ECE4703 REAL-TIME DSP: INTERFACING WITH I/O, DEBUGGING, AND PROFILING
Interfacing a DSP With the Real World

TMS320C6713 DSK:
- digital inputs = 4 DIP switches
- digital outputs = 4 LEDs
- ADC and DAC = AIC23 codec
DIP Switches and LEDs

LED and DIP switch interface functions are provided in dsk6713bsl.lib.

- Initialize the DSK with the BSL function DSK6713_init();
- Initialize DIP/LEDs with DSK6713_DIP_init() and/or DSK6713_LED_init()
- Read state of DIP switches with DSK6713_DIP_get(n)
- Change state of LEDs with DSK6713_LED_on(n) or DSK6713_LED_off(n) or DSK6713_LED_toggle(n)

where n=0, 1, 2, or 3.

Documentation is available in Board Support Library API (on course website).
AIC23 Codec

- AIC23 codec performs both ADC and DAC functions
- Stereo input and output (left+right channels)
- Initialization steps:
  - Initialize the DSK with the BSL function `DSK6713_init();`
  - Open the codec with the BSL function
    `hCodec = DSK6713_AIC23_openCodec(0,&config);`
    - “hCodec” is the codec “handle”. You can think of this as a unique address of the codec on the McBSP bus.
    - “config” is the default configuration of the codec. See the header file `dsk6713_aic23.h` and the AIC23 codec datasheet (link on the course web page) for details.
  - Optional: Set the codec sampling frequency.
  - Configure the McBSP to transmit/receive 32 bits (two 16 bit samples) with the CSL function `McBSP_FSETS()`
  - Set up and enable interrupts
Codec Initialization Example (from Kehtarnavaz)

**Initialization steps:**
1. Initialize the DSK
2. Open the codec with the default configuration.
3. Configure multi-channel buffered serial port (McBSP)
   - SPCR = serial port control register
   - RCR = receive control register
   - XCR = transmit control register
   - See SPRU508e.pdf
4. Set the sampling rate
5. Configure and enable interrupts
6. Do normal processing (we just enter a loop here)

```c
interrupt void serialPortRcvISR(void); // ISR function prototype

void main()
{
  DSK6713_init(); // Initialize the board support library, must be called first
  hCodec = DSK6713_AIC23_openCodec(0, &config); // Open the codec

  // Configure buffered serial ports for 32 bit operation
  // This allows transfer of both right and left channels in one read/write
  MCBSP_FSETS(SPCR1, RINTM, FRM);
  MCBSP_FSETS(SPCR1, XINTM, FRM);
  MCBSP_FSETS(RCR1, RWDLEN1, 32BIT);
  MCBSP_FSETS(XCR1, XWDLEN1, 32BIT);

  DSK6713_AIC23_setFreq(hCodec, DSK6713_AIC23_FREQ_48KHZ); // set the sampling rate

  // Interrupt setup
  IRQ_globalDisable(); // Globally disables interrupts
  IRQ_nmiEnable(); // Enables the NMI interrupt
  IRQ_map(IRQ_EVT_RINT1, 15); // Maps an event to a physical interrupt
  IRQ_enable(IRQ_EVT_RINT1); // Enables the event
  IRQ_globalEnable(); // Globally enables interrupts

  while(1)
  {
  }
}```
AIC23 Codec: Interrupts

- We will use an **interrupt interface** between the DSP and the codec.
- DSP can do useful things while waiting for samples to arrive from codec, e.g. check DIP switches, toggle LEDs
- **C6x interrupt basics:**
  - Interrupt sources must be mapped to interrupt events
    - 16 physical “interrupt sources” (timers, serial ports, codec, ...)
    - 12 logical “interrupt events” (INT4 to INT15)
  - Interrupt events have associated “interrupt vectors”. An “interrupt vector” is a special pointer to the start of the “interrupt service routine” (ISR).
  - Interrupt vectors must be set up in your code (usually in the file “vectors.asm”).
  - You are also responsible for writing the ISR.
Interrupts

**main code**

*physical interrupt source X linked to logical interrupt event N*

*interrupts enabled*

*interrupt event N occurs (state is automatically saved)*

**interrupt vector N**

*branch to interrupt service routine*

**interrupt service routine**

*do something useful*

*make sure the ISR completes before the next interrupt occurs*

*return to main code*
Interrupt Vector

- We usually link the physical codec interrupt to INT15.
- The ISR in this example is called “serialPortRcvISR” (you can rename it if you like).
- C function “x” is called “_x” in ASM files.
- The interrupt vector is usually in the vectors.asm file:
- Each interrupt vector must be exactly 8 ASM instructions

```
INT15:
  MVKL .S2 _serialPortRcvISR, B0
  MVKH .S2 _serialPortRcvISR, B0
  B .S2 B0
  NOP
  NOP
  NOP
  NOP
  NOP
  NOP
```
A Simple Interrupt Service Routine

Remarks:
• `MCBSP_read()` requests L+R samples from the codec’s ADC
• `MCBSP_write()` sends L+R samples to the codec’s DAC
• This ISR simply reads in samples and then sends them back out.
Setting the Codec Sampling Frequency

Here we open the codec with the default configuration:

```c
hCodec = DSK6713_AIC23_openCodec(0, &config); // Open the codec
```

The structure “config” is declared in `dsk6713_aic23.h`

Rather than editing the default configuration in the header file, we can change the sampling frequency after the initial configuration:

```c
DSK6713_AIC23_setFreq(hCodec, DSK6713_AIC23_FREQ_48KHZ); // set the sampling rate
```

Frequency definitions are in `dsk6713_aic.h`

```c
#ifdef Frequency_Definitions */
#define DSK6713_AIC23_FREQ_8KHZ 1
#define DSK6713_AIC23_FREQ_16KHZ 2
#define DSK6713_AIC23_FREQ_24KHZ 3
#define DSK6713_AIC23_FREQ_32KHZ 4
#define DSK6713_AIC23_FREQ_44KHZ 5
#define DSK6713_AIC23_FREQ_48KHZ 6
#define DSK6713_AIC23_FREQ_96KHZ 7

This is actually 44.1kHz
```
Other Codec Configuration

- Line input volume level (individually controllable for left and right channels)
- Headphone output volume level (individually controllable for left and right channels)
- Digital word size (16, 20, 24, or 32 bit)
- Other settings, e.g. byte order, etc. For more details, see:
  - dsk6713_aic23.h
  - AIC23 codec datasheet (link on course web page)
Codec Data Format and How To Separate the Left/Right Channels

// we can use the union construct in C to have
// the same memory referenced by two different variables
union {Uint32 combo; short channel[2];} temp;

// the McBSP functions require that we
// read/write data to/from the Uint32 variable
temp.combo = MCBSP_read(DSK6713_AIC23_DATAHANDLE);
MCBSP_write(DSK6713_AIC23_DATAHANDLE, temp.combo);

// but if we want to access the left/right channels individually
// we can do this through the short variables
Leftchannel = temp.channel[1];
Rightchannel = temp.channel[0];
Final Remarks on DSP/Codec Interface

- In most real-time DSP applications, you process samples as they become available from the codec’s ADC (sample-by-sample operation).
- This means that all processing will be done in the ISR.
  - MCBSP_read()
  - --- processing here ---
  - MCBSP_write()
- The ISR must run in real-time, i.e. the total execution time must be less than one sampling period.
- You can do other tasks, e.g. DIP/LED processing, outside of the ISR (in your main code).
C6713 DSK Memory Architecture

- TSM320C6713 DSP chip has 256kB internal SRAM
  - Up to 64kB of this SRAM can be configured as shared L2 cache
- DSK provides additional 16MB external RAM (SDRAM)
- DSK also provides 512kB external FLASH memory
- Code location (.text in linker command file)
  - internal SRAM memory (fast)
  - external SDRAM memory (typically 2-4x slower, depends on cache configuration)
- Data location (.data in linker command file)
  - internal SRAM memory (fast)
  - external SDRAM memory (slower, depends on datatypes and cache configuration)
- Code+data for all projects assigned in ECE4703 should fit in the C6713 internal SRAM
TMS320C6713 DSK Memory Map

0000 0000

0003 FFFF

Internal SRAM (256kB)

8000 0000

8007 FFFF

FLASH

8000 0000

8FFF FFFF

External SDRAM (16MB)

8000 0000

8007 FFFF

your code+data here
Linker Command File Example (part 1)

```
--diag Suppress=16002
```

suppress warnings about missing vendor id

```
MEMORY
{
  VECS o = 0x00000000 l = 0x00000200 /* interrupt vectors */
  IRAM  o = 0x00000200 l = 0x0002FE00 /* 192kB - Internal RAM */
  L2RAM o = 0x00030000 l = 0x00010000 /* 64kB - Internal RAM/CACHE */
  EMIFCE0 o = 0x80000000 l = 0x10000000 /* SDRAM in 6713 DSK */
  EMIFCE1 o = 0x90000000 l = 0x10000000 /* Flash/CPLD in 6713 DSK */
  EMIFCE2 o = 0xA0000000 l = 0x10000000 /* Daughterboard in 6713 DSK */
  EMIFCE3 o = 0xB0000000 l = 0x10000000 /* Daughterboard in 6713 DSK */
}
```

Interrupt vectors start at 00000000.

Addresses 00000000-0002FFFFF correspond to the lowest 192kB of internal memory (SRAM) and are labeled “IRAM”.

External memory is mapped to address range 80000000 – 80FFFFFF. This is 16MB and is labeled “EMIFCE0”.

Memory map with labels
Linker Command File Example (part 2)

**SECTIONS**
*Tells the compiler/linker where to put things in memory*

```
{ 
    "vectors" > VECS
    .text > IRAM
    .stack > IRAM
    .bss > IRAM
    .cio > IRAM
    .const > IRAM
    .data > IRAM
    .switch > IRAM
    .sysmem > IRAM
    .far > IRAM
    .args > IRAM
    .ppinfo > IRAM
    .ppdata > IRAM
    /* COFF sections */
    .pinit > IRAM
    .cinit > IRAM
    /* EABI sections */
    .binit > IRAM
    .init_array > IRAM
    .neardata > IRAM
    .fardata > IRAM
    .rodata > IRAM
    .rodata > IRAM
    .c6xabi.exidx > IRAM
    .c6xabi.extab > IRAM
}
```

- **Interrupt vectors go here**
- **Code goes here**
- **Data goes here**

Both code and data are placed in the C6713 internal SRAM in this example. Interrupt vectors are also in SRAM.
vectors.asm

- This file contains your interrupt vectors
- "sect" directive at top of file tells linker where (in memory) to put this code
- Each interrupt vector is composed of exactly 8 assembly language instructions
- Example:

```assembly
INT15:
MVKL .S2 _serialPortRcvISR, B0
MVKH .S2 _serialPortRcvISR, B0
B .S2 B0
NOP
NOP
NOP
NOP
NOP
```
Debugging and Other Useful Features of the CCS IDE

- Breakpoints and stepping through your code
- Watch variables
- Registers
- Plotting arrays of data
Breakpoints: Just Double-Click

- **Breakpoints**: stop code execution at this point to allow state examination and step-by-step execution.
- Also try View->Breakpoints
Using Breakpoints

- ASM step into
- ASM step over
- source step into
- source step over
- suspend
- run/resume
- terminate
- CPU reset
- restart
- refresh
View Local Variables

- View -> Variables

- All local variables should appear automatically. You can’t see global variables here.
View Global Variables

- View->Expressions

- Type in any global variable name (or drag a variable name from the editor)
Some tips:

- You can change the number format (right click on the “type”)

- You can force data into global/local variables by double clicking on the “value” and putting a new value in.
## Registers: View->Registers

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>0x000000F</td>
<td>Core</td>
</tr>
<tr>
<td>A1</td>
<td>0x0000001</td>
<td>Core</td>
</tr>
<tr>
<td>A2</td>
<td>0x0000000</td>
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<td>A3</td>
<td>0x24000000</td>
<td>Core</td>
</tr>
<tr>
<td>A4</td>
<td>0x0000000</td>
<td>Core</td>
</tr>
<tr>
<td>A5</td>
<td>0x0000001</td>
<td>Core</td>
</tr>
<tr>
<td>A6</td>
<td>0x0000000</td>
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<td>A13</td>
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<tr>
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<td>0x799FE1C</td>
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<td>0xEFFFFFE</td>
<td>Core</td>
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<td>Core</td>
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<td>B1</td>
<td>0x000000DC</td>
<td>Core</td>
</tr>
<tr>
<td>B2</td>
<td>0x00000004</td>
<td>Core</td>
</tr>
<tr>
<td>B3</td>
<td>0x00000F8E</td>
<td>Core</td>
</tr>
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<td>B4</td>
<td>0x20301010</td>
<td>Core</td>
</tr>
<tr>
<td>B5</td>
<td>0x2C000000</td>
<td>Core</td>
</tr>
<tr>
<td>B6</td>
<td>0xFFFFFFFF</td>
<td>Core</td>
</tr>
<tr>
<td>B7</td>
<td>0x7C000000</td>
<td>Core</td>
</tr>
<tr>
<td>B8</td>
<td>0x00000010</td>
<td>Core</td>
</tr>
<tr>
<td>B9</td>
<td>0x000011A0</td>
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<td>Core</td>
</tr>
<tr>
<td>ISTP</td>
<td>0x00000000</td>
<td>Core</td>
</tr>
</tbody>
</table>
Plotting Arrays of Data

- Tools -> Graph -> (Typically “Single Time”)

Can type array name here
Graph Windows: Plotting Arrays of Data

Right click for lots of options.
Profiling Your Code and Making it More Efficient

- How to estimate the **execution time** of your code.
- How to use the **optimizing compiler** to produce more efficient code.
- Other factors affecting the efficiency of your code.
How to estimate code execution time when connected to the DSK

1. Open the source file you wish to profile
2. Set two breakpoints for the start/end of the code range you wish to profile
3. Build it and load .out file to the DSK
4. Run -> Clock -> Enable
5. Run -> Clock -> View
6. Run to the first breakpoint
7. Run -> Clock -> Reset (or double click the clock to reset the clock to zero)
8. Run to the second breakpoint
9. Clock will show raw number of execution cycles between breakpoints.
Optimizing Compiler

- Configuration: Debug [ Active ]
- Optimization level (--opt_level, -O)
- Optimize for code size (--opt_for_space, -ms)
Profiling results after compiler optimization

- Rebuild and reload the program to the DSK
- Use your breakpoint/clock method to profile the execution time
- In this example, we get a 5x-6x improvement with Level-3 Optimization
- Optimization gains can be much larger, e.g. 20x
Limitations of hardware profiling

- Variability of results
- Profiling is known to be somewhat inaccurate when connected to real hardware
- Breakpoint/clock profiling method may not always work with compiler-optimized code
- For the best results, TI recommends profiling your code in a cycle accurate simulator:
  - Change target configuration:
    - Connection = Texas Instruments Simulator
    - Device = C6713 Device Cycle Accurate Simulator, Little Endian
  - Need to create a new project for the simulator and copy your functions/code for profiling to this project without calls to board-specific functions
  - Tools -> Profile -> Setup and then Tools-> Profile -> View
Change target configuration for project to use cycle accurate simulator.
Code from ISR placed in a regular function called from main()

All calls to BSL functions removed

Not running on DSK
Inclusive: Includes calls to other functions
Exclusive: Does not include calls to other functions
Results should be more accurate than hardware profiling.
Other factors affecting code efficiency

- **Memory**
  - Code location (`.text` in linker command file)
    - Internal SRAM memory (fast)
    - External SDRAM memory (typically 2-4x slower, depends on cache configuration)
  - Data location (`.data` in linker command file)
    - Internal SRAM memory (fast)
    - External SDRAM memory (slower, depends on datatypes and cache configuration)

- **Data types**
  - Slowest execution is double-precision floating point
  - Fastest execution is fixed point, e.g. short

Example: Stereoloop project, changing `.text` and `.data` to external SDRAM: About 2.5x slower than SRAM (can be worse)
<table>
<thead>
<tr>
<th>Type</th>
<th>Size</th>
<th>Representation</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>char, signed char</td>
<td>8 bits</td>
<td>ASCII</td>
<td>-128</td>
<td>127</td>
</tr>
<tr>
<td>unsigned char</td>
<td>8 bits</td>
<td>ASCII</td>
<td>0</td>
<td>255</td>
</tr>
<tr>
<td>short</td>
<td>16 bits</td>
<td>2s complement</td>
<td>-32768</td>
<td>32767</td>
</tr>
<tr>
<td>unsigned short</td>
<td>16 bits</td>
<td>Binary</td>
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<td>int, signed int</td>
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<td>IEEE 32-bit</td>
<td>2.22507385e-308†</td>
<td>1.79769313e+308</td>
</tr>
</tbody>
</table>
Final Remarks

- You should have enough information to complete Lab 1
  - Tutorials on course website
  - Lab/lecture slides
  - Reference material noted in slides
  - Textbooks listed in syllabus
  - Please make sure you understand what you are doing. Please ask questions if you are unsure.