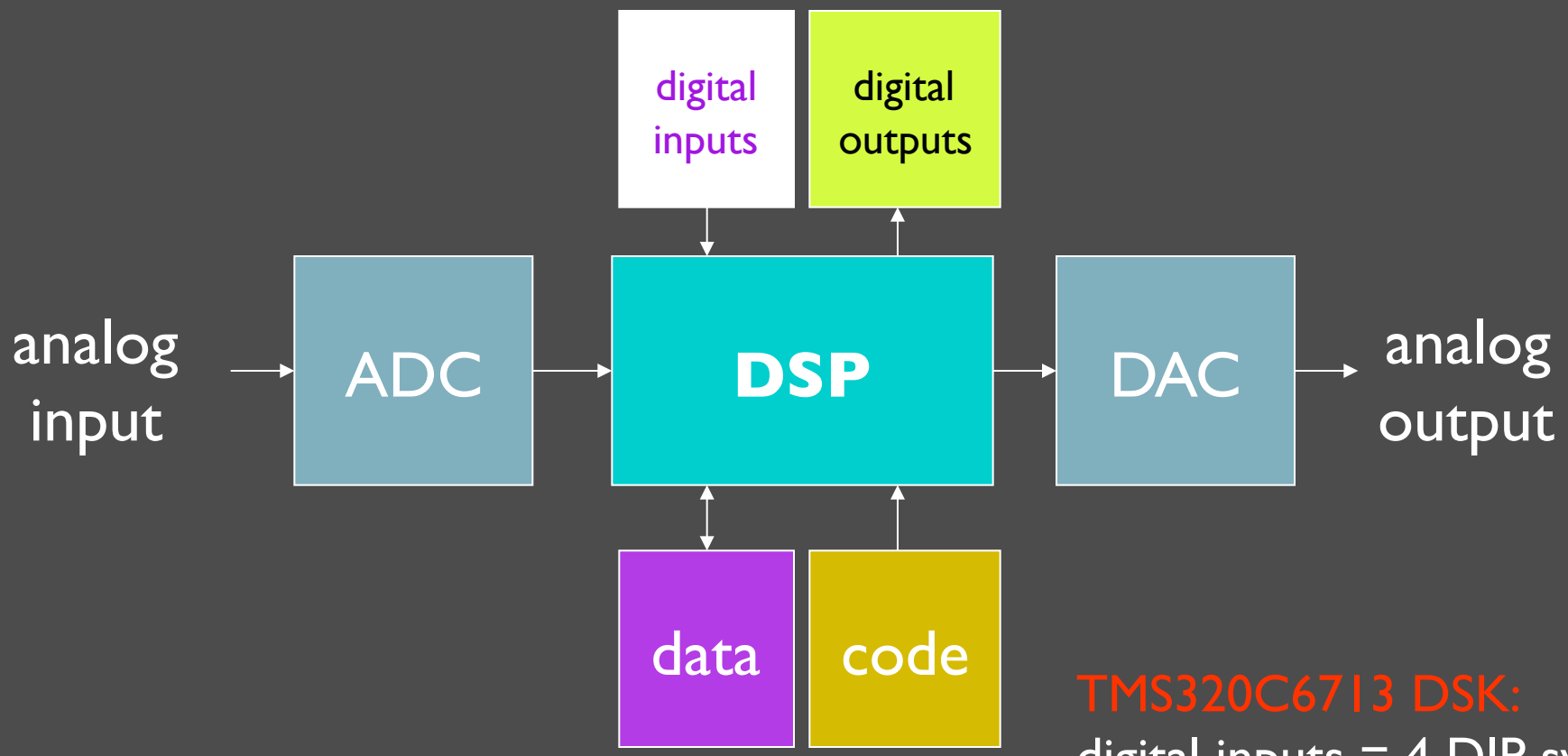
D. Richard Brown III
Associate Professor
Worcester Polytechnic Institute
Electrical and Computer Engineering Department
drb@ece.wpi.edu

29-October-2009

# 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 C:\CCStudio_v3.1\docs\hlp\c6713dsk.hlp

# 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:

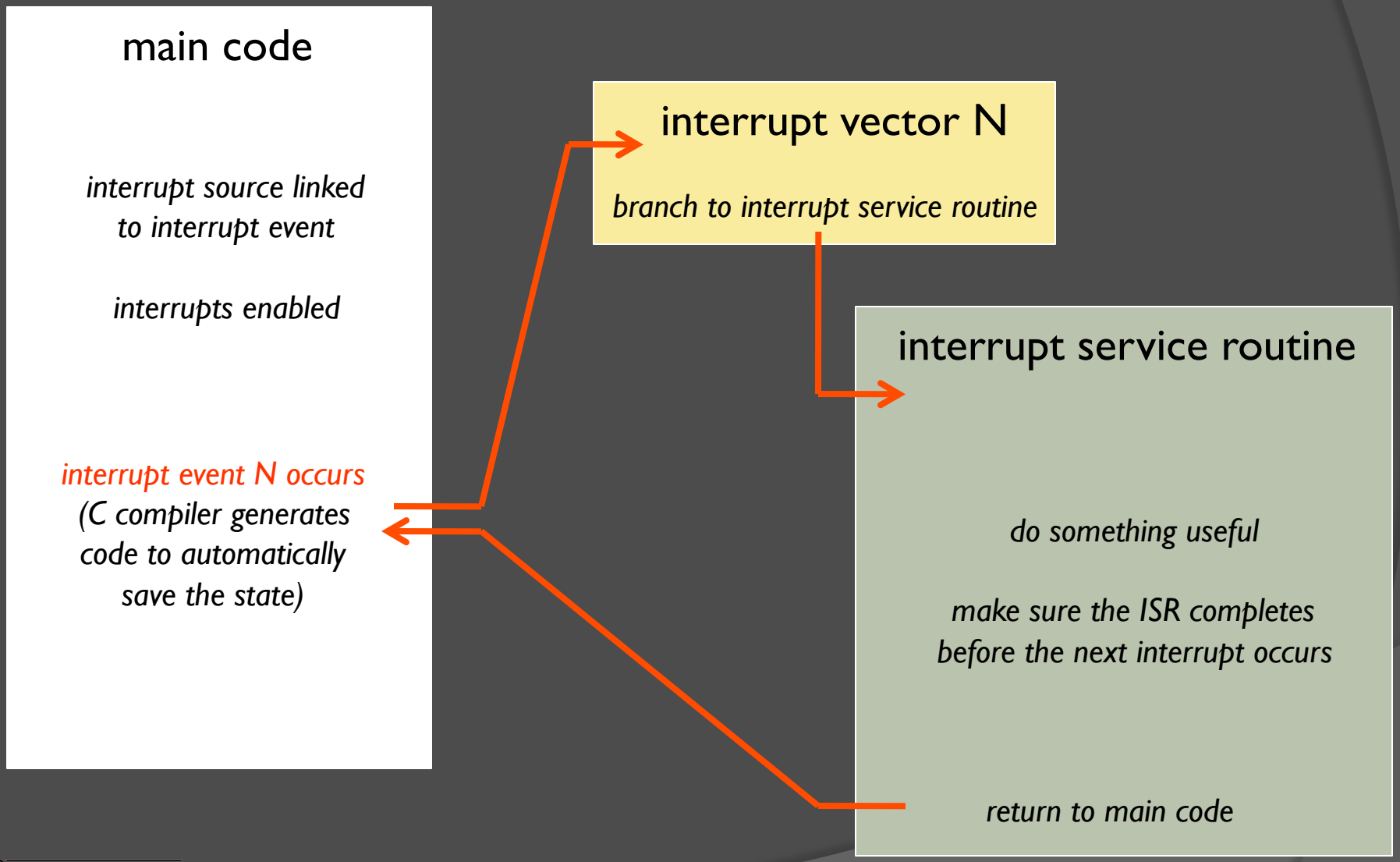
1. Initialize the DSK
2. Open the codec with the default configuration.
3. Configure multi-channel buffered serial port (McBSP)
   - SPCR = serial port control register
   - RCR = receive control register
   - XCR = transmit control register
   - See SPRU508e.pdf
4. Set the sampling rate
5. Configure 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
- C6x interrupt basics:
  - Interrupt sources must be mapped to interrupt events
    - 16 "interrupt sources" (timers, serial ports, codec, …)
    - 12 "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
interrupt source linked to interrupt event
interrupts enabled
interrupt event N occurs
(C compiler generates code to automatically save the state)
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 have linked the codec interrupt event to INT15.
- The ISR in this example is called "serialPortRcvISR".
- The interrupt vector is usually in the vectors.asm file:

```
INT15:
    MVKL .S2 _serialPortRcvISR, B0
    MVKH .S2 _serialPortRcvISR, B0
    B    .S2 B0
    NOP
    NOP
    NOP
    NOP
    NOP
```

# A Simple Interrupt Service Routine

```
interrupt void serialPortRcvISR()
{
    Uint32 temp;

    temp = MCBSP_read(DSK6713_AIC23_DATAHANDLE);  // read L+R channels
    MCBSP_write(DSK6713_AIC23_DATAHANDLE,temp);   // write L+R channels
}
```

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:

```
26    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:

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

Frequency definitions are in dsk6713_aic.h

```
/* 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
```

# 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)
  - C:\CCStudio_v3.1\docs\hlp\c6713dsk.hlp

# 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];
```

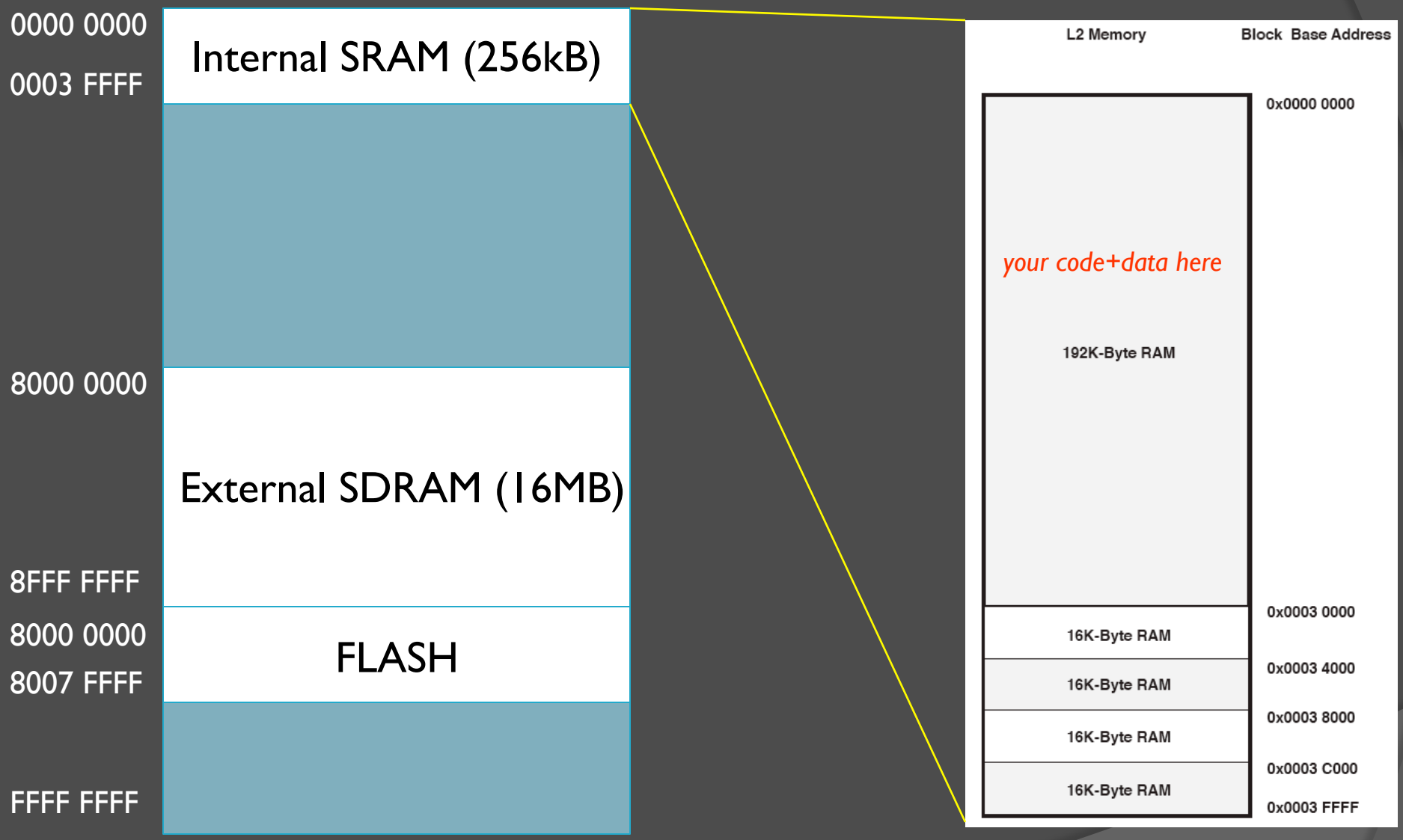
# Final Remarks on DSP/Codec Interface

- In real-time DSP applications, we will process samples as they become available from the codec's ADC.
- This means that all processing will be done in the ISR.
- The ISR must run in real-time, i.e. the total execution time must be less than one sampling period.
- You can do DIP/LED processing outside of the ISR (in your main code).
- Look at Kehtarnavaz Lab 2 for examples.

# 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 this class should fit in the C6713 internal SRAM

# TMS320C6713 DSK Memory Map



# Linker Command File Example

```
MEMORY
{
    vecs:       o = 00000000h       l = 00000200h
    IRAM:       o = 00000200h       l = 0002FE00h
    CE0:        o = 80000000h       l = 01000000h
}

SECTIONS
{
    .vectors    >       vecs
    .cinit      >       IRAM
    .text       >       IRAM
    .stack      >       IRAM
    .bss        >       IRAM
    .const      >       IRAM
    .data       >       IRAM
    .far        >       IRAM
    .switch     >       IRAM
    .sysmem     >       IRAM
    .tables     >       IRAM
    .cio        >       IRAM
}
```

*Code goes here*

*Data goes here*

Addresses 00000000-0002FFFF 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 "CE0".

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

# vectors.asm

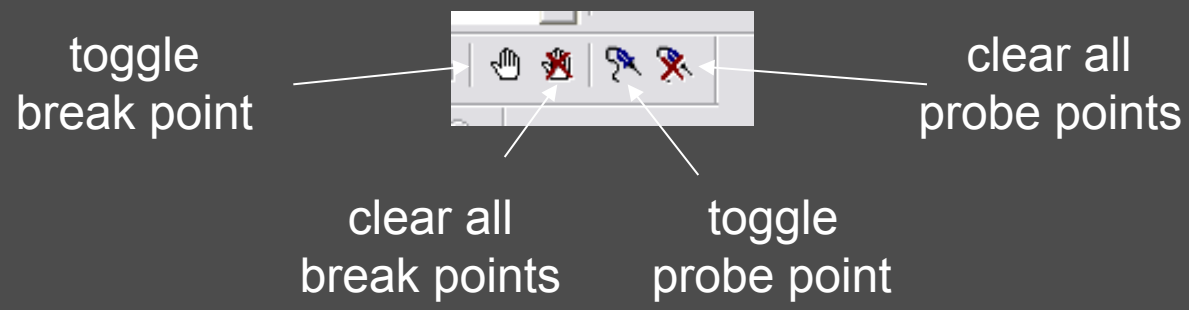
- This file contains your interrupt vectors
- ".sect" directive at top of file tells linker where (in memory) to put the code
- Each interrupt vector is composed of exactly 8 assembly language instructions
- Example:

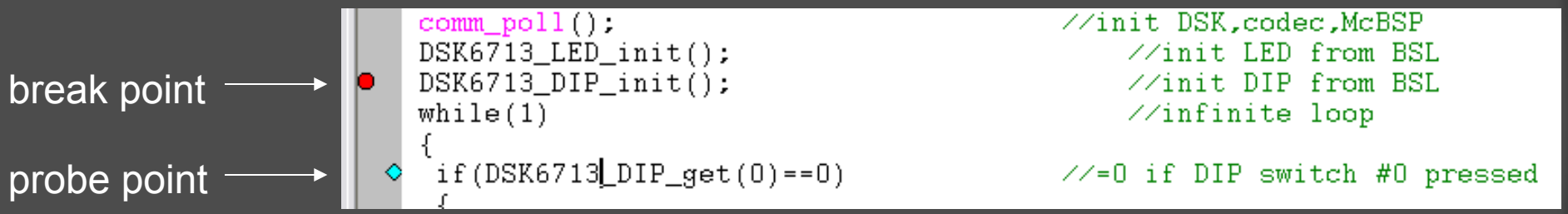
```
INT15:
        MVKL .S2 _serialPortRcvISR, B0
        MVKH .S2 _serialPortRcvISR, B0
        B    .S2 B0
        NOP
        NOP
        NOP
        NOP
        NOP
```

# Debugging and Other Useful Features of the CCS IDE

- Breakpoints
- Probe points
- Watch variables
- Plotting arrays of data
- Animation
- General Extension Language (GEL)

# Breakpoints and Probe Points



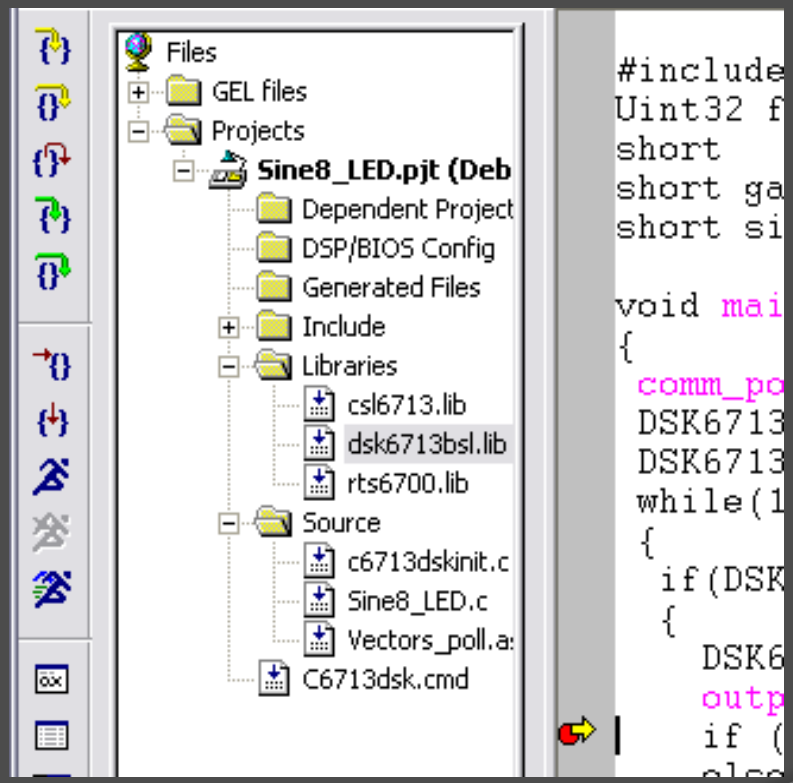




- Breakpoints: stop code execution at this point to allow state examination and step-by-step execution.
- Probe points: force window updates and/or read/write samples from/to a file at a specific point in your code.

# Breakpoints

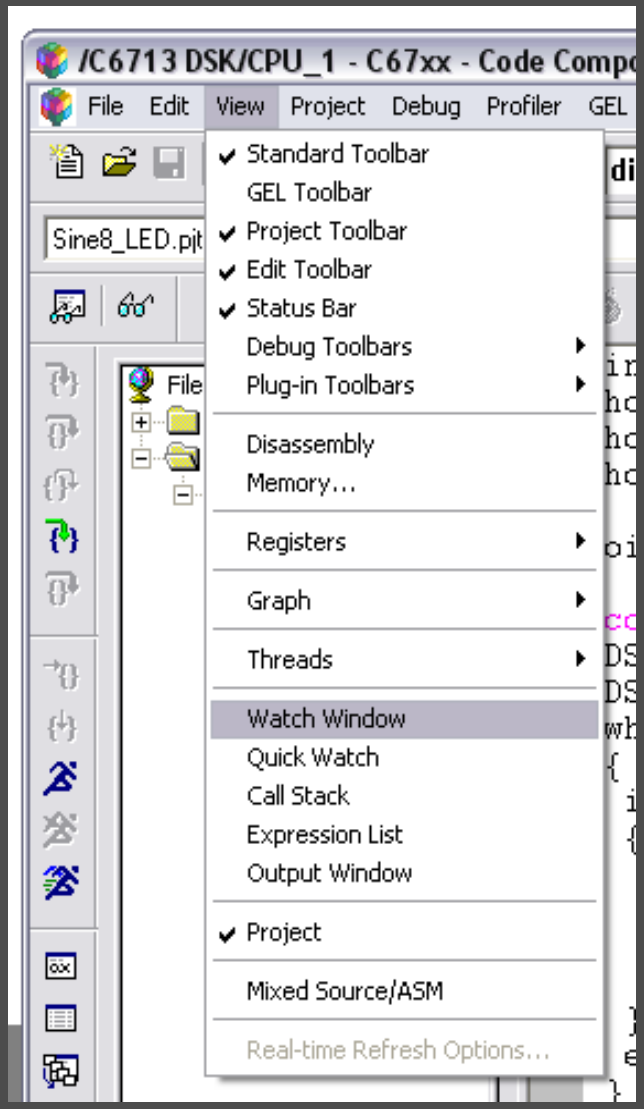
source step into
source step over
step out
ASM step into
ASM step over

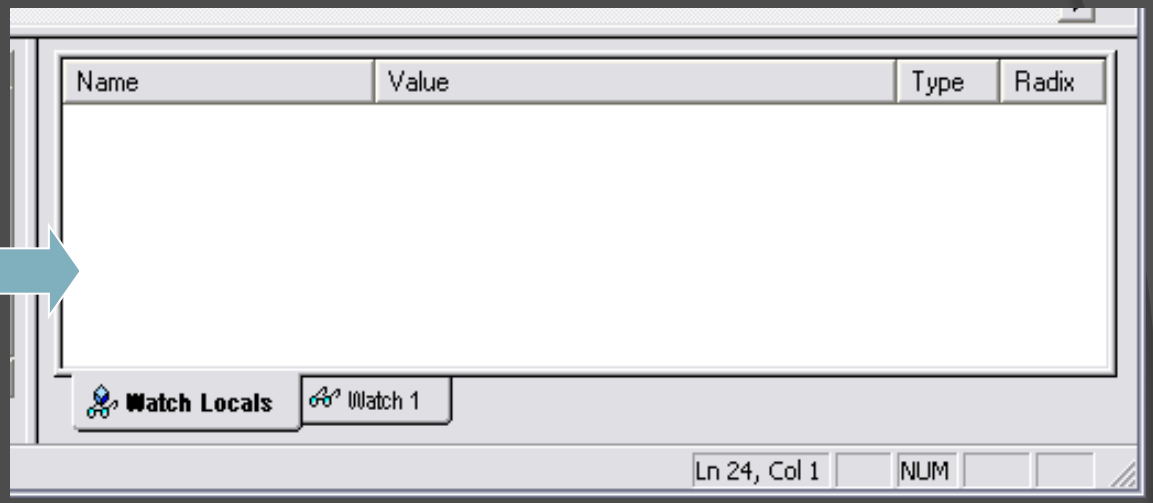
run to cursor
set progam counter to cursor

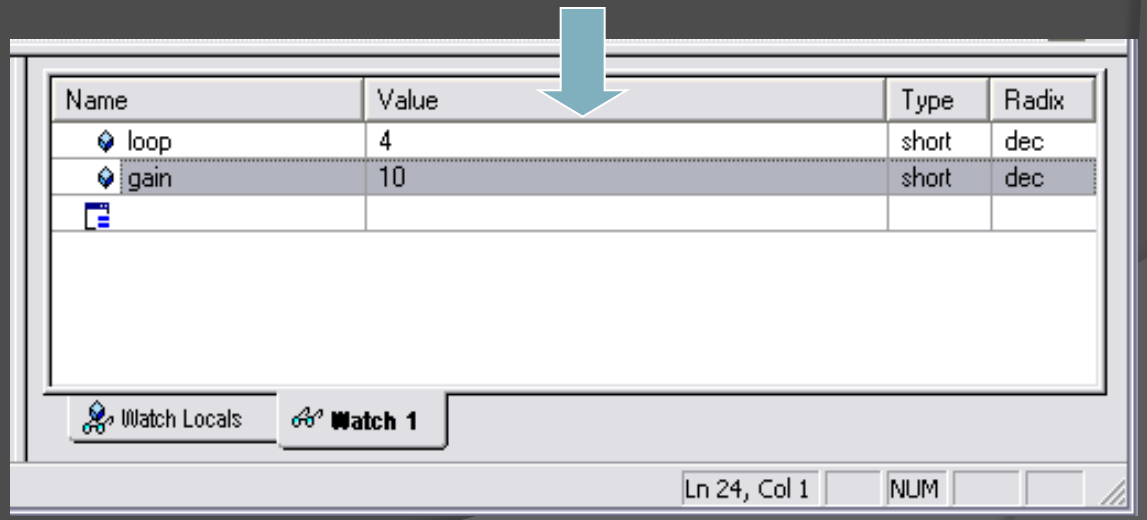



"Run to Cursor" is a handy shortcut instead of setting a breakpoint

# Watch Variables



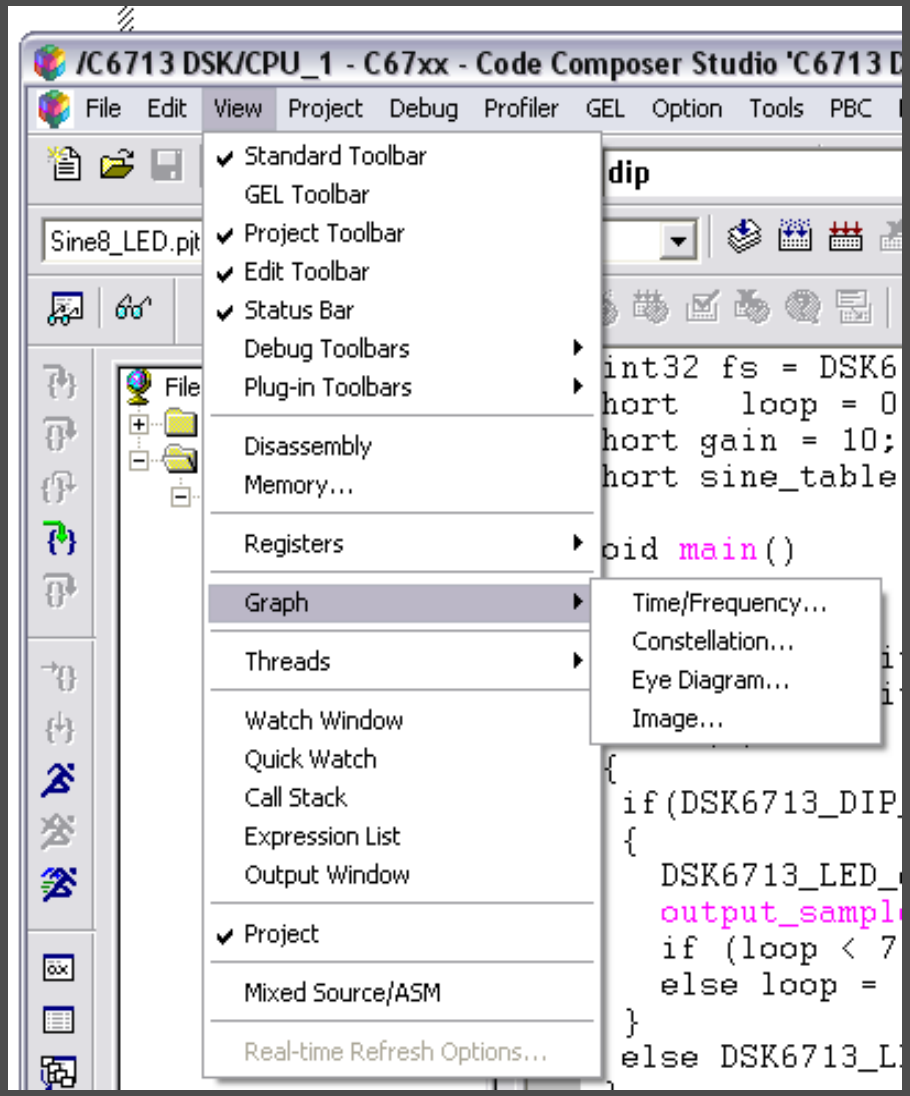



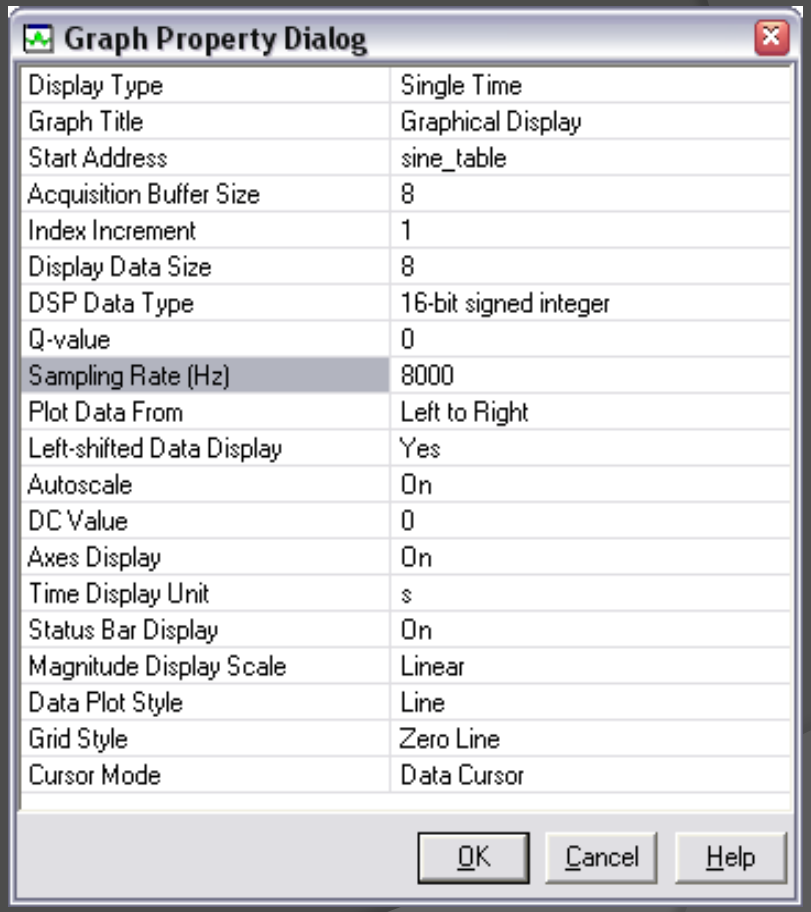



# Watch Variables

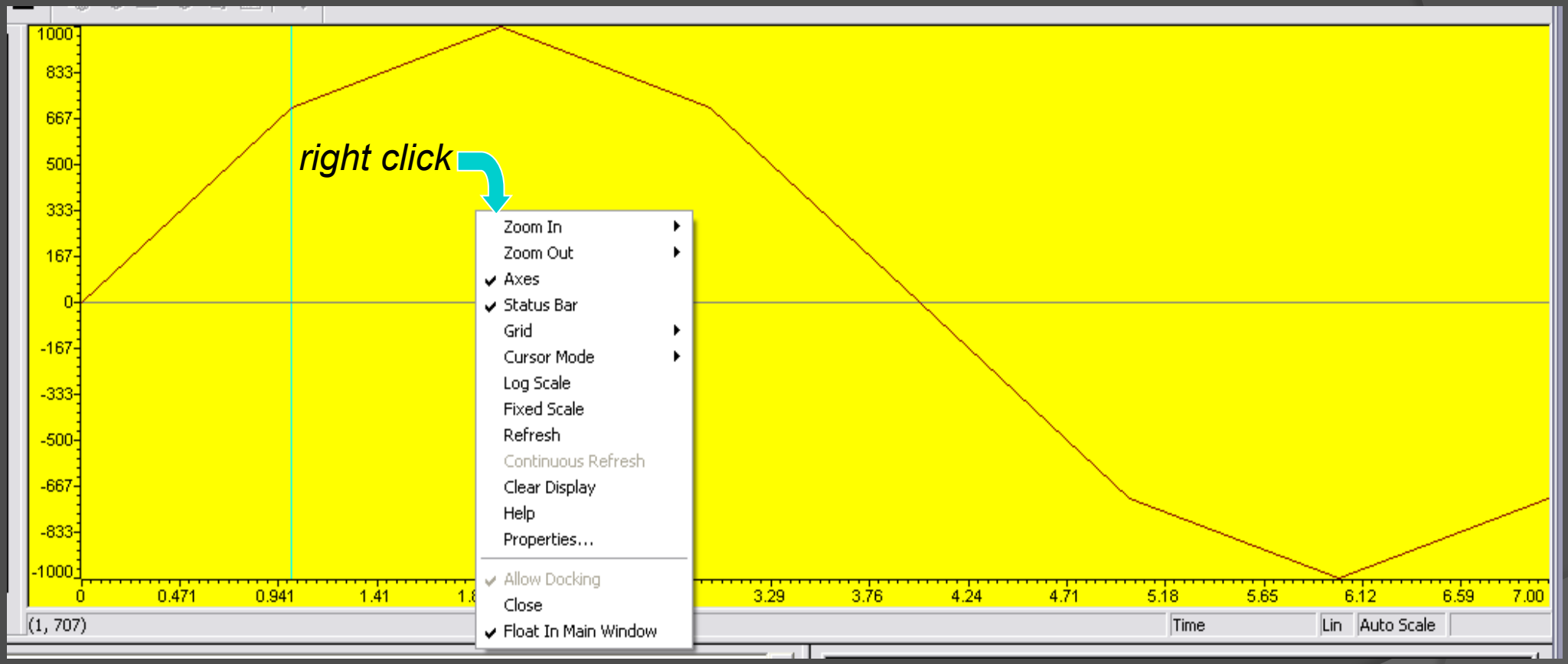
- In the Watch Locals tab, the debugger *automatically* displays the Name, Value, and Type of the variables that are *local* to the currently executing function.
- In the Watch tab, the debugger displays the Name, Value, and Type of the local and global variables and expressions that *you specify*.
- Can add/delete tabs.

# Plotting Arrays of Data



# Graph Windows: Plotting Arrays of Data

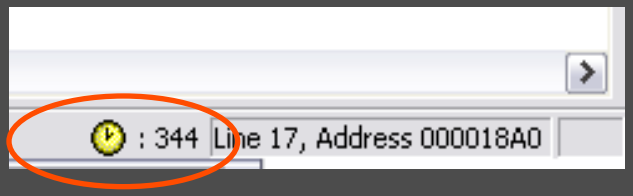


# Profiling Your Code and Making it More Efficient

- 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. Start CCS with the C6713 DSK connected
2. Debug -> Connect (or alt+C)
3. Open project, build it, and load .out file to the DSK
4. Open the source file you wish to profile
5. Set two breakpoints for the start/end of the code range you wish to profile
6. Profile -> Clock -> Enable
7. Profile -> Clock -> View
8. Run to the first breakpoint
9. Reset the clock
10. Run to the second breakpoint
11. Clock will show raw number of execution cycles between breakpoints.



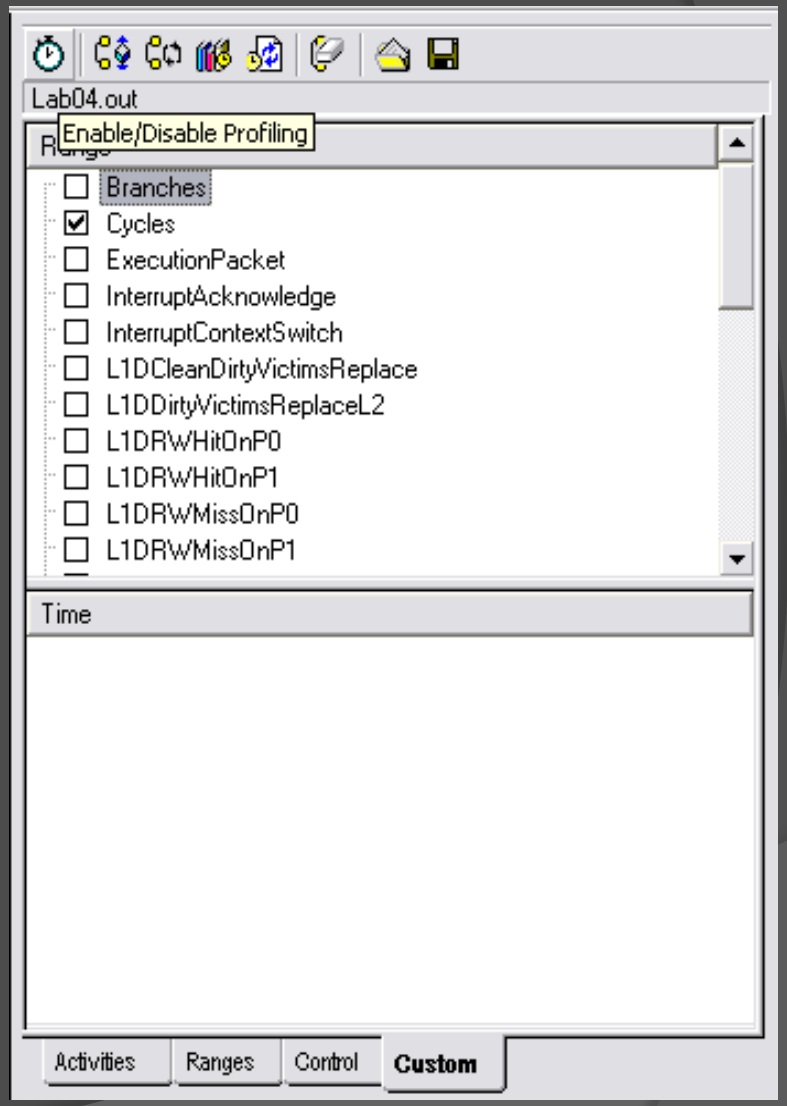

Tip: You can save your breakpoints, probe points, graphs, and watch windows with

File -> Workspace -> Save Workspace As

# Another method for estimating code execution time (part 1 of 3)

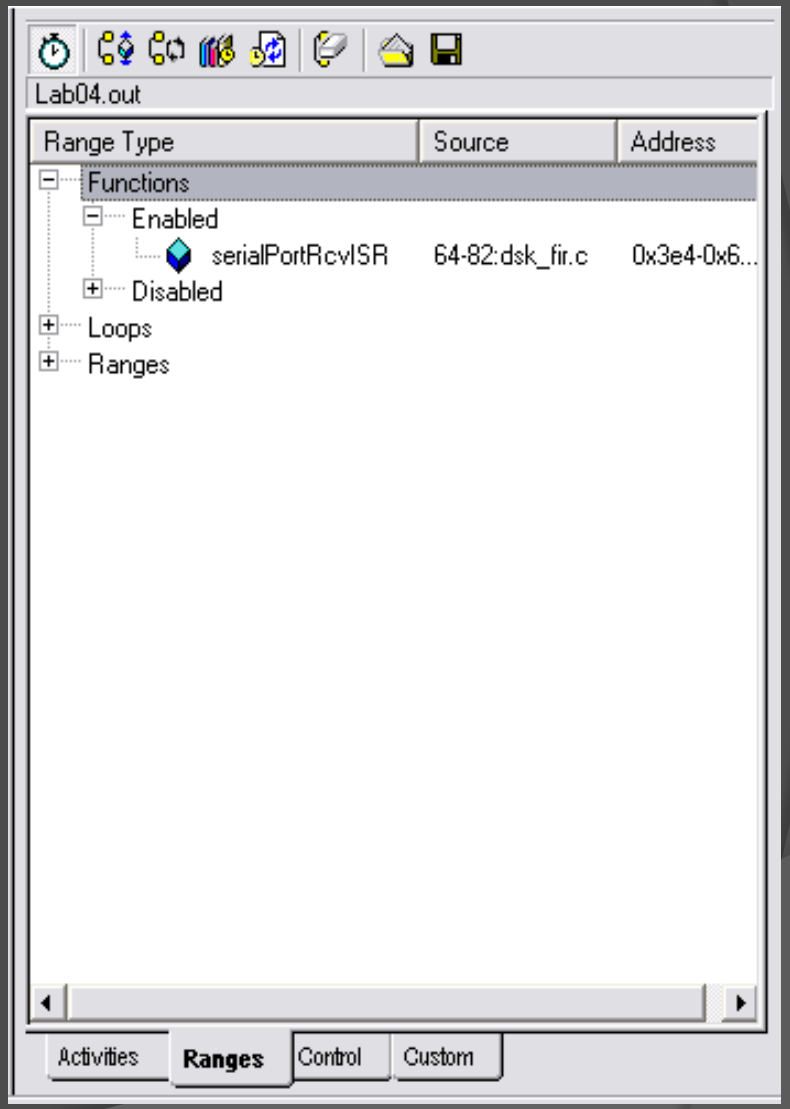
Repeat steps 1-4 previous method.

5. Clear any breakpoints in your code
6. Profile -> Setup
7. Click on Custom tab
8. Select "Cycles"
9. Click on clock (enable profiling)



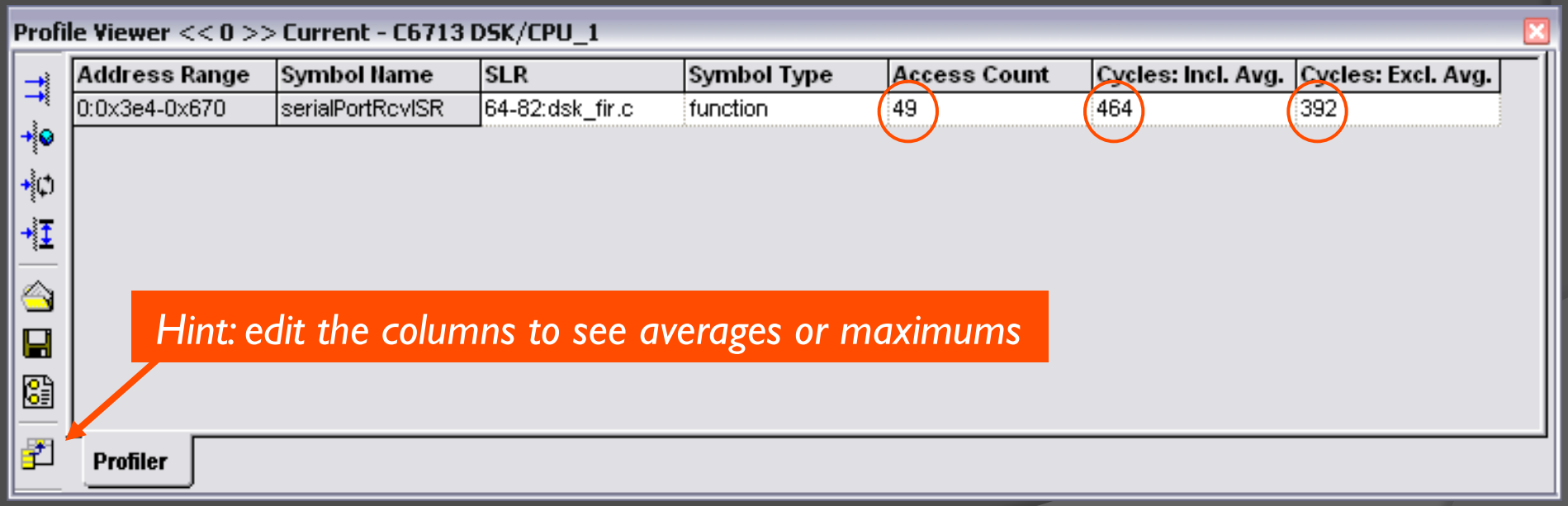
# Another method for estimating code execution time (part 2 of 3)

10. Select Ranges tab
11. Highlight code you want to profile and drag into ranges window (hint: you can drag whole functions into this window)
12. Repeat for other ranges if desired



# Another method for estimating code execution time (part 3 of 3)

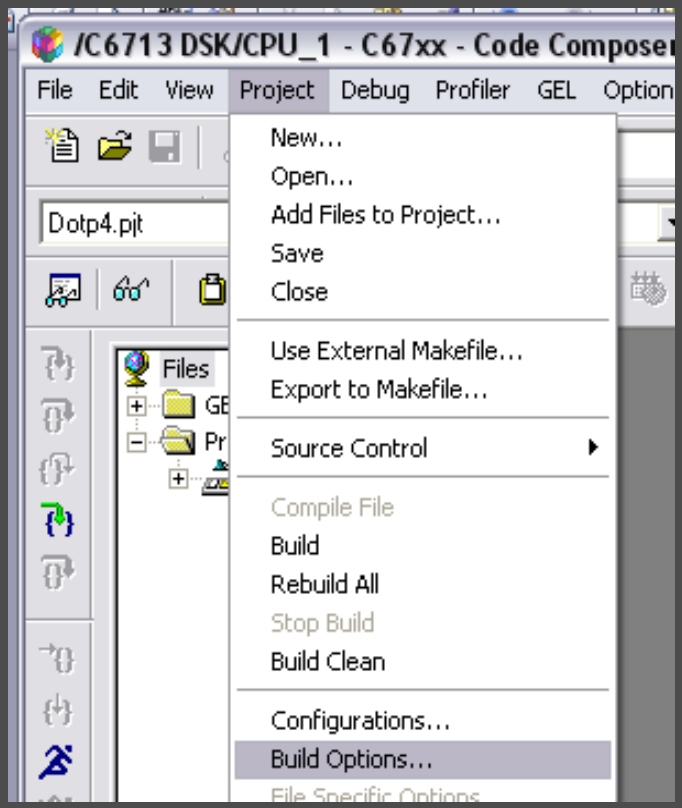
13. Profile -> Viewer
14. Run (let it run for a minute or more)
15. Halt
16. Observe profiling results in Profile Viewer window

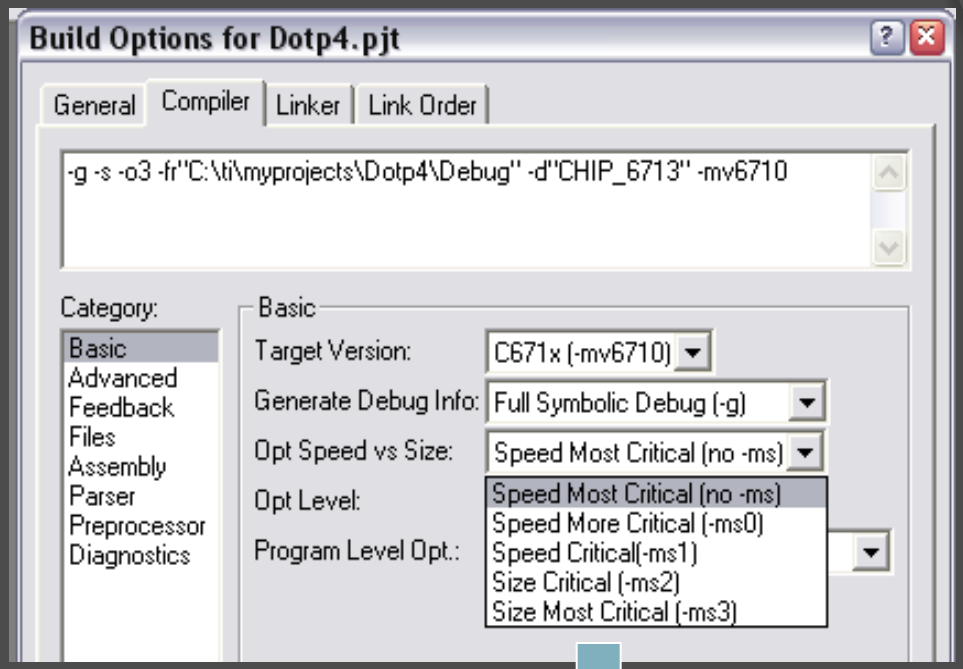


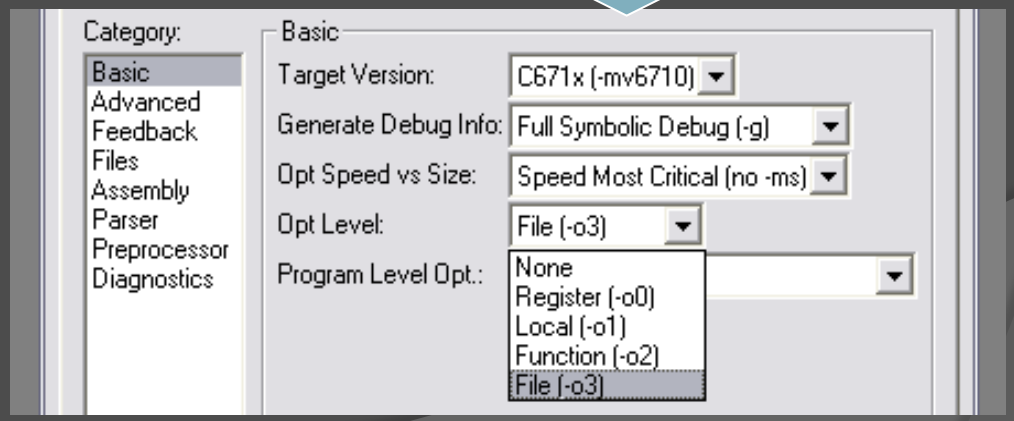
# What does it mean?

- Access count is the number of times that CCS profiled the function
  - Note that the function was probably called more than 49 times. CCS only timed it 49 times.
- Inclusive average is the average number of cycles needed to run the function *including* any calls to subroutines
- Exclusive average is the average number of cycles needed to run the function *excluding* any calls to subroutines

# Optimizing Compiler



# Profiling results after compiler optimization

- In this example, we get a 3x-4x improvement with "Speed Most Critical" and "File (-o3)" optimization
- Optimization gains can be much larger, e.g. 20x

Profile Viewer << 0 >> Current - C6713 DSK/CPU_1

| Address Range | Symbol Name | SLR | Symbol Type | Access Count | Cycles: Incl. Avg. | Cycles: Excl. Avg. |
|---|---|---|---|---|---|---|
| 0:0x9a0-0xadc | serialPortRcvISR | 64-82:dsk_fir.c | function | 117 | 127 | 127 |

Profiler

# Limitations of hardware profiling

- Breakpoint/clock profiling method may not work with compiler-optimized code
- Profile -> View method is known to be somewhat inaccurate when connected to real hardware (see "profiling limitations" in CCS help)
  - Accuracy is better when only one or two ranges are profiled
  - Best accuracy is achieved by running a simulator

# 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

## TMS320C6000 C/C++Data Types

| Type | Size | Representation | Range Minimum | Range Maximum |
|---|---|---|---|---|
| char, signed char | 8 bits | ASCII | -128 | 127 |
| unsigned char | 8 bits | ASCII | 0 | 255 |
| short | 16 bits | 2s complement | -32768 | 32767 |
| unsigned short | 16 bits | Binary | 0 | 65535 |
| int, signed int | 32 bits | 2s complement | -2147483648 | 214783647 |
| unsigned int | 32 bits | Binary | 0 | 4294967295 |
| long, signed long | 40 bits | 2s complement | -549755813888 | 549755813887 |
| unsigned long | 40 bits | Binary | 0 | 1099511627775 |
| enum | 32 bits | 2s complement | -2147483648 | 214783647 |
| float | 32 bits | IEEE 32-bit | 1.175494e-38† | 3.40282346e+38 |
| double | 64 bits | IEEE 64-bit | 2.22507385e-308† | 1.79769313e+308 |
| long double | 64 bits | IEEE 32-bit | 2.22507385e-308† | 1.79769313e+308 |

# Final Remarks

- You should have enough information to complete Lab 1
  - Refer to Lab 2 example code and discussions in Kehtarnavaz
  - Lecture notes
  - Reference material noted in lecture notes
  - Please make sure you understand what you are doing. Don't just copy and paste from Kehtarnavaz.
- Lab 1 Part 3: Level Meter
  - Important practical consideration in real DSP systems
  - The goal is to use the full range of the ADC and DAC but avoid clipping (clipping = very bad nonlinear distortion)
  - Your level meter code may be useful for later projects