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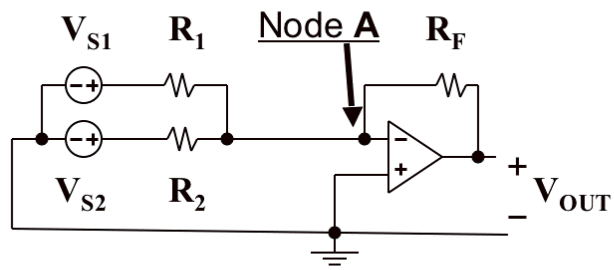
Problem 1 (30 points) Summing Amplifier, or Adder; Application for sensor circuits

In all parts of this problem, use the "Golden Rules"



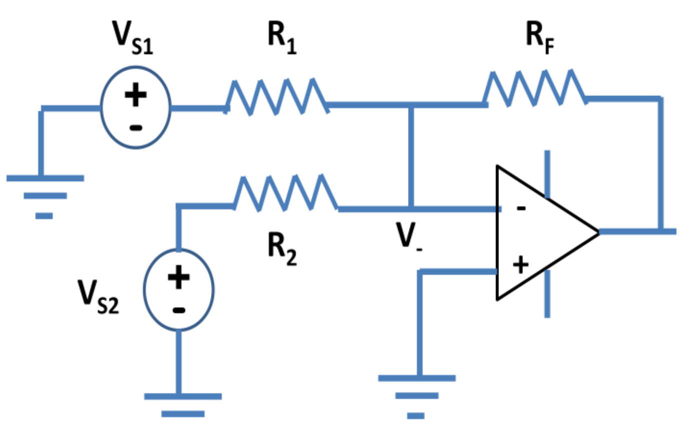
Part 1 (10 points)

Use the node voltage equation for node A to express the output voltage as the sum of two amplified input voltages in the form:

$$V_{OUT} = V_{S1} \cdot Gain_1 + V_{S2} \cdot Gain_2 \qquad \text{[equation 1]}$$

Express the gain values in terms of the resistances R_F, R_1 and R_2; pay attention to the signs. **Show your work on a separate page.** Your answers:

$Gain_1 = -\frac{R_f}{R_1}$ $Gain_2 = -\frac{R_f}{R_2}$



The node voltage equation for the above circuit is

$$\frac{V_- - V_{S1}}{R_1} + \frac{V_- - V_{S2}}{R_2} - \frac{V_- - V_{out}}{R_F} = 0$$

Using the golden rule we have

$$V_{out} = V_{S1} \times -\frac{R_f}{R_1} + V_{S2} \times -\frac{R_f}{R_2}$$

$$Gain_1 = -\frac{R_f}{R_1};\ Gain_2 = -\frac{R_f}{R_2}$$

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Part 2 (20 points) Practical Perspective

The pressure sensor for your project has the zero offset equal to 0.25 V and the sensitivity equal to 0.15 V/psi. (See the file "Pressure sensor specs" for more detail.) Thus, at 5 psi the sensor's output equals:

$$V_{S1,\,5\ psi} = (0.25\ V) + (5\ psi)\frac{0.15\ V}{psi} = 1.00\ V$$

You need the V_{OUT} readings: exactly 0 V at 5 psi and exactly 10 V at 10 psi.
To achieve this goal, use an adder circuit with two sources – the pressure sensor as V_{S1} and a 1.5 V battery as V_{S2}. Use R_F = 100 kΩ. Calculate the input resistances R_1 and R_2 in kΩ. **Show your work on a separate page.** Your answers:

R_1 = ___7.5___ kΩ R_2 = __11.25__ kΩ

Hints:

1. Algebraically, you have to write [equation 1] twice: for the output at 5 psi and for the output at 10 psi, thus obtain two equations with two unknown resistances R_1 and R_2 ; then solve for R_1 and R_2.
2. To match the desired polarity of the output voltage, you can connect the sensor and/or the battery in any of the two ways; for example, at 5 psi, you can obtain either V_{S1} = +1 V or V_{S1} = – 1 V. Keep the chosen connection at all pressures. **Clearly explain which connection you choose.**

Using the equation derived in the part 1 of the problem

$$V_{out} = V_{S1} \times -\frac{R_f}{R_1} + V_{S2} \times -\frac{R_f}{R_2}$$

Here R_f = 100 kΩ and V_{s2} = 1.5 V and R_1 and R_2 are in kΩ

The value of V_{s1} at 5 psi is 0.25 + 0.15 x 5 = 1.0 V

V_{s1} at 10 psi is 0.25 + 0.15 x 10 = 1.75 V

Here the objective is to achieve a positive output voltage. In the inverting configuration we have to connect both the voltages sources in the reverse way as shown in the diagram.

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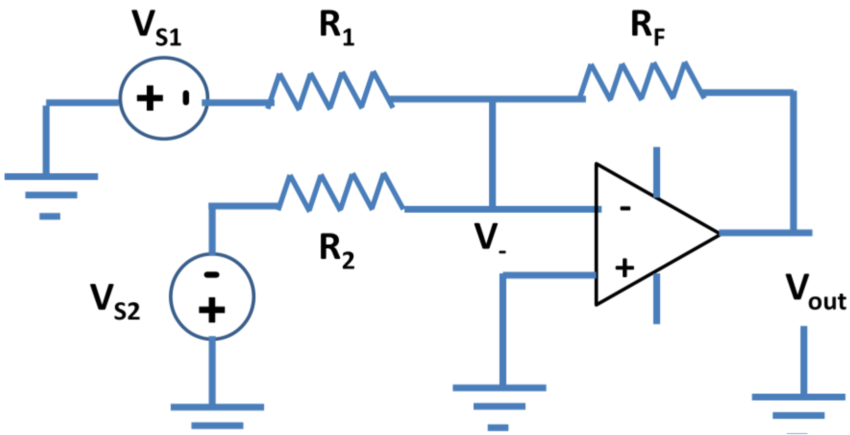

From the node voltage equations we obtain

$$1 \times \frac{100}{R_1} + 1.5 \times \frac{100}{R_2} = 0; \quad (eqn.1)$$

$$1.75 \times \frac{100}{R_1} + 1.5 \times \frac{100}{R_2} = 10; \quad (eqn.2)$$

Upon solving these equations we get

R_1 = 7.5 kΩ and R_2 = 11.25 kΩ.

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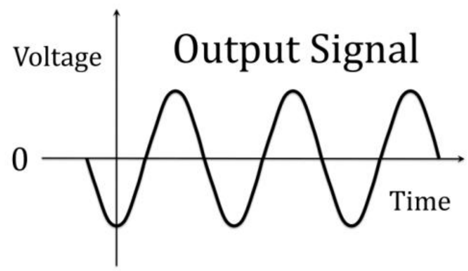
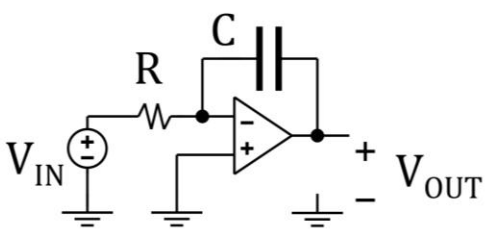
Problem 2 (30 points) Integrator and Differentiator based on Op Amps; Prototype of PID control circuit

In both parts, apply the "Golden Rules"

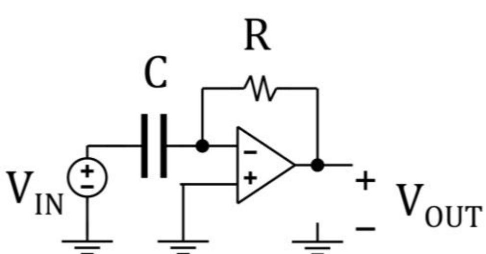
Part 1 (10 points)

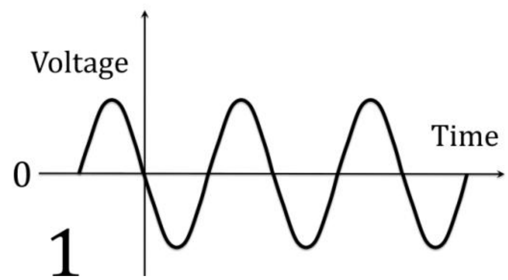


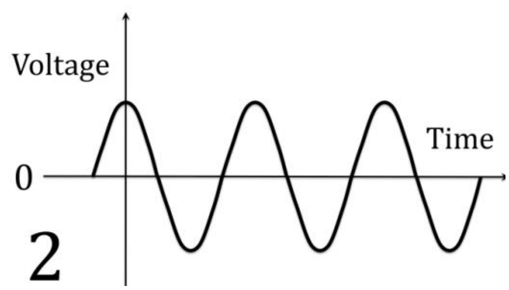
Integrator

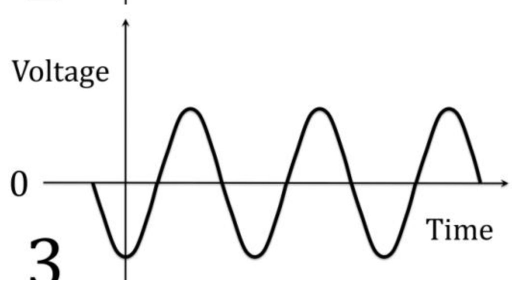


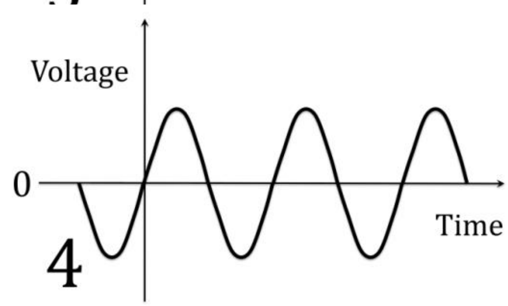
Differentiator











Which of the sketches 1-4 most likely represents the input voltage? Your answers:

For the Integrator: ___________1______________

For the Differentiator: ______4______________

An alternative is: *None of the above.*

On a separate page, show your work: use equations to justify your answers.

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The output signal can be represented as a sinusoidal wave of the form

V_{out}= A Sin (ωt-π/2) = -A_1 cos (ωt)

The inverting integrator integrates a input function and the resulting wave will be
$$V_{out} = -\frac{1}{RC}\int V_{in}(t)dt$$
Therefore
V_{in}= -A_2 Sin (ωt)
This waveform is similar to #1

For an inverting differentiator we have
$$V_{out} = -RC\frac{dV}{dt}$$
V_{in}= A_3 Sin (ωt)
This waveform is similar to #4

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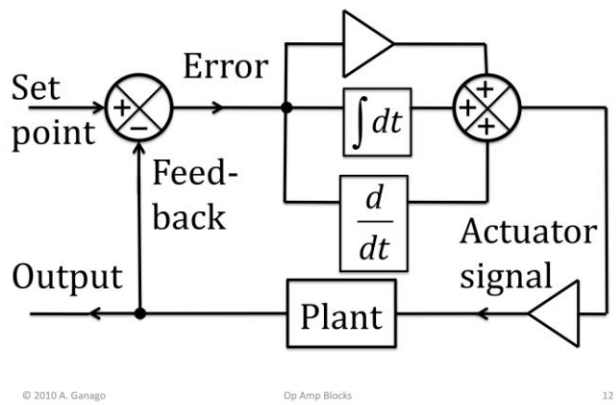
Problem 2
Part 2 (20 points)

PID Control System

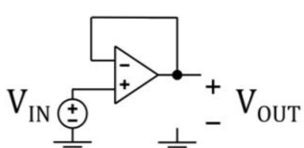


A control system measures the error, or difference between the set point and the actual output of the Plant (the device to be controlled).

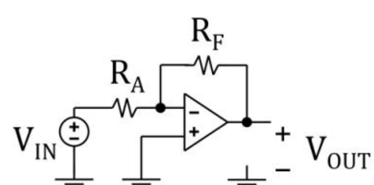
In PID (Proportional, Integral, and Differential) control system, the error is amplified (triangular symbol on the diagram), integrated, and differentiated; the sum of all three parts is further amplified and fed into an actuator (such as motor, heater, cooler, lighting, etc.) that takes action on the Plant. The output of a sensor installed in the Plant is fed back to the input of the control system.

All components of such system can be implemented with Op Amps. The necessary blocks include: Integrator and Differentiator, Amplifiers (Inverting, Non-Inverting, and Difference), and the Buffer, or Voltage Follower: see the diagrams below.

Buffer, or Voltage Follower



Inverting Amplifier



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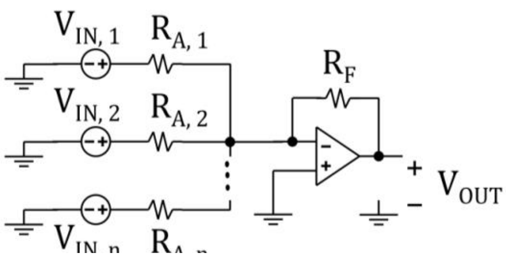
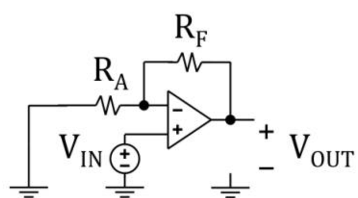
Inverting Adder, or Summer

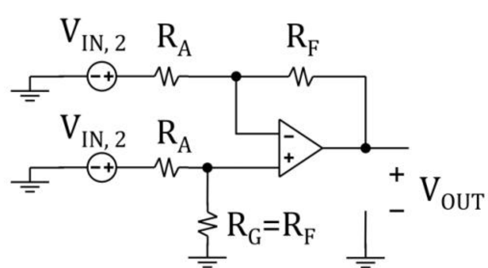


Non-Inverting Amplifier



Problem 2 Part 2, continued

Difference Amplifier



The output of the Difference Amplifier shown on this diagram equals:

$$V_{OUT} = \left(V_{IN,1} - V_{IN,2}\right)\frac{R_F}{R_A}$$

Consider the prototype of a PID control circuit shown below.

Assume that the Actuator signal should be:

$$Actuator\ \ Signal = \left[0.5 \cdot \left(Error\right) + \frac{d}{dt}\left(Error\right) + \int \left(Error\right) dt\right]$$

where *Error* is the output of the Difference Amplifier. For simplicity, assume R·C =1.

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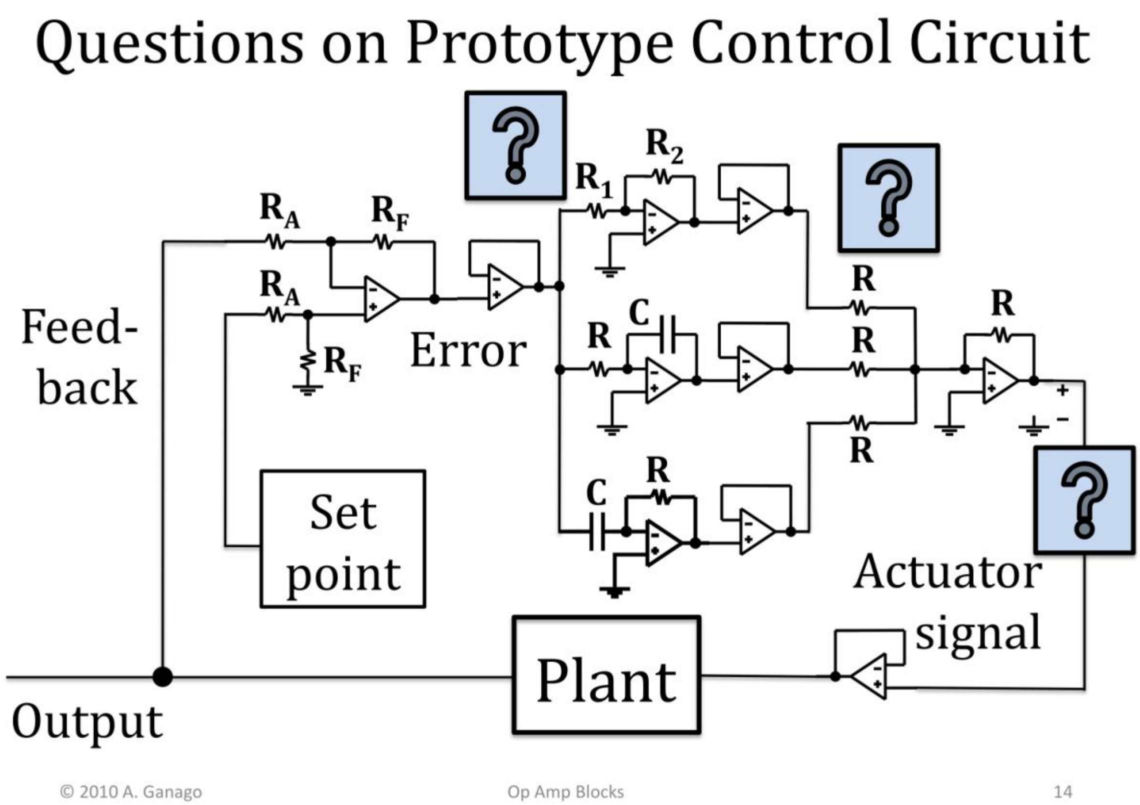

Answer the following questions:

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Problem 2 Part 2, continued

1. Given $R_2 = 100$ kΩ, determine R_1 in kΩ.

   Your answer: R_1 = ___200___ kΩ.

   From the actuator signal relation we see that the proportional part of the PID controller has a factor of 0.5. This can be achieved only when the gain of the inverting amplifier that is part of the P section has a gain of 0.5.

   Gain = $-R_2/R_1 = 0.5$; therefore $R_1 = 200$ kΩ.

2. Note that the diagram includes an inverting amplifier for the error signal.

   Is an additional inverting amplifier needed before the adder?

   Your answer: Yes No (circle one)

If you answered *Yes*, calculate R_1 in kΩ for the additional inverting amplifier (assume $R_2 = 100$ kΩ, as above).

Your answer: R_1 = ___NA___ kΩ.

Inverter is not necessary here. The polarity of the signal output from the voltage follower stages is negative. This results in the adder output voltage being positive. The input or the outcome does not in any way affect the functionality of the circuit.

3. Is an additional inverting amplifier needed after the adder?

   Your answer: Yes No (circle one)

If you answered *Yes*, calculate R_1 in kΩ for the additional inverting amplifier (assume $R_2 = 100$ kΩ, as above).

Your answer: R_1 = ___N/A___ kΩ.

Justify your answers. Show your work below and/or on additional pages.

The signal input from the PID section has to be subtracted from the setpoint value in order to get the error. Thus an inverter is not required as the difference amplifier stage requires positive voltage inputs in order to function as a subtractor.

<u>Comment.</u>

An inverter with R1 = R2 multiplies the signal by (– 1); thus putting two inverters in series produces multiplication by (– 1)·(– 1) = +1, which is unnecessary. Your design should avoid unnecessary inverters.

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Problem 3 (30 points) Active filters based on Op Amps

In both parts, apply the "Golden Rules"

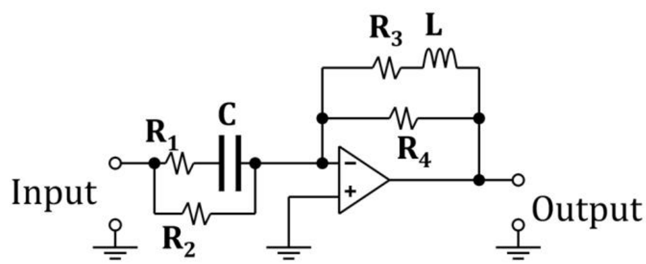
Part 1 (10 points)

Determine the type of filter (LP, HP, BP, or BR) for the circuit shown here.

Your answer: **High-Pass**

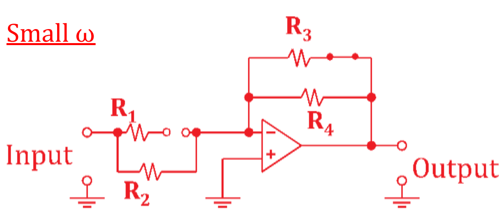
Show your work on a separate page:

Old exam problem:
Determine the type of filter

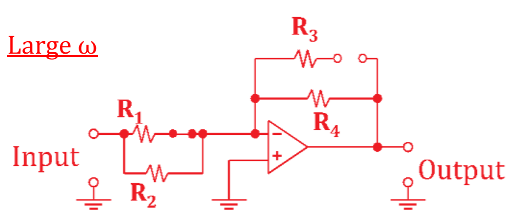


(A) Redraw the circuit at a very low frequency $\omega \to 0$ and at a very high frequency $\omega \to \infty$

Small ω



Large ω



(B) On each redrawn circuit, show the capacitor and inductor as an open/closed switch

With small ω, inductors act as short circuits, and capacitors act as open circuits.

With large ω, inductors act as open circuits, and capacitors act as short circuits.

(C) Write the algebraic expression for the transfer function magnitude at $\omega \to 0$ and at $\omega \to \infty$

Small ω
This is an inverting op-amp with $R_f = R_3||R_4$ and $R_i = R_2$. Thus, the transfer function is

$$\frac{R_3R_4}{R_3+R_4} * \frac{1}{R_2} = \frac{R_3R_4}{R_2(R_3+R_4)}$$

Large ω
This is an inverting op-amp with $R_f = R_4$ and $R_i = R_2||R_1$. Thus, the transfer function is

$$R_4 * \frac{R_1+R_2}{R_1R_2} = \frac{R_4(R_1+R_2)}{R_1R_2}$$

We see that a R_4/R_2 is present in each term. Because $R_3/(R_3+R_4) < 1$ and $(R_1+R_2)/R_1 > 1$, the transfer function is larger for large ω. As a result, we are working with a high-pass filter.

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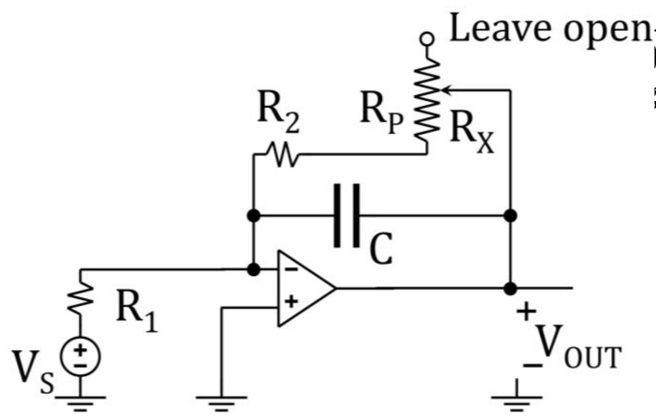

Problem 3

Part 2 (20 points)

For the circuit shown here, do the following:

(A) Determine the type of filter. Your answer: **Low-Pass**

(B) Derive the algebraic expression for the transfer function $H(\omega)=\frac{V_{OUT}(\omega)}{V_S(\omega)}$.

$$H(j\omega) = -\frac{R_f}{R_i} = -\frac{(R_2+R_X)||C}{R_1} = -\frac{(R_2+R_X)\frac{1}{j\omega C}}{R_1(R_2+R_X+\frac{1}{j\omega C})} = -\frac{\boldsymbol{R_2+R_X}}{\boldsymbol{R_1+j\omega C R_1(R_2+R_X)}}$$

(C) Derive the algebraic expression for the cutoff frequency ω_C

$$\frac{\max(|H(j\omega)|)}{\sqrt{2}} = \frac{R_2+R_X}{R_1\sqrt{2}} = |H(j\omega_C)| = \frac{R_2+R_X}{\sqrt{R_1^2+\omega_C{}^2C^2R_1^2(R_2+R_X)^2}}$$

$$\frac{1}{\sqrt{2}} = \frac{1}{\sqrt{1+\omega_C{}^2C^2(R_2+R_X)^2}}$$

$$1+\omega_C{}^2C^2(R_2+R_x)^2 = 2$$

$$\boldsymbol{\omega_C = \frac{1}{C(R_2+R_x)}}$$

(C) Derive the algebraic expression for zero-frequency gain for any value of R_X

$$|H(\omega=0)| = \left|\frac{V_{OUT}(\omega=0)}{V_S(\omega=0)}\right|$$ *When ω=0, the imaginary term of the denominator drops out.*

Your answer: $\boldsymbol{\frac{R_2+R_X}{R_1}}$

(D) Derive the algebraic expression for the product of zero-frequency gain and the cutoff frequency ω_C (called the "Gain · Bandwidth" product) for any value of R_X

Your answer:

$$\frac{1}{C(R_2+R_x)} * \frac{R_2+R_X}{R_1} = \boldsymbol{\frac{1}{CR_1}}$$

Does it depend on the value of R_X? Yes **No** (circle one)

(E) Use the following circuit parameters: $R_1 = R_2 = 1$ kΩ; $R_P = 100$ kΩ; $C = 100$ nF. Given that V_S is a sine wave at 100 mV peak amplitude, calculate the peak

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amplitude of the output sine wave at the maximal and minimal values of R_X for two frequencies: 200 Hz and 5 kHz. Compare with the circuit, from which the capacitor is disconnected. Write the results in the table below:

Input signal frequency	Peak amplitude (in volts) of the output in the given circuit		Peak amplitude (in volts) of the output in the circuit without C	
	$R_X = 0$	$R_X = R_P$	$R_X = 0$	$R_X = R_P$
200 Hz	**99.2 mV**	**793 mV**	**100 mV**	**10.1 V**
5 kHz	**30.3 mV**	**31.8 mV**	**100 mV**	**10.1 V**

On a separate page, show your work for all parts of this problem.

- *Row 1, Column 1:*

$$|H(j2\pi * 200)| = \left|\frac{1000 + 0}{1000 + j(2\pi * 200)(100 * 10^{-9})(1000)(1000 + 0)}\right| = 0.992$$

Peak output = $|H(\omega)| * V_{IN}$ = 0.992 * 100 mV = **99.2 mV**

- *Row 1, Column 2:*

$$|H(j2\pi * 200)| = \left|\frac{1000 + 100 * 10^3}{1000 + j(2\pi * 200)(100 * 10^{-9})(1000)(1000 + 100 * 10^3)}\right| = 7.93$$

Peak output = $|H(\omega)| * V_{IN}$ = 7.93 * 100 mV = **793 mV**

- *Row 1, Column 3:*

$$|H(j2\pi * 200)| = \left|\frac{1000}{1000}\right| = 1.00$$

Peak output = $|H(\omega)| * V_{IN}$ = 1.00 * 100 mV = **100 mV**

- *Row 1, Column 4:*

$$|H(j2\pi * 200)| = \left|\frac{1000 + 100 * 10^3}{1000}\right| = 101$$

Peak output = $|H(\omega)| * V_{IN}$ = 101 * 100 mV = **10.1 V**

- *Row 2, Column 1:*

$$|H(j2\pi * 5000)| = \left|\frac{1000 + 0}{1000 + j(2\pi * 5000)(100 * 10^{-9})(1000)(1000 + 0)}\right| = 0.303$$

Peak output = $|H(\omega)| * V_{IN}$ = 0.303 * 100 mV = **30.3 mV**

- Repeat this pattern for the last three entries.

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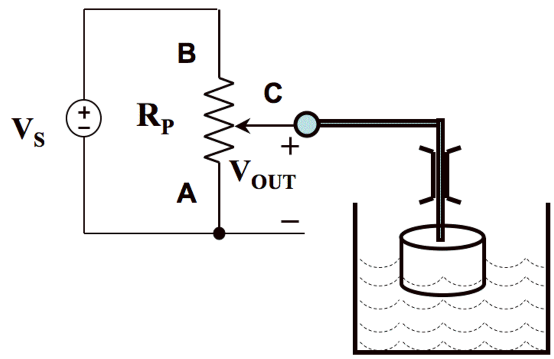
Problem 4 (30 points) Control circuits with Comparator, MOSFET, and the Wheatstone bridge: Position sensor

Part 1 (10 points)

Potentiometer as a sensor for linear displacement



The linear potentiometer used is used to measure the amount of liquid in a cylindrical tank. This is similar to how your fuel gage measures how much gas you have in the tank of your car.

Assume the following parameters: the cross-section area of the tank equals S = 800 cm^2; the length of the linear potentiometer (from A to B) equals L = 12 cm; the middle position of the potentiometer's tap corresponds to the liquid level equal to H = 7 cm; the total resistance of the potentiometer is R_P = 240 kΩ; the source voltage is V_S = 14 V.

Evidently, the circuit's readings are accurate only if the volume of liquid in the tank P remains within certain limits: if the float moves too low, the output voltage equals zero regardless of the amount of liquid; if the float moves too high, the output voltage saturates at V_S regardless of the amount of liquid.

Obtain and record the algebraic expressions for P_{MIN} and P_{MAX} in terms of S, L, and H. Neglect the volume of the float.

Your answers: $P_{MIN} = \boldsymbol{S(H - \frac{L}{2})}$ $P_{MAX} = \boldsymbol{S(H + \frac{L}{2})}$

Calculate and record below the minimal and maximal volumes of liquid in the tank P_{MIN} and P_{MAX} in liters (1 liter = 1,000 cm^3) that can be accurately measured with this circuit.

Your answers: P_{MIN} = **0.8 L** P_{MAX} = **10.4 L**

Show your work below and/or on additional pages.

Volume = Surface Area · Depth, so we just need to find the minimum and maximum depths. We know that H = 7cm corresponds to the center point of the potentiometer, 6cm. Thus, the minimum potentiometer position will occur at H – L/2 = 1cm, and the maximum will occur at H + L/2 = 13cm. P_{MIN} = 800cm^2·1cm = 800cm^3=0.8L. P_{MAX} = 800cm^2·13cm = 1040cm^3=10.4L.

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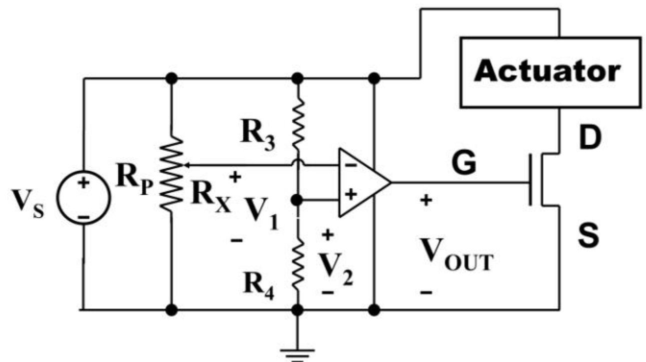
Problem 4

Part 2 (10 points) Operation of the control circuit



Position sensor based on potentiometer

Assume that the potentiometer as the liquid level sensor, which you studied in Part 1 of this problem, is connected to the circuit shown here: R_X is the resistance between A and B; voltage V_{OUT} of the diagram in Part 1 is labeled V_1 on the diagram in Part 2.

The circuit must keep the level of liquid in the tank below the safe limit.

Determine what kind of Actuator should be used:

a) Pump that adds liquid to the tank, or

b) Valve that blocks the flow of liquid into the tank.

Your answer: **a** b (circle one)

On a separate page, explain how the circuit operates and justify your answer.

In this circuit, the op-amp acts as a comparator. When the water is low, R_X is also low. As a result, $V_1 > V_2$, meaning that $V_{OUT} = V_{OUT,\,MAX}$ and the actuator is turned on. We want to fill the tank, so the "on" state of the actuator should correspond to when a pump is pumping liquid into the tank. When the water reaches the safe limit, R_X will be larger and we have $V_1 < V_2$. As a result, the pump will turn off, and the water in the tank will remain safe.

Part 3 (10 points)

Use the circuit parameters and tank sizes given in Part 1 and design the control circuit that limits the amount of liquid in the tank at exactly 10 liters.

Assume that $R_3 = 20$ kΩ, calculate R_4 in kΩ.

Your answer: R_4 = **460 kΩ**

$$x = \frac{10\ L}{0.8\ cm} = 12.5\ cm \qquad \frac{x-1}{L} = \frac{R_X}{R_P} = \frac{11.5}{12} = 0.958$$

$$With\ voltage\ division, \frac{R_X}{R_P} = \frac{R_3}{R_3 + R_4} = 0.958.\ Knowing\ R_3 = 20\ k\Omega, R_4 = \mathbf{460\ k\Omega}$$

EECS 314 Winter 2010 Homework set 8

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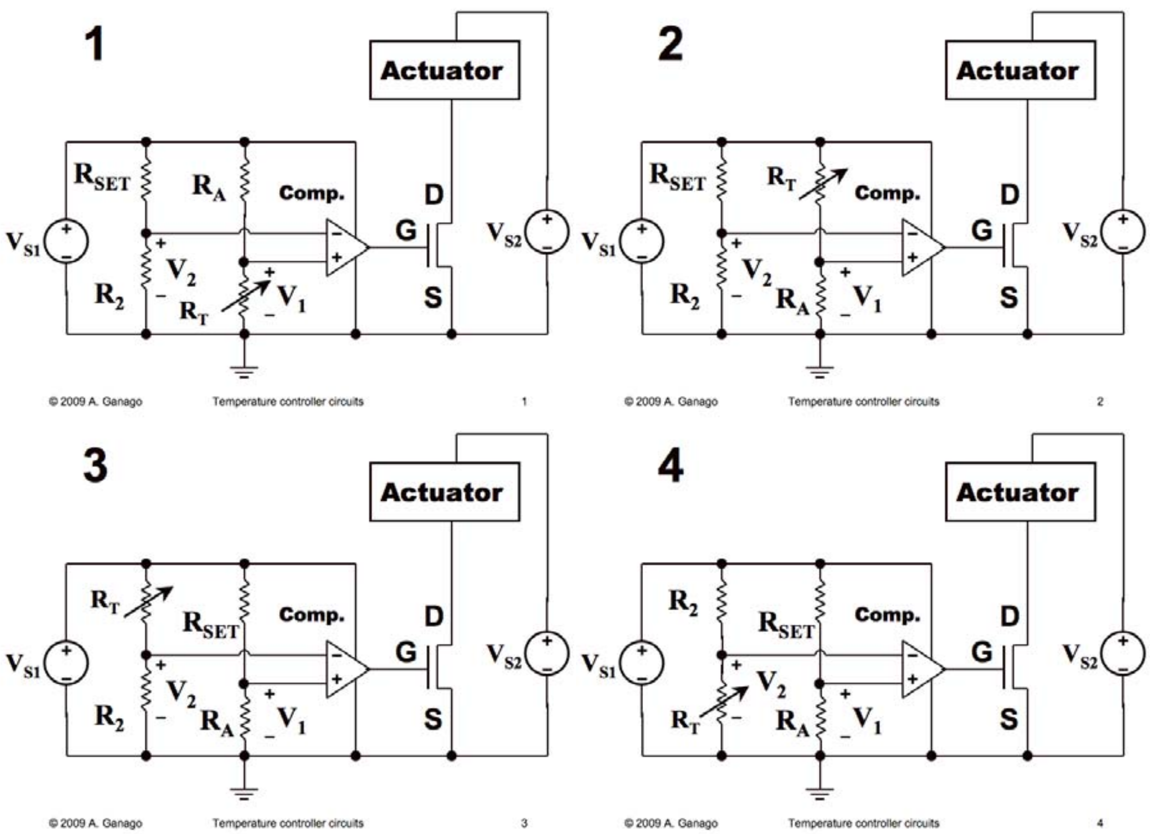
Problem 5 (30 points) Resistive sensors: Temperature controller circuit; Real sensors' parameters

In all parts, use "Golden Rule" #1.

Part 1 (10 points)



The four circuits shown above are built to maintain the temperature within the desired limits, that is turn on a heater when it gets too cold. We will call the circuit that operates this way a "good" one.

Two types of sensors can be used as R_T:

a) Thermistor with Negative Temperature Coefficient (NTC), and
b) Temperature-Dependent Resistor (TDR) with Positive Temperature Coefficient (PTC).

For each of type of sensor, briefly explain (on a separate page) which of the circuits on diagrams 1 – 4 is "good". Explain why each of the "bad" circuits is "bad."

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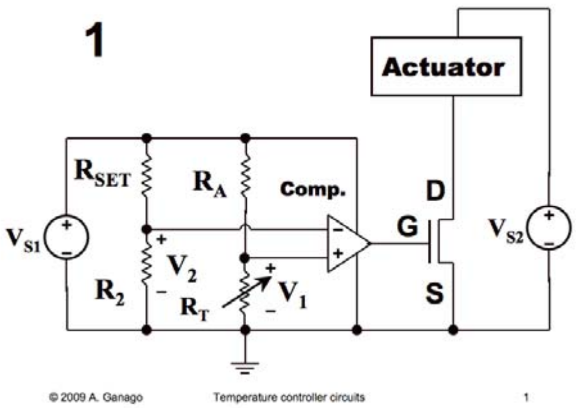
Notes

- R_T can be PTC or NTC
  - For PTC, as temperature increases resistance increases ($T\uparrow$ $R\uparrow$)
  - For NTC, as temperature increases resistance decreases ($T\uparrow$ $R\downarrow$)
- Output of comparator goes to V_{S1} when $V_+ > V_-$ or $V_1 > V_2$
- Want heater to be turned on when temperature gets too low
- Heater is turned on when $V_{GS} > V_T$ of MOSFET, this occurs when output of comparator which equals V_{GS} goes to V_{S1}
- Heater is on when $V_+ > V_-$ or $V_1 > V_2$
- Heater is off when $V_+ < V_-$ or $V_1 < V_2$

Circuit 1

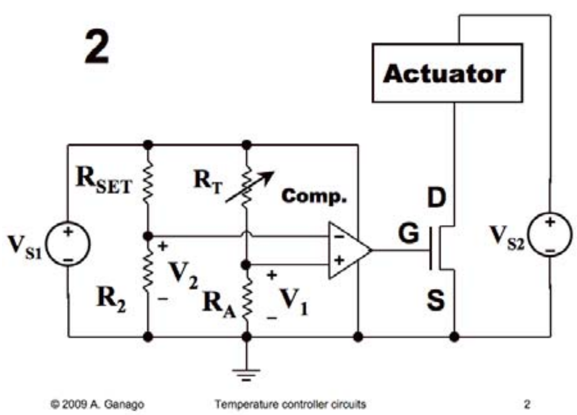
$V_2 = V_{S1} * \frac{R_2}{R_2+R_{SET}}$ $V_1 = V_{S1} * \frac{R_T}{R_T+R_A}$



V_2 is constant and $V_1\uparrow$ as $R_T\uparrow$
Assume heater off, $V_1 < V_2$
So as $T\downarrow$ want $V_1\uparrow$ or $R_T\uparrow$
NTC R_T would be good choice for this
PTC R_T would have $V_1\downarrow$ as $T\downarrow$
and heater won't turn on as $T\downarrow$, bad choice

Circuit 2

$V_2 = V_{S1} * \frac{R_2}{R_2+R_{SET}}$ $V_1 = V_{S1} * \frac{R_A}{R_T+R_A}$



V_2 is constant and $V_1\uparrow$ as $R_T\downarrow$
Assume heater off, $V_1 < V_2$
So as $T\downarrow$ want $V_1\uparrow$ or $R_T\downarrow$
PTC R_T would be good choice for this
NTC R_T would have $V_1\downarrow$ as $T\downarrow$
and heater won't turn on as $T\downarrow$, bad choice

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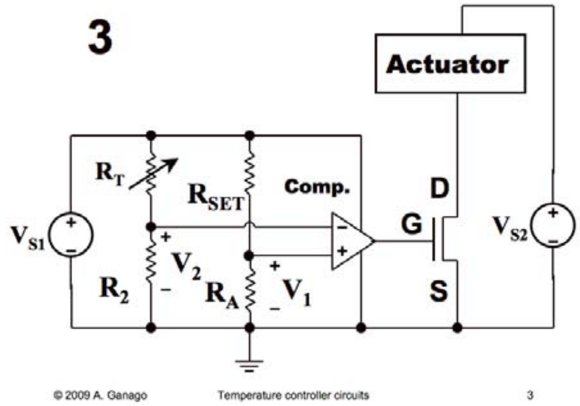
Circuit 3

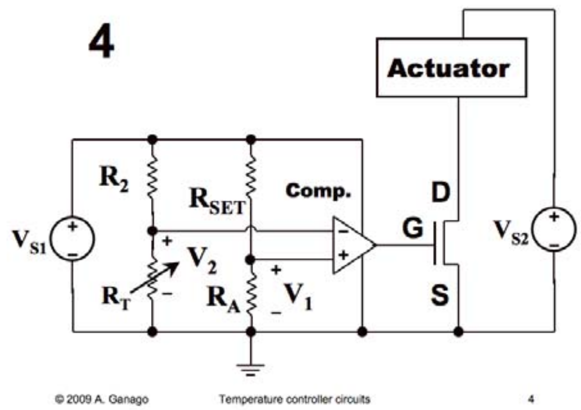
$V_2 = V_{S1} * \frac{R_2}{R_2+R_T}$ $V_1 = V_{S1} * \frac{R_A}{R_{SET}+R_A}$



V_1 is constant and $V_2\downarrow$ as $R_T\uparrow$
Assume heater off, $V_2 > V_1$
So as T↓ want $V_2\downarrow$ or $R_T\uparrow$
NTC R_T would be good choice for this
PTC R_T would have $V_2\uparrow$ as T↓
and heater won't turn on as T↓, bad choice

Circuit 4

$V_2 = V_{S1} * \frac{R_T}{R_2+R_T}$ $V_1 = V_{S1} * \frac{R_A}{R_{SET}+R_A}$



V_1 is constant and $V_2\downarrow$ as $R_T\downarrow$
Assume heater off, $V_2 > V_1$
So as T↓ want $V_2\downarrow$ or $R_T\downarrow$
PTC R_T would be good choice for this
NTC R_T would have $V_2\uparrow$ as T↓
and heater won't turn on as T↓, bad choice

Summary

	Circuit 1	Circuit 2	Circuit 3	Circuit 4
NTC R_T	Good	Bad	Good	Bad
PTC R_T	Bad	Good	Bad	Good

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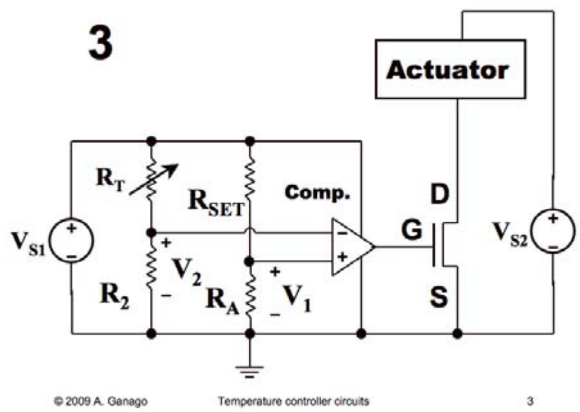
Problem 5

In Parts 2 and 3, consider the circuits listed below regardless of whether you found them "good" in Part 1.

Part 2 (10 points)

Consider circuit diagram 3 where R_T is a thermistor with 1000 Ω resistance at 25 °C (see *US Sensor catalog*, page 40, attached), R_A = 1 kΩ, and R_{SET} = 2 kΩ. Calculate the resistance R_2 to ensure that the actuator is turned on/off at – 20 ˚C. Show your work.



Actuator is turned on/off when inputs of comparator are equal or $V_1 = V_2$

From voltage division,

$$V_2 = V_{S1}\frac{R_2}{R_2 + R_T} \qquad V_1 = V_{S1}\frac{R_A}{R_A + R_{SET}}$$

Setting $V_1 = V_2$ yields:

$$\frac{R_2}{R_2 + R_T} = \frac{R_A}{R_A + R_{SET}}$$

$$\frac{1}{1+\frac{R_T}{R_2}} = \frac{1}{1+\frac{R_{SET}}{R_A}}$$

$$\frac{R_T}{R_2} = \frac{R_{SET}}{R_A}$$

$$\frac{R_2}{R_T} = \frac{R_A}{R_{SET}}$$

From the given resistances R_A = 1 kΩ, R_{SET} = 2 kΩ,

$$\frac{R_2}{R_T} = \frac{R_A}{R_{SET}} = \frac{1k}{2k} = \frac{1}{2} \qquad R_2 = \frac{1}{2}R_T$$

Looking up thermistor's resistance from table for -20ºC, R_T = 9708 Ω. So,

$$R_2 = \frac{1}{2}(9708) = 4854\ \Omega$$

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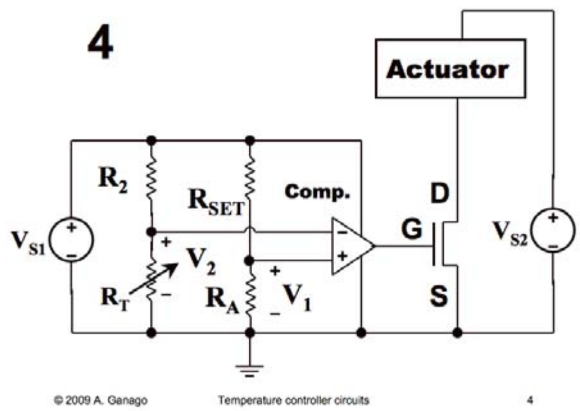
Part 3 (10 points)

Consider circuit diagram 4 where R_T is a TDR with 1000 Ω resistance at 0 °C (see *Vishay Beyschlag catalog*, attached), R_2 = 2.2 kΩ, and R_{SET} = 3.3 kΩ. Calculate the resistance R_A to ensure that the actuator is turned on/off at – 20 ˚C. Show your work.



Actuator is turned on/off when inputs of comparator are equal or $V_1 = V_2$

From voltage division,

$$V_2 = V_{S1}\frac{R_T}{R_T + R_2} \qquad V_1 = V_{S1}\frac{R_A}{R_A + R_{SET}}$$

Setting $V_1 = V_2$ yields:

$$\frac{R_T}{R_T + R_2} = \frac{R_A}{R_A + R_{SET}}$$

$$\frac{1}{1+\frac{R_2}{R_T}} = \frac{1}{1+\frac{R_{SET}}{R_A}}$$

$$\frac{R_2}{R_T} = \frac{R_{SET}}{R_A}$$

$$\frac{R_A}{R_T} = \frac{R_{SET}}{R_2}$$

From the given resistances R_2 = 2.2 kΩ, R_{SET} = 3.3 kΩ,

$$\frac{R_A}{R_T} = \frac{R_{SET}}{R_2} = \frac{3.3k}{2.2k} = \frac{3}{2} \qquad R_A = \frac{3}{2}R_T$$

Looking up TDR's resistance from data sheet for -20ºC, R_T = 920 Ω. So,

$$R_A = \frac{3}{2}(920) = 1380\ \Omega$$