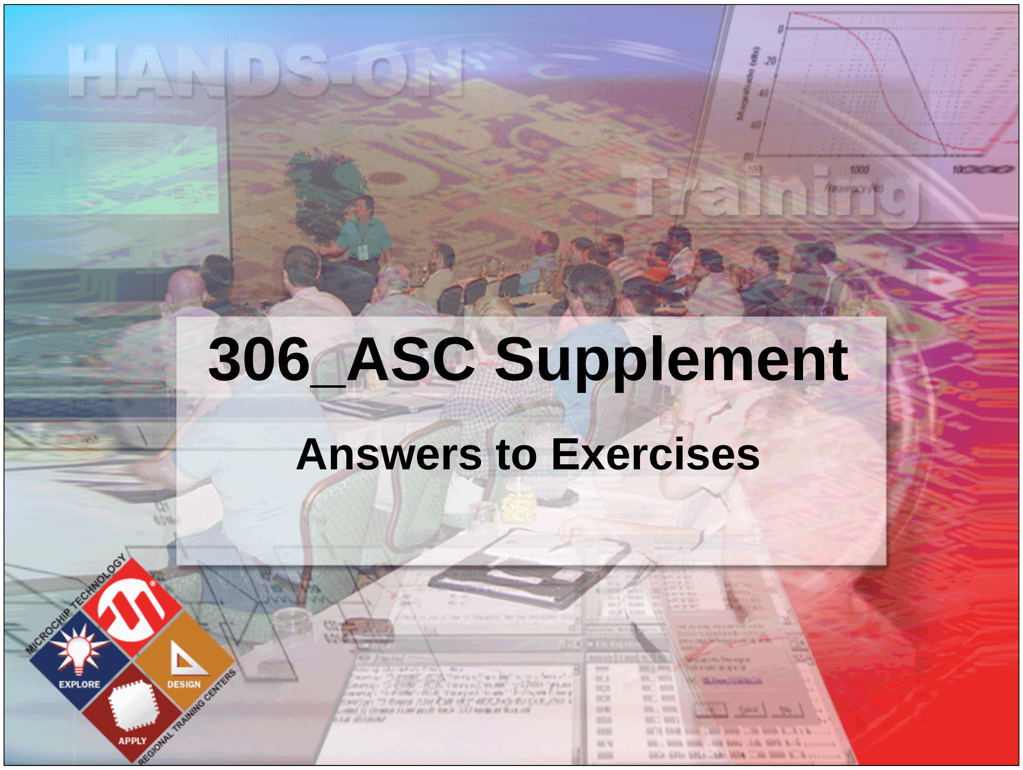
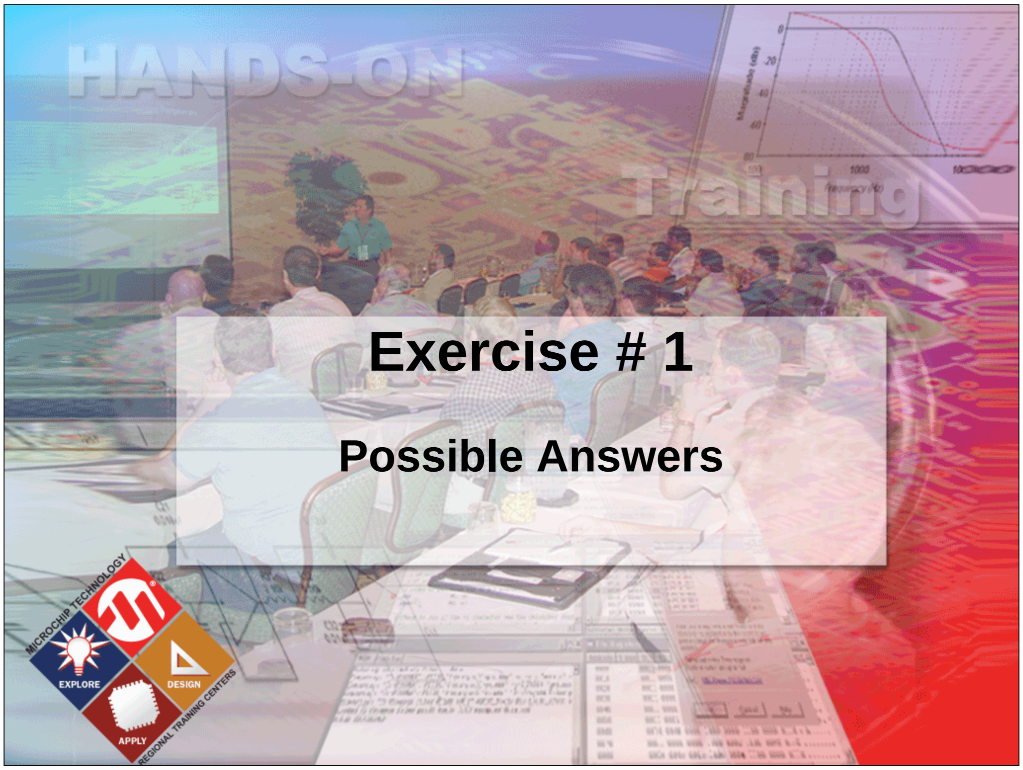


This is a set of possible answers and hints to the Exercises for the2006 Masters presentation 1051 ASC, *Analog Sensor Conditioning Overview*.

Hints on setting up the hardware for these labs is covered in another file.

The Answers to the Exercises PDF file for 306_ASC are generated from this file; use the Notes View option on the print driver.

Display the Notes view on the screen, not the presentation view.



Other answers are possible, depending on the application and its requirements.

Analog Filters
Exercise 1

- **Hint # 1**
  - **Rise Time of cascaded components**

$$t_{R\_TOT} \approx \sqrt{\sum_k t_{R,k}^2}\,, \quad \text{a RMS sum}$$

$$\sqrt{t_{R,1}^2 + t_{R,2}^2} \approx t_{R,1}\left(1 + 0.5\left(t_{R,2}/t_{R,1}\right)^2\right), \quad t_{R,2} < t_{R,1}$$

$\left(t_{R,2}/t_{R,1}\right)$	$\sqrt{1+\left(t_{R,2}/t_{R,1}\right)^2}$	$\left(1+0.5\left(t_{R,2}/t_{R,1}\right)^2\right)$	Relative Error
0	1.0000	1.0000	0%
0.1	1.0050	1.0050	0.00012%
0.2	1.0198	1.0200	0.019%
$\boxed{0.5}$	$\boxed{1.1180}$	1.1250	0.62%
1.0	1.4142	1.5000	6.1%

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Hint # 1:

- With the filter rise time ≤ 1/2 the thermistor rise time, the total rise time only increases 12%
- This helps set the maximum filter rise time
- The Relative Error in the table compares the 3rd column to the 2nd

Analog Filters
Exercise 1

- **Hint # 2**
  - **Rise Time vs. Bandwidth**

$$BW \approx \frac{0.35}{t_R}, \quad \text{for all lowpass filters}$$

- **Hint # 3**
  - **Sample Rate**

$$\begin{aligned}\frac{f}{BW} &> 2, \quad \text{to meet the Nyquist criterion} \\ &\geq 4 \text{ to } 10, \quad \text{usually} \\ &\approx 2 \times \text{interference frequency}, \quad \text{with digital filtering}\end{aligned}$$

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Hint # 2:

• This helps set the minimum desired bandwidth (the maximum BW depends on filter approximation and order)

• This equation is approximate; the constant on top can vary ±10%, or so

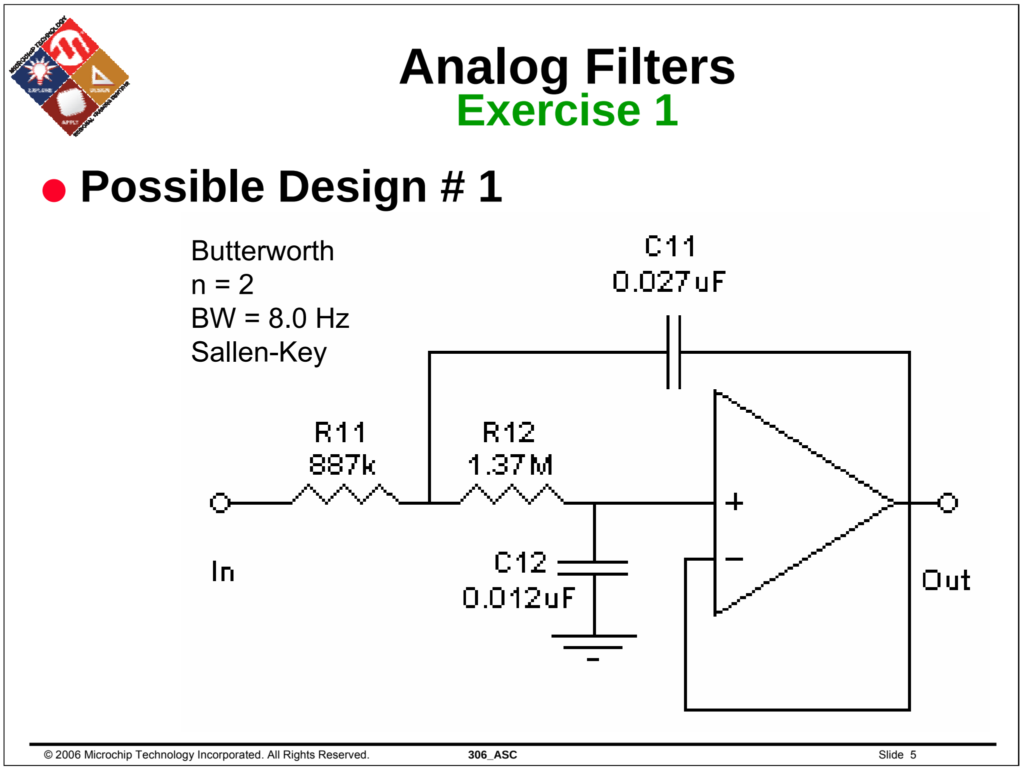
• Handy reference on filter/signal rise times

Howard Johnson & Martin Graham, *High-Speed Digital Design: A Handbook of Black Magic*, (Appendix B), Prentice Hall, 1993.

Hint # 3:

• Selecting a digital rate depends on many factor; the ones listed above are not the only ones

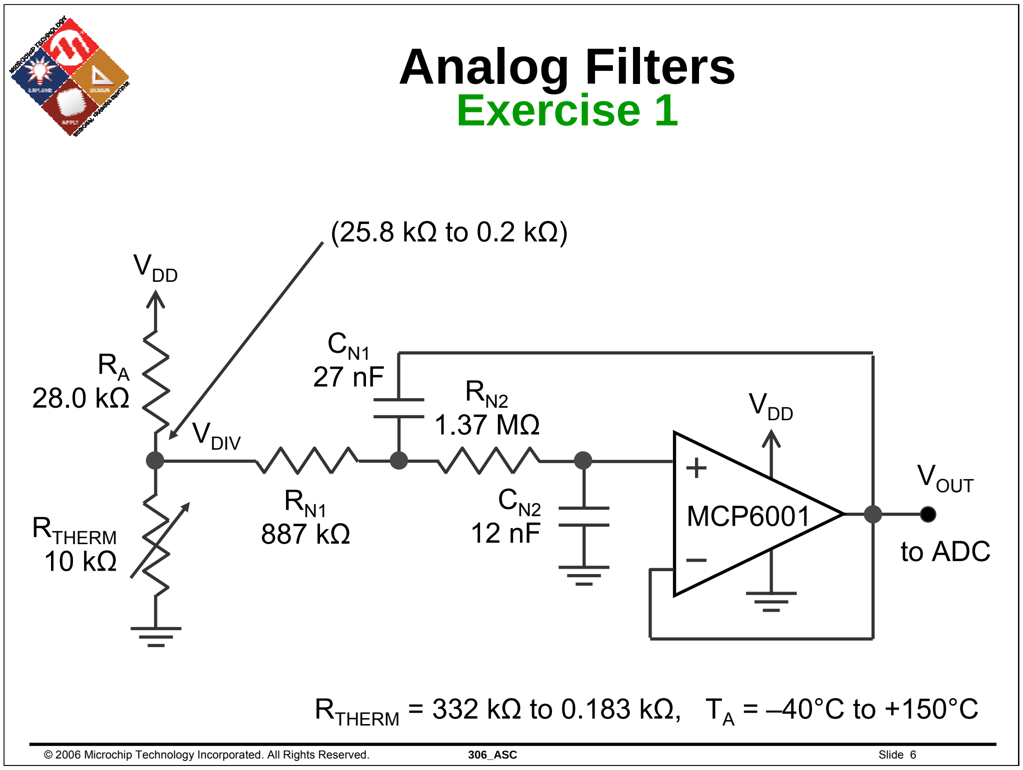
• The minimum sampling rate of the chosen ADC may be higher than these numbers



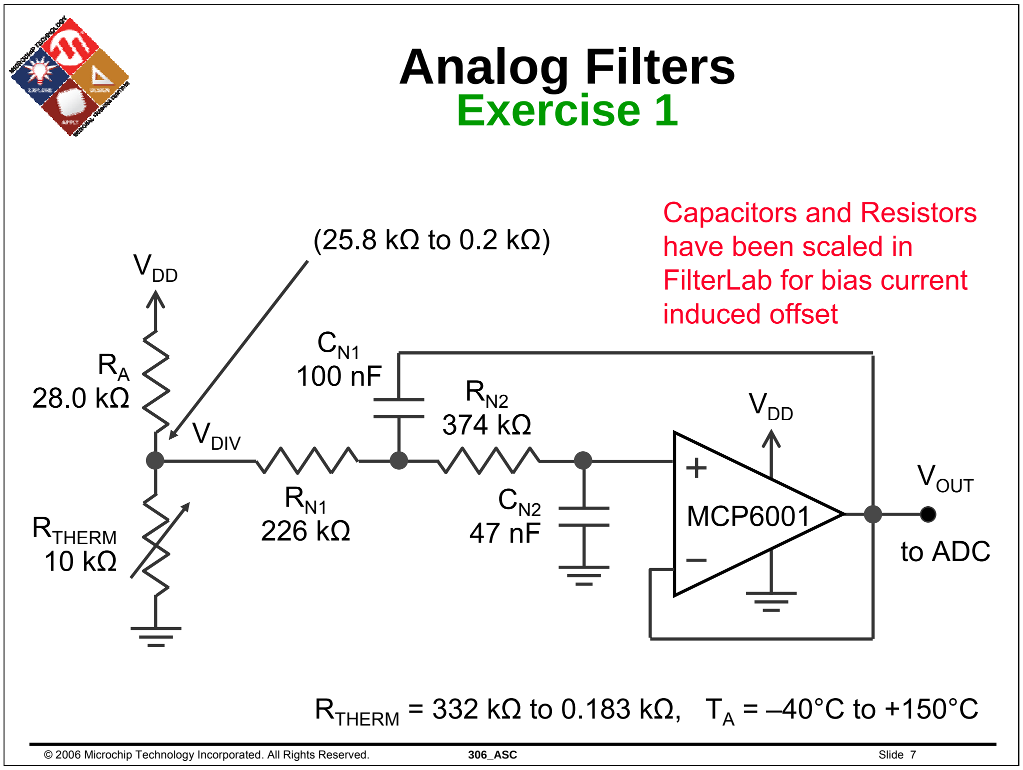
Possible Design # 1:

- Preliminary Analysis
  - 1 LSb = 5.0V × 2^{-10} = 4.88 mV
  - Want noise < 1 LSb / 4 = 1.22 mV, so
    - A_S = 32.3 dB, f_S = 60 Hz
    - A = 24.3 dB, f = 500 kHz (attenuation at 500 kHz)
  - Want fast response to temperature changes
    - $t_{R\_FILTER} < \tau_{THERM} / 2 \approx 0.85$ s, gives ≈ 12% increase in t_R
    - $BW_{FILTER} > 0.35 / t_{R\_FILTER} = 0.41$ Hz
- Selected
  - Filter
    - Approximation = Butterworth
    - BW = 8.0 Hz (for smaller capacitors)
    - order = 2
    - A_S = 34.9 dB
    - A = 191.8 db, f = 500 kHz (noise will go through supply)
  - ADC's f_{SMPL} > 60 Hz + BW = 62 Samples/s, (for anti-aliasing)

    = 100 Samples/s, (digitally filter 60 Hz)



- DC Errors
    - Offset
        - $V_{OS} < \pm 4.5$ mV
        - $I_B < 5$ nA (approximately), $T_A = +125°C$
        - Output Offset $< \pm 4.5$ mV – 5 nA × 2.3 MΩ
          $= \pm 4.5$ mV – 11.5 mV
          $\approx \pm 1 - 2$ LSb
        - We *must* scale the resistors to smaller values
            - $R \leftarrow R / 4$
            - $C \leftarrow 4\ C$, to keep the same bandwidths (do in FilterLab)
    - PSRR > 70 dB (approximately) for f < 60 Hz
        - Should be negligible for 60 Hz noise
        - Need excellent bypass at f > 500 kHz for SMPS noise
- R_A and R_{THERM} cause a small change in the equivalent R_{N1} value, so the filter behaves very much like a Butterworth of order 2



- Noise Error
  - Device Noise
    - 24 nV/√Hz, white noise
    - 430 nV/√Hz, 1/f noise at 1 Hz
    - NPBW ≈ BW = 8.0 Hz
    - E_{ni}(0.1 Hz to 8.0 Hz) = 0.4 $\mu V_{P\text{-}P}$, op amp white noise
      = 5.9 $\mu V_{P\text{-}P}$, op amp 1/f noise
      = 0.7 $\mu V_{P\text{-}P}$, thermal noise
      = 6.0 $\mu V_{P\text{-}P}$, all noise

(negligible)

Analog Filters
Exercise 1

Parameter	Value
V_{DD}	5.0V
Noise at V_{DIV}	50 mV_{P-P} @ 60 Hz
	20 mV_{P-P} @ 500 kHz
ADC Resolution	10 bit
τ_{THERM}	1.7 s
Filter Approximation	Butterworth
Filter BW	8.0 Hz
Filter Order	2
Filter f_S	60 Hz
Filter A_S	> 35 dB
ADC's f_{SMPL}	100 Samples/s

(could be 30 Samples/s)

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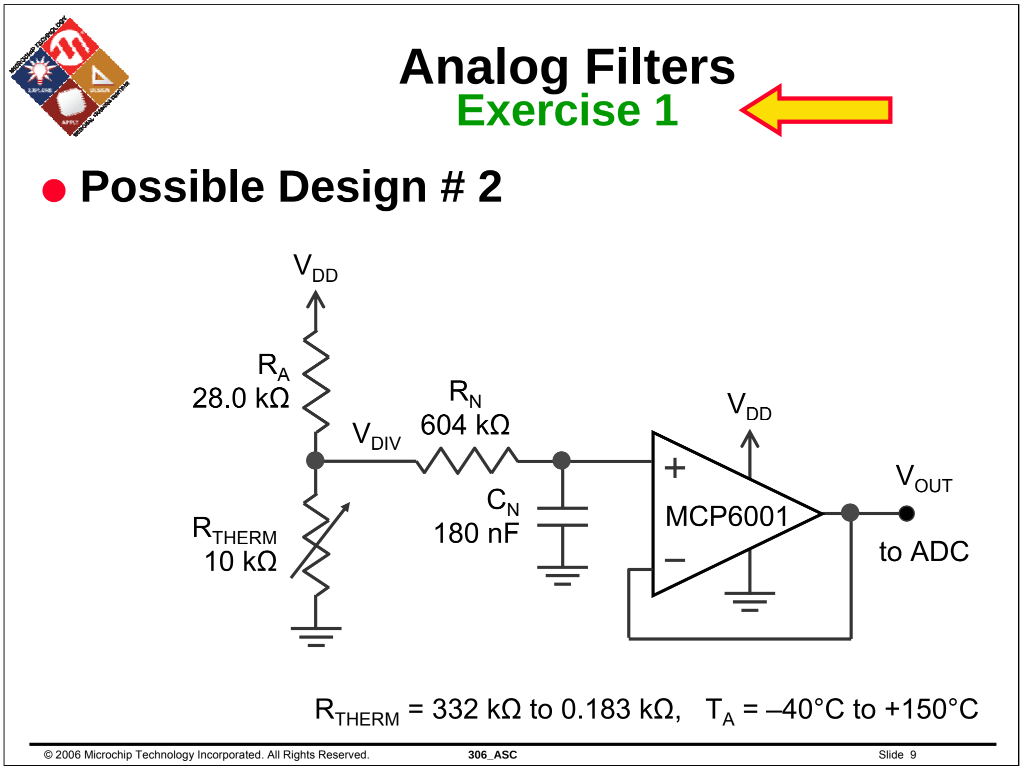


Possible Design # 2:

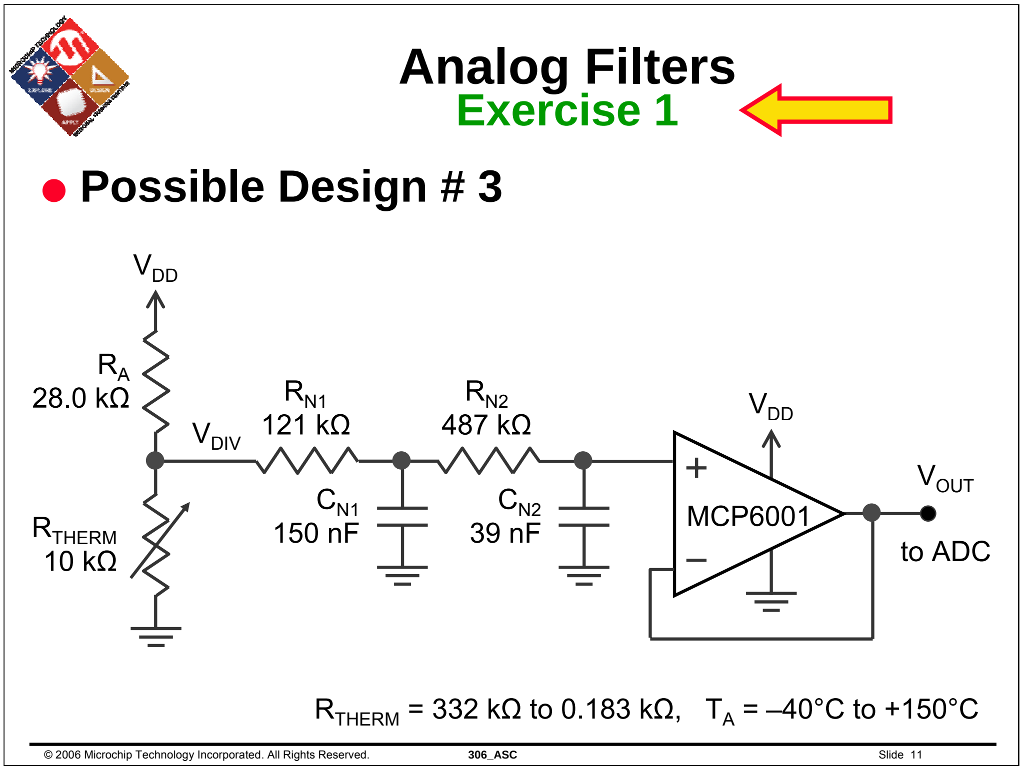
- Preliminary Analysis
  - (same as Possible Design # 1)
- Selected
  - Filter
    - Approximation = RC
    - BW ≈ 1.46 Hz
    - order = 1
    - $A_S = 32.3$, $f_S = 60$ Hz
    - A = 111 db, f = 500 kHz
  - ADC's $f_{SMPL} = 100$ Samples/s, (same as Possible Design # 1)

Analog Filters
Exercise 1

Parameter	Value
V_{DD}	5.0V
Noise at V_{DIV}	50 $mV_{P\text{-}P}$ @ 60 Hz
	20 $mV_{P\text{-}P}$ @ 500 kHz
ADC Resolution	10 bit
τ_{THERM}	1.7 s
Filter Approximation	RC
Filter BW	1.5 Hz
Filter Order	1
Filter f_S	60 Hz
Filter A_S	> 32 dB
ADC's f_{SMPL}	100 Samples/s

(could be 6 Samples/s)

- Other Errors
  - Offset
    - (same as Design # 1)
  - PSRR
    - (same as Design # 1)
  - Device Noise
    - (still negligible)



Possible Design # 3:

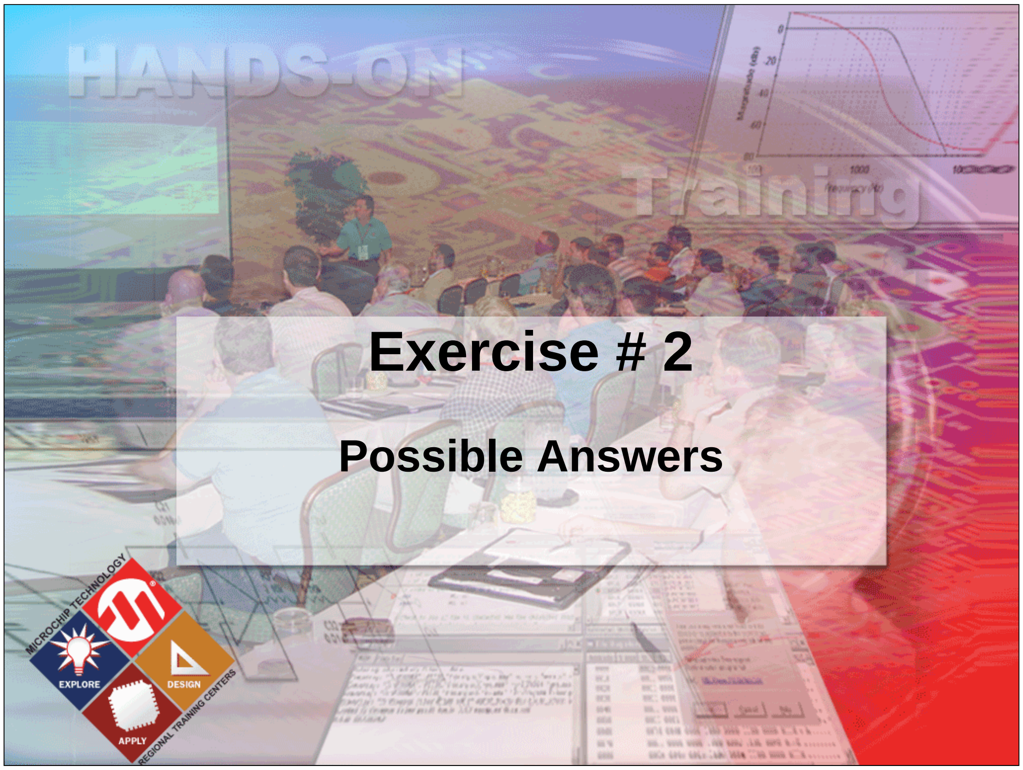
- Preliminary Analysis
  - (same as Possible Design # 1)
- Selected
  - Filter
    - Approximation = RC
    - order = 2
    - $\rho^2 \approx 4$
    - $f_P = 1 / 2\pi\, sqrt(R_{N1}R_{N2}C_{N1}C_{N2}) = 8.6$ Hz
    - $BW \approx 0.55\ f_P = 4.7$ Hz
    - A = attenuation $\approx (f / f_P)^2$, $\quad f >> f_P$
    - $A_S > 33.8$ dB, $\quad f_S = 60$ Hz
    - $A >> 120$ dB, $\quad f = 500$ kHz
  - ADC's $f_{SMPL} = 100$ Samples/s, (same as Possible Design # 1)

Analog Filters
Exercise 1

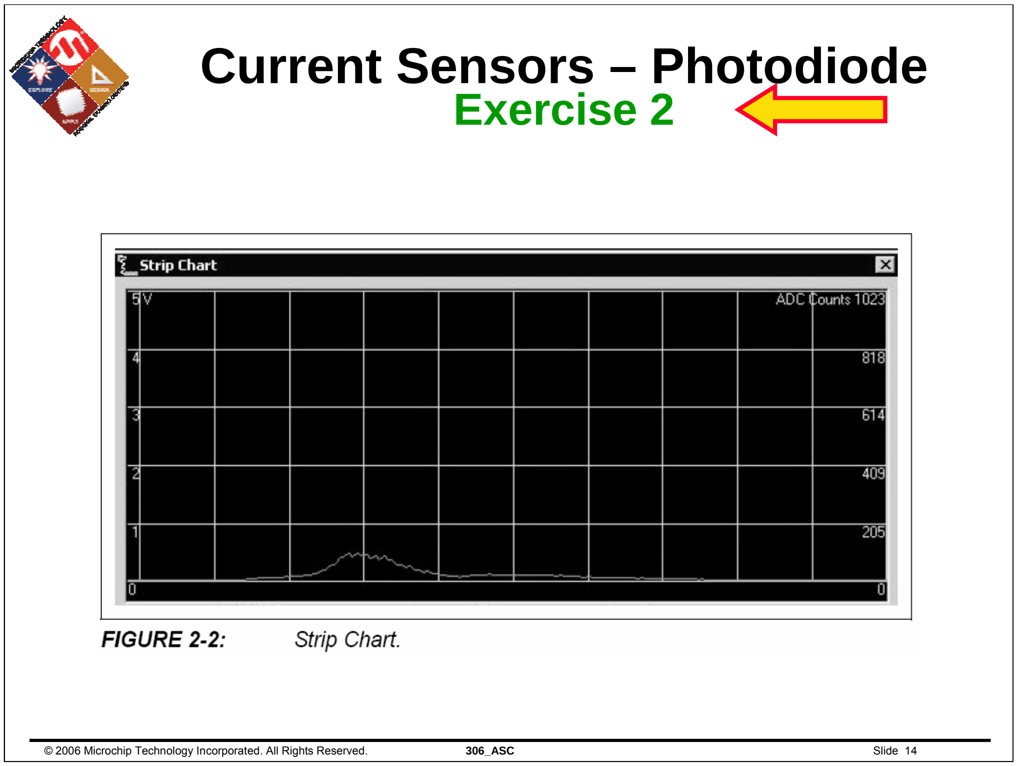
Parameter	Value
V_{DD}	5.0V
Noise at V_{DIV}	50 mV_{P-P} @ 60 Hz
	20 mV_{P-P} @ 500 kHz
ADC Resolution	10 bit
τ_{THERM}	1.7 s
Filter Approximation	RC
Filter BW	5 Hz
Filter Order	2
Filter f_S	60 Hz
Filter A_S	> 34 dB
ADC's f_{SMPL}	100 Samples/s

(could be 20 Samples/s)

- Other Errors
  - Offset
    - (same as Design # 1)
  - PSRR
    - (same as Design # 1)
  - Device Noise
    - (still negligible)



Other answers are possible, depending on the application and its requirements.

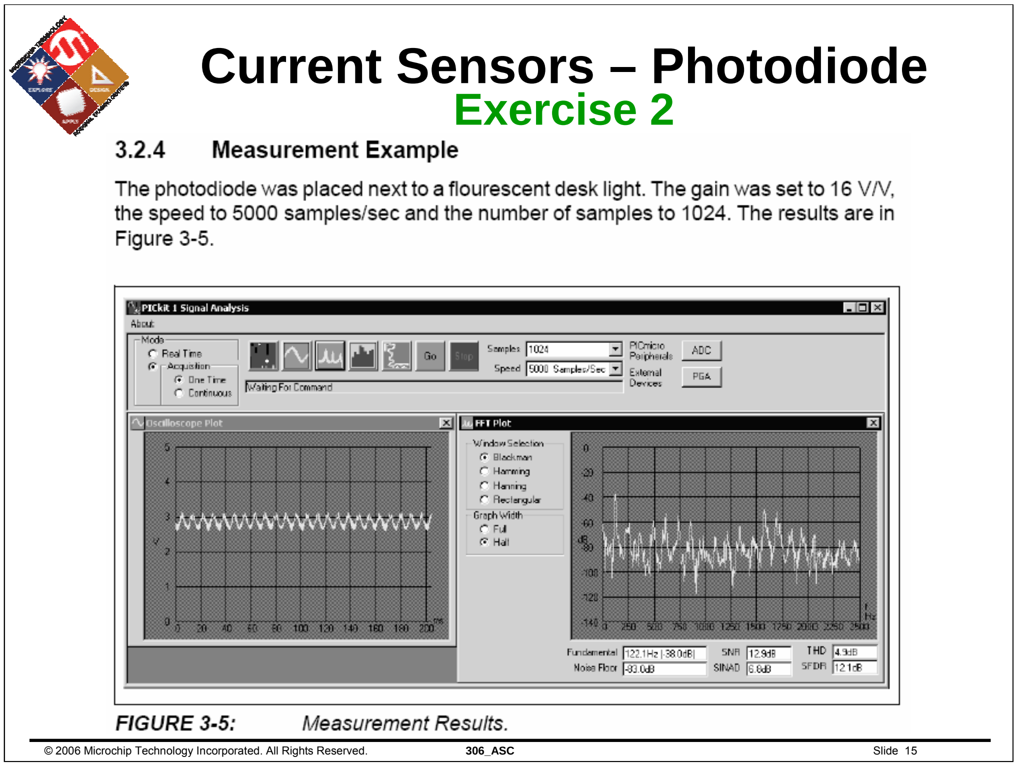


Measurement Results

• Shown in the User’s Guide (DS51514)

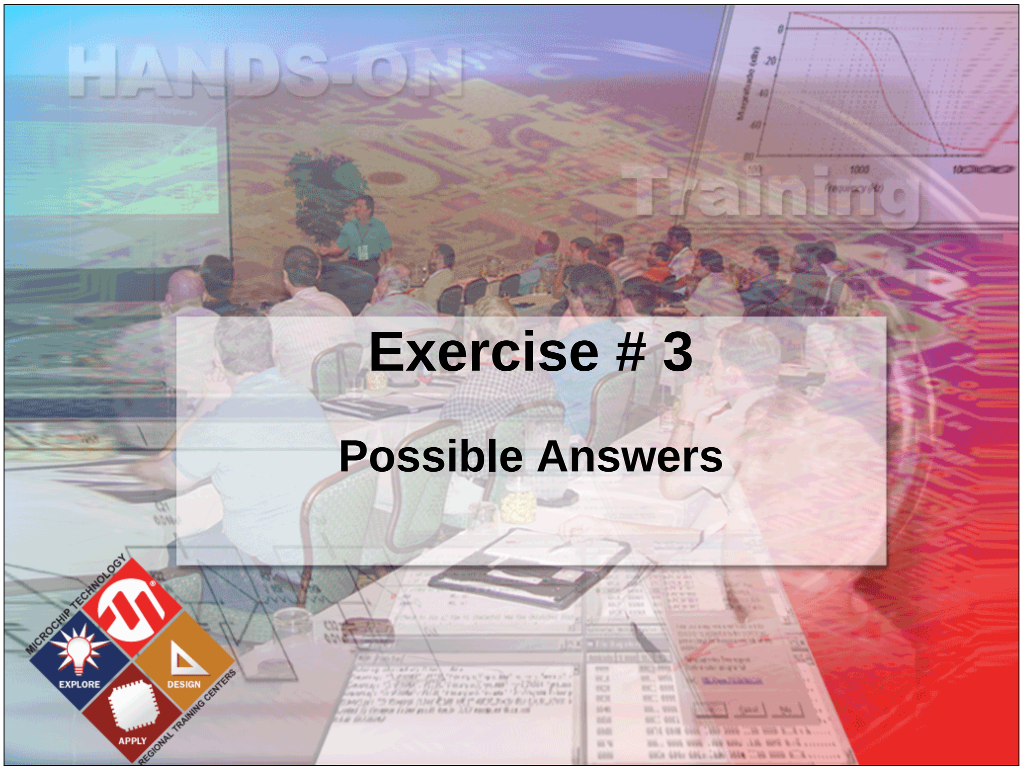
Strip Chart.

Photodiode was brought close to a light source for a short period of time.

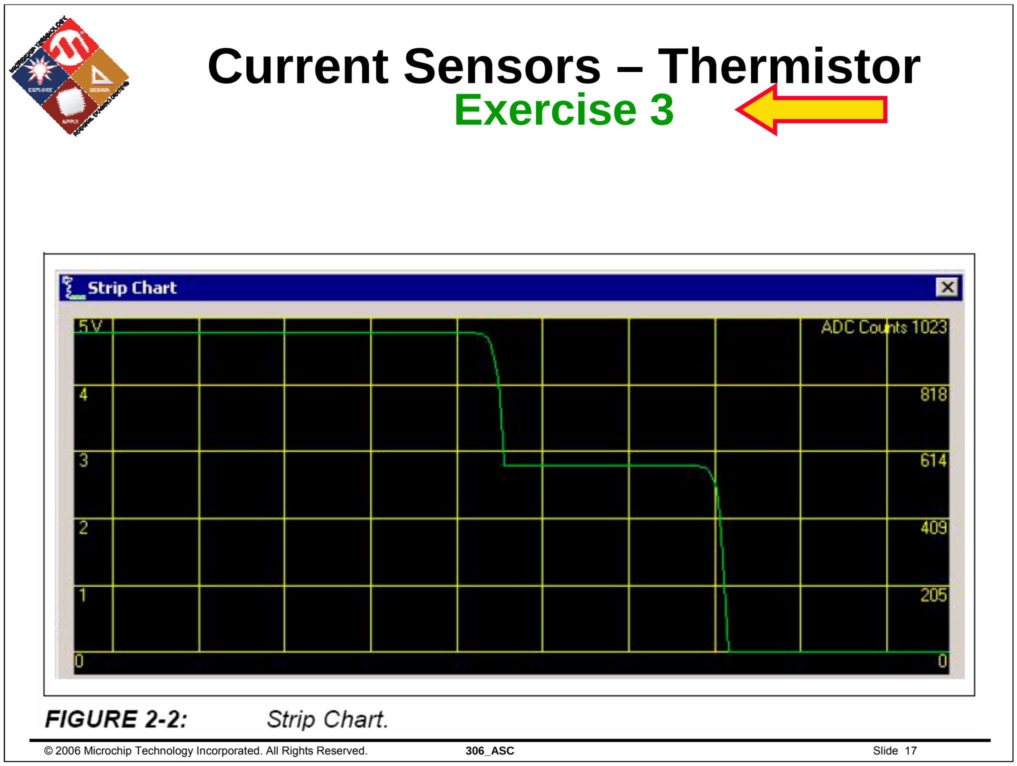


Oscilloscope and FFT.

Photodiode was kept close to a florescent light. The 120 Hz noise was due to the ballast rectifying the 60 Hz line/mains current.



Other answers are possible, depending on the application and its requirements.



Measurement Results

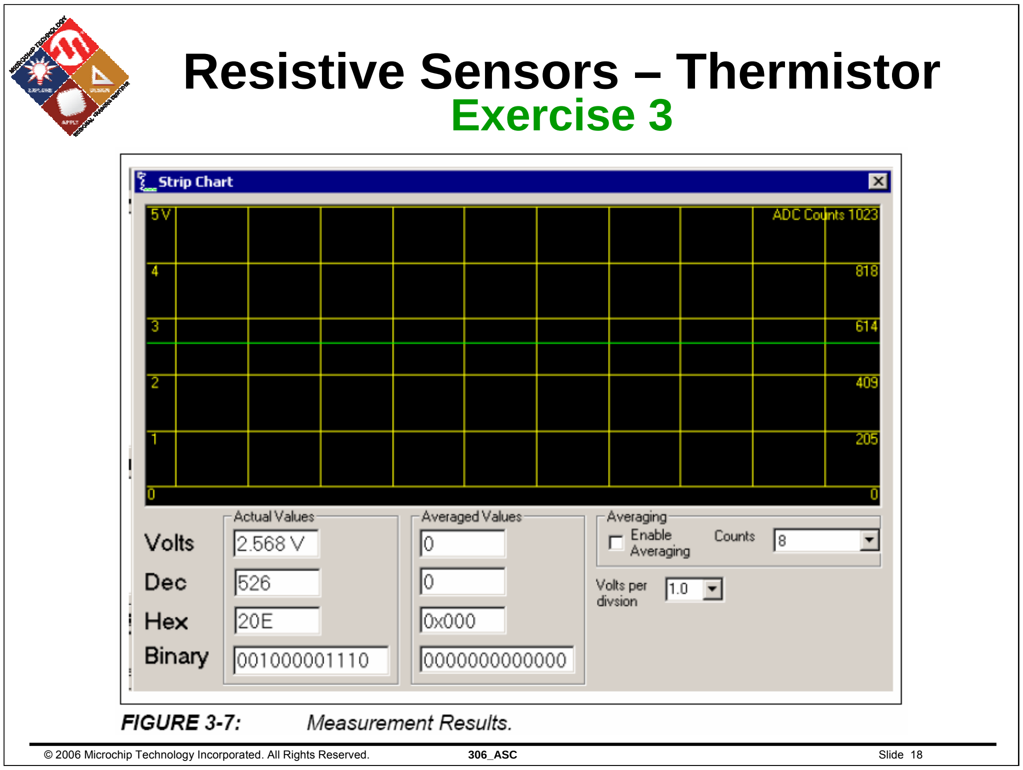
- Shown in the User's Guide (DS51517)

Strip Chart.

R_A was set to 10 kΩ.

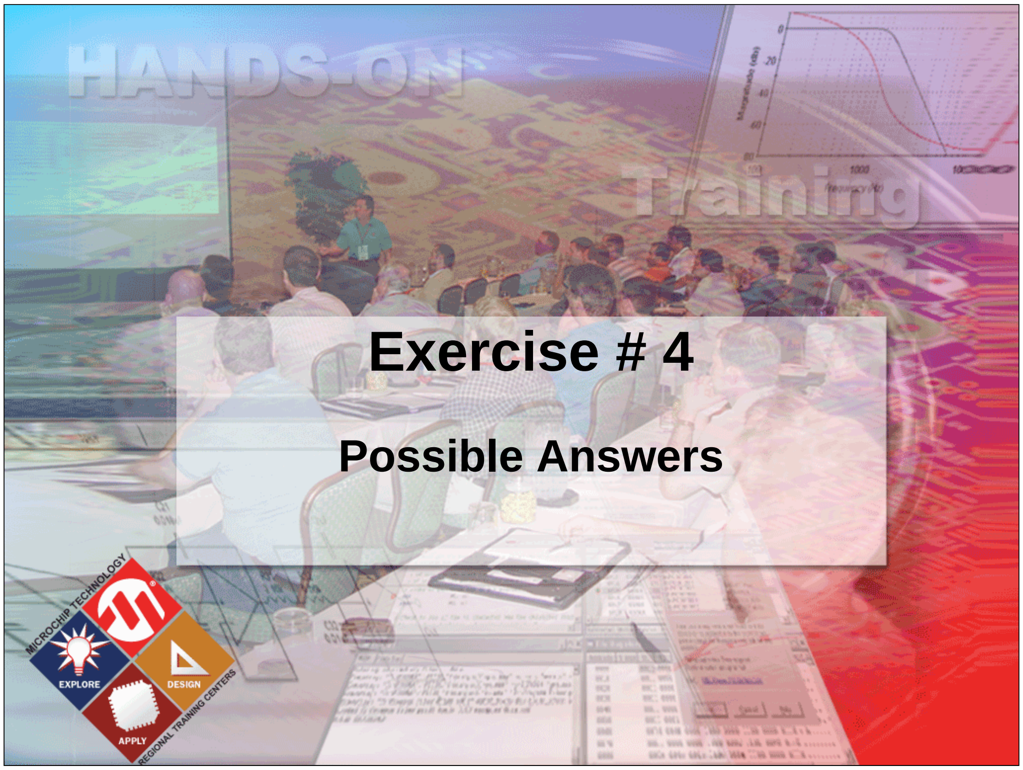
R_{VAR} was set to 217.6 kΩ, then 12.8 kΩ, and then 0Ω.

V_{OUT} was 0.000V, then 2.807V, and then 4.780V.

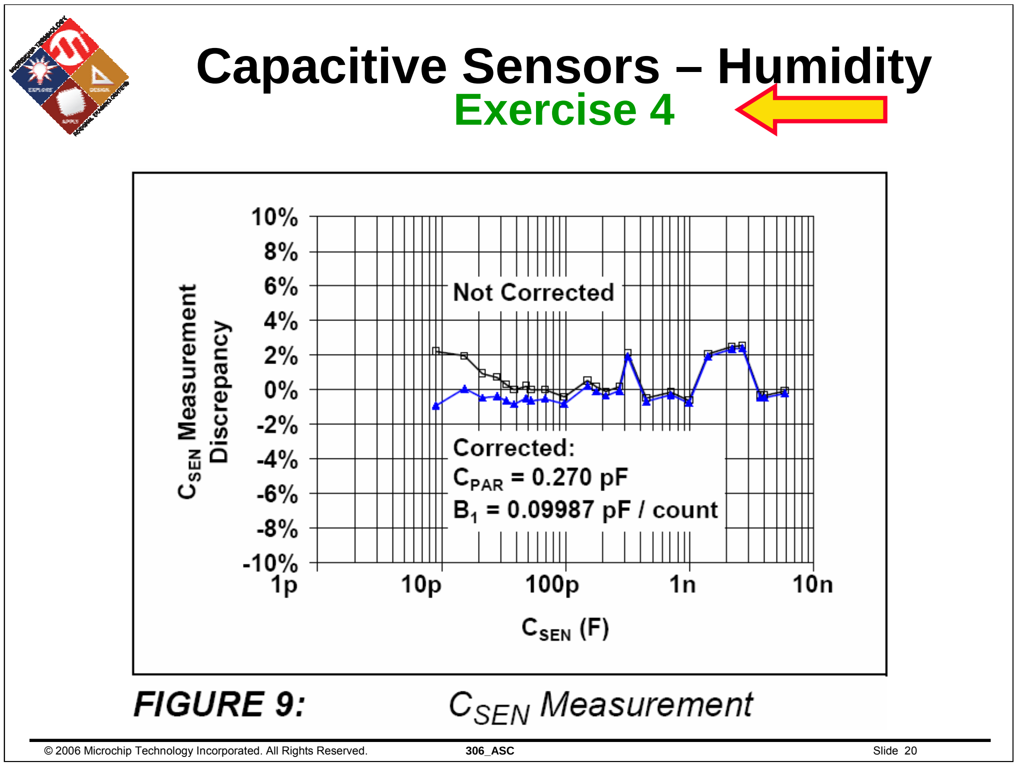


Strip Chart.

The output voltage (2.568V), or the ADC Code (526) was used to calculate $R_{TH} \approx 10.56\ k\Omega$ and $T_{TH} \approx 23.5°C$ (74.3°F).



Other answers are possible, depending on the application and its requirements.



Measurement Results

• Shown in the Application Note (AN1016)

The top curve shows the measurement results when using the circuit and F/W as designed. It is possible to do further correction to improve the accuracy:

• Subtract the parasitic capacitance in parallel with C_{SEN} (mainly the op amp's pin-to-pin package capacitance)

• Correct for the circuit's gain error (e.g., R_{INT} is too high, or the PIC's clock is too slow)

As can be seen in the plot, these corrections may, or may not, be of use in a particular application.

Capacitive Sensors – Humidity

Exercise 4

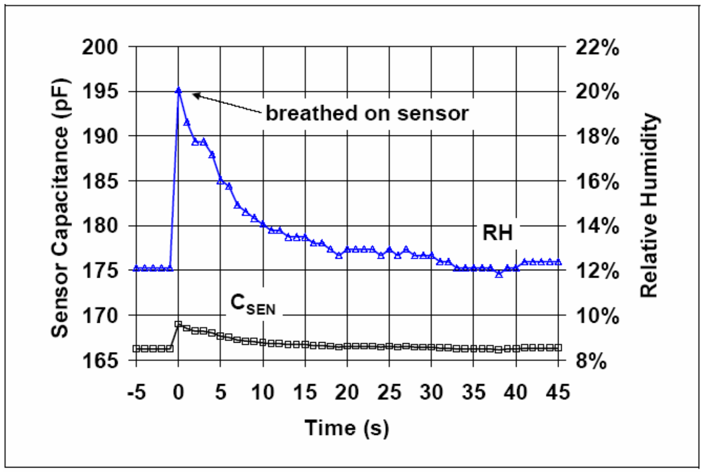


FIGURE 10: *HS1101LF Impulse Response.*

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Since the measurement resolution is 0.1 pF / count, the resolution in relative humidity (RH) is 0.6% RH. The application was set to take one reading every second.

Breathing on the humidity sensor is a quick way to verify its time constant, and that the circuit is operating properly.

