code is executed on the DE2 board it displays a rotating pattern on the HEX 7-segment displays. The pattern rotates to the right if pushbutton KEY1 is pressed, and to the left if KEY2 is pressed. Pressing KEY3 causes the pattern to be set using the SW switch values. Two types of interrupts are used in the code. The HEX displays are controlled by an interrupt service routine for the interval timer, and another interrupt service routine is used to handle the pushbutton keys. The speed at which the HEX displays are rotated is set in the main program, by using a counter value in the interval timer that causes an interrupt to occur every 33 msec.

```assembly
.equ KEY1, 0
.equ KEY2, 1

/* This program demonstrates use of interrupts in the DE2 Basic Computer. It first starts the
* interval timer with 33 msec timeouts, and then enables interrupts from the interval timer
* and pushbutton KEYs
*
* The interrupt service routine for the interval timer displays a pattern on the HEX displays, and
* shifts this pattern either left or right. The shifting direction is set in the pushbutton
* interrupt service routine, as follows:
* KEY[1]: shifts the displayed pattern to the right
* KEY[2]: shifts the displayed pattern to the left
* KEY[3]: changes the pattern using the settings on the SW switches

.text
.global _start
/_* executable code follows */

_start:
/* set up stack pointer */
movia sp, 0x007FFFFC /* stack starts from highest memory address in SDRAM */

movia r16, 0x10002000 /* internal timer base address */
/* set the interval timer period for scrolling the HEX displays */
movia r12, 0x190000 /* 1/(50 MHz) × (0x190000) = 33 msec */
sthio r12, 8(r16) /* store the low halfword of counter start value */
srii r12, r12, 16
sthio r12, 0xC(r16) /* high halfword of counter start value */
```

Figure 18. An example of assembly language code that uses interrupts (Part a).
/* start interval timer, enable its interrupts */

movi r15, 0b0111 /* START = 1, CONT = 1, ITO = 1 */
sthio r15, 4(r16)

/* write to the pushbutton port interrupt mask register */

movia r15, 0x10000050 /* pushbutton key base address */
movi r7, 0b01110 /* set 3 interrupt mask bits (bit 0 is Nios II reset) */
stwio r7, 8(r15) /* interrupt mask register is (base + 8) */

/* enable Nios II processor interrupts */

movi r7, 0b011 /* set interrupt mask bits for levels 0 (interval) */
wrctl ienable, r7 /* timer) and level 1 (pushbuttons) */
movi r7, 1
wrctl status, r7 /* turn on Nios II interrupt processing */

IDLE:

br IDLE /* main program simply idles */

.data

/* The two global variables used by the interrupt service routines for the interval timer and the pushbutton keys are declared below */

global PATTERN

PATTERN:

.word 0x0000000F /* pattern to show on the HEX displays */

.global KEY_PRESSED

KEY_PRESSED:

.word KEY2 /* stores code representing pushbutton key pressed */

.end

Figure 18. An example of assembly language code that uses interrupts (Part b).

The reset and exception handlers for the main program in Figure 18 are given in Figure 19. The reset handler simply jumps to the _start symbol in the main program. The exception handler first checks if the exception that has occurred is an external interrupt or an internal one. In the case of an internal exception, such as an illegal instruction opcode or a trap instruction, the handler simply exits, because it does not handle these cases. For external exceptions, it calls either the interval timer interrupt service routine, for a level 0 interrupt, or the pushbutton key interrupt service routine for level 1. These routines are shown in Figures 20 and 21, respectively.
/********************************************************************************
* RESET SECTION
* The Monitor Program automatically places the ".reset" section at the reset location
* specified in the CPU settings in SOPC Builder.
* Note: "ax" is REQUIRED to designate the section as allocatable and executable.
*/
.section .reset, "ax"
movia r2, _start
jmp r2 /* branch to main program */

/********************************************************************************
* EXCEPTIONS SECTION
* The Monitor Program automatically places the ".exceptions" section at the
* exception location specified in the CPU settings in SOPC Builder.
* Note: "ax" is REQUIRED to designate the section as allocatable and executable.
*/
.section .exceptions, "ax"
global EXCEPTION_HANDLER
EXCEPTION_HANDLER:
subi sp, sp, 16 /* make room on the stack */
stw et, 0(sp)

rdctl et, ctl4
beq et, r0, SKIP_EA_DEC /* interrupt is not external */

subi ea, ea, 4 /* must decrement ea by one instruction */
/* for external interrupts, so that the */
/* interrupted instruction will be run after eret */

SKIP_EA_DEC:
stw ea, 4(sp) /* save all used registers on the Stack */
stw ra, 8(sp) /* needed if call inst is used */
stw r22, 12(sp)

rdctl et, ctl4
bne et, r0, CHECK_LEVEL_0 /* exception is an external interrupt */

NOT_EI: /* exception must be unimplemented instruction or TRAP */
br END_ISR /* instruction. This code does not handle those cases */

Figure 19. Reset and exception handler assembly language code (Part a).
CHECK_LEVEL_0: /* interval timer is interrupt level 0 */
   andi  r22, et, 0b1
   beq   r22, r0, CHECK_LEVEL_1
   call  INTERVAL_TIMER_ISR
   br    END_ISR

CHECK_LEVEL_1: /* pushbutton port is interrupt level 1 */
   andi  r22, et, 0b10
   beq   r22, r0, END_ISR /* other interrupt levels are not handled in this code */
   call  PUSHBUTTON_ISR

END_ISR:
   ldw   et, 0(sp) /* restore all used register to previous values */
   ldw   ea, 4(sp)
   ldw   ra, 8(sp) /* needed if call inst is used */
   addi  sp, sp, 16
   eret  
.end

Figure 19. Reset and exception handler assembly language code (Part b).

.include    "key_codes.s" /* includes EQU for KEY1, KEY2 */
.extern    PATTERN /* externally defined variables */
.extern    KEY_PRESSED

*******************************************************************************
 * Interval timer interrupt service routine
 *
 * Shifts a PATTERN being displayed on the HEX displays. The shift direction
 * is determined by the external variable KEY_PRESSED.
 *
*******************************************************************************

.global  INTERVAL_TIMER_ISR
INTERVAL_TIMER_ISR:
   subi   sp, sp, 40 /* reserve space on the stack */
   stw    ra, 0(sp)
   stw    r4, 4(sp)
   stw    r5, 8(sp)
   stw    r6, 12(sp)

Figure 20. Interrupt service routine for the interval timer (Part a).
stw      r8, 16(sp)
stw      r10, 20(sp)
stw      r20, 24(sp)
stw      r21, 28(sp)
stw      r22, 32(sp)
stw      r23, 36(sp)

movia    r10, 0x10002000 /* interval timer base address */
sthio    r0, 0(r10) /* clear the interrupt */

movia    r20, 0x10000020 /* HEX3_HEX0 base address */
movia    r21, 0x10000030 /* HEX7_HEX4 base address */
addi     r5, r0, 1 /* set r5 to the constant value 1 */
movia    r22, PATTERN /* set up a pointer to the pattern for HEX displays */
movia    r23, KEY_PRESSED /* set up a pointer to the key pressed */

ldw      r6, 0(r22) /* load pattern for HEX displays */
stwio    r6, 0(r20) /* store to HEX3 ... HEX0 */
stwio    r6, 0(r21) /* store to HEX7 ... HEX4 */

ldw      r4, 0(r23) /* check which key has been pressed */
movi     r8, KEY1 /* code to check for KEY1 */
beq      r4, r8, LEFT /* for KEY1 pressed, shift right */
rol      r6, r6, r5 /* else (for KEY2) pressed, shift left */
br        END_INTERVAL_TIMER_ISR

LEFT:
ror      r6, r6, r5 /* rotate the displayed pattern right */

END_INTERVAL_TIMER_ISR:
    stw      r6, 0(r22) /* store HEX display pattern */
    ldw      ra, 0(sp) /* Restore all used register to previous */
    ldw      r4, 4(sp)
    ldw      r5, 8(sp)
    ldw      r6, 12(sp)
    ldw      r8, 16(sp)
    ldw      r10, 20(sp)
    ldw      r20, 24(sp)
    ldw      r21, 28(sp)
    ldw      r22, 32(sp)
    ldw      r23, 36(sp)
    addi     sp, sp, 40 /* release the reserved space on the stack */
    ret
.end

Figure 20. Interrupt service routine for the interval timer (Part b).
.include "key_codes.s" /* includes EQU for KEY1, KEY2 */
.extern PATTERN /* externally defined variables */
.extern KEY_PRESSED

Pushbutton - Interrupt Service Routine

This routine checks which KEY has been pressed. If it is KEY1 or KEY2, it writes this value to the global variable KEY_PRESSED. If it is KEY3 then it loads the SW switch values and stores in the variable PATTERN.

Figure 21. Interrupt service routine for the pushbutton keys (Part a).
END_PUSHBUTTON_ISR:
<table>
<thead>
<tr>
<th>Instruction</th>
<th>Register, Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>ldw</td>
<td>ra, 0(sp)</td>
</tr>
<tr>
<td>ldw</td>
<td>r10, 4(sp)</td>
</tr>
<tr>
<td>ldw</td>
<td>r11, 8(sp)</td>
</tr>
<tr>
<td>ldw</td>
<td>r12, 12(sp)</td>
</tr>
<tr>
<td>ldw</td>
<td>r13, 16(sp)</td>
</tr>
<tr>
<td>addi</td>
<td>sp, sp, 20</td>
</tr>
<tr>
<td>ret</td>
<td></td>
</tr>
<tr>
<td>.end</td>
<td></td>
</tr>
</tbody>
</table>

Figure 21. Interrupt service routine for the pushbutton keys (Part b).

3.6 Using Interrupts with C Language Code

An example of C language code for the DE2 Basic Computer that uses interrupts is shown in Figure 22. This code performs exactly the same operations as the code described in Figure 18.

To enable interrupts the code in Figure 22 uses macros that provide access to the Nios II status and control registers. A collection of such macros, which can be used in any C program, are provided in Figure 23.

The reset and exception handlers for the main program in Figure 22 are given in Figure 24. The function called the_reset provides a simple reset mechanism by performing a branch to the main program. The function named the_exception represents a general exception handler that can be used with any C program. It includes assembly language code to check if the exception is caused by an external interrupt, and, if so, calls a C language routine named interrupt_handler. This routine can then perform whatever action is needed for the specific application. In Figure 24, the interrupt_handler code first determines which exception has occurred, by using a macro from Figure 23 that reads the content of the Nios II interrupt pending register. The interrupt service routine that is invoked for the interval timer is shown in 25, and the interrupt service routine for the pushbutton switches appears in Figure 26.

The source code files shown in Figure 18 to Figure 26 are distributed as part of the Altera Monitor Program. The files can be found under the heading sample programs, and are identified by the name Interrupt Example.
```c
#include "nios2_ctrl_reg_macros.h"
#include "key_codes.h"  // defines values for KEY1, KEY2

/* key_pressed and pattern are written by interrupt service routines; we have to declare
* these as volatile to avoid the compiler caching their values in registers */
volatile int key_pressed = KEY2;  // shows which key was last pressed
volatile int pattern = 0x0000000F;  // pattern for HEX displays

/********************************************************************************
* This program demonstrates use of interrupts in the DE2 Basic Computer. It first starts the
* interval timer with 33 msec timeouts, and then enables interrupts from the interval timer
* and pushbutton KEYS
* 
* The interrupt service routine for the interval timer displays a pattern on the HEX displays, and
* shifts this pattern either left or right. The shifting direction is set in the pushbutton
* interrupt service routine, as follows:
* KEY[1]: shifts the displayed pattern to the right
* KEY[2]: shifts the displayed pattern to the left
* KEY[3]: changes the pattern using the settings on the SW switches
********************************************************************************/

int main(void)
{
/* Declare volatile pointers to I/O registers (volatile means that IO load and store instructions
* will be used to access these pointer locations instead of regular memory loads and stores) */
volatile int * interval_timer_ptr = (int *) 0x10002000;  // interval timer base address
volatile int * KEY_ptr = (int *) 0x10000050;  // pushbutton KEY address

/* set the interval timer period for scrolling the HEX displays */
int counter = 0x190000;  // 1/(50 MHz) x (0x190000) = 33 msec
*(interval_timer_ptr + 0x2) = (counter & 0xFFFF);
*(interval_timer_ptr + 0x3) = (counter >> 16) & 0xFFFF;

/* start interval timer, enable its interrupts */
*(interval_timer_ptr + 1) = 0x7;  // STOP = 0, START = 1, CONT = 1, ITO = 1

*(KEY_ptr + 2) = 0xE;  /* write to the pushbutton interrupt mask register, and
* set 3 mask bits to 1 (bit 0 is Nios II reset) */

NIOS2_WRITE_IENABLE( 0x3 );  /* set interrupt mask bits for levels 0 (interval timer)
* and level 1 (pushbuttons) */

NIOS2_WRITE_STATUS( 1 );  // enable Nios II interrupts

while(1);  // main program simply idles
}

Figure 22. An example of C code that uses interrupts.
```
Figure 23. Macros for accessing Nios II status and control registers.
#include "nios2_ctrl_reg_macros.h"

/* function prototypes */
void main(void);
void interrupt_handler(void);
void interval_timer_isr(void);
void pushbutton_ISR(void);

/* global variables */
extern int key_pressed;

/* The assembly language code below handles Nios II reset processing */
void the_reset (void) __attribute__((section (".reset")));

void the_reset (void)
/*******************************************************************************
* Reset code; by using the section attribute with the name ".reset" we allow the linker program
* to locate this code at the proper reset vector address. This code just calls the main program
******************************************************************************/
{
    asm (".set noat"); // magic, for the C compiler
    asm (".set nobreak"); // magic, for the C compiler
    asm ("movia r2, main"); // call the C language main program
    asm ("jmp r2");
}

/* The assembly language code below handles Nios II exception processing. This code should not be
* modified; instead, the C language code in the function interrupt_handler() can be modified as
* needed for a given application. */
void the_exception (void) __attribute__((section (".exceptions")));
void the_exception (void)
/*******************************************************************************
* Exceptions code; by giving the code a section attribute with the name ".exceptions" we allow
* the linker to locate this code at the proper exceptions vector address. This code calls the
* interrupt handler and later returns from the exception.
******************************************************************************/
{
    asm (".set noat"); // magic, for the C compiler
    asm (".set nobreak"); // magic, for the C compiler
    asm ("subi sp, sp, 128");
    asm ("stw et, 96(sp)";
    asm ("rdctl et, ctl4");
    asm ("beq et, r0, SKIP_EA_DEC"); // interrupt is not external
    asm ("subi ea, ea, 4"); /* must decrement ea by one instruction for external
* interrupts, so that the instruction will be run */

Figure 24. Reset and exception handler C code (Part a).
asm ( "SKIP_EA_DEC:" );
asm ( "stw r1, 4(sp)" ); // save all registers
asm ( "stw r2, 8(sp)" );
asm ( "stw r3, 12(sp)" );
asm ( "stw r4, 16(sp)" );
asm ( "stw r5, 20(sp)" );
asm ( "stw r6, 24(sp)" );
asm ( "stw r7, 28(sp)" );
asm ( "stw r8, 32(sp)" );
asm ( "stw r9, 36(sp)" );
asm ( "stw r10, 40(sp)" );
asm ( "stw r11, 44(sp)" );
asm ( "stw r12, 48(sp)" );
asm ( "stw r13, 52(sp)" );
asm ( "stw r14, 56(sp)" );
asm ( "stw r15, 60(sp)" );
asm ( "stw r16, 64(sp)" );
asm ( "stw r17, 68(sp)" );
asm ( "stw r18, 72(sp)" );
asm ( "stw r19, 76(sp)" );
asm ( "stw r20, 80(sp)" );
asm ( "stw r21, 84(sp)" );
asm ( "stw r22, 88(sp)" );
asm ( "stw r23, 92(sp)" );
asm ( "stw r25, 100(sp)" ); // r25 = bt (skip r24 = et, because it was saved above)
asm ( "stw r26, 104(sp)" ); // r26 = gp
// skip r27 because it is sp, and there is no point in saving this
asm ( "stw r28, 112(sp)" ); // r28 = fp
asm ( "stw r29, 116(sp)" ); // r29 = ea
asm ( "stw r30, 120(sp)" ); // r30 = ea
asm ( "stw r31, 124(sp)" ); // r31 = ra
asm ( "addi fp, sp, 128" );
asm ( "call interrupt_handler" ); // call the C language interrupt handler
asm ( "ldw r1, 4(sp)" ); // restore all registers
asm ( "ldw r2, 8(sp)" );
asm ( "ldw r3, 12(sp)" );
asm ( "ldw r4, 16(sp)" );
asm ( "ldw r5, 20(sp)" );
asm ( "ldw r6, 24(sp)" );
asm ( "ldw r7, 28(sp)" );

Figure 24. Reset and exception handler C language code (Part b).
asm ( "ldw r8, 32(sp)" );
asm ( "ldw r9, 36(sp)" );
asm ( "ldw r10, 40(sp)" );
asm ( "ldw r11, 44(sp)" );
asm ( "ldw r12, 48(sp)" );
asm ( "ldw r13, 52(sp)" );
asm ( "ldw r14, 56(sp)" );
asm ( "ldw r15, 60(sp)" );
asm ( "ldw r16, 64(sp)" );
asm ( "ldw r17, 68(sp)" );
asm ( "ldw r18, 72(sp)" );
asm ( "ldw r19, 76(sp)" );
asm ( "ldw r20, 80(sp)" );
asm ( "ldw r21, 84(sp)" );
asm ( "ldw r22, 88(sp)" );
asm ( "ldw r23, 92(sp)" );
asm ( "ldw r24, 96(sp)" );
asm ( "ldw r25, 100(sp)" );       // r25 = bt
asm ( "ldw r26, 104(sp)" );       // r26 = gp
// skip r27 because it is sp, and we did not save this on the stack
asm ( "ldw r28, 112(sp)" );       // r28 = fp
asm ( "ldw r29, 116(sp)" );       // r29 = ca
asm ( "ldw r30, 120(sp)" );       // r30 = ba
asm ( "ldw r31, 124(sp)" );       // r31 = ra
asm ( "addi sp, sp, 128" );
asm ( "eret" );
}

//******************************************************************************
/* Interrupt Service Routine: Determines the interrupt source and calls the appropriate subroutine
*******************************************************************************/

void interrupt_handler(void)
{
    int ipending;
    NIOS2_READ_IPENDING(ipending);
    if ( ipending & 0x1 )           // interval timer is interrupt level 0
        interval_timer_isr( );
    if ( ipending & 0x2 )           // pushbuttons are interrupt level 1
        pushbutton_ISR();
    else                           // else, ignore the interrupt
        return;
}

Figure 24. Reset and exception handler C code (Part c).
#include "key_codes.h" // defines values for KEY1, KEY2

eextern volatile int key_pressed;
eextern volatile int pattern;
/******************************************************************************/
* Interval timer interrupt service routine
*
* Shifts a pattern being displayed on the HEX displays. The shift direction is determined
* by the external variable key_pressed.
*
******************************************************************************/

void interval_timer_isr( )
{
    volatile int * interval_timer_ptr = (int *) 0x10002000;
    volatile int * HEX3_HEX0_ptr = (int *) 0x10000020; // HEX3_HEX0 address
    volatile int * HEX7_HEX4_ptr = (int *) 0x10000030; // HEX7_HEX4 address

    *(interval_timer_ptr) = 0; // clear the interrupt

    *(HEX3_HEX0_ptr) = pattern; // display pattern on HEX3 ... HEX0
    *(HEX7_HEX4_ptr) = pattern; // display pattern on HEX7 ... HEX4

    /* rotate the pattern shown on the HEX displays */
    if (key_pressed == KEY2) // for KEY2 rotate left
        if (pattern & 0x80000000)
            pattern = (pattern << 1) | 1;
        else
            pattern = pattern << 1;
    else if (key_pressed == KEY1) // for KEY1 rotate right
        if (pattern & 0x00000001)
            pattern = (pattern >> 1) | 0x80000000;
        else
            pattern = (pattern >> 1) & 0x7FFFFFFF;

    return;
}

Figure 25. Interrupt service routine for the interval timer.
```c
#include "key_codes.h" // defines values for KEY1, KEY2

extern volatile int key_pressed;
extern volatile int pattern;

/************************************************************
 * Pushbutton - Interrupt Service Routine
 * This routine checks which KEY has been pressed. If it is KEY1 or KEY2, it writes this value
 * to the global variable key_pressed. If it is KEY3 then it loads the SW switch values and
 * stores in the variable pattern
 ************************************************************/
void pushbutton_ISR( void )
{
    volatile int * KEY_ptr = (int *) 0x10000050;
    volatile int * slider_switch_ptr = (int *) 0x10000040;
    int press;

    press = *(KEY_ptr + 3); // read the pushbutton interrupt register
    *(KEY_ptr + 3) = 0; // clear the interrupt

    if (press & 0x2) // KEY1
        key_pressed = KEY1;
    else if (press & 0x4) // KEY2
        key_pressed = KEY2;
    else // press & 0x8, which is KEY3
        pattern = *(slider_switch_ptr); // read the SW slider switch values; store in pattern

    return;
}
```

Figure 26. Interrupt service routine for the pushbutton keys.
4 Modifying the DE2 Basic Computer

It is possible to modify the DE2 Basic Computer by using Altera’s Quartus II software and SOPC Builder tool. Tutorials that introduce this software are provided in the University Program section of Altera’s web site. To modify the system it is first necessary to obtain all of the relevant design source code files. The DE2 Basic Computer is available in two versions that specify the system using either Verilog HDL or VHDL. After these files have been obtained it is also necessary to install the source code for the I/O peripherals in the system. These peripherals are provided in the form of SOPC Builder IP cores and are included in a package available from Altera’s University Program web site, called the *Altera University Program IP Cores*

Table 2 lists the names of the SOPC Builder IP cores that are used in this system. When the DE2 Basic Computer design files are opened in the Quartus II software, these cores can be examined using the SOPC Builder tool. Each core has a number of settings that are selectable in the SOPC Builder tool, and includes a datasheet that provides detailed documentation.

<table>
<thead>
<tr>
<th>I/O Peripheral</th>
<th>SOPC Builder Core</th>
</tr>
</thead>
<tbody>
<tr>
<td>SDRAM</td>
<td>SDRAM Controller</td>
</tr>
<tr>
<td>SRAM</td>
<td>SRAM</td>
</tr>
<tr>
<td>On-chip Memory</td>
<td>On-Chip Memory (RAM or ROM)</td>
</tr>
<tr>
<td>Red LED parallel port</td>
<td>Parallel Port</td>
</tr>
<tr>
<td>Green LED parallel port</td>
<td>Parallel Port</td>
</tr>
<tr>
<td>7-segment displays parallel port</td>
<td>Parallel Port</td>
</tr>
<tr>
<td>Expansion parallel ports</td>
<td>Parallel Port</td>
</tr>
<tr>
<td>Slider switch parallel port</td>
<td>Parallel Port</td>
</tr>
<tr>
<td>Pushbutton parallel port</td>
<td>Parallel Port</td>
</tr>
<tr>
<td>JTAG port</td>
<td>JTAG UART</td>
</tr>
<tr>
<td>Serial port</td>
<td>RS232 UART</td>
</tr>
<tr>
<td>Interval timer</td>
<td>Interval timer</td>
</tr>
<tr>
<td>System ID</td>
<td>System ID Peripheral</td>
</tr>
</tbody>
</table>

Table 2. SOPC Builder cores used in the DE2 Basic Computer.

The steps needed to modify the system are:

1. Install the *University Program IP Cores* from Altera’s University Program web site
2. Copy the design source files for the DE2 Basic Computer from the University Program web site. These files can be found in the *Design Examples* section of the web site
3. Open the *DE2_Basic_Computer.qpf* project in the Quartus II software
4. Open the SOPC Builder tool in the Quartus II software, and modify the system as desired
5. Generate the modified system by using the SOPC Builder tool
6. It may be necessary to modify the Verilog or VHDL code in the top-level module, *DE2_Basic_System.v/vhd*, if any I/O peripherals have been added or removed from the system
7. Compile the project in the Quartus II software
8. Download the modified system into the DE2 board

5 Making the System the Default Configuration

The DE2 Basic Computer can be loaded into the nonvolatile FPGA configuration memory on the DE2 board, so that it becomes the default system whenever the board is powered on. Instructions for configuring the DE2 board in this manner can be found in the tutorial Introduction to the Quartus II Software, which is available from Altera’s University Program.

6 Memory Layout

Table 3 summarizes the memory map used in the DE2 Basic Computer.

<table>
<thead>
<tr>
<th>Base Address</th>
<th>End Address</th>
<th>I/O Peripheral</th>
</tr>
</thead>
<tbody>
<tr>
<td>0x00000000</td>
<td>0x007FFFFF</td>
<td>SDRAM</td>
</tr>
<tr>
<td>0x08000000</td>
<td>0x087FFFFF</td>
<td>SRAM</td>
</tr>
<tr>
<td>0x09000000</td>
<td>0x0901FFF</td>
<td>On-chip Memory</td>
</tr>
<tr>
<td>0x10000000</td>
<td>0x1000000F</td>
<td>Red LED parallel port</td>
</tr>
<tr>
<td>0x10000100</td>
<td>0x1000011F</td>
<td>Green LED parallel port</td>
</tr>
<tr>
<td>0x10000200</td>
<td>0x100002FF</td>
<td>7-segment HEX3–HEX0 displays parallel port</td>
</tr>
<tr>
<td>0x10000300</td>
<td>0x100003FF</td>
<td>7-segment HEX7–HEX4 displays parallel port</td>
</tr>
<tr>
<td>0x10000400</td>
<td>0x100004FF</td>
<td>Slider switch parallel port</td>
</tr>
<tr>
<td>0x10000500</td>
<td>0x100005FF</td>
<td>Pushbutton parallel port</td>
</tr>
<tr>
<td>0x10000600</td>
<td>0x100006FF</td>
<td>JP1 Expansion parallel port</td>
</tr>
<tr>
<td>0x10000700</td>
<td>0x100007FF</td>
<td>JP2 Expansion parallel port</td>
</tr>
<tr>
<td>0x10001000</td>
<td>0x1000107F</td>
<td>JTAG UART port</td>
</tr>
<tr>
<td>0x10001100</td>
<td>0x1000117</td>
<td>Serial port</td>
</tr>
<tr>
<td>0x10002000</td>
<td>0x100021FF</td>
<td>Interval timer</td>
</tr>
<tr>
<td>0x10002200</td>
<td>0x1000227</td>
<td>System ID</td>
</tr>
</tbody>
</table>

Table 3. Memory layout used in the DE2 Basic Computer.

7 Altera Monitor Program Integration

As we mentioned earlier, the DE2 Basic Computer system, and the sample programs described in this document, are made available as part of the Altera Monitor Program. Figures 27 to 30 show a series of windows that are used in the Monitor Program to create a new project. In the first screen, shown in Figure 27, the user specifies a file system folder where the project will be stored, and gives the project a name. Pressing Next opens the window in Figure 28. Here, the user can select the DE2 Basic Computer as a predesigned system. The Monitor Program then fills in the relevant information in the System details box, which includes the files called nios_system.ptf and DE2_Basic_Computer.sof.
The first of these files specifies to the Monitor Program information about the components that are available in the
DE2 Basic Computer, such as the type of processor and memory components, and the address map. The second file
is an FPGA programming bitstream for the DE2 Basic Computer, which can downloaded by the Monitor Program
into the DE2 board.

Pressing Next again opens the window in Figure 29. Here the user selects the type of program that will be used,
such as Assembly language, or C. Then, the check box shown in the figure can be used to display the list of sample
programs for the DE2 Basic Computer that are described in this document. When a sample program is selected in
this list, its source files, and other settings, can be copied into the project folder in subsequent screens of the Monitor
Program.

Figure 30 gives the final screen that is used to create a new project in the Monitor Program. This screen shows the
addresses of the reset and exception vectors for the system being used (the reset vector address in the DE2 Basic
Computer is 0, and the exception address is 0x20), and allows the user to specify the type of memory and offset
address that should be used for the .text and .data sections of the user’s program. In cases where the reset vector can
be set to the start of the user’s program, and no interrupts are being used, the offset addresses for the .text and .data
sections would normally be left at 0. However, when interrupts are used, it is necessary to specify a value for the
.text and .data sections such that enough space is available in the memory before the start of these sections to hold
the executable code of the interrupt service routine. In the example shown in the figure, which corresponds to the
sample program using interrupts in section 3, the offset of 0x400 is used.
Figure 28. Specifying the Nios II system.

Figure 29. Selecting sample programs.
Figure 30. Setting offsets for `.text` and `.data`. 