EE 443

Design & Application of DSP

Spring 2016

UNIVERSITY OF WASHINGTON
ELECTRICAL ENGINEERING

Introduction

- Prof. Jenq-Neng Hwang, (hwang@uw.edu)
- Office Hours: EEB M426, TTh 1:00—2:30 pm
- Two courses sequence: EE442 (signal transforms and filtering) and EE443 (applications and real-time DSP microprocessor design)
- The prerequisite for this course is **EE442**
    - **DFT and FFT Computation**
    - **FIR Filter Design**
    - **IIR Filter Design**
    - **Adaptive Filter Design**
- TAs: Jounsup KIm
- TA Office Hours:
- Lab HW Demo: (15 min/group)
- Credits: 1 Science and 4 Design

Goals and Grading

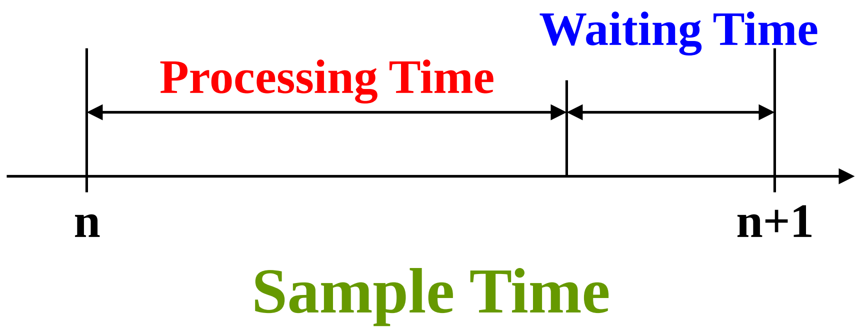
- **Goals:** The goal of this course is to introduce students, who are majoring in Signal/Image Processing and Communications, the important laboratory components of real-time DSP based on commercially available DSP microprocessors.
- **Grading:** Homework: 30%, Final Report Proposal: 10%, Final Project Presentation 10%, Final Project Demo & Report 50%.
- **Textbook:**
- **Ref:** Lori M. Matassa and Max Domeika, Break Away with Intel Atom Processors, Intel Press, 2010.

Topics

- De2i-150: NIOS II software processor and the Cyclone IV FPGA (0.5 week)
- Input/Output via AIC23 daughter card (0.5 week)
- Assembly (0.5 week)
- Intel Atom Processor and Image/Video Acquisition (0.5 week)
- FIR Filters and IIR Filters Implementations (0.5 week)
- FFT Implementations and Adaptive Filters (0.5 week)
- TI’s DSP board, DSK6713 (0.5 week)
- Digital Speech Recognition (0.5 week)
- Face Detection and Recognition (0.5 week)
- Video Object Segmentation and Shadow Removing (0.5 week)

Real-Time DSP Processing

- Note that the processing can involve many past sampled data, not just the most recently sampled one
- We can say that we have a real-time application if:
  - Waiting Time ≥ 0



Why DSP Processors?

- Use a digital signal processor (DSP) when the following are required:
    - Cost saving.
    - Smaller size.
    - Low power consumption.
    - Processing of many “high” frequency signals in real-time.
- Use a general purpose processor (GPP) when the following are required:
    - Large memory.
    - Advanced operating systems.

Typical DSP Algorithms

- The Sum of Products (SOP), or called Multiply & Accumulation (MAC), is the key element in most DSP algorithms:

Algorithm	**Equation**
Finite Impulse Response Filter	$y(n)=\sum_{k=0}^{M} a_k\, x(n-k)$
Infinite Impulse Response Filter	$y(n)=\sum_{k=0}^{M} a_k\, x(n-k)+\sum_{k=1}^{N} b_k\, y(n-k)$
Convolution	$y(n)=\sum_{k=0}^{N} x(k)h(n-k)$
Discrete Fourier Transform	$X(k)=\sum_{n=0}^{N-1} x(n)\exp[-j(2\pi / N)nk]$
Discrete Cosine Transform	$F(u)=\sum_{x=0}^{N-1} c(u).f(x).\cos\left[\frac{\pi}{2N}u(2x+1)\right]$

Hardware vs. Microcode Multiplication

- DSP processors are optimized to perform multiplication and addition operations.
- Multiplication and addition are normally done in hardware and in one cycle.
- Example: 4-bit multiply (unsigned).

Hardware

```
    1011
  x 1110
--------
10011010
```

Microcode

```
    1011
  x 1110
--------
    0000    Cycle 1
   1011.    Cycle 2
  1011..    Cycle 3
 1011...    Cycle 4
--------
10011010    Cycle 5
```

Floating vs. Fixed Point Processors

- Applications which require:
  - High precision, and wide dynamic range.
  - High signal-to-noise ratio, and ease of use.

  Need a floating point processor.
- Drawback of floating point processors:
  - Higher power consumption.
  - Can be higher cost.
  - Can be slower than fixed-point counterparts and larger in size.
- For educational purposes, use the floating-point device (e.g., C6713) as it can support both fixed and floating point operations.

General Purpose DSP vs. DSP in ASIC (or SoC)

- Application Specific Integrated Circuits (ASICs) and System on Chips (SoCs) are semiconductors designed for dedicated functions.
- The advantages and disadvantages of using ASICs (or SoCs) are listed below:

Advantages of ASIC/SoC	**Disadvantages**
• High throughput • Lower silicon area • Lower power consumption • Improved reliability • Reduction in system noise • Low overall system cost	• High investment cost • Less flexibility • Long time from design to market

Commercially Available DSP Chips

- The "big four" programmable DSP chip manufacturers are Texas Instruments, with the TMS320 series of chips; Motorola, with the DSP56000 and DSP96000 series; AT&T, with the DSP16 and DSP32 series; and Analog Devices, with the ADSP2100 series.
- Also Zilog, NEC, Xilink FPGA, etc

Company	Part	MAC time (ns)	No. bits fixed pt.	No. bits float pt.
	DSP16	55	16/36	
AT&T	DSP16A	33	16/36	
	DSP32	160	16	32/40
	DSP32C	80	16 or 24	32/40
Motorola	DSP56001	74	24/56	
	DSP96002	75	32/64	44/96
	TMS320C10	114-280	16/32	
Texas Inst.	TMS32C25	80-100	16/32	
	TMS320C50	25-50	16/32	
	TMS320C30	50-75	24/32	32/40
	TMS320C40	40-50		32/40
	TMS320C6201	5	32	
Analog Devices	ADSP2100	125	16/40	
	ADSP2100A	80	16/40	
	ADSP21065L	6	32	32/40

Texas Instruments' TMS320 Family

C2000

Lowest Cost

Control Systems

- Motor Control
- Storage
- Digital Ctrl Systems

C5000

Efficiency

Best MIPS per Watt / Dollar / Size

- Wireless phones
- Internet audio players
- Digital still cameras
- Modems
- Telephony
- VoIP

C6000

Performance & Ease-of-Use

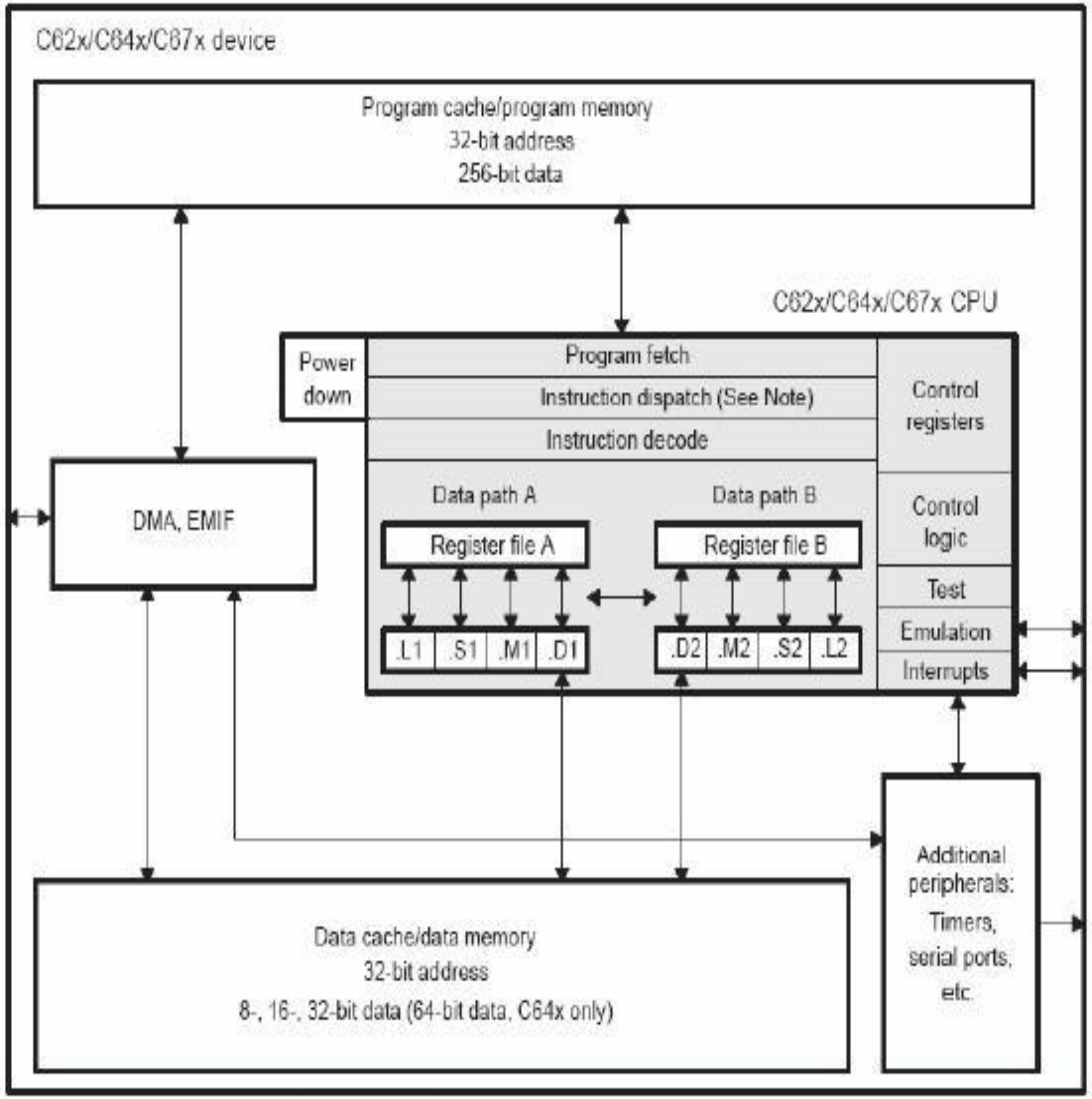
Multi Channel and Multi Function App's

- Comm. Infrastructure
- Wireless Base-stations
- DSL
- Imaging & Video
- Multimedia Servers

C6713 Floating Point DSPs

- The highest performance floating-point DSP
- Based on the high-performance, advanced VelociTI very-long-instruction-word (VLIW) architecture.
- Eight 32-bit instructions/cycle: 1800/1350 (225MHz), 1600/1200 (200 MHz), 1336/1000 (167MHz) MIPs/FLOPs
- The eight functional units provide four floating-/fixed-point ALUs, two fixed-point ALUs, and two floating-/fixed-point multipliers.
- 32 load-store structure general-purpose registers of 32-bit word length and eight highly independent functional units.

C67x CPU Diagram



One instruction is 32 bits. Program bus is 256 bits wide.

⇨Can execute <u>up to</u> 8 instructions per clock cycle (225MHz->4.4ns clock cycle).

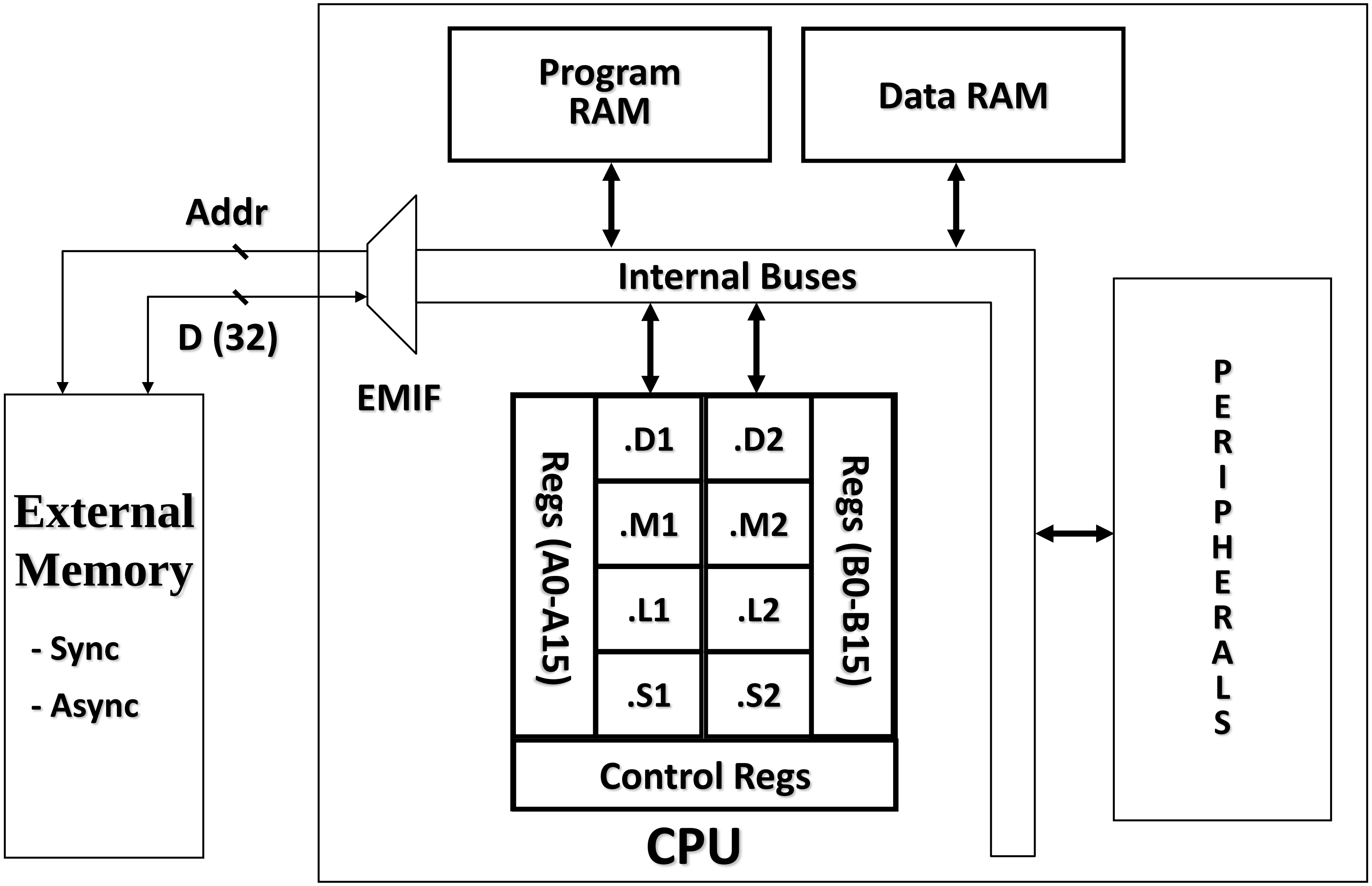
8 independent functional units:
- 2 multipliers
- 6 ALUs

Code is efficient if all 8 functional units are always busy.

Register files each have 16 general purpose registers, each 32-bits wide (A0-A15, B0-B15).

Data paths are each 64 bits wide.

C6713 CPU System Block



NI’s myRIO Board

- 10 analog inputs, 6 analog outputs, 40 digital I/O lines
- Wireless, LEDs, push button, accelerometer onboard
- Xilinx FPGA and dual-core ARM Cortex-A9 processor
- Programmable with LabVIEW or C; adaptable for different programming levels

DE2i-150 FPGA Development Kit

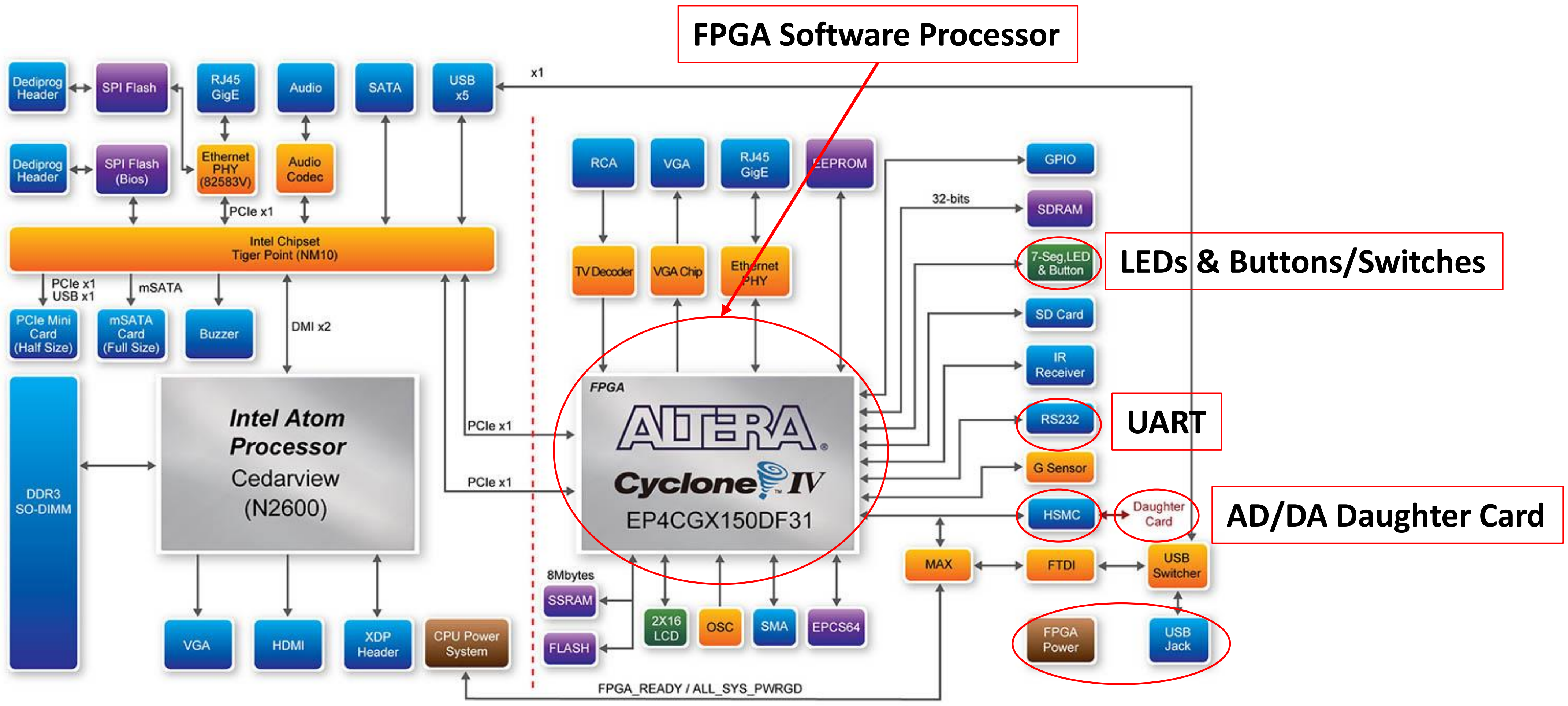
DE2i-150 FPGA Development Kit

- Donated by Intel to replace the old TI DSK DSP Development Kit in 2014
- Includes
  - Intel Atom N2600 Processor
  - Altera Cyclone IV GX EP4CGX150DF31 FPGA
- Not a traditional DSP development environment
- Will utilize a software processor (NIOS II) running on the Cyclone IV FPGA to emulate a microprocessor (for final project)
- We will have some image/video HWs using the Intel Atom Processor

DE2i-150 EE443 Supported Interfaces

- Libraries have been prepared for these peripherals:
  - 18 switches and 4 push-buttons (keys) for user input
  - 18 red and 9 green LEDs
  - UART interface to Matlab through RS232 port
  - Audio Codec (see AD/DA board)

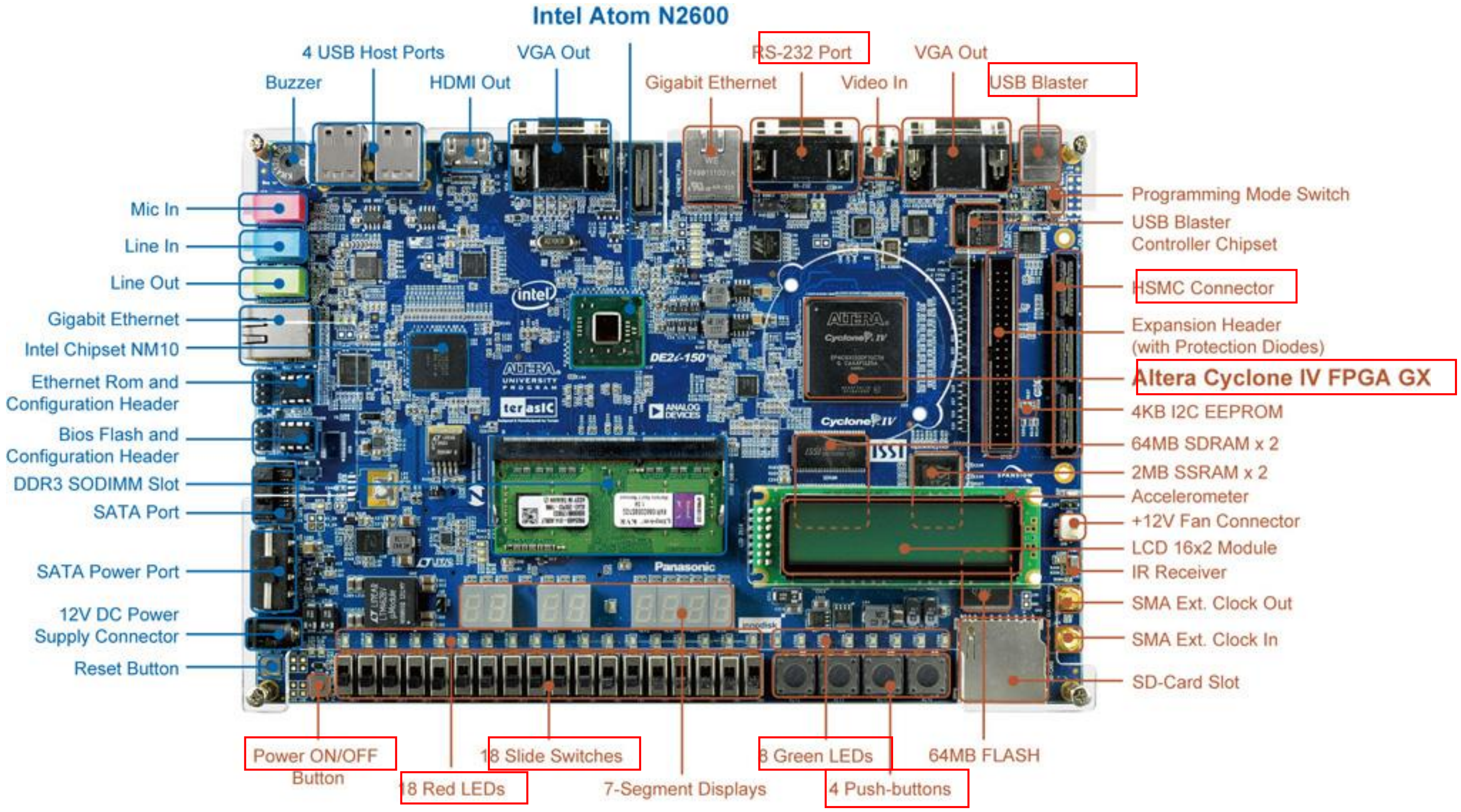
DE2i-150 Block Diagram



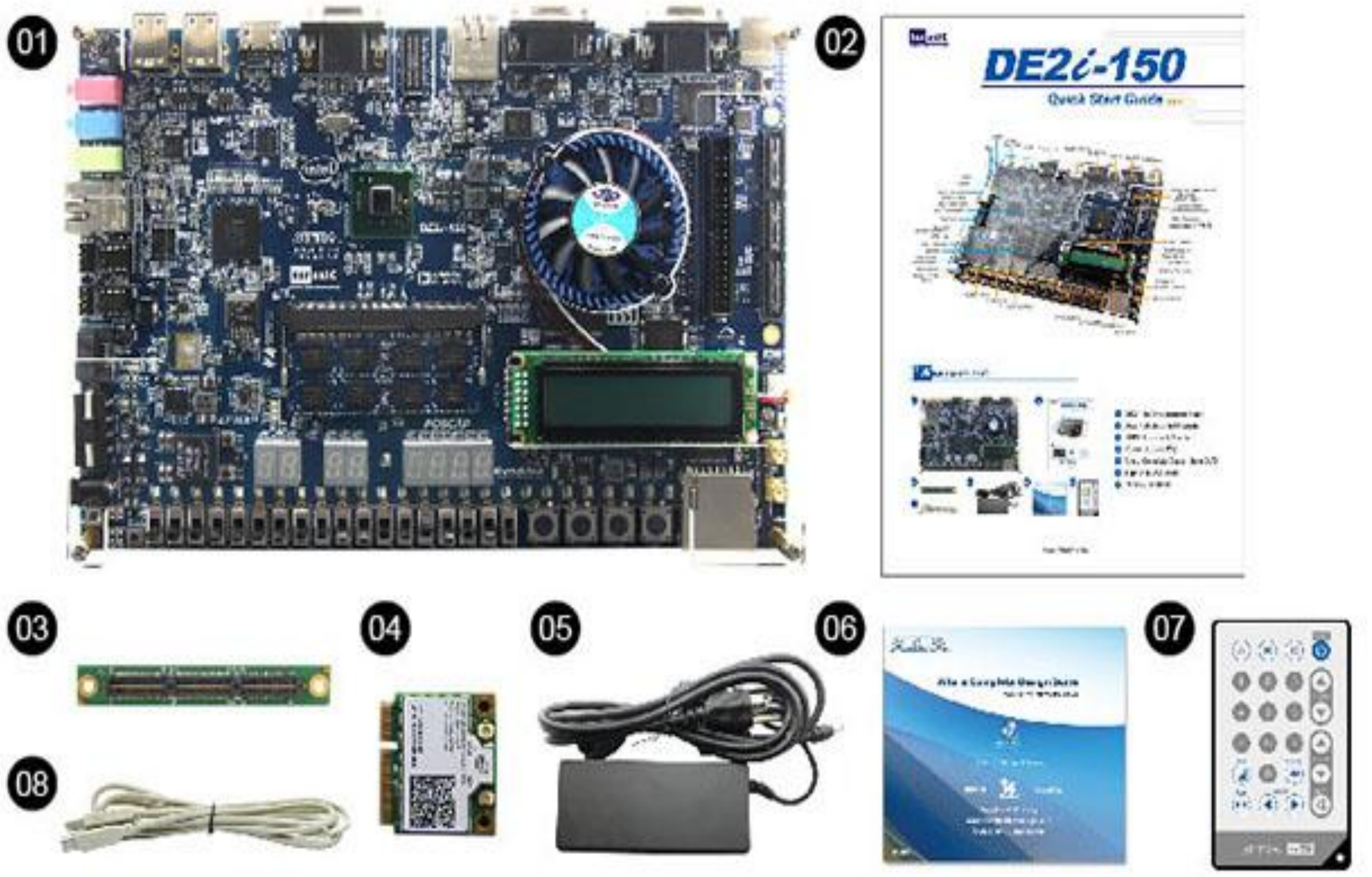
DE2i-150 EE443 Non-Supported Interfaces

- There are several components of this board from NIOS II libraries are available to you for your project. Just a few include:
  - The ENTIRE Intel Atom Processor side running Yocto (embedded Linux)
  - 7 segment displays
  - HDMI, VGA
  - Wifi, Ethernet
  - IR Receiver, Accelerometer
  - PCIe, USB

DE2i-150 Layout

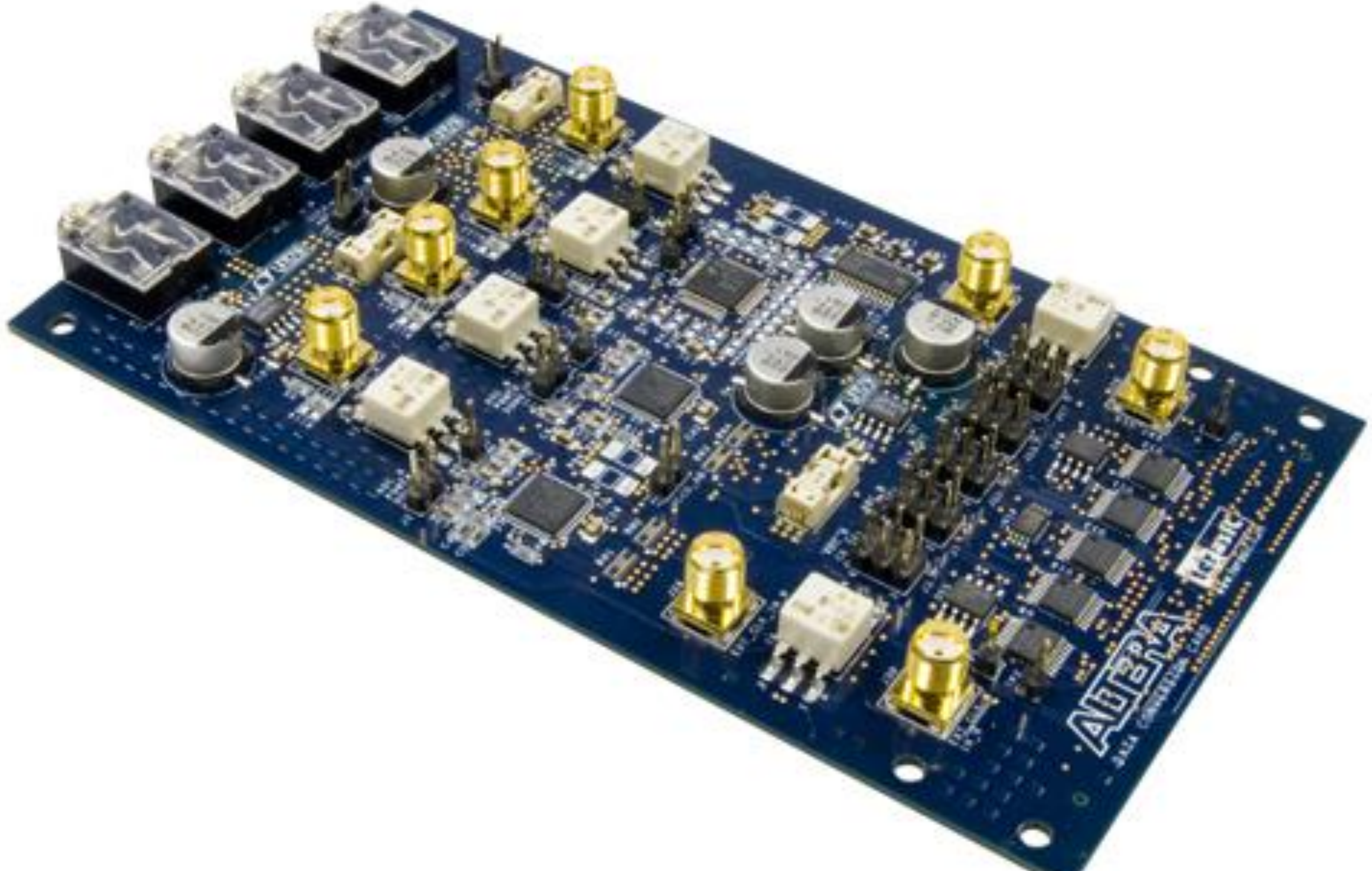


What's in the Kit?



- 01 DE2i-150 Development Board
- 02 DE2i-150 Quick Start Guide
- 03 HSMC Loopback Adapter
- 04 Intel WiFi Module
- 05 Power Supply (12V)
- 06 Altera Complete Design Suite DVD
- 07 Remote Controller
- 08 Type A-B USB cable

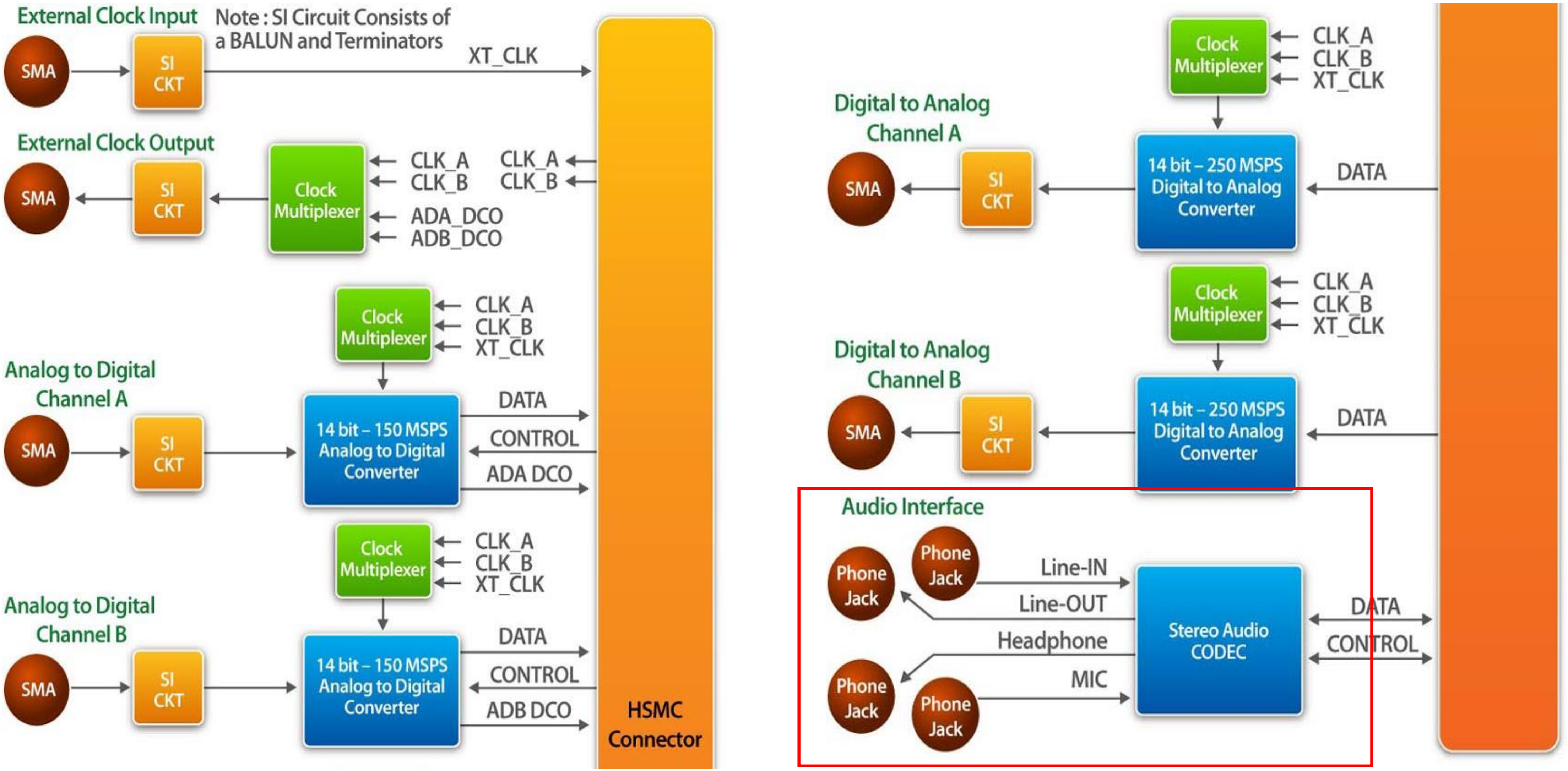
AD/DA Daughter Card: AIC23



AD/DA Daughter Card

- Plugs into DE2i-150 Development board via High Speed Mezzanine Card (HSMC) connector
- Adds Functionality
  - 2 Channel 14 bit ADC @ 150MS/s
  - 2 Channel 14 bit DAC @ 250MS/s
  - TI AIC23 Audio Codec
- SMA (surface-mount assembly) and Audio Jack input/output
- TI AIC23 will handle all of the audio input/output and data collection for this course

AD/DA Daughter Card Block Diagram



NIOS II Embedded Processor

- Configurable processor unit with customizable peripherals
- Ability to program in C/C++ using Eclipse IDE
- **Nios II** is a RISC soft-core 32-bit embedded-processor architecture designed specifically for the Altera family of FPGAs. Nios II incorporates many enhancements over the original Nios architecture, making it more suitable for a wider range of embedded computing applications, from DSP to system-control.
- Nios II is comparable to MicroBlaze, a competing softcore CPU for the Xilinx family of FPGA. Unlike Microblaze, Nios II is licensable for standard-cell ASICs through a third-party IP provider, Synopsys Designware. Through the Designware license, designers can port Nios-based designs from an FPGA-platform to a mass production ASIC-device.

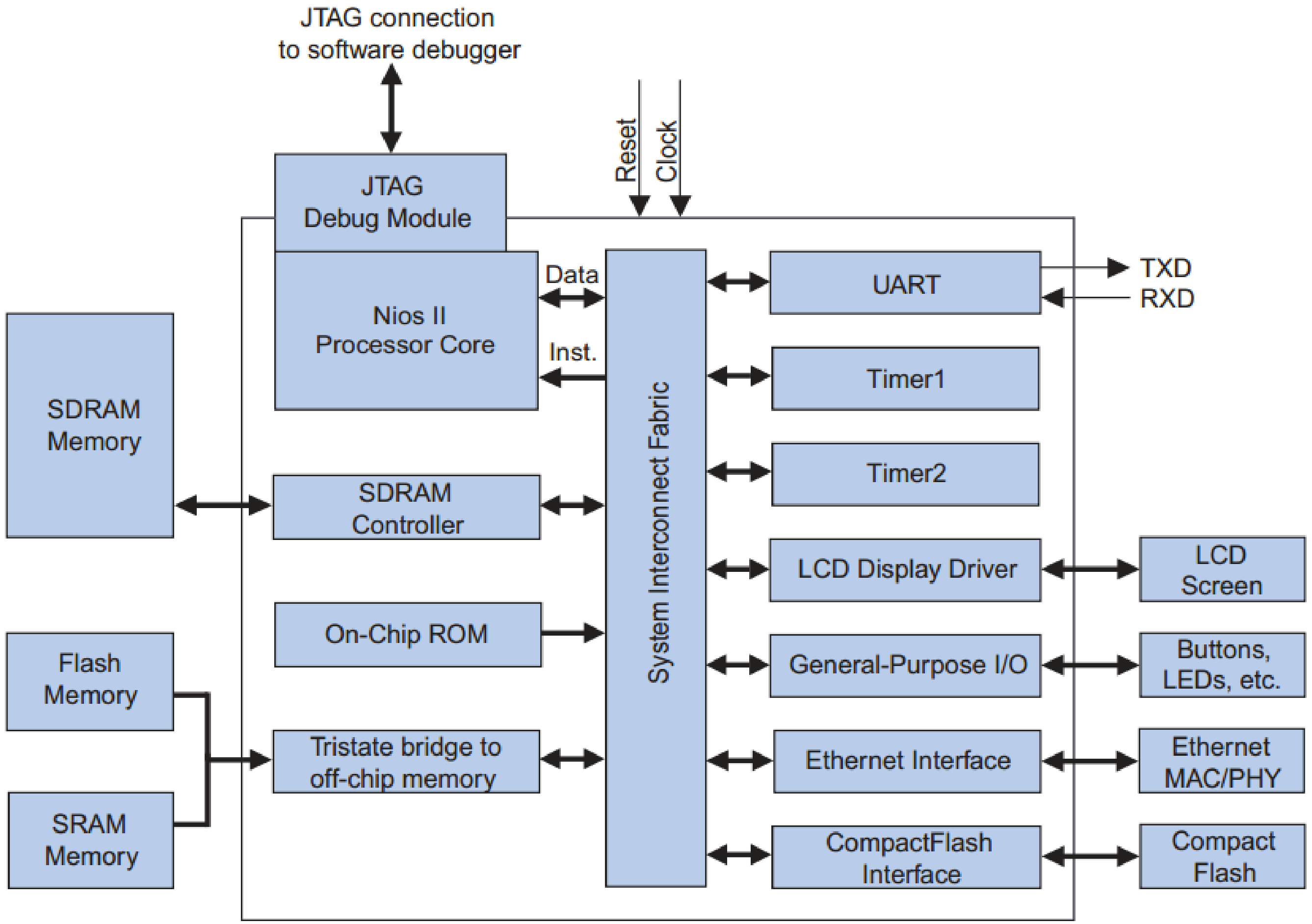
Development for Nios II

- **Hardware generation process**
- Nios II hardware designers use the Qsys system integration tool, a component of the Quartus-II package, to configure and generate a Nios system. The configuration graphical user interface (GUI) allows users to choose the Nios-II's feature-set, and to add peripheral and I/O-blocks (timers, memory-controllers, serial interface, etc.) to the embedded system. When the hardware specification is complete, Quartus-II performs the synthesis, place & route to implement the entire system on the selected FPGA target.

- **Software creation process**
- A separate package, called the Embedded Design Suite (EDS), manages the software development. Based on the Eclipse IDE, the EDS includes a C/C++ compiler (based on the GNU toolchain), debugger, and an instruction-set simulator. EDS allows programmers to test their application in simulation, or download and run their compiled application on the actual FPGA host.

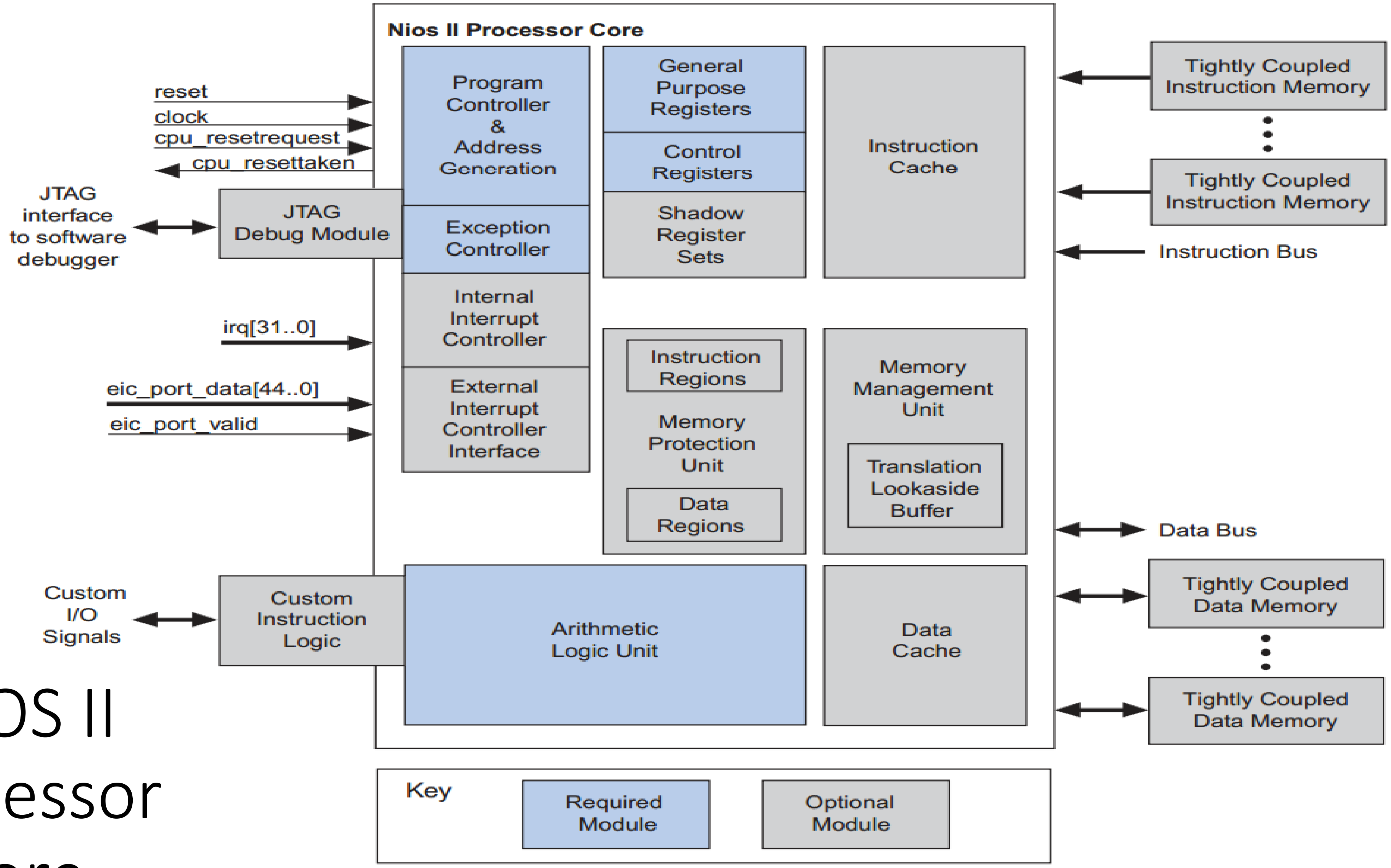
NIOS II Embedded Processor

Figure 1–1. Example of a Nios II Processor System



http://www.altera.com/literature/hb/nios2/n2cpu_nii5v1.pdf

Figure 2–1. Nios II Processor Core Block Diagram



NIOS II Processor Core

Basic Functions EE443

- Parallel Input/Output
  - LEDs, KEYS (buttons), SWITCHES
- AIC23 Audio Codec Control
- UART-RS232 Data Transmission
- DSP Algorithms
  - FFT, FIR, IIR, etc
- HAL API
  - Interrupts

Parallel I/O Peripherals

- Peripherals that pass data to the NIOS processor in parallel
- Common Functions:
  - IORD_ALTERA_AVALON_PIO_DATA(BASE); // Read
  - IOWR_ALTERA_AVALON_PIO_DATA(BASE, DATA); // Write
  - IORD_ALTERA_AVALON_PIO_EDGE_CAP(BASE); // Edge of Capture
  - IOWR_ALTERA_AVALON_PIO_EDGE_CAP(BASE, DATA); // Resets Edge Capture
- BASE – The base address of the peripheral. e.g. LED_BASE, SWITCH_BASE
- DATA – The data to be sent to the base. e.g. 0x01C3F
- BASEs for the different peripherals can be found in the file “system.h”
- EDGE_CAP is to be used with interrupt applications

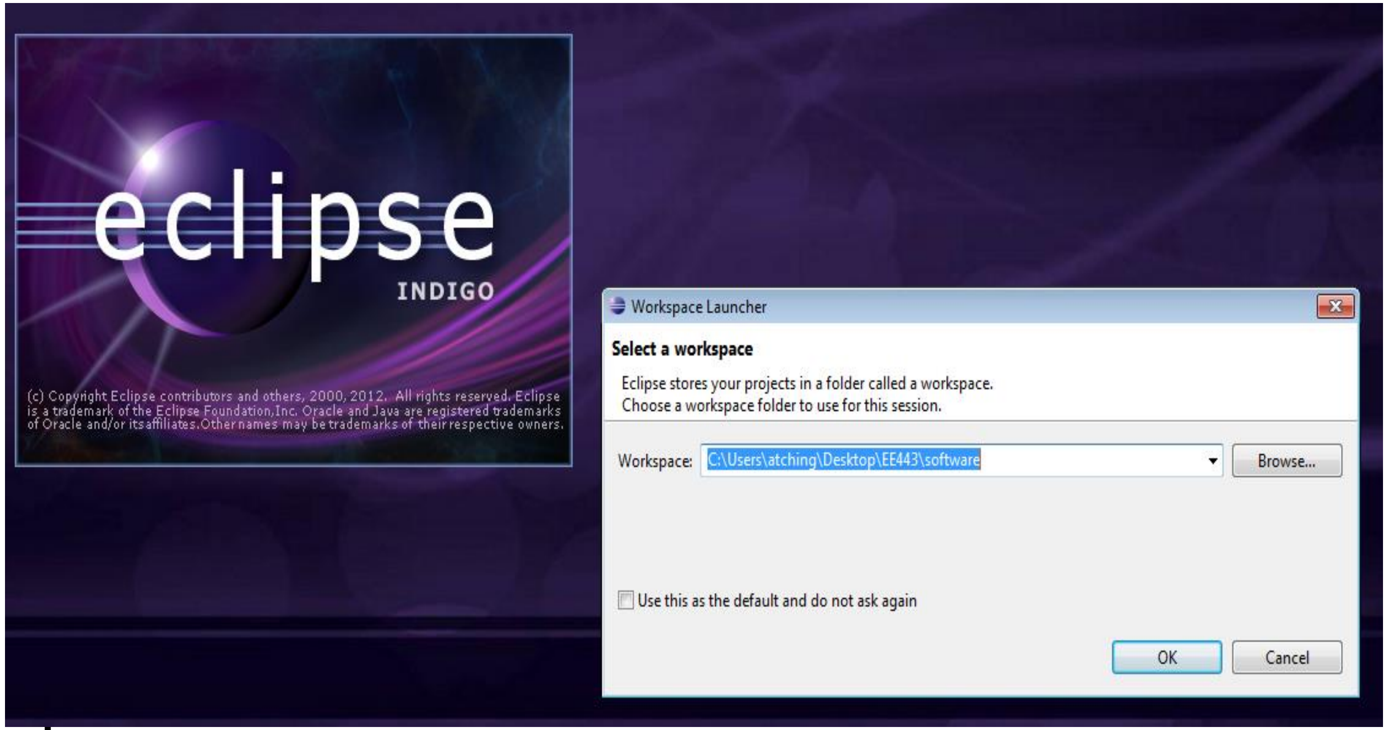
Basic Development Example

- Developing on NIOS II Platform
- Interfacing with DE2i-150 board Peripherals
- Interfacing with Matlab or LabVIEW for GUI
- Debugging

Developing on NIOS II

http://www.altera.com/devices/processor/nios2/tools/ide/ni2-ide.html

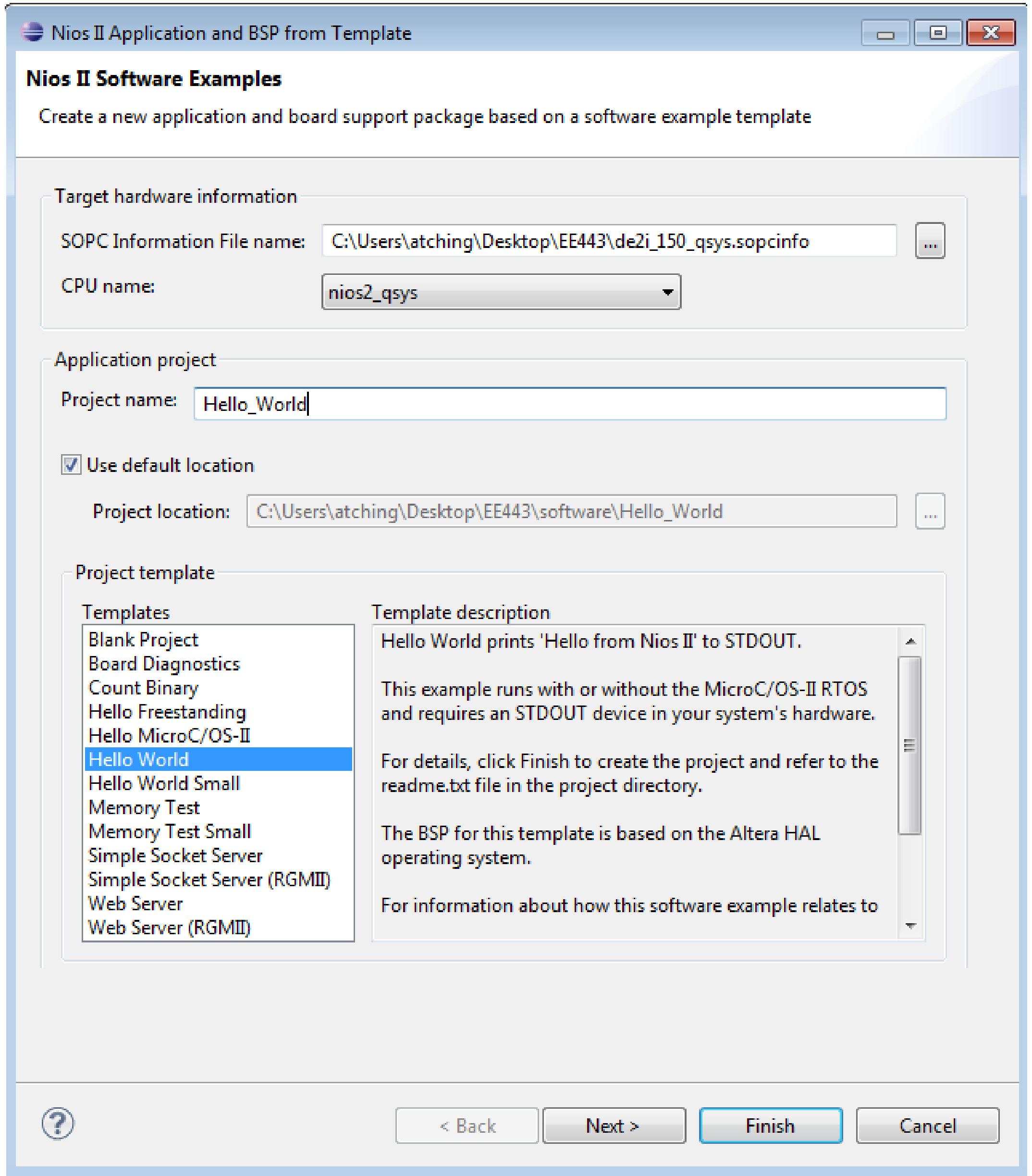
- Open Nios II 13.0sp1 Software Build Tools (SBT) for Eclipse
- Select EE443\software folder
- You will develop all software projects within this folder
- It contains all of the libraries and configurations made for this board.
- Can choose another workspace as long as you include those files



- New project wizards and software templates
- Compiler for C and C++ (GNU)
- Source navigator, editor, and debugger
- Eclipse project-based tools
- Software build tools

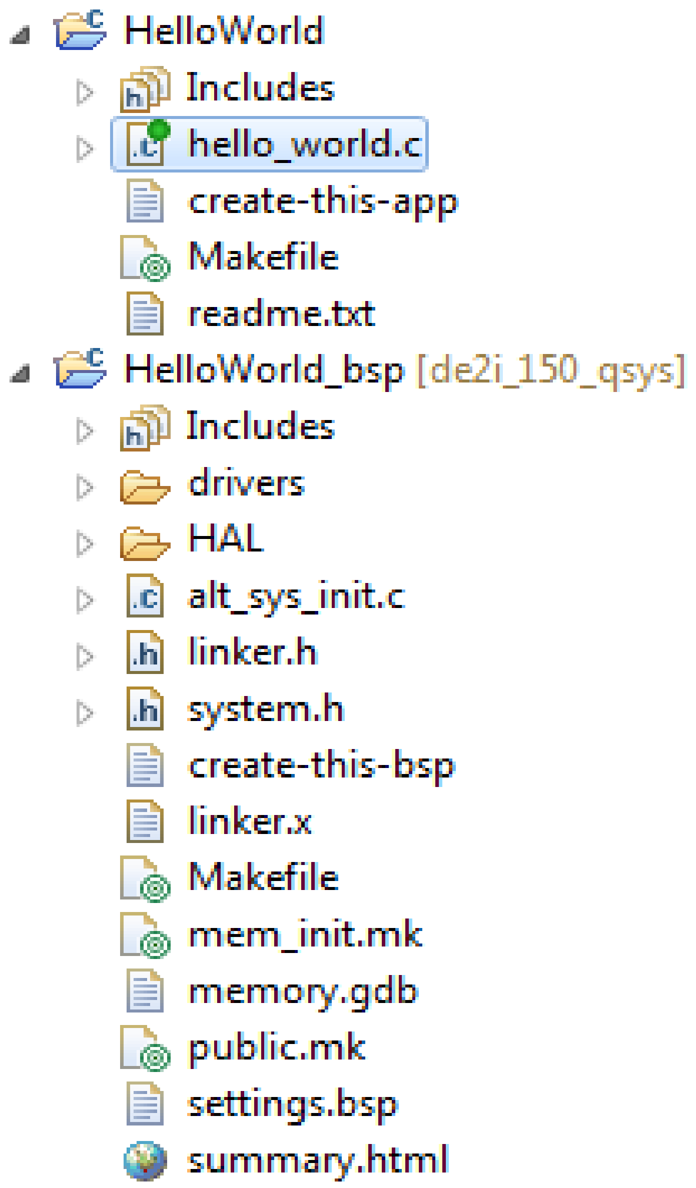
Your First Program

- File > New > NIOS II Application and BSP (board support package) from Template
- Select the de2i_150_qsys.sopcinfo file
- Choose the Hello World template
- Name your project
- Click finish



Setup

- Open up the hello_world.c file
- You can always select this template in the menu and change the file names after the project is created
- Import all libraries from ee443_libs folder
- Right click the project folder and click “Build Project”



```c
//UART_example.c  128-length data transmission from the board to PC (Matlab)
#define PI 3.141592                              //pre-define PI = 3.141592
#include "system_init.h"                                 //table index

void main()
{
     int counter;
     int Data[128];
    sampleFrequency = 0x000C;                                                        //8k
    system_initialization();                                                         //init switches and UART

    for(int ii=0; ii<128; ii++) Data[ii] = (int)1000*sin(2*PI*ii/128);               //sample data to transmit

     while(1)                                                                                  //infinite loop
    {
            if(uartStartSendFlag){                                                   //monitor the push button (defined in yourISR.h)
                    for (counter = 0; counter < 128; counter++){
                            uart_sendInt16(Data[counter]);                                    //send the data through UART
                    }
                    uartStartSendFlag = 0;                                                    //finish the transmission
                }
    }                                                                                         //end of while (1) infinite loop
}                                                                                    //end of main
```

Press the push button #0, which should send the 128-length integer data stored in the Data buffer through UART.

```matlab
%% PC-side (Matlab): receiving data from UART

close all; clc; clear all;

s = serial('COM3', 'BaudRate',115200); % Open the serial port to receive the data
set(s,'InputBufferSize',20000); % set the size of input buffer
fopen(s); % get ready to receive the data
buffersize = 128; % set the size of instant read of buffer
a = fread(s,buffersize,'int16'); % read the buffer when data arrive

plot(a);
fclose(s);
delete(s);
'done'
```

Adding Peripherals

- Add #include “system.h” to your program to import the peripherals on the DE2i board
- Add the appropriate control libraries for your peripherals
- This example will be using the switches, LEDs, and UART
- Refer to the examples in the EE443 lab manual and online material from Altera for specifics

```
#include <stdio.h>
#include "system.h"
#include "altera_avalon_uart_regs.h"
#include "altera_avalon_pio_regs.h"
```

Example

- Your program will run in an infinite loop within while(1) in your main() function
- This example will turn the first 3 green LEDs on/off based on the first 3 switches (via PIO)
- The 4^{th} switch will send "Hello World" through the RS232 (UART) port to Matlab to print on the screen
- The 5^{th} switch will send "012345" to Matlab

```c
printf("Hello from Nios II!\n");
char hello[11] = "Hello World";
int i = 0;

while(1){

    // Checks if switch 0 is on
    if(IORD_ALTERA_AVALON_PIO_DATA(SWITCH0_BASE)){
        IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) | 0x01); // Turns on 1st LED
    } else{
        IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) & ~0x01);// Turns off 1st LED
    }

    // Checks if switch 1 is on
    if(IORD_ALTERA_AVALON_PIO_DATA(SWITCH1_BASE)){
        IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) | 0x02); // Turns on 2nd LED
    } else{
        IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) & ~0x02);// Turns off 2nd LED
    }

    // Checks if switch 2 is on
    if(IORD_ALTERA_AVALON_PIO_DATA(SWITCH2_BASE)){
        IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) | 0x04); // Turns on 3rd LED
    } else{
        IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) & ~0x04);// Turns off 3rd LED
    }

    // Checks if switch 3 is on
    if(IORD_ALTERA_AVALON_PIO_DATA(SWITCH3_BASE)){
        for(i = 0; i < sizeof(hello); i++){
            IOWR_ALTERA_AVALON_UART_TXDATA(UART_BASE, hello[i]); // Send individual characters over UART to Matlab
            delay(2000); // Delay necessary to slow data transmission to within UART speeds of 115200kpbs
        }
        IOWR_ALTERA_AVALON_UART_TXDATA(UART_BASE, 0x0A); // Matlab requires an end of line character to terminate transmission
        delay(2000);
    }

    // Checks if switch 3 is on
    if(IORD_ALTERA_AVALON_PIO_DATA(SWITCH4_BASE)){
        for(i = 0; i < 6; i++){
            IOWR_ALTERA_AVALON_UART_TXDATA(UART_BASE, (i + 48)); // Send ASCII equivalent of 012345 over UART to Matlab
            delay(2000);
        }

        IOWR_ALTERA_AVALON_UART_TXDATA(UART_BASE, 0x0A); // Matlab requires an end of line character to terminate transmission
        delay(2000);
    }

}
```

Switch 4

ASCII 0=48, 1=49, …..

MATLAB

- Create a serial object at the COM port via USB cable, connected to COM4 here, to expect the data from UART tranmission
- fopen(<serial object>) to open the communication channel
- fscanf(s) reads the raw character data
- You can use MATLAB to interpret the data as decimal, float, etc using fprintf()
- You need a termination character in the NIOS II code (0x0A)

UART_RX.m

```
clear all
close all
clc

% Create Serial Object
s = serial('COM4', 'BaudRate', 115200);

% Open Serial Port
fopen(s);
i = 0;

while(1)
    i = i+1;
    fscanf(s)% Interpret as decimal number
end

% Close Serial Port When Done - VERY IMPORTANT
fclose(s);
```

Command Window

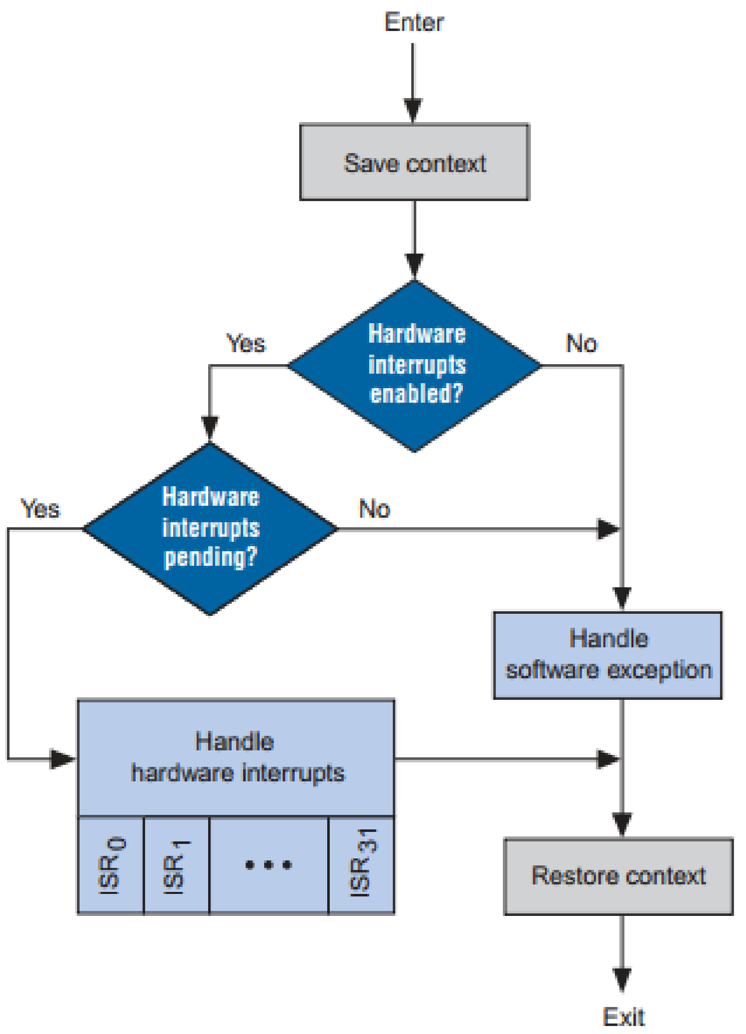
New to MATLAB? Watch this Video, see Examples, or read Getting Started.

```
Hello World


ans =

Hello World
```

Interrupt Example

- Interrupts happen outside the while(1) loop when an event is triggered (like a switch) and pause the CPU to execute, then return to normal CPU execution
- NIOS II uses the hardware abstraction layer (HAL) API to register and control interrupt handling
- Example will use KEY0 to turn LED 3 ON and KEY1 to turn LED3 OFF

Figure 8–1. HAL Exception Handling System with the Internal Interrupt Controller



Include HAL API Interrupt Libraries

```c
#include "sys/alt_irq.h"
#include "priv/alt_legacy_irq.h"
#include "os/alt_hooks.h"
#include "alt_types.h"
#include "sys/alt_irq_entry.h"
#include "priv/alt_irq_table.h"
#include "sys/alt_irq.h"

// OR #include system_init.h for everything
```

Cast the IRQ IDs

```c
// Global Variables
alt_u32 key0_id = KEY0_IRQ;
volatile int key0 = 0;

alt_u32 key1_id = KEY1_IRQ;
volatile int key1 = 0;
```

Interrupt Handler for KEY0

```c
// Interrupt Handler for KEY0
static void handle_key0_interrupt(void* context, alt_u32 id) {
     volatile int* key0ptr = (volatile int *)context;
     *key0ptr = IORD_ALTERA_AVALON_PIO_EDGE_CAP(KEY0_BASE);

     /* Write to the edge capture register to reset it. */
     IOWR_ALTERA_AVALON_PIO_EDGE_CAP(KEY0_BASE, 0);

     IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) | 0x08); // Turns on 4th LED
}
```

Interrupt Handler for KEY1

```c
// Interrupt Handler for KEY1
static void handle_key1_interrupt(void* context, alt_u32 id) {
     volatile int* key1ptr = (volatile int *)context;
     *key1ptr = IORD_ALTERA_AVALON_PIO_EDGE_CAP(KEY1_BASE);

     /* Write to the edge capture register to reset it. */
     IOWR_ALTERA_AVALON_PIO_EDGE_CAP(KEY1_BASE, 0);

     IOWR_ALTERA_AVALON_PIO_DATA(LED_BASE, IORD_ALTERA_AVALON_PIO_DATA(LED_BASE) & ~0x08); // Turns off 4th LED
}

int main()
{
```

Register & Initialize Interrupts

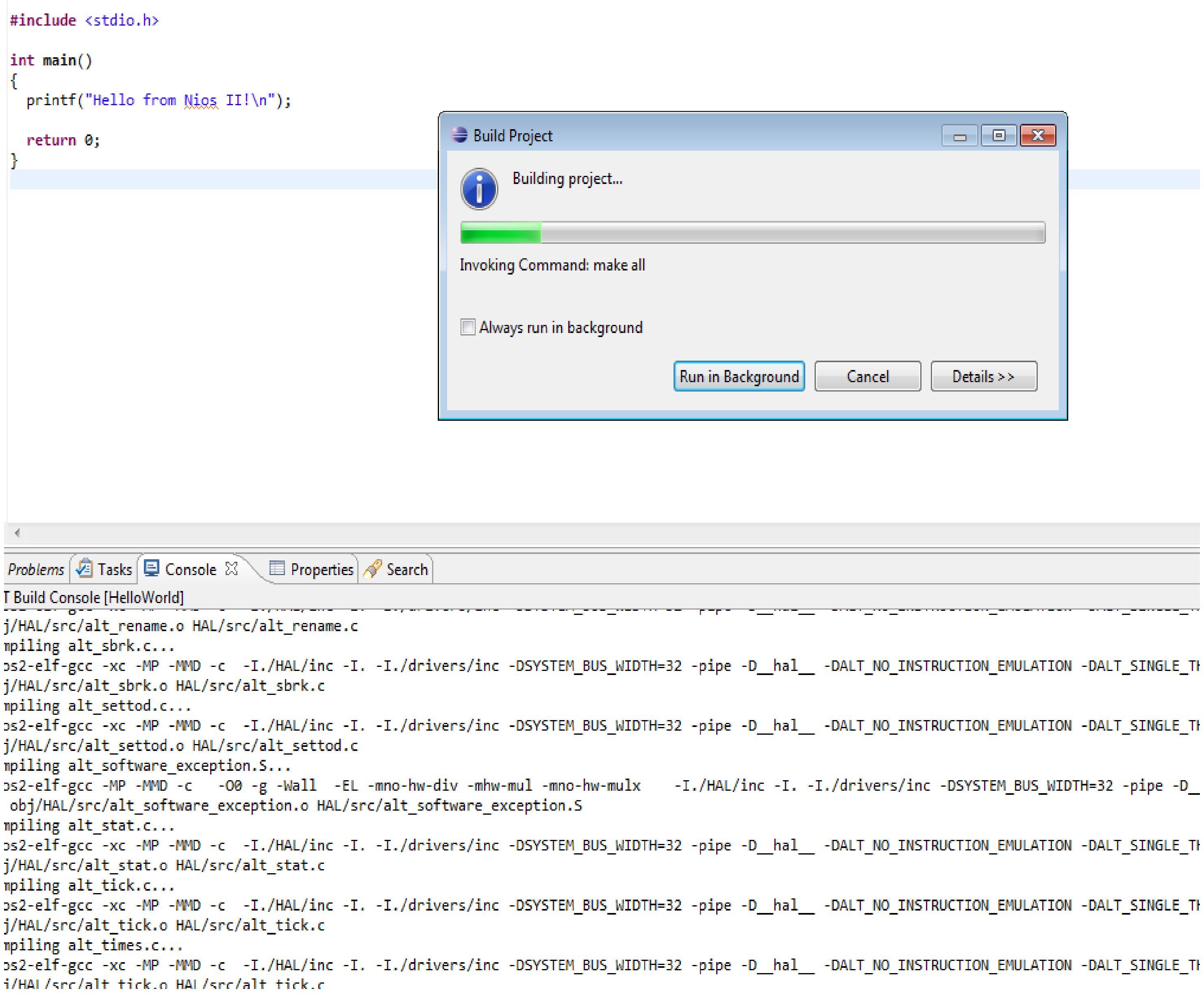
```c
  // Interrupt setup. Mostly DONE for you in library. This is just example so
  // you can write your own if you want to.
  alt_irq_register(key0_id, (void *)&key0, handle_key0_interrupt); // Register interrupt
  IOWR_ALTERA_AVALON_PIO_IRQ_MASK(KEY0_BASE, 1); // Enable Interrupt
  IOWR_ALTERA_AVALON_PIO_EDGE_CAP(KEY0_BASE, 0); // Reset Edge Capture Bit

  alt_irq_register(key1_id, (void *)&key1, handle_key1_interrupt); // Register interrupt
  IOWR_ALTERA_AVALON_PIO_IRQ_MASK(KEY1_BASE, 1); // Enable Interrupt
  IOWR_ALTERA_AVALON_PIO_EDGE_CAP(KEY1_BASE, 0); // Reset Edge Capture Bit
```

Rest of the program

```c
  printf("Hello from Nios II!\n");
  char hello[11] = "Hello World";
  int i = 0;

  while(1){
```

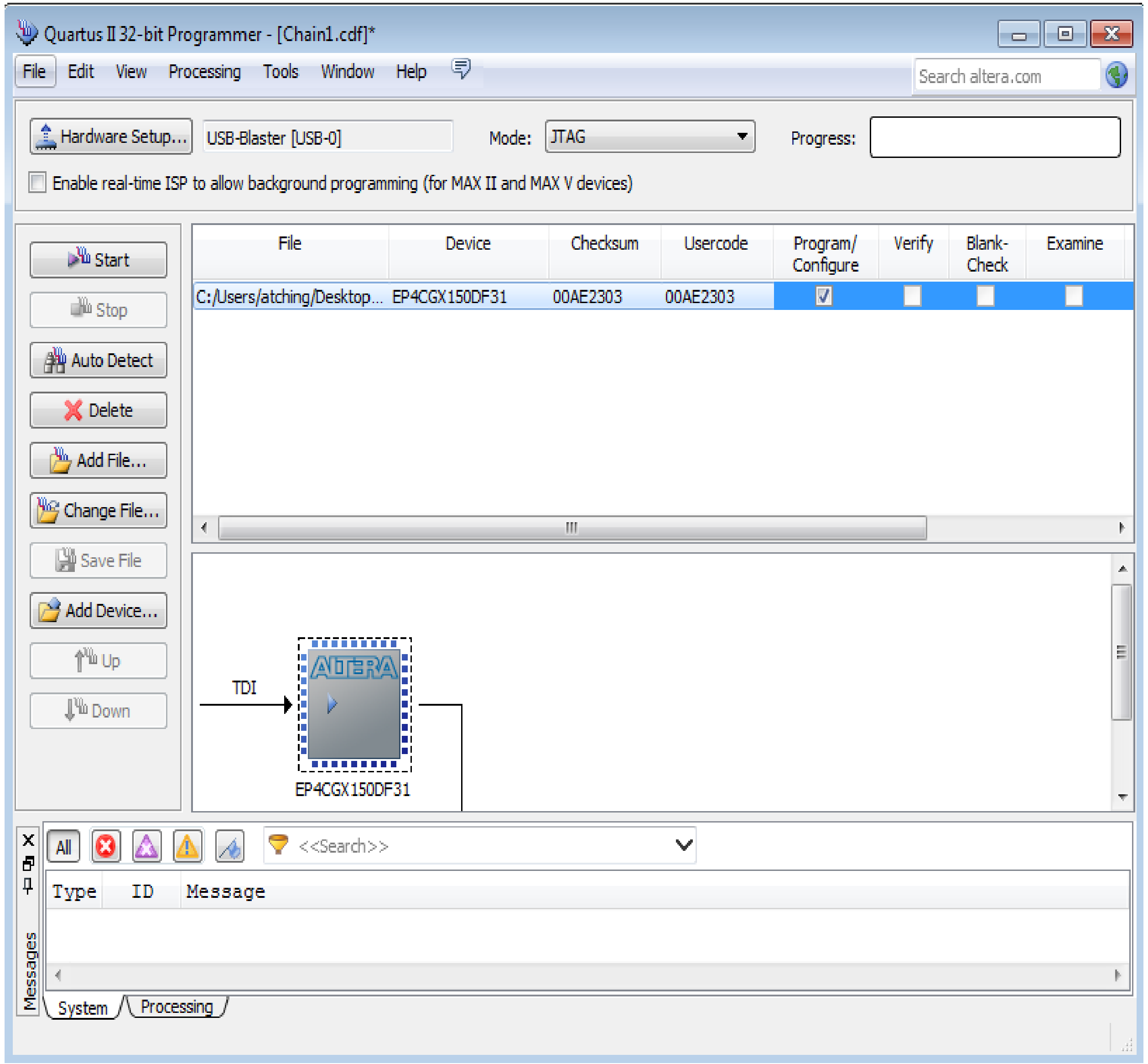
Build Project

- Build the program to compile the code so it is ready to be uploaded to the DE2i-150 board



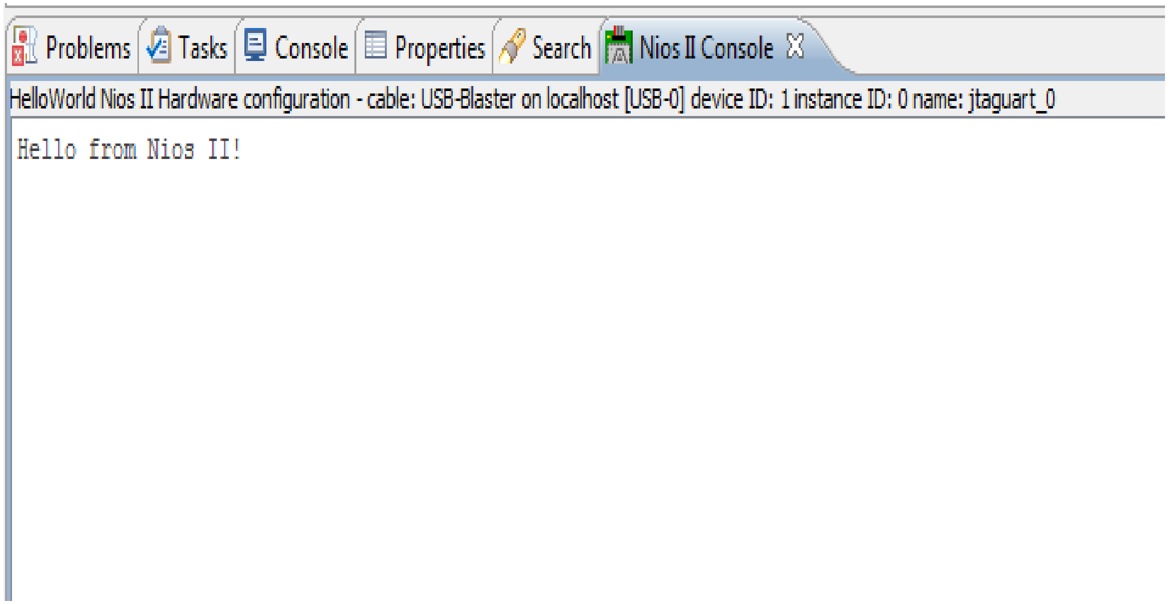
NIOS II Quartus Programmer

- NIOS II > Quartus II Programmer
- Make sure your DE2i-150 board is plugged into the USB port
- Hit Auto Detect
- Add File and select the EE443.sof file located in the EE443 folder
- Check Program/Configure
- Hit Start
- This configures FPGA to the NIOS II processor so you can use C



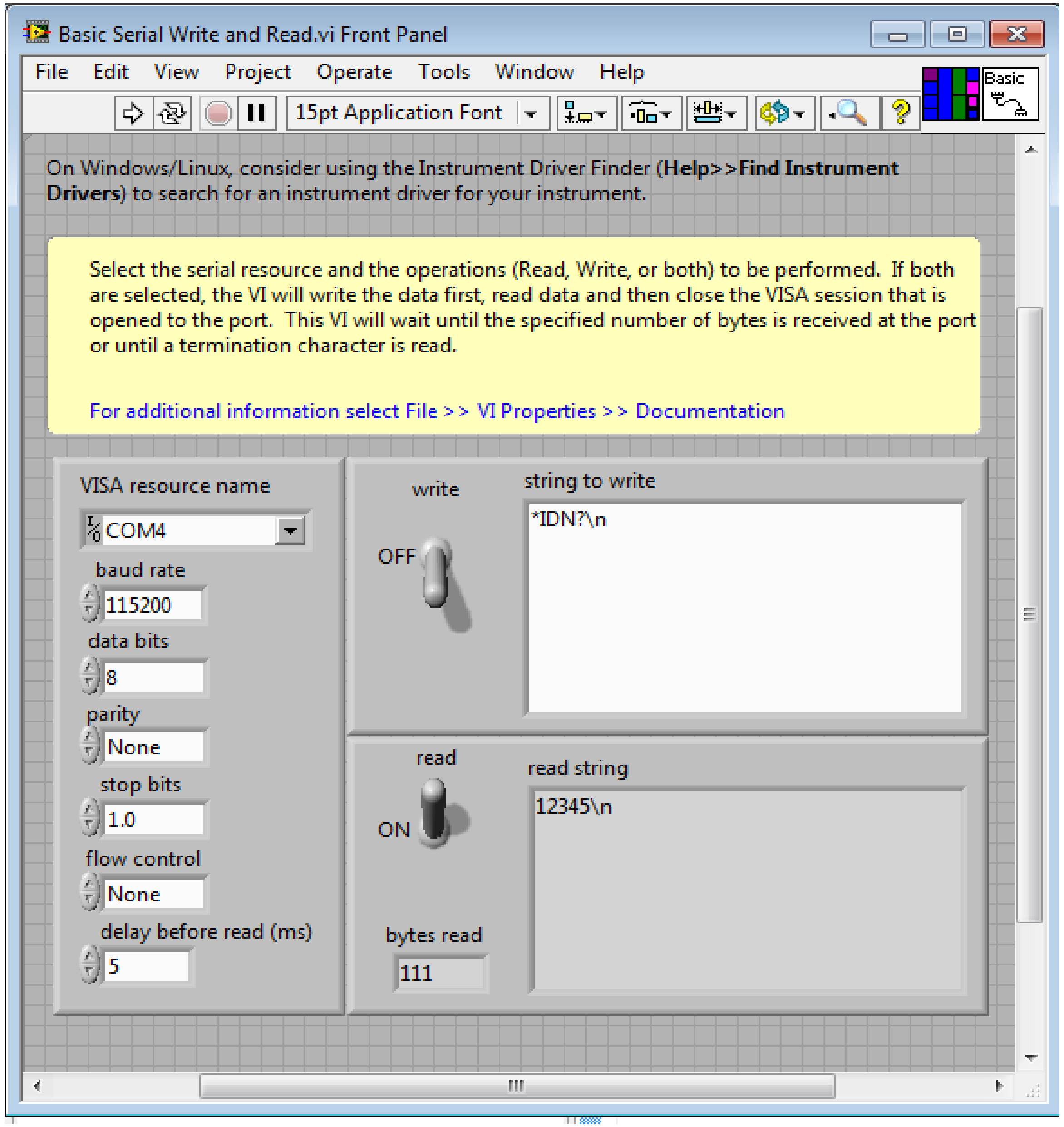
Running Program on DE2i-150

- Right click project folder
- Select Run As > NIOS II Hardware
- It should print out the words in the NIOS II Console tab at the bottom of the NIOS II Eclipse IDE
- Use the switches and keys to control the LEDs
- Run the Matlab program to print received data from the UART



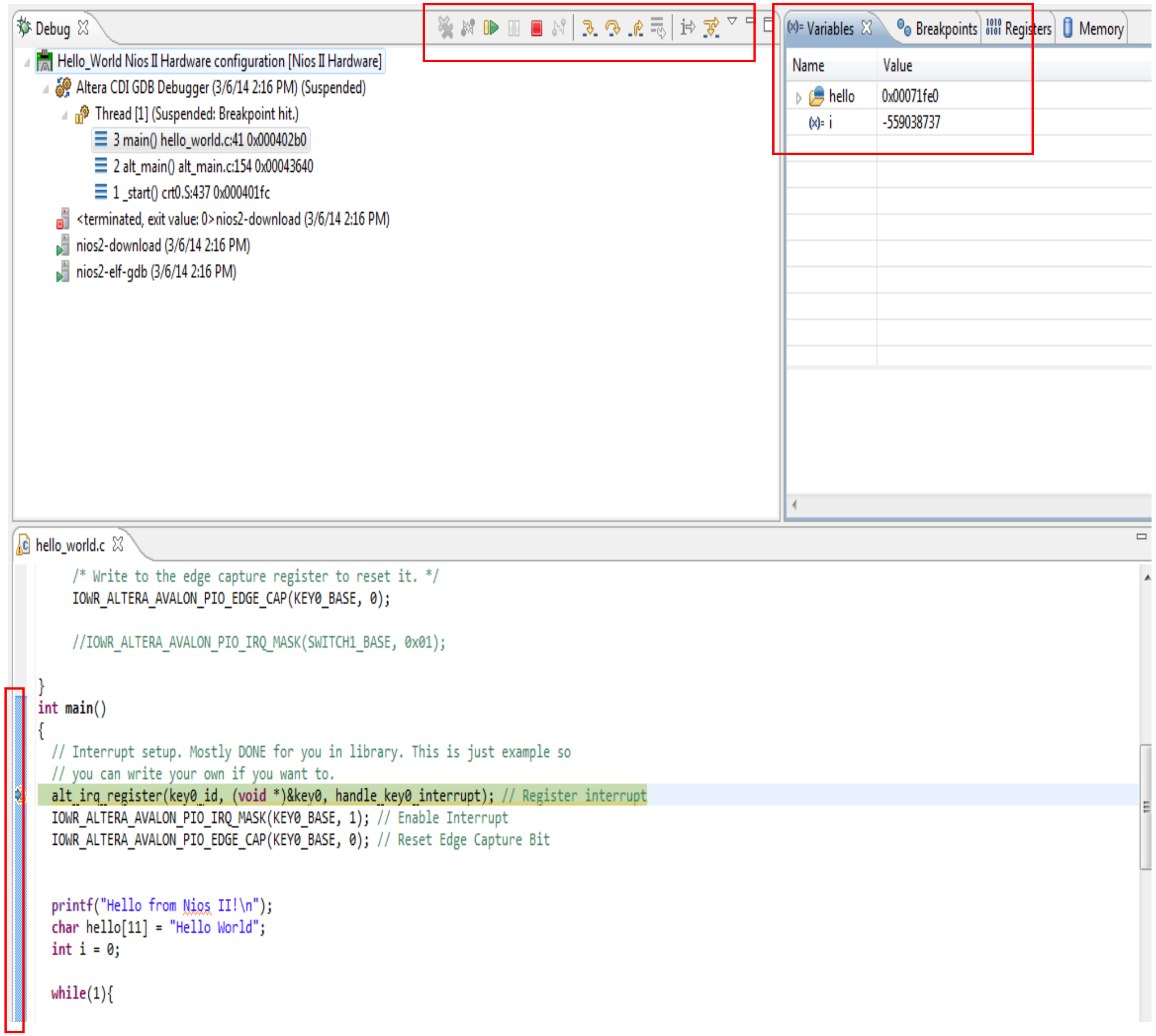
LabVIEW

- Locate the Basic Serial Write and Read.vi LabVIEW example from the Help Menu
- Not as accurate as MATLAB when tested but LabVIEW is much better at GUI creation and plotting support
- You can find better examples online
- Up to you to choose which one to use



Debugger

- Use debugger to step through the execution of your code and check variables, registers, etc for bugs
- Hit the  icon instead of the run icon to enter Debug Mode.
- You can then use the controls to step through your code
- Add breakpoints to pause code during execution



Bugs

- If your board becomes unresponsive, reload the EE443.sof file using the Quartus II Programmer to reset it.
- Then reprogram the NIOS II Project onto the board
- Will fix most unresponsive programs
- If you don’t close the serial COM port in Matlab when finished, you will have to restart Matlab

Yocto

- Embedded Linux platform called Yocto on the Intel Atom
- Has a graphical interface if you plug into a monitor via VGA
- Can use mouse and keyboard
- Has gcc compiler for C programs and basic programs installed
- No Desktop
- Remote access via PuTTY and VNC
- Can play .wav files and input into AIC23 to process