EET 438b
Sequential Digital Control Systems and Data Acquisition
Homework Assignments

Assignment #	Lesson#	Problems	Location
1	2	P2.3, P2.4	handout
2	2	P2.8	handout
3	3	slew.wp5	handout
4	3	6.4 6.5	Chapter 6 Bateson
5	4	gaphw.wp5	handout
6	5	window.wp5	handout
7	6	6.31, 6.32	Chapter 6 Bateson
8	6	amhw.wp5, specan.wp5	handout
9	6,7,8	6.33, dachw2.wp5 dac_hw1.wp5	handout, Chapter 6
10	8,9	bonus3.wp	handout
11	8,9	6.34	Chapter 6 Bateson
12	9	diohw1.wp5	handout
13	9	mask.wp5	handout
14	10	5.5, 5.7, 5.19	Chapter 5 Bateson
15	11	differ.wp5	handout
16	11,12	diffsen.wp5	handout
17	12	6.22 *	Chapter 6 Bateson
18	13	7.1, 7.2, 7.3, 7.4	Chapter 7 Bateson
19	13	7.17, 7.18	Chapter 7 Bateson
20	13	7.20	Chapter 7 Bateson
21	13	8.4, 8.6	Chapter 8 Bateson
22	13	8.12, 8.16	Chapter 8 Bateson
23	14	seqhw38.wp5	handout
24	14	ladder.wp5	handout
25	14, 15	xorlad.wp5	handout
26	15,16,17	lad2log.wp5, log2lad.wp5	handout
27	18,19	addrplc.wp5	handout
28	18,19	plcpgm1.wp5	handout

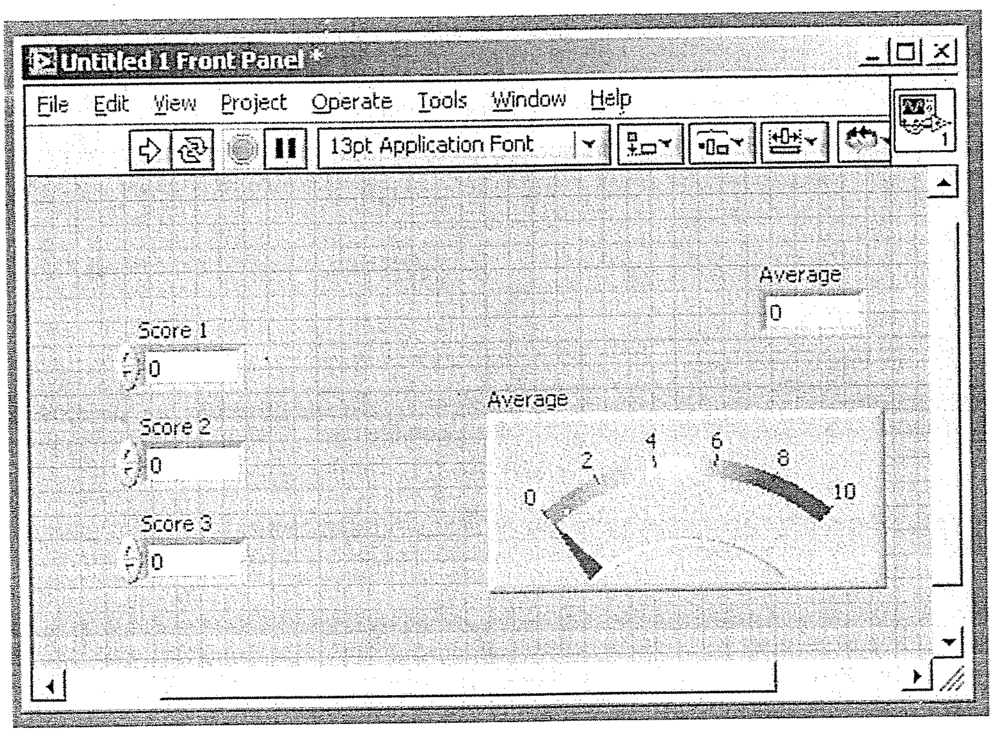
* Use resistance range of 149-151 ohms from 6.21

HW 1

ET 438B
LabVIEW Practice Programs

P2.3

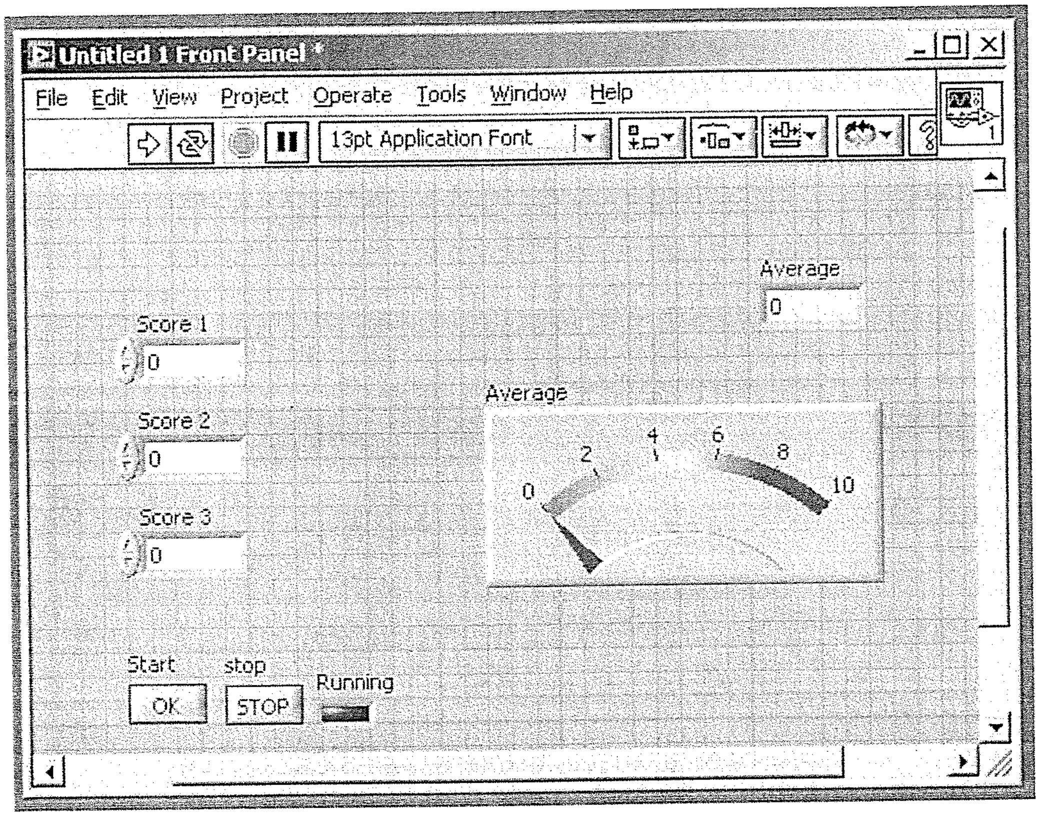
Create a program the will take the average of three inputs and display a numerical value. The program should also display the result on a meter. The figure below shows the desired front panel.



HW 1

P2.4

Use the results of P2.3, and add start/stop controls to the averaging program. See the figure below for the desired front panel layout.



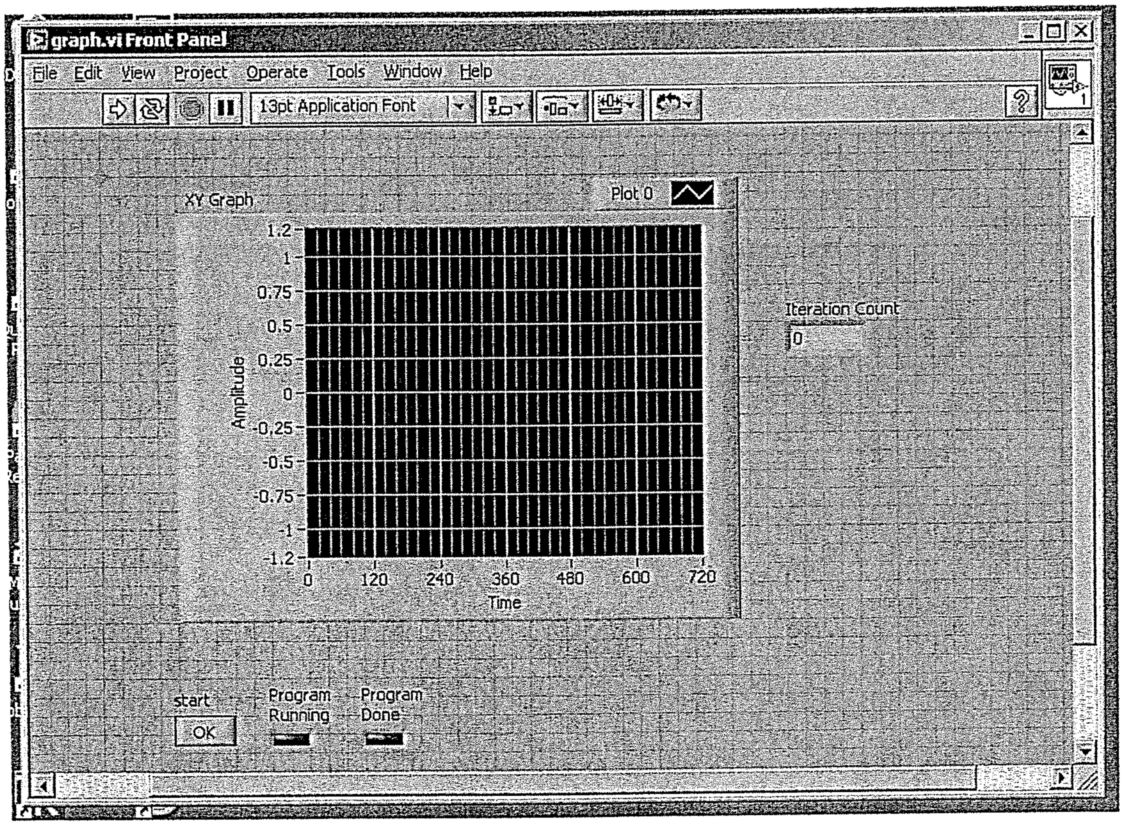
The button labeled "OK" will start an averaging operation and cause the Running LED to light. Depressing the "STOP" button ends the program. Use While loops to accomplish the desired functionality.

Hw 2

ET 438B
LabVIEW Practice Programs
Boolean I/O and Graphing

P2.8

Create a LabVIEW program that has the front panel shown below.



This program should plot two cycles (4π radians) of a cosine wave using 720 data points. Plot the cosine on an XY graph. The program will start and the **Program Running** indicator will light when the **"OK"** button labeled **start** is pressed.
The plot should display when the program completes the last iteration and the **Program Done** indicator should light. The iteration count indicator will show the current iteration count. Insert a 50 mS delay in the loop generating the data points to be able to see the counter change.

You will need to use a FOR loop and a WHILE loop with correct stopping conditions to produce this program. The WHILE loop is ideal for delaying the program start until a user presses the correct button. View the Graphing with LabVIEW online video to help you get started.

Hw 3

ET 438b
Continuous and Digital Control
Non-Ideal OP AMP Operation

1.) A 0-5 V pulse is to be applied to a LM741 OP AMP operating as a comparator. What is the maximum input frequency that the pulse can have before the OP AMP's slew rate will affect the pulse response?

2.) If the 0-5 V pulse input frequency will be no greater that 25 kHz, find the slew rate specification that the OP AMP must have in this circuit.

Successive approximation ADC: An analog-to-digital converter that sequentially compares a series of binary-weighted values with the analog input to generate a digital code word that represents the analog input voltage. (6.5)

Summing amplifier: A circuit with several inputs that produces an output voltage that is the inverted, weighted sum of the input voltages. (6.3)

Voltage follower: A circuit with a very high input impedance, a very low output impedance, and an output voltage that is equal to the input voltage. (6.3)

Wheatstone bridge: A circuit used to measure the value of an unknown resistor in which the unknown resistor and three other resistors are connected in a diamond configuration. (6.4)

◆ EXERCISES

Section 6.2

6.1 Determine the values of $v_2 - v_1$ that will saturate an op amp for each of the following condition sets:
(a) $A = 10^4$, $+V_{cc} = 20$ V, $-V_{cc} = -20$ V
(b) $A = 10^7$, $+V_{cc} = 20$ V, $-V_{cc} = -20$ V
(c) $A = 4 \times 10^5$, $+V_{cc} = 16$ V, $-V_{cc} = -18$ V
(d) $A = 2 \times 10^6$, $+V_{cc} = 18$ V, $-V_{cc} = -16$ V

6.2 Determine the value of $v_2 - v_1$ that will produce positive saturation of an op amp for each of the following condition sets:
(a) $A = 10^4$, $+V_{cc} = 20$ V, $A_c = 0.1$, $v_c = 8$ V
(b) $A = 10^7$, $+V_{cc} = 20$ V, $A_c = 0.1$, $v_c = 8$ V
(c) $A = 4 \times 10^5$, $+V_{cc} = 16$ V, $A_c = 0.08$, $v_c = 6$ V
(d) $A = 2 \times 10^6$, $+V_{cc} = 18$ V, $A_c = 0.12$, $v_c = 5$ V

6.3 For each of the following condition sets, determine the CMMR and CMR required to limit the common-mode error to a maximum of 2% of the output when $v_c = 0$ V
(a) $A = 10^4$, $v_2 - v_1 = 1.0$ mV, maximum $v_c = 8$ V
(b) $A = 10^7$, $v_2 - v_1 = 0.8$ μV, maximum $v_c = 8$ V
(c) $A = 4 \times 10^5$, $v_2 - v_1 = 20$ μV, maximum $v_c = 6$ V
(d) $A = 2 \times 10^6$, $v_2 - v_1 = 5$ μV, maximum $v_c = 5$ V
(e) $A = 2 \times 10^5$, $v_2 - v_1 = 80$ μV, maximum $v_c = 5$ V

Section 6.3

6.4 (a) Revise the high-level indicator in Figure 6.4a so that the HI lamp will be ON only when $v_{in} > 9$ V.
(b) Revise the low-level indicator in Figure 6.4b so that the LO lamp will be ON only when $v_{in} < 1$ V.
(c) Revise the high-low-level indicator in Figure 6.4c so that the LO lamp will be ON only when $v_{in} < 1$ V and the HI lamp will be ON only when $v_{in} > 9$ V.

6.5 Design a three-level indicator with three comparators and three lamps, marked (1/4), (1/2), and (3/4). The (1/4) indicator lamp will be ON only when $v_{in} > 2.5$ V. The (1/2) indicator lamp will be ON only when $v_{in} > 5$ V. The (3/4) indicator lamp will be ON only when $v_{in} > 7.5$ V. When v_{in} is less than 2.5 V, all lamps are OFF. When v_{in} is greater than 7.5 V, all lamps are ON.

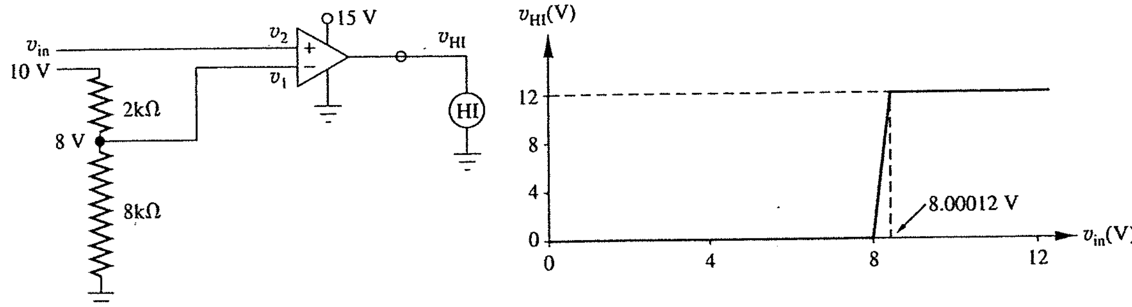
6.6 The following conditions give the input and output voltages of an inverting amplifier, and one of its two resistors, R_f or R_{in}. Determine the value of the unknown resistor.
(a) $v_{in} = 6$ V, $v_{out} = -15$ V, $R_f = 10$ kΩ
(b) $v_{in} = 1.2$ V, $v_{out} = -12$ V, $R_f = 50$ kΩ
(c) $v_{in} = 0.2$ V, $v_{out} = -8$ V, $R_{in} = 2$ kΩ
(d) $v_{in} = 0.75$ V, $v_{out} = -12$ V, $R_{in} = 4$ kΩ
(e) $v_{in} = 10$ V, $v_{out} = -2$ V, $R_f = 5$ kΩ

6.7 A primary element produces an output voltage that ranges from 0 to 22 mV. Design an inverting amplifier that produces an output voltage with a range of 0 to −4 V. Use a 1-kΩ resistor for R_{in}.

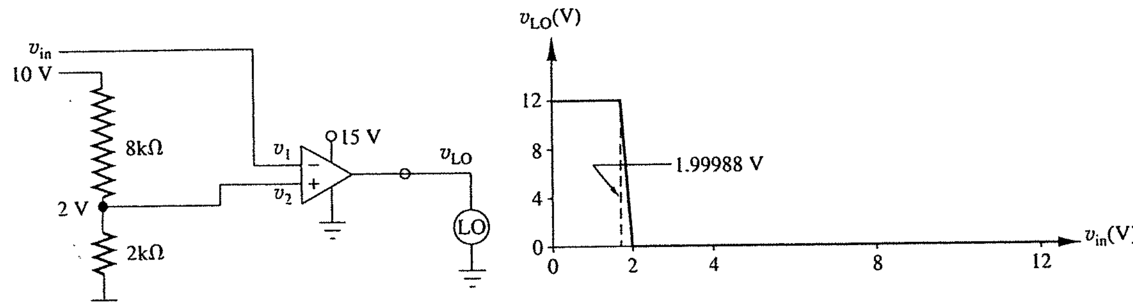
6.8 The following conditions give the input and output voltages of a noninverting amplifier, and one of its two resistors, R_f or R_{in}. Determine the value of the unknown resistor.
(a) $v_{in} = 6$ V, $v_{out} = 15$ V, $R_f = 10$ kΩ
(b) $v_{in} = 1.2$ V, $v_{out} = 12$ V, $R_f = 50$ kΩ
(c) $v_{in} = 0.2$ V, $v_{out} = 8$ V, $R_{in} = 2$ kΩ
(d) $v_{in} = 0.75$ V, $v_{out} = 2$ V, $R_{in} = 4$ kΩ

6.9 Repeat Exercise 6.7, but change the output voltage range to 0 to 4 V and use a noninverting amplifier.

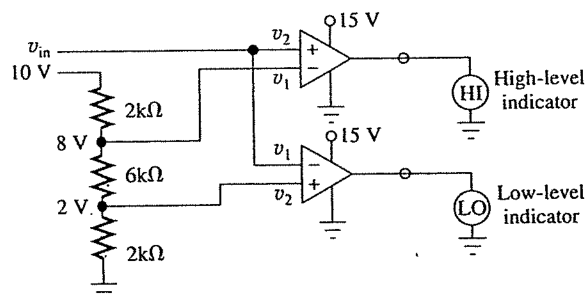
6.10 Determine the output of a two-input summing amplifier for each of the following condition sets.
(a) $v_a = 2$ V, $v_b = 4$ V, $R_f = 5$ kΩ, $R_a = R_b = 10$ kΩ
(b) $v_a = 2$ V, $v_b = 4$ V, $R_f = R_a = R_b = 10$ kΩ
(c) $v_a = -2$ V, $v_b = 6$ V, $R_f = 10$ kΩ, $R_a = 8$ kΩ, $R_b = 6$ kΩ
(d) $v_a = -6$ V, $v_b = 4$ V, $R_f = 16$ kΩ, $R_a = 12$ kΩ, $R_b = 8$ kΩ



a) A high-level indicator. When $v_{in} < 8$ V, the HI lamp is OFF. As v_{in} increases from 8 V to 8.00012 V, the HI lamp goes from OFF to ON. When $v_{in} > 8.00012$ V, the HI lamp is ON.



b) A low-level indicator. When $v_{in} < 1.99988$ V, the LO lamp is ON. As v_{in} increases from 1.99988 V to 2 V, the LO lamp goes from ON to OFF. When $v_{in} > 2$ V, the LO lamp is OFF.

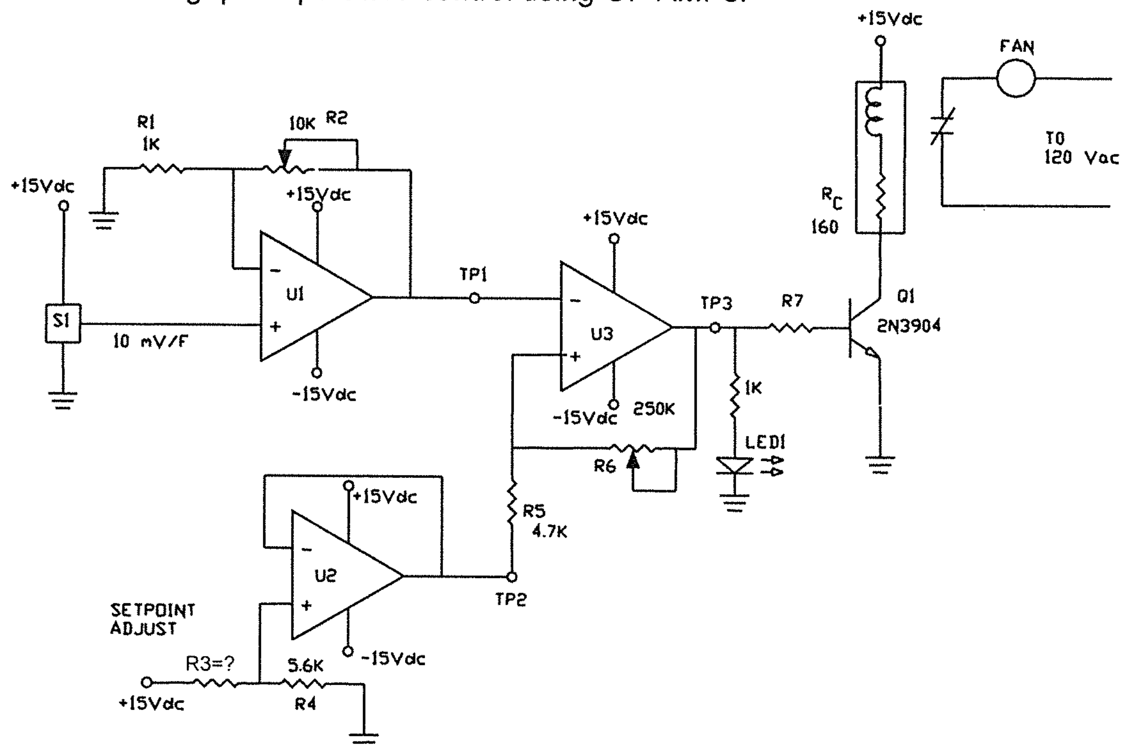


c) A high-low-level indicator combines the high-level and low-level indicators into a single circuit. In this circuit, the HI and LO lamps operate the same as they do in (a) and (b) above.

◆ **Figure 6.4** These voltage-level-indicator circuits use a voltage divider to produce reference voltages of 2 V and 8 V.

ET 438b
Continuous and Digital Control
Differential Gap Controller

Refer to the schematic diagram below for the following questions. This circuit implements a differential gap temperature control using OP AMPs.



1.) Calculate the setting of R2 so that a sensor, S1, input of 50 F will give a voltage of 5.0 V at TP1.
2.) Determine the setting of R6 so that U3 has a 10 F deadband voltage scaled to be compatible with the input at TP1. Assume that $V_{sat} = 0.8V_{cc}$.
3.) Determine the voltage at TP2 so that the LTP of the comparator U3 will be 90 F.
4.) Calculate the value of R3 so that the voltage at TP2 is equal to the LTP value.
5.) Make a sketch of the input/output response of U3 and mark the input voltage values where 65 F, 95 F and 120 F are located. Also identify the voltages of the upper and lower trip points.
6.) Calculate the value of R7 so that the cooling fan relay will be activated when the control circuit detects an over temperature. (h_{FE} = 200 for 2N3904) Use the 10 times rule to assure that Q1 goes into saturation.
7.) For what range of temperatures will LED1 be on?

HW 6

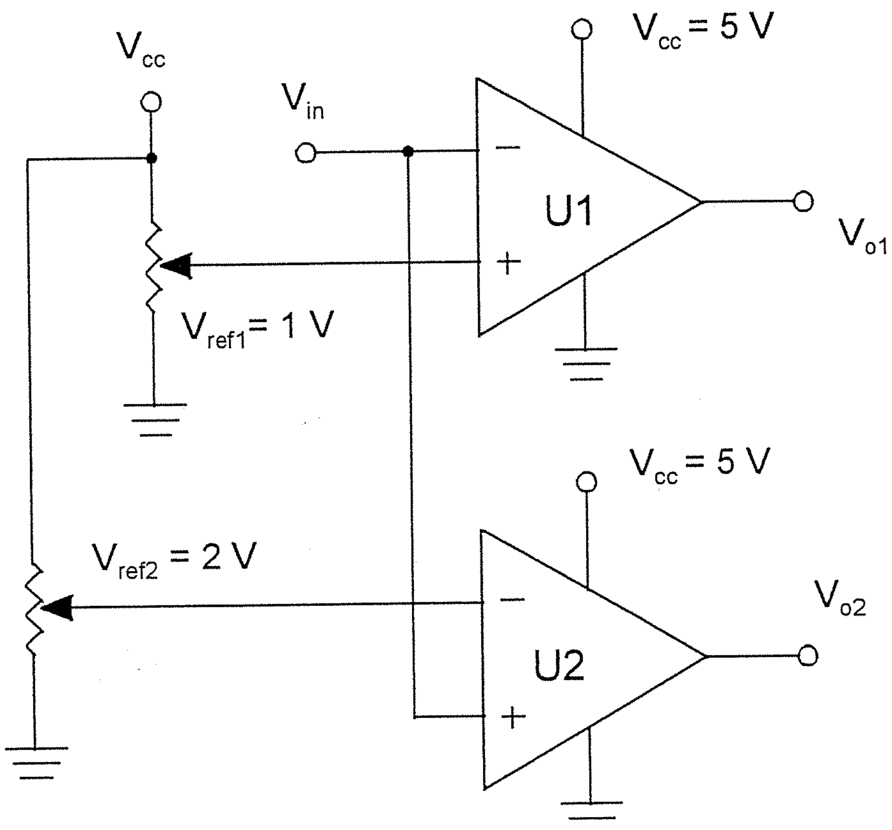
ET438B

Window Comparator Homework

For the comparator circuit shown below,

1.) Determine the input/output curves for the outputs, V_{o1} and V_{o2}. Label the trip voltages on the curves.

2.) Determine what logic function will give a high output only when the input voltage V_{in} is between the upper and lower trip values.



2. Use a -1 V supply for v_c, a 1-kΩ resistor for R_c, and compute the resistance of R_1 that will result in an output voltage of 1 V when $T = 0$°C.
3. Complete the v_{out} column in the results table.

(f) Determine the terminal-based linearity of the output voltage, v_{out}.

Section 6.5

6.30 Determine the time constant and the 99.3% acquisition time of a sample-and-hold circuit if $C = 100\ \mu$F and $R = 1$ kΩ.

6.31 Determine the minimum sampling rate to get all the information from a signal that has a maximum frequency of 1200 Hz.

6.32 Determine the alias frequency that is produced when a 16-kHz signal is sampled at a rate of 20 kHz.

6.33 The logic levels of the input to the 4-bit binary-weighted DAC in Figure 6.32 are 5 V for a logic 1 and 0 V for a logic 0. The resistance values are $R_f = 2$ kΩ and $R = 1$ kΩ.

(a) Determine V_{LSB}, V_{MSB}, and V_{FS}.

(b) Determine v_0 for each of the following binary inputs:

0101 1011 1111 0111

6.34 Use the successive approximation technique outlined in Figure 6.36 to convert each of the following analog voltages to 4-bit digital words. Use $V_{FS} = 20$ V.

(a) 4.2 V **(b)** 19.6 V

(c) 9.25 V **(d)** 14.71 V

6.35 Determine the quantization error in volts and percentage of the full-scale range for each of the following ADCs. The input voltage is 10 V at the center of the top step.

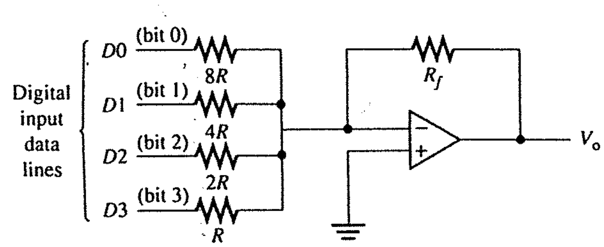
(a) Resolution = 4 bits; error = $\pm\frac{1}{2}$ bit

(b) Resolution = 8 bits; error = ± 1 bit

(c) Resolution = 10 bits; error = $\pm\frac{1}{2}$ bit

(d) Resolution = 12 bits; error = $\pm\frac{1}{2}$ bit

Figure Problem 6.33



Digital inputs = 5 volts for binary 1
= 0 volts for binary 2

Digital input	V_o	Digital input	V_o
0000	0	1000	FS/2
0001	FS/16	1001	9FS/16
0010	FS/8	1010	5FS/8
0011	3FS/16	1011	11FS/16
0100	FS/4	1100	3FS/4
0101	5FS/16	1101	13FS/16
0110	3FS/8	1110	7FS/8
0111	7FS/16	1111	15FS/16

$$V_o = -\frac{R_f}{R}\left[D3 + \frac{1}{2}D2 + \frac{1}{4}D1 + \frac{1}{8}D0\right]$$

$$V_{LSB} = -\frac{R_f}{R}\left[\frac{1}{8}D0\right]$$

$$V_{MSB} = -\frac{R_f}{R}[D3]$$

$$V_{FS} = 2V_{MSB}$$

◆ **Figure 6.32** A 4-bit binary-weighted D/A converter. Weighting is provided by input resistors R, $2R$, $4R$, and $8R$. Each digital input ($D0$–$D3$) has a value of 0 or 5 V, depending on the corresponding bit in the input code. The output is the weighted sum of only those inputs that have a value of 5 V.

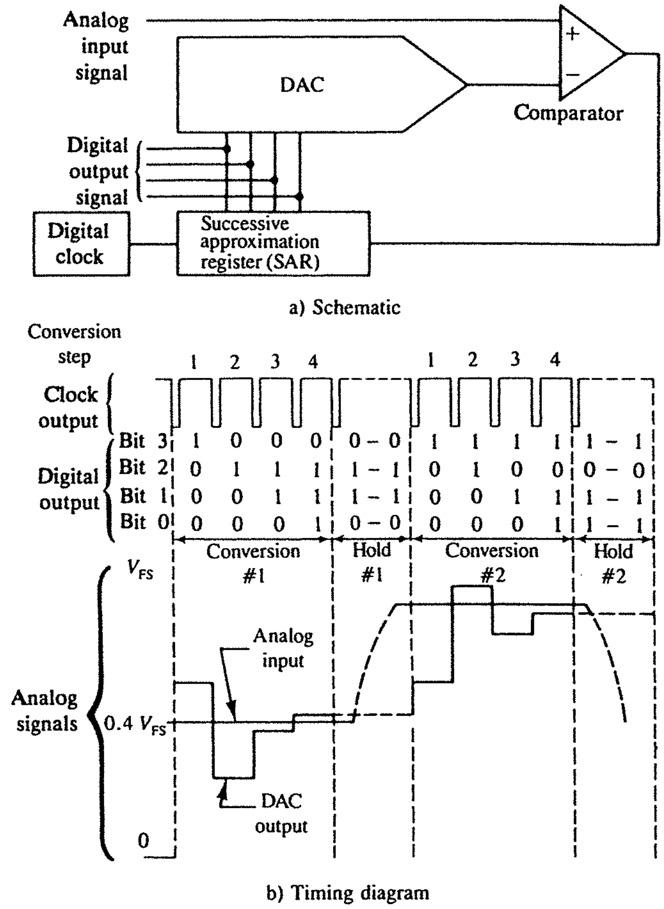
$$V_{MSB} = \frac{-R_f V_1}{R} \tag{6.50}$$

$$V_{FS} = 2 \times V_{MSB} \tag{6.51}$$

$$V_{LSB} = \frac{V_{MSB}}{2^n} \tag{6.52}$$

Although simple to understand, there are many disadvantages to the binary-weighted DAC. Each input resistor has a different resistance based upon the ratio of R–$2R$–$4R$–$8R$, and so on. It is difficult to build IC resistors that can be accurately matched at ratios greater than 20:1. This limits binary-weighted DACs to 5 bits or less. Precision resistors or 10-turn potentiometers could be used, but that would be expensive. In addition, each binary bit position is represented by a different Thévenin equivalent resistance, and the devices that provide the inputs to the DAC will see different loads.

Figure Problem 6.34



◆ **Figure 6.36** A 4-bit successive approximation A/D converter. A conversion takes place in four steps, each initiated by a negative clock pulse. The four steps for conversion 1 are as follows:

1. The SAR outputs digital word 1000, producing a DAC output of $V_{FS}/2$ V. This is higher than the analog input, so bit 3 is reset to 0 and latched for the duration of the conversion.
2. The SAR outputs word 0100, producing a DAC output of $V_{FS}/4$ V. This is lower than the analog input, so bit 2 is set to 1 and latched for the duration.
3. The SAR outputs word 0110, producing a DAC output of $3V_{FS}/8$ V. This is lower than the analog input, so bit 1 is set to 1 and latched for the duration.
4. The SAR outputs digital word 0111, producing a DAC output of $7V_{FS}/16$ V. This is higher than the analog input, so bit 0 is reset to 0 and latched for the duration.

The final digital output is 0110.

Hw8

ET 438b
Continuous and Digital Control

1.) A carrier signal of $V_c(t) = 2\sin(2\pi(2500)t)$ is used to AM modulate the following information signals:

a.) $V_1(t) = \sin(2\pi 100t) + \sin(2\pi 175t)$
b.) $V_2(t) = \sin(377t) + \sin(754t)$

Find the frequency components of $V_c(t) \cdot V_1(t)$ and $V_c(t) \cdot V_2(t)$ in Hertz. Sketch two plots of the frequency components that show the magnitude and the frequencies found in the AM signals of each of the above products.

2.) For the information signals in problem 1, determine the minimum sampling frequency that can be used to convert these analog signal into discrete values.

HW8

ET 438b
Spectrum Analysis of Undersampling

A 200 Hz sinusoidal signal is sampled at a rate of 150 samples/second.

a.) Sketch the frequency spectrum of the signals generated by this sampling process.

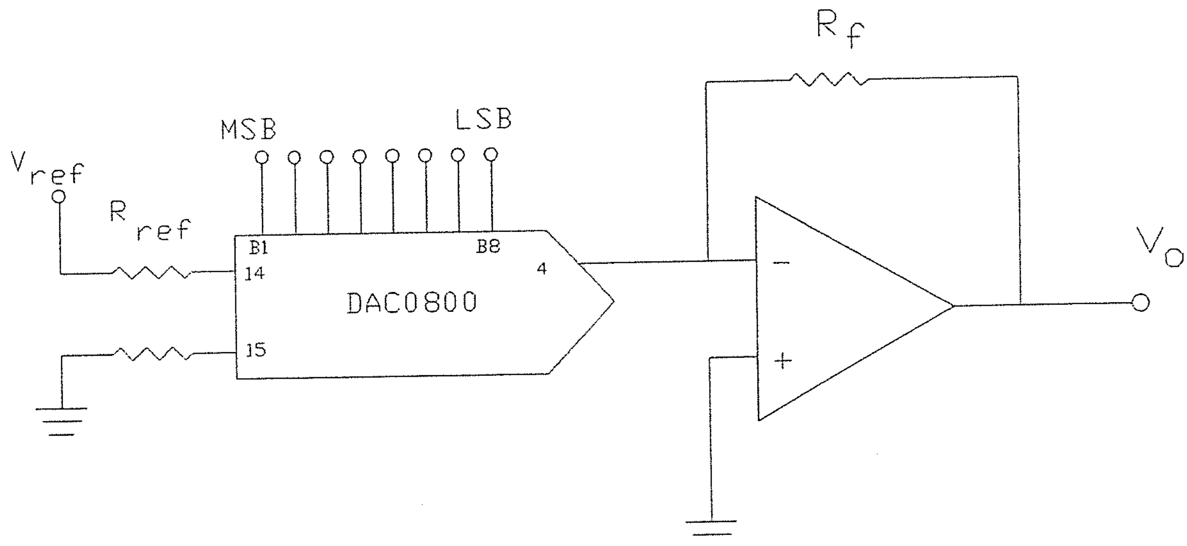
b.) Show the range of frequencies that can be reconstructed without aliasing on the sketch.

c.) What signal, if any, will be reconstructed from this sampling

Hw 9

ET 438b
Continuous And Digital Control
Commercial DAC Design

The DAC0800 DAC connection shown has the following values



V_{ref} = 5 Vdc R_f = 10 kΩ
R_{ref} = 5 kΩ

1.) Determine the output voltage when the digital input has the following values:

a.) 11111111_2
b.) 10000000_2
c.) 00000001_2

2.) Convert the binary values of parts 1a, 1b, and 1c into decimal.
3.) Calculate the percent resolution of the DAC. What is the value of the LSB?
4.) Determine the value of R_f such that the output voltage will be 12 Vdc when the digital input is 11111111_2.
5.) The DAC output is to be used to control a voltage control oscillator (VCO) that has a sensitivity of .5 Hz/mV. What is the smallest change in frequency that the DAC digital input can produce in the VCO frequency output.

Hw 9

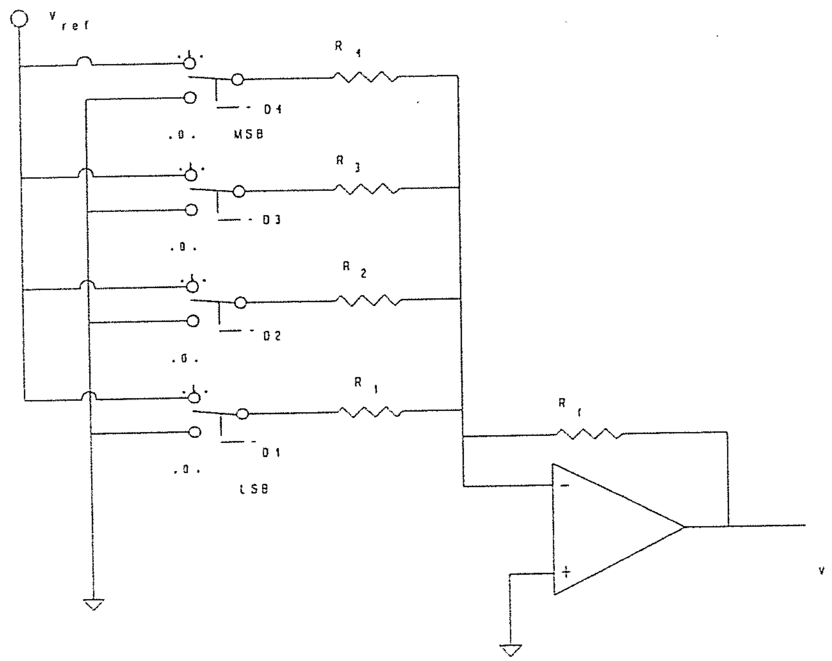
Binary-Weighted Resistor DAC

20 pts

For the DAC shown at the left the values of resistors are:

R_1 = 20 kΩ
R_2 = 10 kΩ
R_3 = 5.0 kΩ
R_4 = 2.5 kΩ

The value for V_{ref} is 0.5 Vdc.



For a digital input of:
D1 = 1
D2 = 1
D3 = 1
D4 = 1

1.) Find the value of R_F that gives an ouput voltage of -10 Vdc.

2.) What is the voltage value of the DAC output with only the least significant bit in the logic 1 position.

3.) calculate the resolution of the DAC above

Hw 10

A/D Homework

Refer to the attached diagram of a counter-type A/D converter for the following questions. The latch and counter control logic tables are:

Counter	
RST	Output
H	count
L	0

Latch Control		
ENB	D	Q
H	H	H
H	L	L
L	x	Q_o

The DAC is a DAC0800.

1.) What logic level must the enable lead take for the converter to function (H, L) ____________

2.) The LED lights when the A/D converter is making the conversion (Yes, No) ____________

3.) Compute the reference current for the DAC ______________

4.) If the value of V_{in} = 3.594 Vdc, how many clock cycles are required to make the conversion. (Hint: compute the voltage value of the LSB of the DAC) SHOW ALL CALCULATIONS.

HW 16

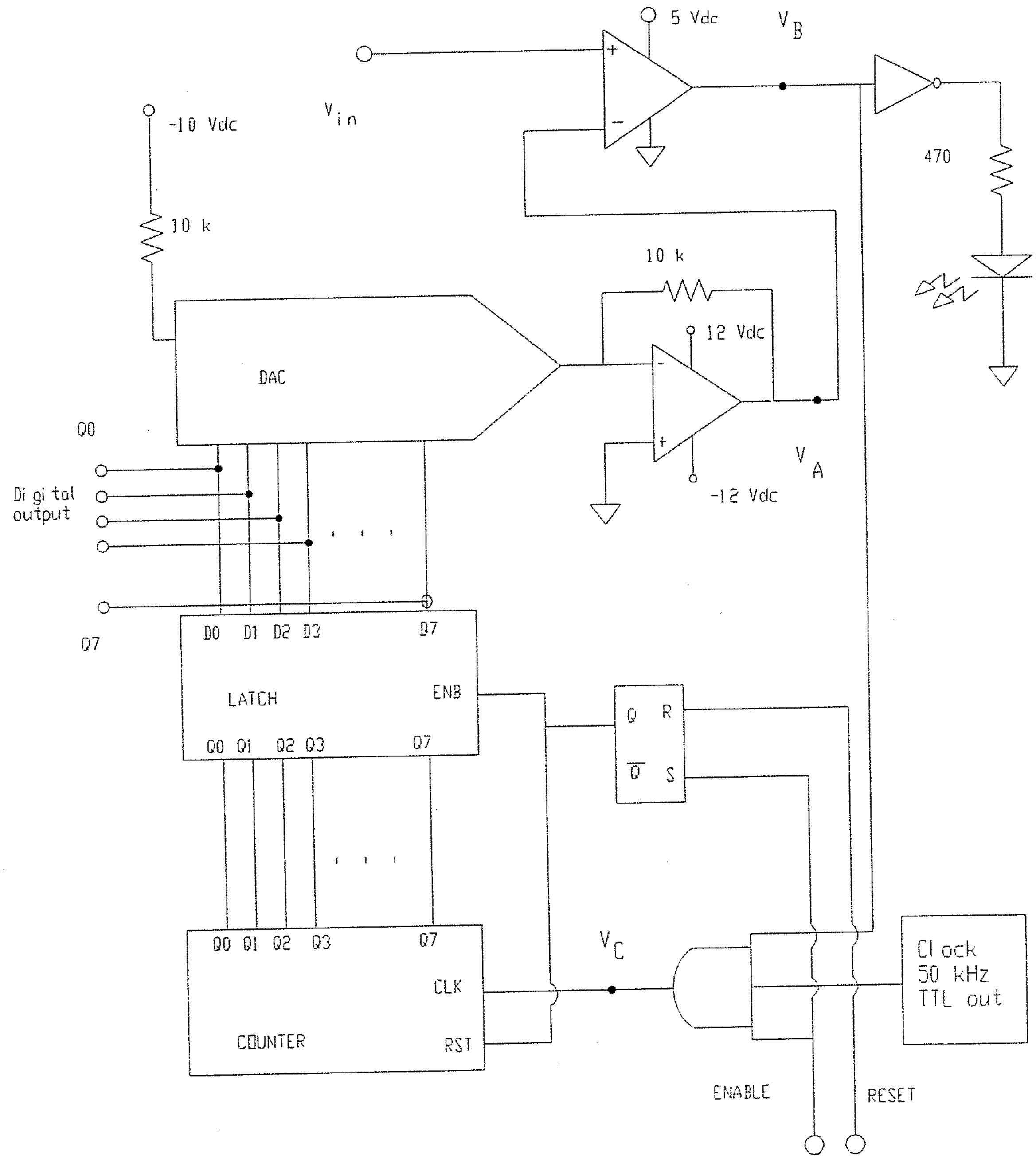


Figure 1. Analog-to-digital Converter.

HW 12

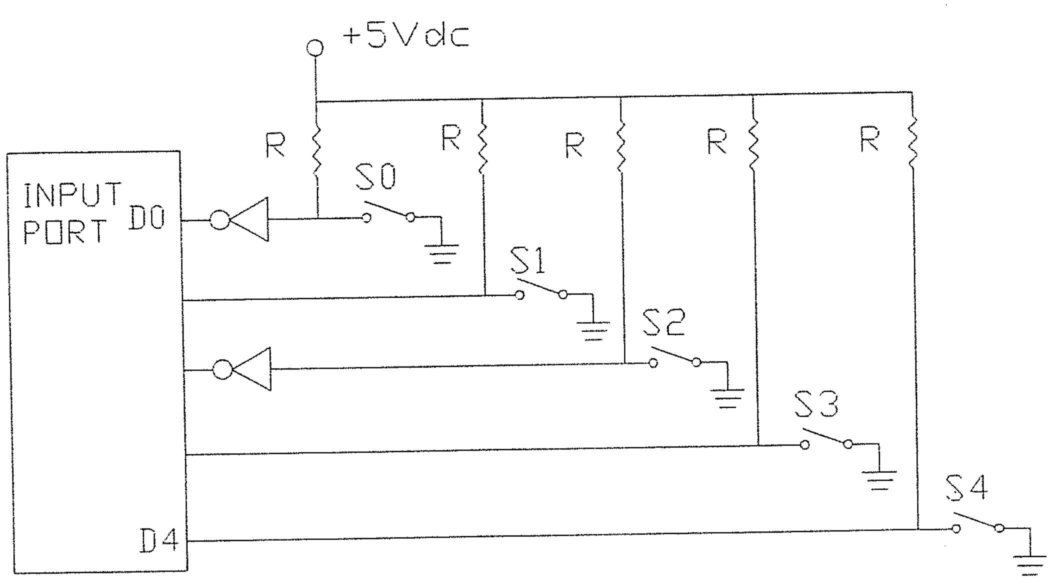
ET 438b
Continuous and Digital Control
Digital Input/Output Homework

The figure below shows a digital input port for a data acquisition system. The port and the inverters connected to the port are TTL compatible devices. With the following parameters.

Max sinking current = 16 mA
Max source current = 200 μA
Logic low Level = 0.8 V

1.) Determine the minimum value of the resistors R in the interface.
2.) Find the decimal values that will be read by the port when the interface switches are in the following states

	S0	S1	S2	S3	S4
a	closed	open	closed	closed	closed
b	closed	closed	closed	open	open
c	open	open	closed	closed	closed
d	open	closed	open	closed	open
e	closed	closed	open	open	open



Hw 12

3.) For the circuits shown below indicate whether the current through the load is being sourced or sunk by the active devices.

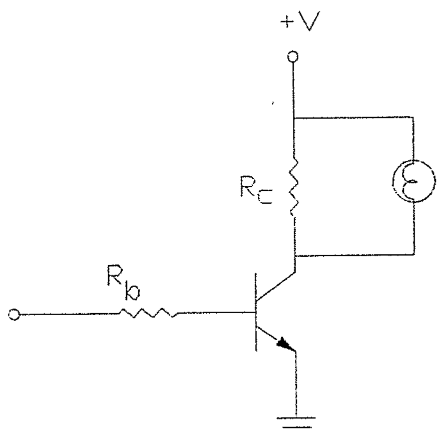


Fig. 1

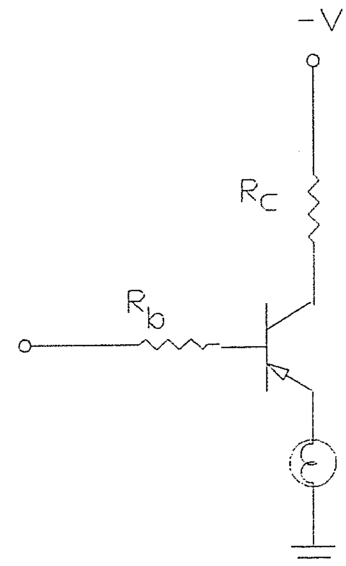


Fig. 2

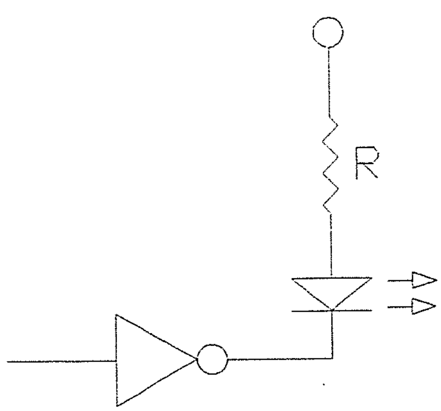


Fig. 3

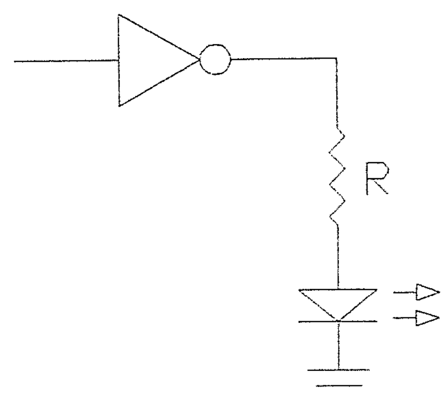


Fig. 4

HW 12

4.) The speed of a permanent magnet dc motor will be controlled by a dc control regulator that has an input range of 0 - 15 Vdc. The regulator has linear output of 0 - 50 Vdc over range of input voltage. The motor has a linear speed characteristic with respect to terminal voltage over the desired range of operation. The gain constant for the motor is 40 rpm/V. This motors speed is to be controlled by a data acquisition system with an 8-bit digital output word from the system through a DAC0800 DAC chip. A 5kΩ resistance is used in the OP AMP circuit connected to the DAC.

a.) determine the values of reference current resistance for the DAC circuit so that a range of 0-15 Vdc is achieved for the span of digital output. The reference voltage is 5 Vdc.

b.) find the binary input values that will produce motor speeds of 600 rpm, 1200 rpm, 1600 rpm.

c.) determine the maximum speed error that can be expected due the quantitization.

Hw 13

ET 438b
Continuous and Digital Control

1.) Determine the mask value and the logic function to get the desired input.

	Input	Desired Input
a.)	10110111	00110111
b.)	11100011	11100000
c.)	10101010	01010101

2.) Determine the mask value and the logic function to get the desired output

	Output	Desired Output
a.)	10111	10010
b.)	11100	00011
c.)	10101	01010
d.)	00101	00000

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Resolution: A single step of output in a measuring instrument whose output changes in discrete steps. (5.3)

Resonant frequency (designated by ω_0): The break-point frequency of an underdamped second-order component. (5.5)

Response time: The time required for the output to reach a designated percentage of the total change, after a step change in input. (5.5)

Rise time: The time required for the output to go from a small percentage of change to a large percentage of change, after a step change in input. Unless otherwise specified, the change is from 10% to 90%. (5.5)

Sensitivity: The ratio of the change in output divided by the change in input that caused the change in output. (5.3)

Settling time: The time it takes for the response of an underdamped component to remain within a small band above and below the 100% change line. (5.5)

Span: The size of the range, equal to the upper range limit minus the lower range limit. (5.3)

Systemic error: Another name for bias. (5.4)

Thermal sensitivity shift: A change in the sensitivity of a measuring instrument caused by a specified change in the ambient temperature. (5.3)

Thermal zero shift: A change in the zero output of a measuring instrument caused by a specified change in the ambient temperature. (5.3)

Time constant (designated by r): The time required for the output of a component to reach 63.2% of the total change after a step change in input. (5.5)

◆ EXERCISES

Section 5.1

1.1 Compute the mean and standard deviation of the following sets of measurements:

(a) 76°C, 77°C, 75°C, 76°C, 75°C

(b) 2.3 gpm, 2.5 gpm, 2.5 gpm, 2.3 gpm, 2.4 gpm

(c) 7.4 lpm, 7.3 lpm, 7.5 lpm, 7.6 lpm, 7.4 lpm

(d) 410 kPa, 411 kPa, 413 kPa, 412 kPa, 413 kPa, 413 kPa

(e) 32.6 psi, 32.5 psi, 32.8 psi, 32.6 psi, 32.9 psi, 32.8 psi

(f) 4.26 m, 4.25 m, 4.26 m, 4.25 m, 4.23 m, 4.24 m

Section 5.2

5.2 A pressure sensor is tested for repeatability by increasing the input pressure from 0 to 15 psi 10 times and recording the output reading each time the input reaches 15 psi. The output readings are as follows:

15.45,	15.53,	15.61,	15.42,	15.55
15.47,	15.51,	15.59,	15.46,	15.60

(a) Calculate the mean and standard deviation of the 10 readings.

(b) Use three standard deviations to estimate the range of readings you would expect in a very large number of test runs.

5.3 Repeat Exercise 5.2 for the following output readings:

14.64,	14.72,	14.69,	14.62,	14.61
14.67,	14.71,	14.78,	14.75,	14.80

Section 5.3

5.4 Determine the span of each of the following measuring transmitters:

Type	Upper Range Limit	Lower Range Limit
(a) Temperature	150°F	−50°F
(b) Pressure	100 psi	0 psi
(c) Level	4 ft	2 ft
(d) Flow rate	15 gpm	5 gpm
(e) Force	210 lbf	200 lbf
(f) Temperature	250°C	50°C
(g) Pressure	200 kPa	0 kPa
(h) Level	1.5 m	1.0 m
(i) Flow rate	12 lpm	8 lpm
(j) Force	10 N	8 N

5.5 A potentiometer has 800 turns of wire, a lower range limit of 0 V, and an upper range limit of 20 V. Determine

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the span in volts, the average resolution as a percentage of the span, and the average resolution in volts.

5.6 A pressure gage with a range from 3 to 15 psi was tested for dead band. When the input pressure was increased from 9.00 to 9.05 psi, the output remained stationary at 9.10 psi. When the input was increased from 9.00 to 9.06 psi, the output changed from 9.10 to 9.11 psi. Express the dead band in pounds per square inch, as a percentage of the lower input value, and as a percentage of the span.

5.7 A potentiometer is used to measure the position of a shaft. The input range of shaft position is from −160° to +160°. The corresponding output range is from −20 to +20 V. What is the span of this position sensor? What is its sensitivity in volts per degree?

5.8 The following results were obtained from the calibration of a force transducer:

Input Force (N)	Output Voltage (V)
0	0.06
2	0.63
4	1.20
6	1.77
8	2.35
10	2.94
12	3.55
14	4.17
16	4.80
18	5.43
20	6.06

Determine the sensitivity of the force transducer in volts per newton at 20 and 80% of full scale. Hint: Divide the change in output voltage between 2 and 6 N by the change in force (i.e., 6 − 2 = 4 N) to determine the sensitivity at 20%.

5.9 At 70°F, an input of 0 psi to a pressure transmitter produces an output of 4 mA, and an input of 100 psi produces an output of 20 mA. The transmitter has a thermal zero shift of 0.02 ma/°F and a thermal sensitivity shift of 0.0004 (mA/psi)/°F. Determine the following:

(a) The sensitivity of the transmitter at 70°F.

(b) The sensitivity of the transmitter at 20°F and 120°F.

(c) The 0-psi output of the transmitter at 20°F and 120°F.

(d) The 100-psi output of the transmitter at 20°F and 120°F.

5.10 A temperature transmitter has an input range of 0 to 100°C, an output range of 4 to 20 mA, and an accuracy of ±0.5%. The ideal transmitter has a linear output from 4 mA at 0°C to 20 mA at 100°C. If the output of the transmitter is 13.6 mA, what are the ideal, minimum, and maximum possible temperatures?

5.11 A pressure transmitter has an input range of 100 kPa to 150 kPa, an output range of 4 to 20 mA, and an accuracy of ±1%. The ideal transmitter has a linear output from 4 mA at 100 kPa to 20 mA at 150 kPa. If the output is 15.2 mA, what are the ideal, minimum, and maximum possible pressures?

Section 5.4

5.12 The accuracy of the position sensor in Exercise 5.7 is ±1% of span. If the output is +8 V, what is the ideal position? What are the minimum and maximum possible positions?

5.13 The measurements in Exercise 5.1 were obtained in tests for repeatability. Each measurement was obtained by traversing the sensor from the lower range limit to the ideal measurement and recording the equilibrium measurement of the sensor. Determine the bias and repeatability of each sensor in terms of the measured variable and as a percentage of span.

Range Limit		Ideal
Upper	Lower	Measurement
(a) 100°C	0°C	75°C
(b) 10 gpm	0 gpm	2.7 gpm
(c) 20 lpm	0 lpm	7.8 lpm
(d) 500 kPa	400 kPa	416 kPa
(e) 40 psi	30 psi	32 psi
(f) 5.0 m	4.0 m	4.2 m

5.14 Determine the following from the test of the pressure sensor in Exercise 5.2:

(a) The bias or systemic error in pounds per square inch and in percentage of span.

(b) The repeatability in pounds per square inch and in percentage of span.

5.15 Repeat Exercise 5.14 for the pressure sensor test in Exercise 5.3.

5.16 Explain the difference between repeatability and reproducibility.

5.17 Determine the measured accuracy of the pressure sensor in Exercise 5.2. Express the maximum positive and negative errors in pounds per square inch and in percentage of span.

5.18 Determine the measured accuracy of the pressure sensor in Exercise 5.3. Express the maximum positive and

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negative errors in pounds per square inch and in percentage of span.

5.19 The following data are the average upscale and downscale values from a calibration report. Both the input and the output are expressed in terms of percentage of span. Plot the calibration curve and determine the combined hysteresis and dead band.

Upscale		*Downscale*	
Input	Output	Input	Output
0	2.5	100	90.2
10	7.2	90	84.8
20	13.4	80	78.0
30	20.6	70	70.0
40	29.1	60	61.3
50	38.3	50	52.2
60	47.8	40	43.1
70	57.1	30	33.9
80	67.0	20	24.0
90	77.5	10	14.0
100	90.2	0	2.5

5.20 Draw the calibration curve for the force transducer in Exercise 5.8. Then draw the straight lines for independent linearity, terminal-based linearity, and zero-based linearity. Determine the maximum error for each straight line.

5.21 The following data are the averages of the upscale and downscale readings from four calibration reports. For each report, draw the calibration curve and then draw the straight lines for independent linearity, terminal-based linearity, and zero-based linearity. Determine the maximum error for each straight line.

	Average Output			
Input	(a)	(b)	(c)	(d)
0	2.8	4.0	3.0	0.0
10	9.6	15.7	10.5	9.9
20	17.4	26.7	18.2	18.8
30	26.5	37.1	27.7	26.7
40	38.7	46.9	38.2	33.6
50	50.5	56.0	50.2	40.0
60	61.1	64.5	61.9	47.4
70	70.0	72.3	72.4	54.8
80	76.8	79.5	81.7	64.2
90	83.2	86.0	89.5	75.1
100	88.8	92.0	97.0	88.0

Section 5.5

5.22 Explain the difference between static characteristics and dynamic characteristics.

5.23 The following data were obtained from four temperature probes that were plunged from a liquid bath maintained at 50°C into a second bath maintained at 100°C. For each probe, plot the response curve and determine the 95% response time, the time constant, and the 10 to 90% rise time.

	Temperature (°C)			
Time (s)	(a)	(b)	(c)	(d)
0	50.0	50.0	50.0	50.0
10	66.0	59.1	62.7	60.6
20	76.8	66.5	72.2	68.9
30	84.2	72.6	79.3	75.5
40	89.3	77.5	84.6	80.7
50	92.7	81.6	88.5	84.8
60	95.0	84.9	91.4	88.0
70	96.6	87.7	93.6	90.6
80	97.7	89.9	95.2	92.6
90	98.4	91.7	96.5	94.1
100	98.9	93.2	97.4	95.4
110	99.3	94.5	98.0	96.4
120	99.5	95.5	98.5	97.1
130	99.7	96.3	98.9	97.7
140	99.8	97.0	99.2	98.2
150	99.8	97.5	99.4	98.6
160	99.9	98.0	99.6	98.9
170	99.9	98.3	99.7	99.1
180	100.0	98.6	99.8	99.3
190	100.0	98.9	99.8	99.5
200	100.0	99.1	99.9	99.6

5.24 The following data were obtained from a step response test of an underdamped component. Plot the response curve and determine the 10 to 90% rise time, the overshoot, and the 2% settling time.

Time (s)	Output (%)
0	0.0
5	36.5
10	74.5
13.5	100.0
15	110.0
18.4	120.0
21.8	110.0
24.0	100.0
25.0	96.0

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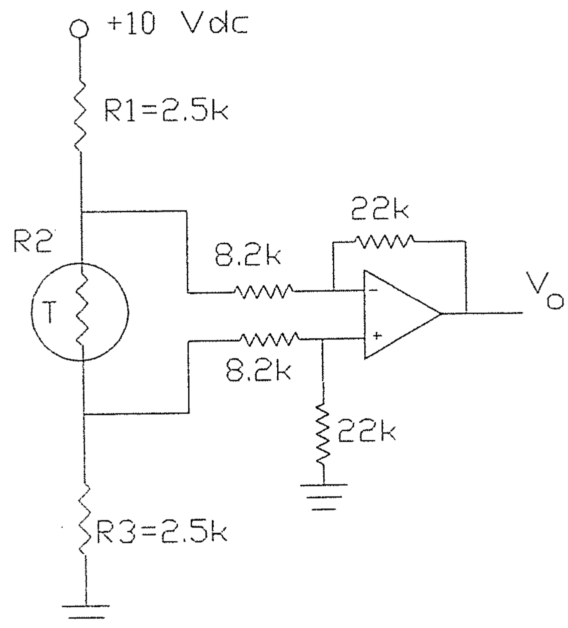
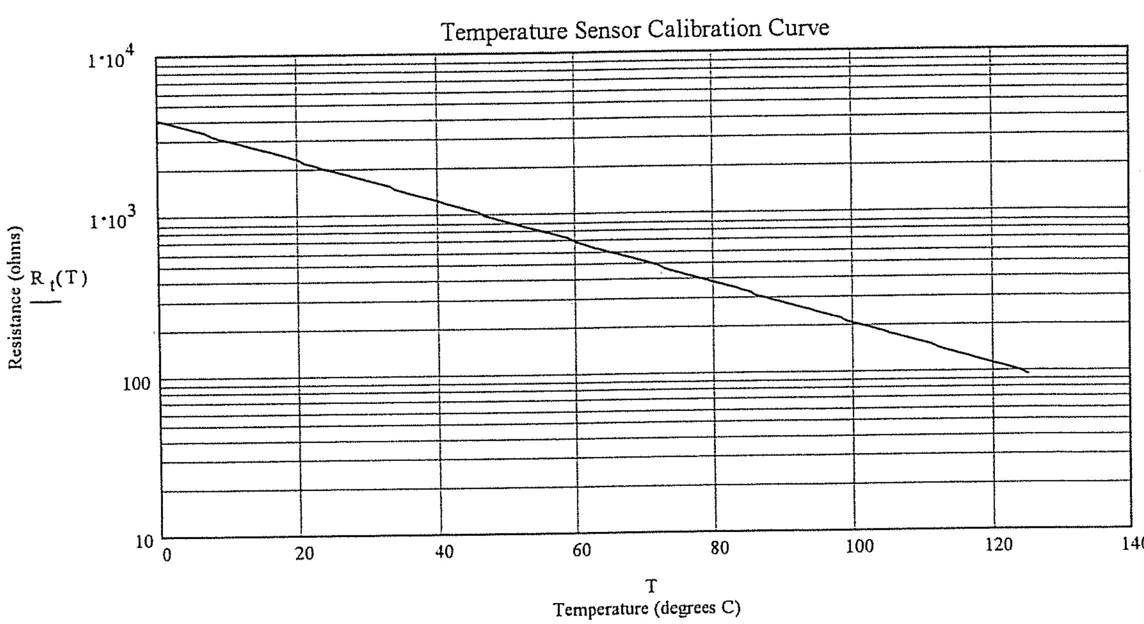
ET438B
Differential Amplifier Homework

In the circuit shown below, R2 is a thermistor. The calibration curve for this device is also shown below. Determine the error voltage that is produced by ignoring the loading effects of the differential amplifier on the sensor circuit when the measured temperature is 60 degrees C.





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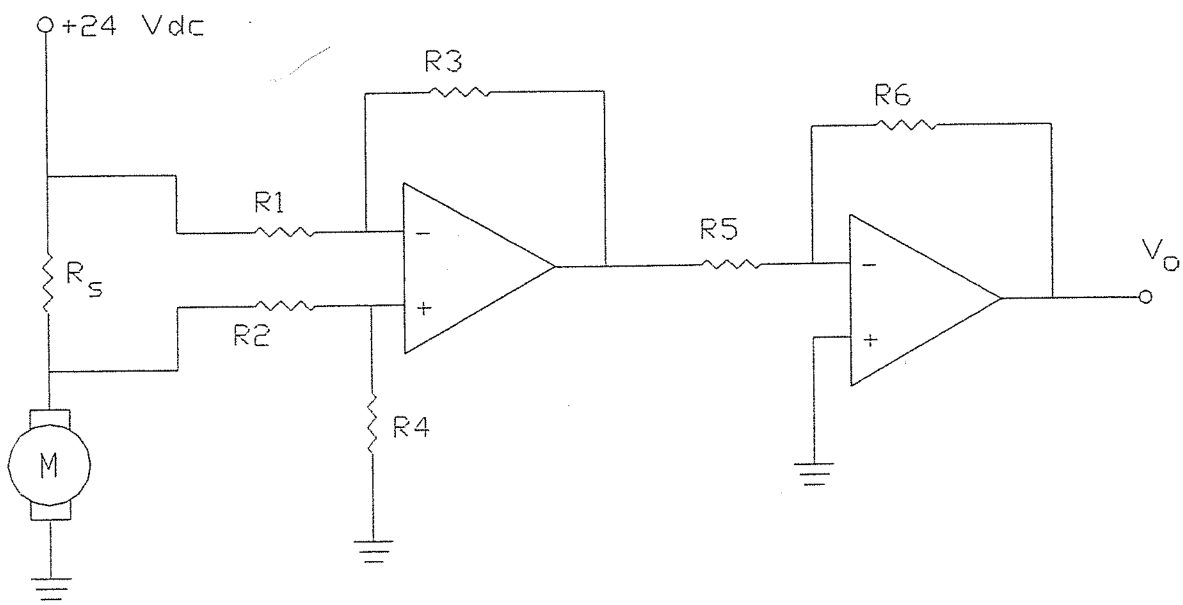
ET 438B
Differential Amplifier Application

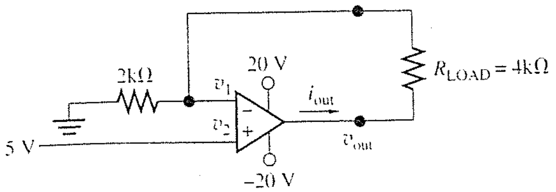
For the circuit below has the following values

$R_s = 0.12\ \Omega$ R1 = R2 = 100 kΩ R3 = R4 = 470 kΩ
R5 = 10 kΩ R6 = 82 kΩ
$V_0 = -7.875$ Vdc

The circuit is designed to sense the load current of the dc motor/generator M by



measuring the voltage drop across the shunt resistor R_s. Find the magnitude and direction of the current supplied to motor/generator.



◆ **Figure 6.40** A constant current source (Exercise 6.18).

Determine the equation of the zero-based linearity line and express the nonlinearity as a percentage of the output span.

6.22 The unbalanced bridge in Figure 6.17 is used to condition the output of the strain-gage load cell described in Exercise 6.21. The parameters in Figure 6.17 have the following values:

R_s = load cell resistance (range = 149 to 150 Ω)
$R_3 = 150\ \Omega$ $R_2 = R_4 = 2\ k\Omega$ $R_{bal} = 150\ \Omega$
$V_{dc} = 1\ V$ $R_f/R_a = 1000$

Determine the values of V_{out} for the following input force conditions. F_{in}: −100, −50, 0, 50, and 100 N.

Determine the equation of the zero-based linearity line and express the nonlinearity of as a percentage of the output span.

6.23 Design a single-stage, active, low-pass filter that will provide an attenuation factor of 50 for a 200-Hz signal. Calculate the resistor size required if a 50-μF capacitor is used in the *RC* circuit.

6.24 Design a two-stage, active, low-pass filter that will provide an attenuation factor of 500 for a 400-Hz signal. Calculate the resistor size required if 0.1-μF capacitors are used in the two *RC* circuits.

6.25 Design (a) a single-stage low-pass filter and (b) a two-stage low-pass filter that will attenuate a 159.2-Hz signal by an attenuation factor of 100. Use the program BODE to generate frequency-response data and plot a Bode magnitude diagram for each filter. Compare the two Bode diagrams and comment.

6.26 Design a notch filter that will attenuate a 159.2-Hz signal by an attenuation factor of 20. Use the program BODE and plot a Bode magnitude diagram for the notch filter. Compare the notch filter Bode diagram with the two low-pass filter diagrams from Exercise 6.25a.

6.27 Change the endpoints of the line segments in Figure 6.22 to minimize the maximum error. Construct a table similar to Table 6.2 showing the error at the midpoints and the endpoints of the line segments.

6.28 Construct a five-step piecewise-linear approximation of the function defined by the input/output table that follows. Construct a graph similar to Figure 6.22 and a table similar to Table 6.2.

Measuring Instrument Input/Output Table

Input	Output	Input	Output	Input	Output
0	2.9	35	31.9	70	69.8
5	6.8	40	36.7	75	75.2
10	10.8	45	41.8	80	80.3
15	14.8	50	47.2	85	85.1
20	18.9	55	52.8	90	89.5
25	23.1	60	58.5	95	93.5
30	27.4	65	64.2	100	97.1

Note: All values are a percentage of full-scale range.

6.29 A plantinum RTD has the following resistance versus temperature characteristic:

Temperature, *T* (°C)	Resistance, R_s (Ω)
0	100.0
25	109.8
50	119.8
75	129.6
100	139.3

An unbalanced Wheatstone bridge is to be used to convert the RTD resistance into a voltage signal. The balance resistance value $R_{bal} = 119.8\ \Omega$, so the bridge output will be 0 V at 50°C.

Your assignment is to design the unbalanced bridge circuit, an instrumentation amplifier, and a summing amplifier that will give a full-scale output from 1 to 5 V as the temperature goes from 0 to 100°C. As part of your design assignment, you are to complete the following table of results from various steps of the design process:

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6.11 A primary element produces an output voltage that ranges from 0 to 22 mV. Design a summing amplifier that will produce an output voltage with a range of -1 to -5 V. Use a 1-kΩ resistor for R_{in}.

6.12 The summing amplifier in Figure 6.8a can be used to implement the equation $y = mx + b$ (the slope-intercept form of the equation of a straight line). Use a 10-kΩ resistor for R_f and determine the values of R_a and R_b to implement the following slope-intercept equation.

$$y = -v_{out}, x = v_a, m = R_f/R_a = 3.42, b = v_b$$

$$y = mx + b$$

$$-v_{out} = 3.42v_a + v_b$$

6.13 Given a 10-μF capacitor, compute the value of R_{in} for an integrator with the following defining equation:

$$v_{out} = -\int_{t_1}^{t_2} v_{in}\,dt + v_{out}(t_1)$$

6.14 Determine $v_{out}(t_2)$ of the integrator in Example 6.6 for each of the following condition sets.

(a) $t_1 = 5$ s, $t_2 = 7$ s, $v_{out}(t_1) = 10$ V
(b) $t_1 = 5$ s, $t_2 = 6$ s, $v_{out}(t_1) = 10$ V
(c) $t_1 = 0$ s, $t_2 = 1.2$ s, $v_{out}(t_1) = 0$ V
(d) $t_1 = 0$ s, $t_2 = 1.6$ s, $v_{out}(t_1) = 0$ V
(e) $t_1 = 0$ s, $t_2 = 2.0$ s, $v_{out}(t_1) = 0$ V

6.15 For each of the following condition sets, determine the value of the external resistor, R_e, for an instrumentation amplifier similar to Figure 6.12.

(a) gain = 100, $R_1 = 1$ kΩ, $R_2 = 10$ kΩ, $R_3 = 1$ kΩ
(b) gain = 100, $R_1 = R_2 = R_3 = 1$ kΩ
(c) gain = 500, $R_1 = R_2 = R_3 = 1$ kΩ
(d) gain = 200, $R_1 = R_2 = R_3 = 1$ kΩ

Section 6.4

6.16 Design a current-to-voltage converter that converts a 10-mA input into a 15-V output (refer to Figure 6.14a and Example 6.9).

(a) Determine the value of resistor R (Figure 6.14a)
(b) Determine the value of V_{cc} necessary for the op amp to be in the linear operating region with 1 V to spare.

6.17 Design a voltage-to-current converter that converts a 6-V input into a 20-mA output (refer to Figure 6.14b and Example 6.10).

(a) Determine the value of resistor R (Figure 6.14b).
(b) Determine the value of R_{LOAD} that will result in an output voltage (v_{out}) of 11 V when $v_{in} = 6$ V.
(c) Determine the value of v_{cc} necessary for the op amp to be in the linear operating region with 1 V to spare if R_{LOAD} has the value determined in step (b).

6.18 A constant current source is shown in Figure 6.40.

(a) Find the value of v_{out}.
(b) Find the value of v_{out}.
(c) Assume that $v_{cc} = 20$ V and $V_{sat} = 0.8\ V_{cc}$. Determine the maximum value of R_{LOAD} for which i_{out} will have the value of step (a).

6.19 Design a current-to-current converter with an input range of 0 to 0.2 mA and an output range of 0 to 1 mA (i.e., a gain of 5). Plan to use the following three resistors in your design:

R_1 (see resistor R in Figure 6.14b)
R_2 (see resistor R in Figure 6.14a)
R_{LOAD} (see resistor R_{LOAD} in Figure 6.14b).

You may use the following assumptions in your design:

$v_{out} = 10$ V when i_{out} 1 mA
$R_{LOAD} = 2$ kΩ
i_{in} can produce 12 V at the v_2 input terminal
$v_{cc} = 15$ V

Use $i_{in} = 0.2$ mA and $i_{out} = 1$ mA as your design conditions when you determine the values of R_1, v_1, v_2, and R_2.

6.20 Find the value of the unknown resistor, R_x, for each of the following balanced Wheatstone bridge conditions (see Figure 6.15).

(a) $R_2 = 5$ kΩ, $R_3 = 1.71$ kΩ, $R_4 = 10$ kΩ
(b) $R_2 = 10$ kΩ, $R_3 = 2.56$ kΩ, $R_4 = 5$ kΩ
(c) $R_2 = 100$ kΩ, $R_3 = 6.27$ kΩ, $R_4 = 1$ kΩ
(d) $R_2 = 20$ kΩ, $R_3 = 3.47$ kΩ, $R_4 = 1$ kΩ

6.21 The self-nulling current balance bridge in Figure 6.16 is used to condition the output of a strain-gage load cell. The load cell has an input force range of ±100 N and an output resistance range of ±1 Ω. An input of −100 N produces an output of 149 Ω, an input of 0 N produces an output of 150 Ω, and an input of +100 N produces an output of 151 Ω.

The strain gage element is designated R_x in Figure 6.16. The bridge is balanced when $R_x = 150$ Ω and $I_N = 0$ A. The other bridge parameters are

$$R_{3a} = 5\ \Omega \quad R_{3b} = 145\ \Omega \quad R_2 = R_4 = 2\ \text{k}\Omega \quad V_{dc} = 10\ \text{V}$$

Determine the values of I_N for the following input force conditions, F_{in}: −100, −50, 0, 50, and 100 N.

Problem 6.22

3. The zero-based linearity line extends in both directions from the point where $i_N = 0$ mA and $R_s = 120\ \Omega$. The line is positioned such that it is an equal distance from i_N at each extremity. We will use L_N for the y-coordinate of the zero-based line. The magnitude of L_N at each extremity is determined by averaging the magnitude of i_N at each extremity.

When $R_s = 140$, $L_N = (17.544 + 18.182)/2 = 17.863$ mA
When $R_s = 100$, $L_N = -17.863$ mA

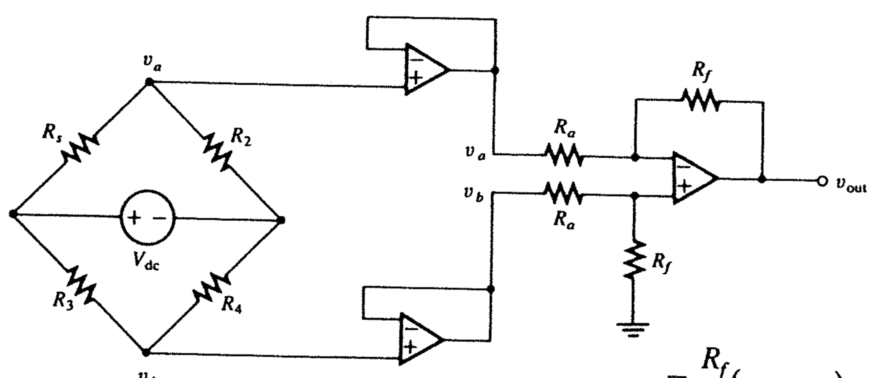
The equation of the zero-based linearity line is determined by the following two points:

$R_s = 120\ \Omega \quad L_N = 0.0$ mA
$R_s = 140\ \Omega \quad L_N = 17.863$ mA

Zero-based linearity line $L_N = 0.89315R_s - 107.178$
The values of L_N, $L_N - i_N$, and the percentage of difference are in the last three columns of the table below.

T (°C)	R_s (Ω)	i_N (mA)	L_N (mA)	$L_N - i_N$	% Diff.
0	100	−18.182	−17.863	0.319	0.89
25	110	−9.009	−8.931	0.078	0.22
50	120	0.000	0.000	0.000	0.00
75	130	8.850	8.931	0.081	0.23
100	140	17.544	17.863	0.319	0.89

◆



$$v_{out} = \frac{R_f}{R_a}(v_b - v_a)$$

$$v_b - v_a = \left[\frac{\alpha(1-\alpha)\epsilon}{1+\alpha\epsilon}\right]V_{dc}$$

$$v_{out} = \frac{R_f}{R_a}\left[\frac{\alpha(1-\alpha)\epsilon}{1+\alpha\epsilon}\right]V_{dc}$$

◆ **Figure 6.17** Unbalanced Wheatstone bridge and instrumentation amplifier circuit. The purpose of the circuit is to produce an output voltage that is proportional to the difference between R_3 and R_{bal}.

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Resolver: A rotary transformer that produces an output signal that is a function of the rotor position. (7.2)

Retroreflective scan method: A method of photoelectric detection in which the light source and the receiver are mounted in the same sensing unit. A special retroreflective target, mounted on the object to be detected, reflects the light beam from the source back to the receiver. (7.2)

Sensing range: The distance from the sensing face of a proximity sensor within which a standard target will be detected. (7.2)

Specular scan method: A method of photoelectric detection that is used only when the object has a mirror-like finish. The light source and the receiver are mounted such that the light beam reflects from the object into the receiver. (7.2)

Strain gage: A sensor that measures the displacement per unit length of an elastic member that is under stress. (7.5)

Synchro: A rotary transducer that converts angular displacement into an ac voltage or vice versa. The three types of synchro are the transmitter, the transformer, and the differential. (7.2)

Tachometer: An electric generator used to measure angular velocity. (7.3)

Unbonded strain gage: A sensor that is attached to an elastic member at two points to measure the total displacement between the two attachment points. (7.5)

◆ EXERCISES

Section 7.2

7.1 Determine the number of turns required to produce a potentiometer with each of the following resolutions.
(a) 1% (b) 0.5% (c) 0.2%
(d) 0.1% (e) 0.01%

7.2 The potentiometer in Figure 7.4 has a resistance of 100,000 Ω. Determine the loading error caused by the following values of R_L and a.
(a) $R_L = 1000\ \Omega$; $a = 0.25, 0.5, 0.75$
(b) $R_L = 10{,}000\ \Omega$; $a = 0.25, 0.5, 0.75$
(c) $R_L = 100{,}000\ \Omega$; $a = 0.25, 0.5, 0.75$

7.3 The synchro system in Figure 7.6 operates at a frequency of 60 Hz. The maximum amplitude of the transformer rotor voltage is 6.2 V. Determine the ac error signal produced by each of the following angular displacements.
(a) $\theta = 75°$
(b) $\theta = 45°$
(c) $\theta = 150°$
(d) $\theta = 110°$

7.4 For the synchro system in Exercise 7.3, determine the angular displacement that will produce each of the following ac error signals.
(a) $3.1 \sin 377t$
(b) $-4.8 \sin 377t$
(c) $5.5 \sin 377t$
(d) $2.7 \sin(377t + 180°)$

7.5 The synchro system in Figure 7.9 operates at a frequency of 400 Hz. The maximum amplitude of the transformer rotor voltage is 22.5 V. Determine the ac error signal produced by each of the following pairs of angular displacements.
(a) $\theta = 60°$, $\theta_d = -60°$
(b) $\theta = -30°$, $\theta_d = -20°$
(c) $\theta = 45°$, $\theta_d = 20°$
(d) $\theta = -18°$, $\theta_d = -17°$

7.6 Equations (7.5) and (7.6) define the stator voltages (E_1 and E_2) of a resolver in terms of the rotor voltages (E_3 and E_4).

$$E_1 = K(E_3 \cos\theta - E_4 \sin\theta) \tag{7.5}$$

$$E_2 = K(E_4 \cos\theta + E_3 \sin\theta) \tag{7.6}$$

Assume that $K = 1$ and show that Equations (7.5) and (7.6) can be rearranged to define the rotor voltages in terms of the stator voltages as follows:

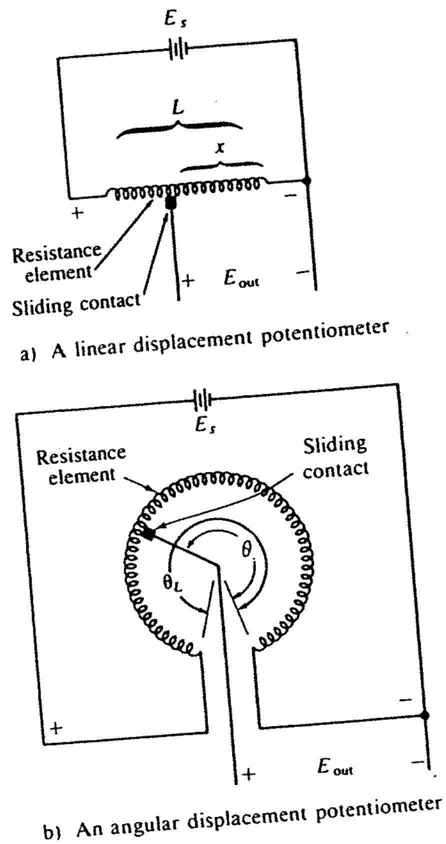
$$E_3 = E_1 \cos\theta + E_2 \sin\theta$$

$$E_4 = E_2 \cos\theta - E_1 \sin\theta$$

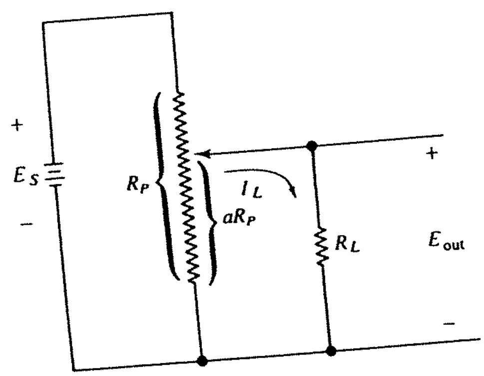
Hint: Use the following equivalent forms of $\cos\theta$ and $\sin\theta$ during the manipulation of the equations.

$$\cos\theta = \frac{x}{\sqrt{x^2 + y^2}}$$

Problem 7.2 figure



◆ **Figure 7.3** Two types of potentiometric displacement sensors: (a) linear; (b) angular. In both types, E_{out} is a measure of the position of the sliding contact.



◆ **Figure 7.4** A loading error is produced in a potentiometer when a load resistor is connected between the sliding contact and the reference terminal.

tiometer and a is the proportionate position of the sliding contact, then aR_p is the resistance of the portion of the potentiometer between the sliding contact and the reference point. The load resistor, R_L, is connected in parallel with resistance aR_p. The equivalent resistance of this parallel combination is $(R_L)(aR_p)/(R_L + aR_p)$.

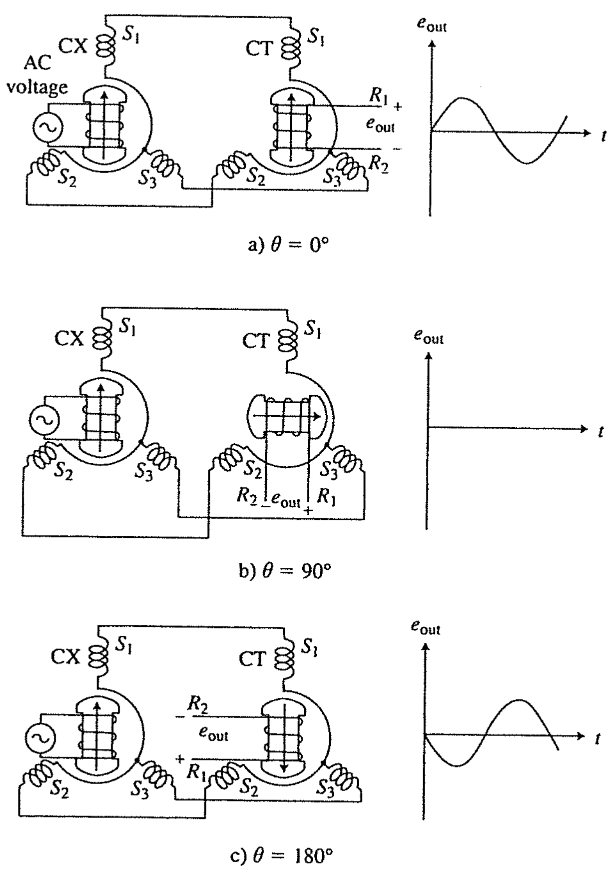
Problem 7.3 figure

Synchro Systems

A *synchro* is a rotary transducer that converts angular displacement into an ac voltage, or an ac voltage into an angular displacement. Three different types of synchros are used in angular displacement transducers: control transmitter, control transformer, and control differential.

Synchros are used in groups of two or three to provide a means of measuring angular displacement. For example, a control transmitter and a control transformer form a two-element system that measures the angular displacement between two rotating shafts. The displacement measurement is then used as an error signal to synchronize the two shafts. The term *electronic gears* is sometimes used to describe this type of system because the two shafts are synchronized as if they were connected by a gear drive. The addition of a control differential forms a three-element system that provides adjustment of the angular relationship of the two shafts during operation.

A two-element synchro system is shown in Figure 7.6. The control transmitter is designated CX, and the control transformer is designated CT. Both the transmitter and the transformer have an H-shaped rotor with a single winding. Connections to the rotor winding are made through slip rings on the shaft. The stators each have three coils spread 120° apart and connected in a Y configuration.



◆ **Figure 7.6** A two-element synchro system measures the phase difference between two rotating shafts.

HW 19, 20

7.17 A dc tachometer has the following specifications:

$$R = 0.025 \text{ m}$$
$$B = 0.22 \text{ Wb/m}^2$$
$$N = 120$$
$$L = 0.25 \text{ m}$$

Determine K_E and construct a calibration curve for a velocity range of 0 to 5000 rpm.

7.18 Determine the speed measured by each of the following incremental optical encoders:

(a) Count = 102, timer interval = 4 ms, N = 500 pulses/revolution
(b) Count = 2800, timer interval = 10 ms, N = 1600 pulses/revolution
(c) Count = 1800, timer interval = 8 ms, N = 2000 pulses/revolution
(d) Count = 1200, timer interval = 10 ms, N = 1000 pulses/revolution

7.19 Determine the count produced by each of the following incremental optical encoders:

(a) Shaft speed = 1800 rpm, timer interval = 40 ms, N = 500 pulses/revolution
(b) Shaft speed = 3600 rpm, timer interval = 10 ms, N = 1800 pulses/revolution
(c) Shaft speed = 5000 rpm, timer interval = 16 ms, N = 2000 pulses/revolution
(d) Shaft speed = 4400 rpm, timer interval = 8 ms, N = 1200 pulses/revolution

Section 7.4

7.20 The accelerometer in Figure 7.18 has the following specifications:

$$M = 0.012 \text{ kg}$$
$$K = 320 \text{ N/m}$$
$$X_{max} = \pm 0.25 \text{ cm}$$

Determine the following:

(a) The maximum acceleration that can be measured.
(b) The resonant frequency, f_0.
(c) The damping constant, b, required to produce a damping ratio of 0.6.
(d) The maximum frequency for which Equation (7.18) can be used with less than 0.5% error.

Section 7.5

7.21 The strain gage force transducer in Figure 7.19 has the following specifications:

Cantilever Beam

Material: steel
$E = 2 \times 10^{11}$ N/m^2
Maximum allowable stress = 5.0×10^8 N/m^2
b = 1.25 cm
h = 0.25 cm
L = 6 cm

Strain Gage

Gage factor = 2
Nominal resistance = 200 Ω

Determine the maximum force that can be measured and the change in resistance produced by the maximum force.

7.22 The pneumatic force transmitter in Figure 7.20 is to have an input of 0 to 50 lb force and an output signal range of 3 to 15 psi. Determine the required effective area.

7.23 The strain gage force transducer in Figure 7.19 has the following specifications:

Cantilever Beam

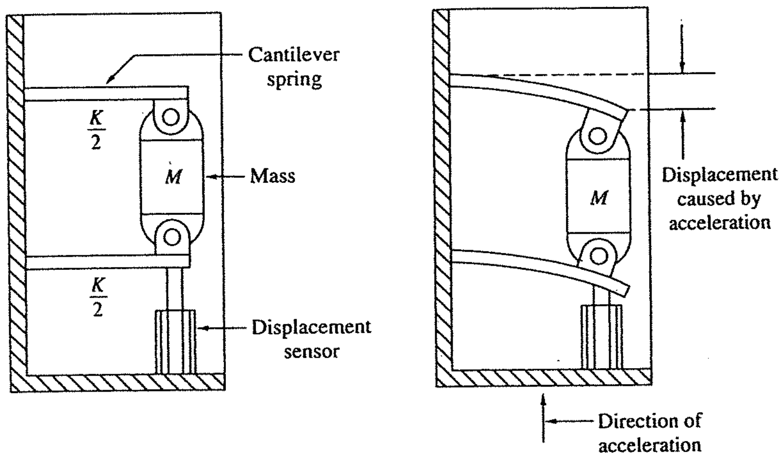
Material: beryllium
$E = 2.9 \times 10^{11}$ N/m^2
Maximum allowable stress = 10.0×10^8 N/m^2
b = 2.1 cm
h = 0.4 cm
L = 12 cm

Strain Gage 2

Gage factor = 2
Nominal resistance = 300 Ω

Determine the maximum force that can be measured and the change in resistance produced by the maximum force.

Problem 7.28



a) At rest b) Accelerating up

◆ **Figure 7.18** Linear accelerometer.

The accelerometer is a spring-mass-damping system similar to the control valve shown in Figure 4.5 and the second-order process shown in Figure 14.9a. A second-order system is characterized by its resonant frequency (f_0) and its damping ratio (ζ), as determined by the following equations:

$$f_0 = \frac{1}{2\pi}\sqrt{\frac{K}{M}} \tag{7.16}$$

$$\zeta = \sqrt{\frac{b^2}{4KM}} \tag{7.17}$$

where f_0 = resonant frequency, Hz
ζ = damping ratio
K = spring constant, N/m ($K = 1/C_m$)
M = mass, kilogram
b = damping constant, N · s/m

Consider the situation in which the accelerometer frame in Figure 7.18b is accelerated upward at a constant rate. The mass M will deflect the cantilever springs down until the springs exert a force large enough to accelerate the mass at the same rate as the frame. When this occurs, the spring force (Kx) is equal to the accelerating force ($f = Ma$).

$$Kx = Ma$$

or

$$x = \frac{M}{K}a \tag{7.18}$$

where x = displacement of the mass, m
M = mass, kg

HW21, 22

Bellows: A thin-walled cylinder with corrugated sides used to measure pressure. (8.3)

Bimetallic thermostat: Two strips of different metals bonded together to form a temperature-activated switch. (8.1)

Blackbody: An ideal body used to model the heat radiated from objects. A blackbody has an emittance of 1. (8.1)

Bourdon element: A flattened tube bent into an incomplete circle, spiral, or helix that is used to measure pressure. (8.3)

Differential pressure: The difference between a measured pressure and a reference pressure. (8.3)

Differential pressure flow meter: A flow meter that operates on the principle that a restriction in a flowing fluid produces a pressure drop that is proportional to the flow rate squared. (8.2)

Emittance: The ratio of the radiant energy emitted from a body to the radiation emitted from an ideal blackbody. (8.1)

Filled thermal system: A temperature sensor that uses a bulb filled with a liquid, gas, vapor, or mercury. Thermal expansion of the fluid in the bulb produces a motion that is a measure of the temperature of the fluid (8.1)

Gage pressure: The difference between a measured pressure and atmospheric pressure. (8.3)

Magnetic flow meter: A flow meter that uses the voltage induced when a conductor moves in a magnetic field (the flowing fluid is the conductor). (8.2)

Perfect vacuum: A pressure of zero. (8.3)

Radiation pyrometer: A temperature sensor that measures the temperature of an object by sensing the thermal radiation emanating from the object. (8.1)

RTD: Abbreviation of resistance temperature detector: a temperature sensor that uses the change in resistance of a conductor due to a change in temperature of the conductor. (8.1)

Strouhal number: A constant used in the flow rate equation of a vortex shedding flow meter. (8.2)

Thermistor: A temperature sensor using a semiconductor that has a large change in resistance with changes in temperature. (8.1)

Thermocouple: A temperature sensor that uses the fact that two dissimilar wires connected at each end generate a voltage that is a measure of the difference in temperature between the two ends. (8.1)

Turbine flow meter: A flow meter that uses the rotation of a turbine blade to measure fluid flow rate. (8.2)

Vacuum: A pressure that is less than atmospheric pressure. (8.3)

Vortex shedding flow meter: A flow meter that uses pulsations caused by an unstreamlined obstruction in the flow stream to measure flow rate. (8.2)

◆ EXERCISES

Section 8.1

8.1 Name the four types of fluids used in filled thermal system temperature sensors.

8.2 The following data were obtained in a calibration test of a class III FTS temperature transmitter similar to Figure 8.3:

Temperature (°C)	0	38	81	120	162	199
Output Signal (psi)	3.01	5.34	7.86	10.14	12.78	15.01

Construct a calibration graph by plotting the data points. Draw a line through the endpoints and estimate the terminal-based nonlinearity of the transmitter in degrees celsius and percentage of full scale.

8.3 Check the equation developed in Example 8.1 at 75°C.

HW21 **8.4** The resistance of nickel wire at 20°C is given by the following equation:

$$R = \frac{\rho L}{A}$$

HW 21, 22

where R = resistance at 20°C, Ω

ρ = resistivity of nickel = 47.0

A = area of the wire, circular mil [circular mil = (diameter in mils)^2]

L = length of the wire, ft

A nickel resistance thermometer element is to have a resistance of 100 Ω at 20°C. Determine the length of wire required if the diameter of the wire is 0.004 in. (4 mils).

8.5 A two-wire direct method is used to measure the resistance of a nickel RTD that has a sensitivity of 0.817 Ω/°C. Determine the lead-wire error caused by 15 ft of each of the wire gages listed in Example 8.2.

HW21 **8.6** Given the following data for the circuit in Figure 8.5b:

i_s = 1 mA.
The sensor is a nickel RTD.
R_s = 120.0 Ω when T = 0°C
R_s = 201.7 Ω when T = 100°C

(a) Determine v_s when T = 0°C and when T = 100°C.
(b) Design an op-amp circuit similar to Figure 8.6 that will convert v_s into a 4- to 20-mA current signal as follows:

$$i_{out} = 4 \text{ mA when } T = 0°\text{C}$$
$$i_{out} = 20 \text{ mA when } T = 100°\text{C}$$

8.7 An RTD is used to measure the temperature of air flowing in a duct at 1.5 m/s. The dissipation constant for this environment is 15 mW/°C. The air temperature is 60°C, and the RTD has a resistance of 120 Ω at 60°C. Determine the self-heating error for each of the following sensor currents: 1 mA, 10 mA, and 20 mA.

8.8 Plot the thermistor resistance values in Table 8.2 with R on the y-axis and T on the x-axis.

8.9 Determine the sensitivity (change in resistance per degree Celsius) of the thermistor in Table 8.2 at −70, 0, 70, and 140°C. Express the resistance change as a percentage of the resistance at the designated temperature. Use the average resistance change over the 20°C band from −80 to −60°C to compute the sensitivity at −70°C, the average change from −10 to +10°C to compute the sensitivity at 0°C, etc. The average resistance change and sensitivity at T = −70°C are computed as follows:

$$\Delta R_{avg}(-70°\text{C}) = \frac{R(-80°\text{C}) - R(-60°\text{C})}{20°\text{C}}, \ \Omega/°\text{C}$$

$$\text{Sensitivity}(-70°\text{C}) = 100 \times \frac{\Delta R_{avg}(-70°\text{C})}{R(-70°\text{C})}$$

8.10 Determine the self-heating error for a thermistor in the voltage divider circuit shown in Figure 8.7. The thermistor has a dissipation constant of 6 mW/°C and a resistance of 3281 Ω @ 20°C. The circuit conditions are

$$T = 20°\text{C}$$
$$R = 3500\ \Omega$$
$$V_{dc} = 10\ \text{V}$$
$$i_{out} = 0 \text{ (zero loading effect)}$$

8.11 A thermistor with the resistance values given in Table 8.2 is used in the voltage divider circuit in Figure 8.7. The output voltage, v_{out}, is easily obtained from the voltage divider rule.

$$v_{out} = \left(\frac{R}{R + R_{thermistor}}\right) V_{dc},\ \text{V}$$

(a) Compute v_{out} for T = 0, 10, 20, 30, . . . , 90, 100°C. Use the following circuit conditions in your calculations:
R = 1400 Ω V_{dc} = 1 V
Plot v_{out} versus T.
(b) Repeat part a with R = 650 Ω, V_{dc} = 1 V

HW22 **8.12** A type J (iron–constantan) thermocouple is used to check the temperature in an oven. The reference junction was placed in an ice bath at 0°C, and the measuring junction was placed in the oven. The thermocouple output voltage was measured to be 28.3 mV.

Use the data in Table 8.4 and the following interpolation formula to determine the oven temperature. Proceed as follows. In Table 8.4, locate the two consecutive lines for which the smaller voltage is less than 28.3 mV and the larger voltage is greater than 28.3. We will use L to indicate the lesser line, H to indicate the greater line, and M to indicate the measurement. Thus $V(L)$ = 27.39 mV, $V(M)$ = 28.3 mV, and $V(H)$ = 33.11 mV. Also, $T(L)$ = 500°C, $T(M)$ = measured temperature, and $T(H)$ = 600°C. Use the following interpolation formula to determine the measured temperature, $T(M)$:

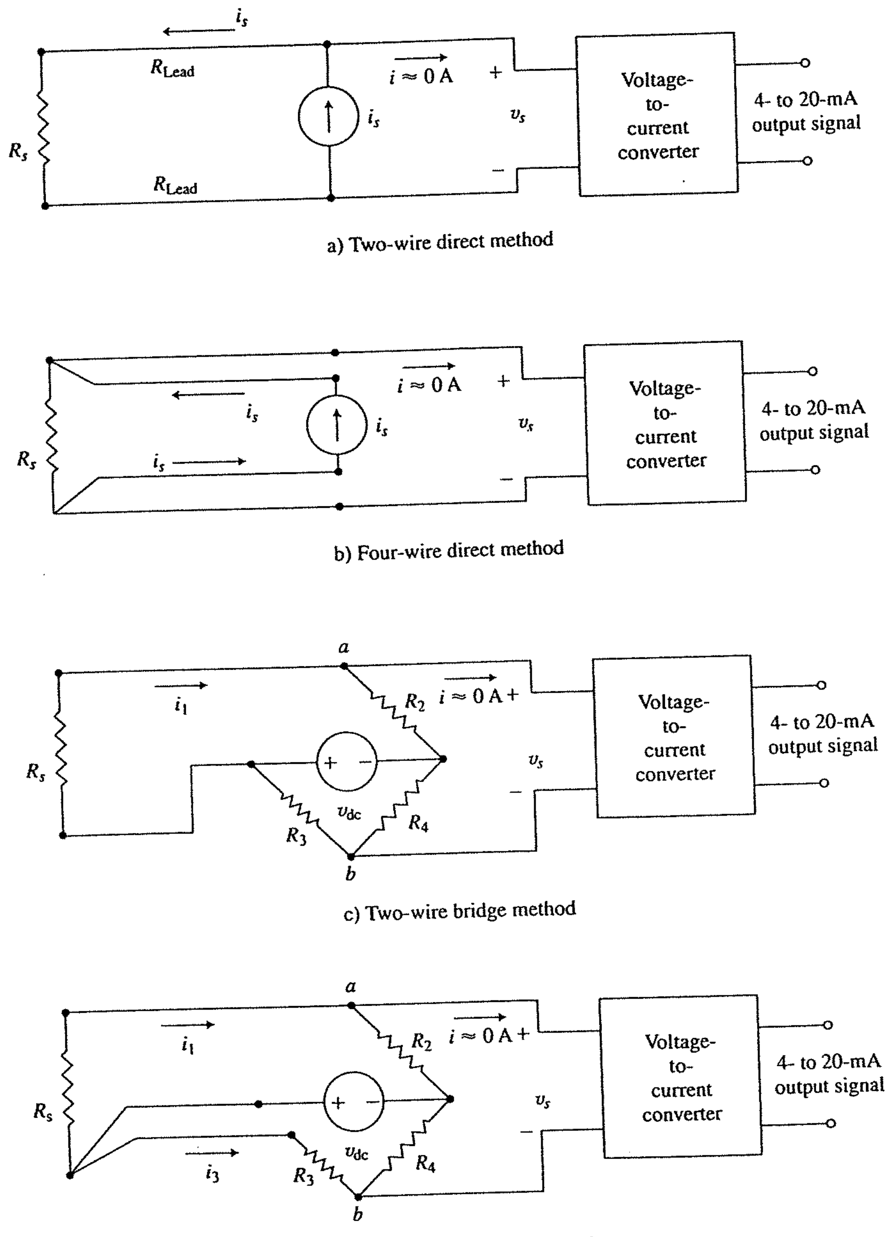
$$T(M) = T(L) + [T(H) - T(L)]\left[\frac{V(M) - V(L)}{V(H) - V(L)}\right],\ °\text{C}$$

8.13 Repeat Exercise 8.12 for a type K thermocouple with an output voltage of 34.2 mV.

HW22 **8.14** The EMF produced by a thermocouple may be approximated by the following equation:

$$E = E_0 + a_1 T + a_2 T^2$$

Problem 8.6



◆ **Figure 8.5** Four signal conditioning methods used to convert resistance changes into usable control signals.

HW 21, 22

where E = thermocouple EMF at T°C, V
E_0 = thermocouple EMF at 0°C, V
T = temperature, °C
a_1, a_2 = constants

Determine the values of E_0, a_1, and a_2 for the iron–constantan thermocouple described in Table 8.5. Use the EMF values at 0, 100, and 200°C to find E_0, a_1, and a_2. Check the accuracy of the equation at 60°C. (Hint: See Example 8.1.)

8.15 Construct a graph of the temperature versus the output signal for the iron–constantan thermocouple in Table 8.5. Determine the terminal-based nonlinearity of the graph (i.e., the maximum difference between the actual curve and a straight line connecting the two endpoints).

8.16 An LM35 integrated circuit temperature sensor has the following output voltage versus temperature values:

$$v_{out} = -500 \text{ mV at } T = -50°C$$
$$v_{out} = 0 \text{ mV at } T = 0°C$$
$$v_{out} = 500 \text{ mV at } T = +50°C$$

Design an op-amp circuit that will convert the output of the LM35 into the following linear current signal:

$$i_{out} = 4 \text{ mA at } T = -50°C$$
$$i_{out} = 20 \text{ mA at } T = +50°C$$

8.17 The signal conditioner in Figure 8.9 will be used to condition the output of a type J thermocouple. The desired input/output conditions are an input temperature range of 0 to 200°C and an output current range of 4 to 20 mA. Table 8.5 lists the thermocouple voltages and the output current values for temperatures from 0 to 200°C in increments of 20°C. Determine the required values of the differential amplifier gain, G_1, the offset voltage, v_0, the summing amplifier gain, G_2, and the voltage-to-current converter resistor, R. Proceed as follows:

(a) Determine the value of G_1 that matches the solid-state compensator to the type J thermocouple over the temperature range of 0 to 40°C (the expected range of reference junction temperatures). The solid-state compensator voltage, v_c, has a slope of 10 mV/°C. Over the range of 0 to 40°C, a type J thermocouple has a slope of 2.06 mV/40°C = 0.0515 mV/°C. Determine the value of G_1 such that G_1 times the thermocouple slope is equal to the compensator slope (i.e., $0.0515G_1 = 10$).

(b) Determine the value of v_0 that matches the ratio v_2 (max)/v_2 (min) to the ratio i_{out} (max)/i_{out} (min) (i.e., to 20/4 = 5). In this computation, assume $G_2 = 1$ and $v_c = 0$ (i.e., $T_{ref} = 0°C$). Under these conditions, v_2 (min) = v_0 and v_2 (max) = $G_1 v_{TC}$ (200°C) + v_0. The required condition is

$$\frac{v_2\,(\text{max})}{v_2\,(\text{min})} = \frac{[G_1 v_{TC}\,(200°C) + v_0]}{v_0} = 5$$

(c) Assume $G_2 = 1$ and determine the value of R that produces the desired 4- to 20-mA current output.

(d) Compute the output current at temperatures of 0, 100, and 200°C with $T_{ref} = 0°C$.

(e) Repeat step d with the reference junction at 20°C and again at 40°C. Compare both sets of results with the results in step d by computing the percentage of difference.

8.18 Repeat Exercise 8.17 for a temperature range of 0 to 400°C and an output current range of 10 to 50 mA. Use Table 8.4 for the mV output at 400°C.

8.19 Complete the following for the iron–constantan thermocouple transmitter described in Table 8.5:

(a) Determine the terminal-based linearity of the transmitter output.

(b) Design a five-step, piecewise linear function that will linearize the transmitter output.

Section 8.2

8.20 Differential pressure flow motors are used as the sensors in six liquid flow control systems. Pretend you were assigned the task of constructing calibration graphs for the six flow controllers. Your first step was to conduct four calibration tests for each control system. In the first test, you set the controller at 25%, collected the output flow in a container of known volume, and measured the time required to fill the container. You then repeated this test at controller settings of 50%, 75%, and 100%. Your test results are summarized in the following table.

Controller Tag Number	Container Volume V (gal.)	*Time in Minutes to Fill the Container (volume = V gal) at Each Controller Setting*			
		25%	50%	75%	100%
(a) FIC 101	0.25	3.32	2.39	1.98	1.72
(b) FIC 112	1.00	1.74	1.22	1.03	0.88
(c) FIC 116	0.25	1.84	1.29	1.04	0.91
(d) FIC 119	5.00	1.49	1.06	0.84	0.74
(e) FIC 134	1.00	2.95	2.05	1.68	1.47
(f) FIC 148	5.00	4.56	3.14	2.66	2.26

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Given the ladder diagram attached, answer the following questions. Assume that all contacts start in the de-energized positions prior to question 1.

1. Push button switch PB2 is pressed. Which indicator lamp(s) will light? ________ (R, G, Y)

2. Will the indicator lamp(s) remained on after the PB2 is released? ______ (yes, no)

3. What combinational logic function is created by the third rung in the ladder? ________ (NOR NAND XOR)

4. After PB2 is pressed, PB4 is pressed. Which indicator lamp(s) will light? _______ (R,G,Y)

5. The relay contact B in ladder rung 2 is in the _______ (open, closed) state after PB2 and PB4 are depressed.

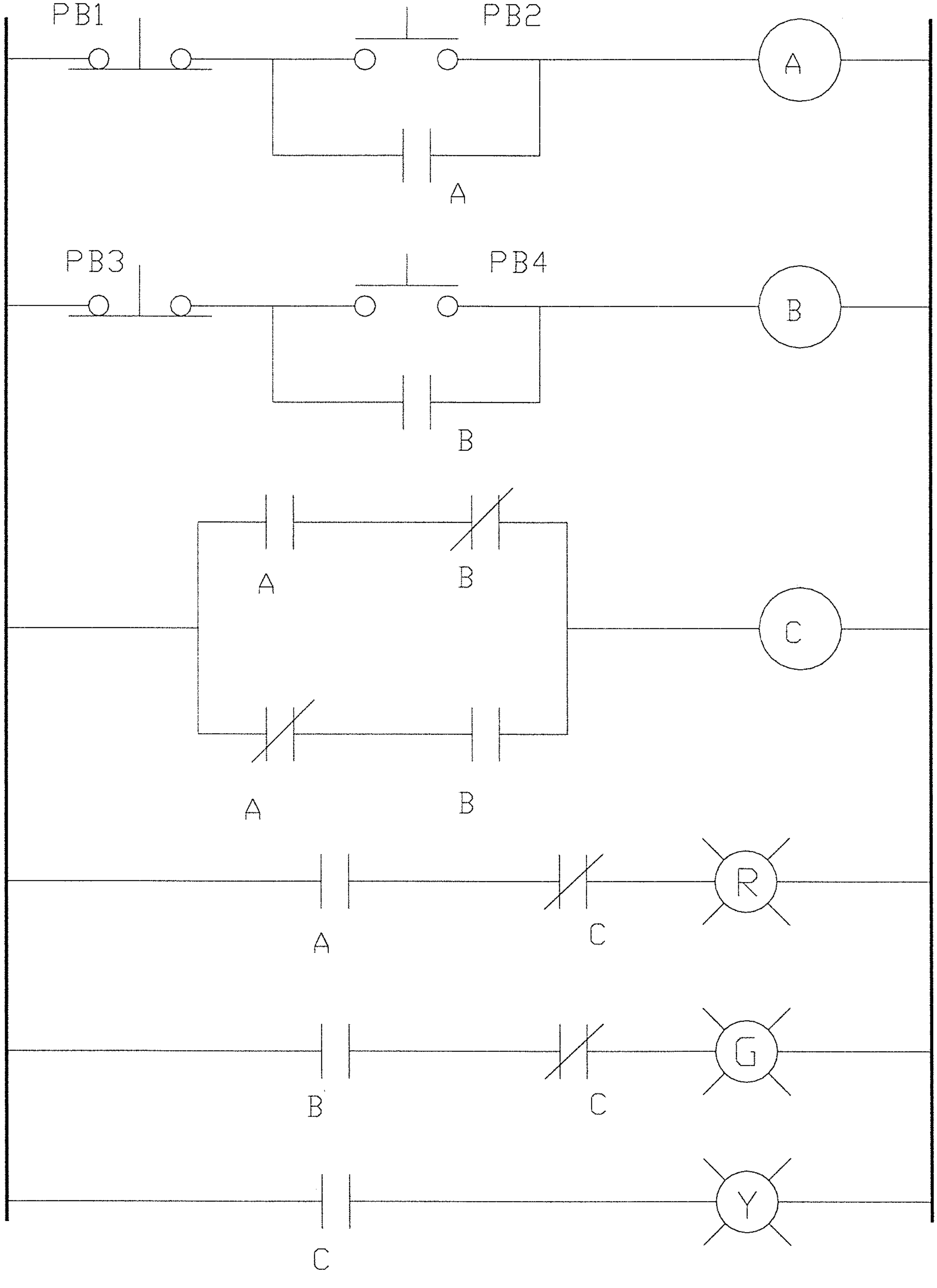
6. The relay contact A in ladder rung 1 is in the _______ (open, closed) state after PB2 and PB4 are depressed.

7. After PB2 and PB4 are depressed, The contact C in ladder rung 4 is in the ________ (open, closed) state.

8. PB2 and PB4 have been depressed. Now both PB1 and PB3 are depressed. Will any indicator lamps remain on? ________ (yes, no)

9. Can the lamps in rungs 5 and 6 light simultaneously for any combination of inputs? ________ (yes, no)

HW23



Hw. 24

ET 438B
Ladder Diagrams Homework

Attached are two typical control and wiring diagrams. Drawing 1 is the control diagram for a power circuit breaker and Drawing 2 is a control and power wiring diagram for a motor starting circuit. Refer to these drawings to answer the following questions.

Refer to Drawing 1 for questions 1 to 13

1.) The voltage for the breaker trip/close circuit is (Include level and type of current is ___________

2.) List the terminal block stud numbers that connect the voltage to the breaker heater circuits.

3.) List the terminal block stud numbers that connect the voltage to the breaker trip/close circuits.

4.) How many 51 devices are there in the trip circuit of the breaker?

5.) CS/T stands for what function in the diagram?

6.) What are the ratings of the fuses in the breaker trip/close circuit?

7.) At what temperature does the thermostat operate in the breaker control circuits?

8.) What is the function of the 52X device?

9.) What are the terminal numbers of the 52X relay coil?

10.) According to the diagram, how many studs for external connections exist on the breaker terminal block?

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11.) What is the name of the 67G device?

12.) What is the wire number on the wire that connects stud number 10 to terminal 2 on the breaker trip coil?

13.) What value of resistance in series with the indicator lights on the control diagram?

Refer to Drawing 2 for the remaining questions. This is a motor starting circuit that uses a reactor to limit the starting current to the motor while it is accelerating up to speed. After a predetermine time interval, which should be long enough to allow the motor to accelerate, the starting reactors are removed from the circuit by shorting them out. The motor draws a large load current, so current transformers are used to couple the overload relay sensors to the main ac power. The control schematic is labelled with wire numbers 1 to 10 to help designers and maintenance personnel identify the circuit connections.

14.) According to the drawing legend, what is the function of the TR coil in the control wiring schematic?

15.) According to the drawing legend, what is the function of the A coil in the control wiring schematic?

16.) Energizing the (A, M, 1CR) _____ relay will directly connect the ac power to the motor?

17.) If the overload devices in the ac power schematic have detected an overload, the OL contacts in the control wiring will be (open, closed)?

18.) For the TR relay to be energized by the start button the A relay must be (energized, de-energized)

19.) The time closing contact connects voltage to the (1CR, 2CR, TR) ______ relay coil.

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20.) How will the ac power circuit be effected when the A relay is energized in control schematic?

21.) To keep the motor running at normal operating speed, which of the following relays must remain energized (A, M, both)? _________

22.) Is the ladder control voltage circuit fused?

23.) If there is no voltage connected to the ac power circuit will an operator be able to start the motor? Explain your answer

24.) The overload contact in the control wiring is connected to the control voltage transformer by wire number ______?

25.) For the motor to keep running, control relay (1CR, 2CR) _______ must remain energized

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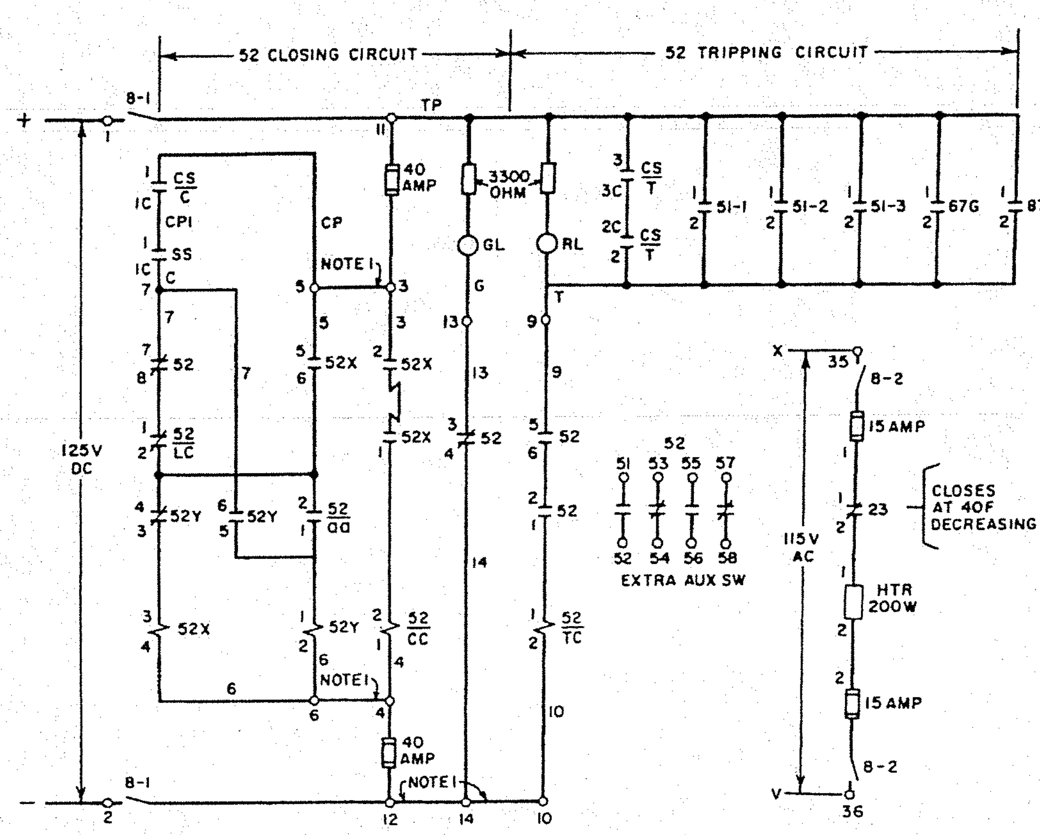
Schematic 1



8 CONTROL POWER DISCONNECTING SWITCH

23 TEMPERATURE CONTROL DEVICE

51 AC TIME OVERCURRENT RELAY

52 AC CIRCUIT BREAKER
- aa AUXILIARY SWITCH OPEN WHEN THE OPERATING MECHANISM IS IN THE NON-OPERATED POSITION
- CC CLOSING COIL
- LC LATCH CHECK SWITCH
- TC TRIP COIL

52X CLOSING RELAY

52Y ANTI-PUMP RELAY

67G AC DIRECTIONAL OVERCURRENT GROUND RELAY

87X DIFFERENTIAL PROTECTIVE AUXILIARY RELAY

CS CONTROL SWITCH
- C CLOSE
- T TRIP

HTR HEATER

SS SYNCHRONIZING SWITCH

-o- AC CIRCUIT BREAKER TERMINAL BLOCK STUDS FOR EXTERNAL CONNECTIONS

GL GREEN LIGHT

RL RED LIGHT

NOTE 1 JUMPERS INSTALLED BY MANUFACTURER

DRAWING REFERENCES

AC SCHEMATIC DIAGRAM..FIG 9-9

DEVICE INTERNAL CONNECTION DIAGRAM..FIG 10-14

FIGURE 9-10 – TYPICAL POWER SWITCHGEAR DC SCHEMATIC DIAGRAM (USING BOTH TERMINAL AND WIRE DESIGNATIONS)

Schematic 2
HW 24

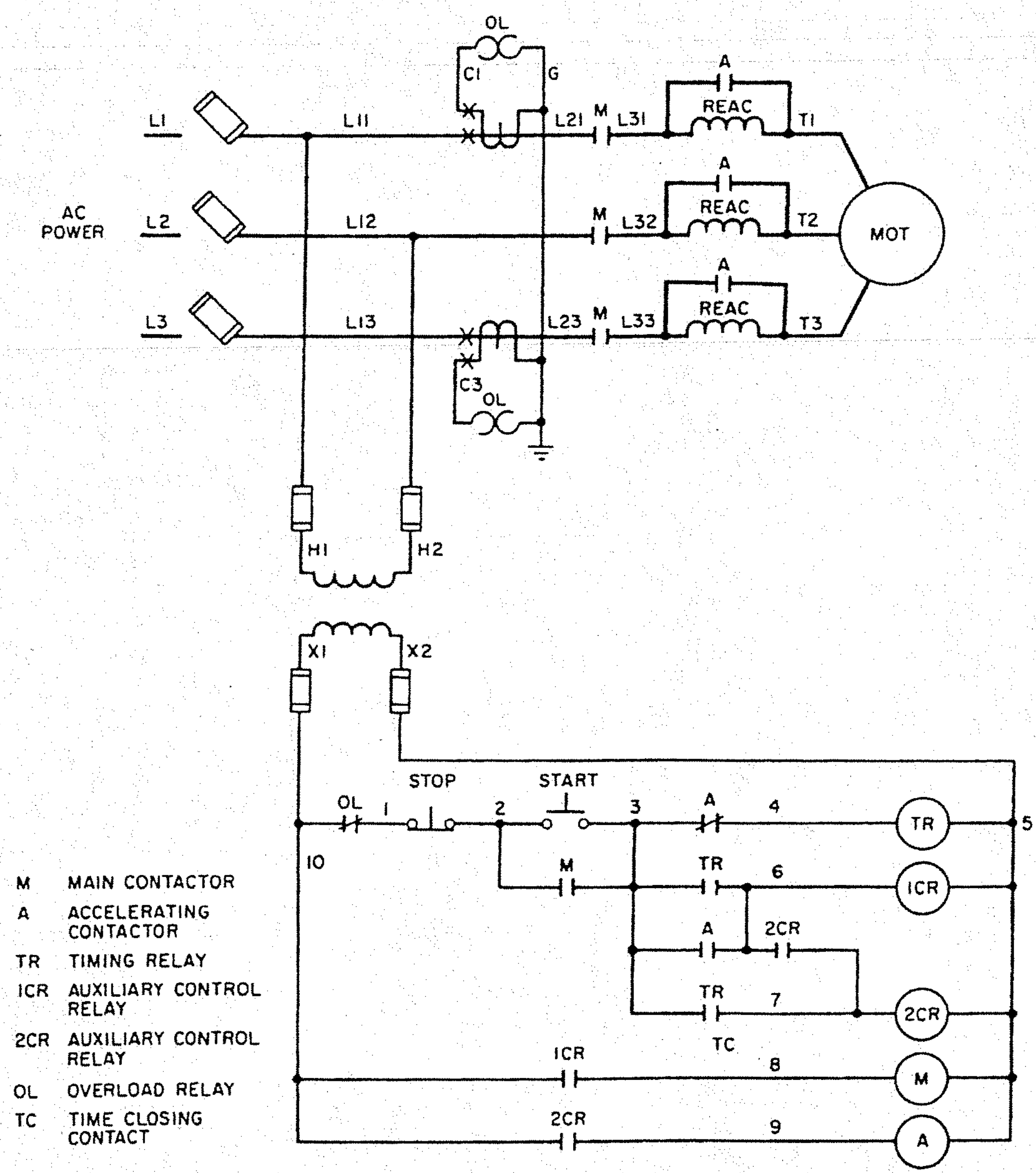
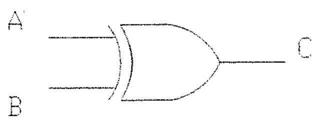


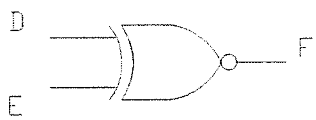
FIGURE 9-11 – TYPICAL INDUSTRIAL CONTROL SCHEMATIC DIAGRAM

Hw 25

ET 438b
Ladder Logic from logic Symbols

Draw a ladder logic circuit that implements the logic functions shown. Label the inputs and output of the ladder contacts and coils to match the logic symbols





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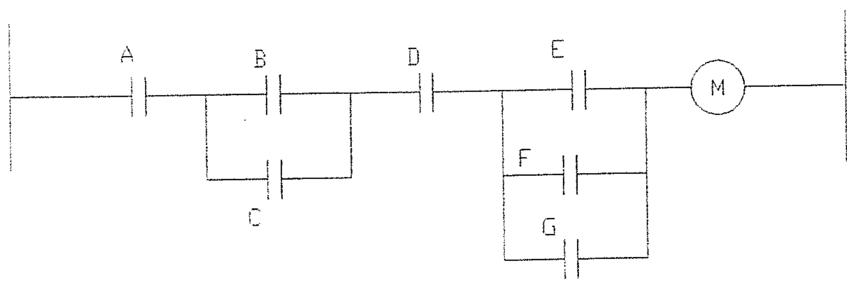
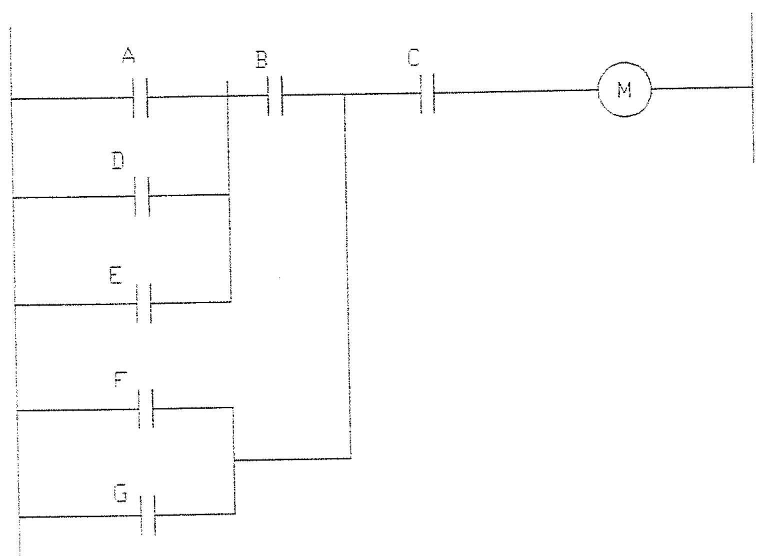
ET 438b
Logic Symbol Circuits from Ladder Logic

Draw the digital logic circuits that implement the ladder logic functions shown. Label the inputs fromand output of schematic to match the ladder logic.





Hw 26

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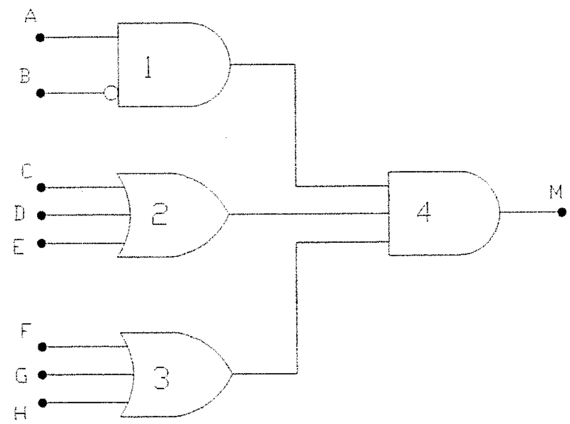
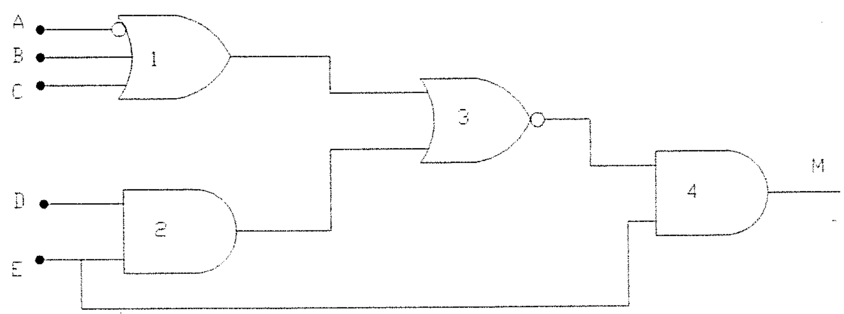
Ladder Logic from logic Symbols

Draw a ladder logic circuits that implement the logic functions shown. Label the inputs and output of the ladder contacts and coils to match the logic circuit.





Hw. 27

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PLC Addressing

1.) The figure below represents an output status file. In the column at the far right, list the address if there were output modules in the following slots on the PLC chassis: 2, 5, 6.

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Addr.
1	0	1	1	0	0	0	1	0	1	1	1	1	1	0	0	
1	0	1	0	0	1	0	0	0	0	1	1	1	0	1	1	
1	1	0	1	0	0	1	1	0	0	1	0	0	0	1	0	
0	1	0	1	1	0	0	0	1	0	0	1	0	0	0	1	

2.) The figure below represents a input status file for a PLC. In the column on the far right enter the address if there were input modules in the following slots of the PLC chassis: 1, 3, 4, 5

15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	Addr.
1	0	1	1	0	0	0	1	0	1	1	1	1	1	0	0	
1	0	1	0	0	1	0	0	0	0	1	1	1	0	1	1	
1	1	0	1	0	0	1	1	0	0	1	0	0	0	1	0	
0	1	0	1	1	0	0	0	1	0	0	1	0	0	0	1	

Hw. 22

3.)The following memory map shows a bit file for a typical PLC. Determine the value of the bit contained in the given addresses

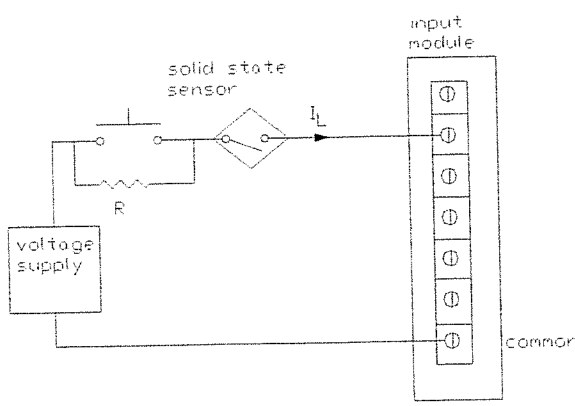
15	14	13	12	11	10	9	8	7	6	5	4	3	2	1	0	element
1	0	1	1	0	0	0	1	0	1	1	1	1	1	0	0	B3:156
1	0	1	0	0	1	0	0	0	0	1	1	1	0	1	1	B3:157
1	1	0	1	0	0	1	1	0	0	1	0	0	0	1	0	B3:158
0	1	0	1	1	0	0	0	1	0	0	1	0	0	0	1	B3:159
0	1	1	0	1	0	1	1	1	0	0	1	1	0	0	1	B3:160
1	0	0	1	1	1	0	0	0	1	0	0	0	1	1	0	B3:161
1	0	0	0	0	0	0	0	1	1	1	1	1	1	0	0	B3:162

a.) B3:156/12 __________
b.) B3:156/9 __________
c.) B3:158/15 __________
d.) B3:159/0 __________
e.) B3:160/2 __________
f.) Bit 14 element 157 ________
g.) Bit 3 element 156 _________

4.) The data type identifier for integer values in Allen-Bradley PLCs is _________

5.) For the circuit shown below, a sourcing 24 Vdc input module is used with a sinking solid state sensor. The sensor must draw 2.7 mA to be in the on state. The maximum off state current of the input card is 4.5 mA.

a.) Indicate the correct polarity for the dc supply.
b.) Size the resistor shown to keep the sensor energized even when contracts are open.

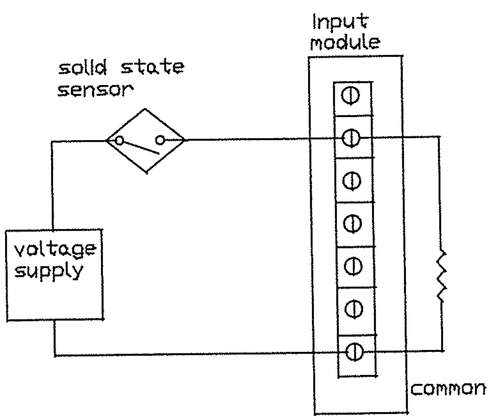


Hw 27

6.) In the figure shown below, the maximum off current of the ac input card is 2.5 mA when energized by the rated value of 120 V ac. An ac solid state sensor is to be connected to the ac input card and must pass 4.5 mA to be in the active state.

a.) find the equivalent resistance of the ac input point when the card is in the off state.

b.) determine the resistance of a bleeder resistor that will keep the sensor energized be will not activate the input card.



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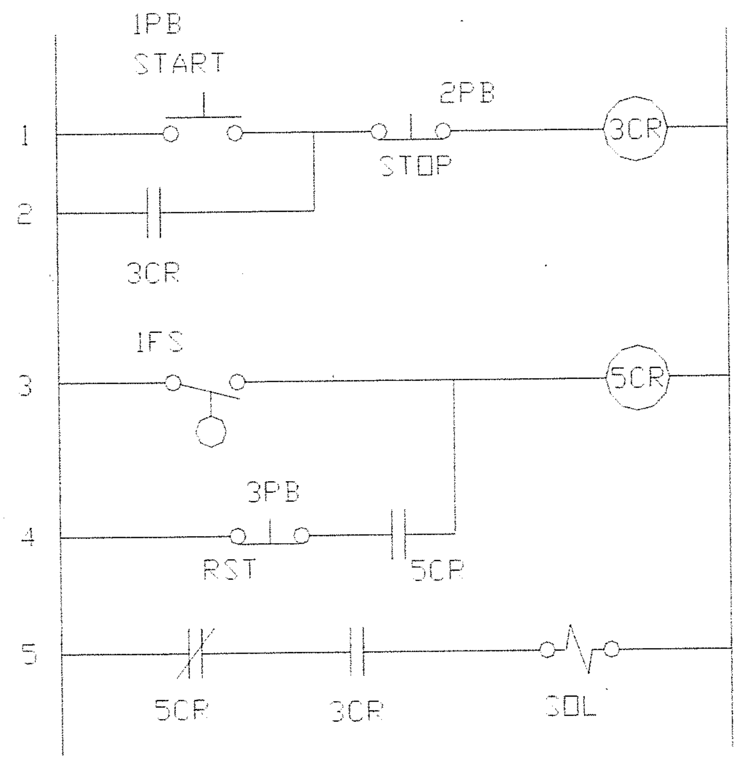
PLC Programming Homework

The circuit shown below is currently implemented using electromechanical relays. Convert it to a PLC rung diagram that uses an Allen-Bradley instruction set. The I/O and bit address are assigned as follows

PB1 = I:0/0
PB2 = I:0/1
1FS = I:0/2
PB3 = I:0/3
SOL = O:0/0
B3:0/0 = 3CR
B3:0/1 = 5CR

If 120 Vac inputs and outputs are used sketch the external connections necessary to interface the field devices (used attached terminal diagrams)



Hw 28:

PLC Input and Output modules