Laboratory 7: Introduction to Op-Amps and High Impedance Amplifier Circuits

- ***Lab Objectives:***

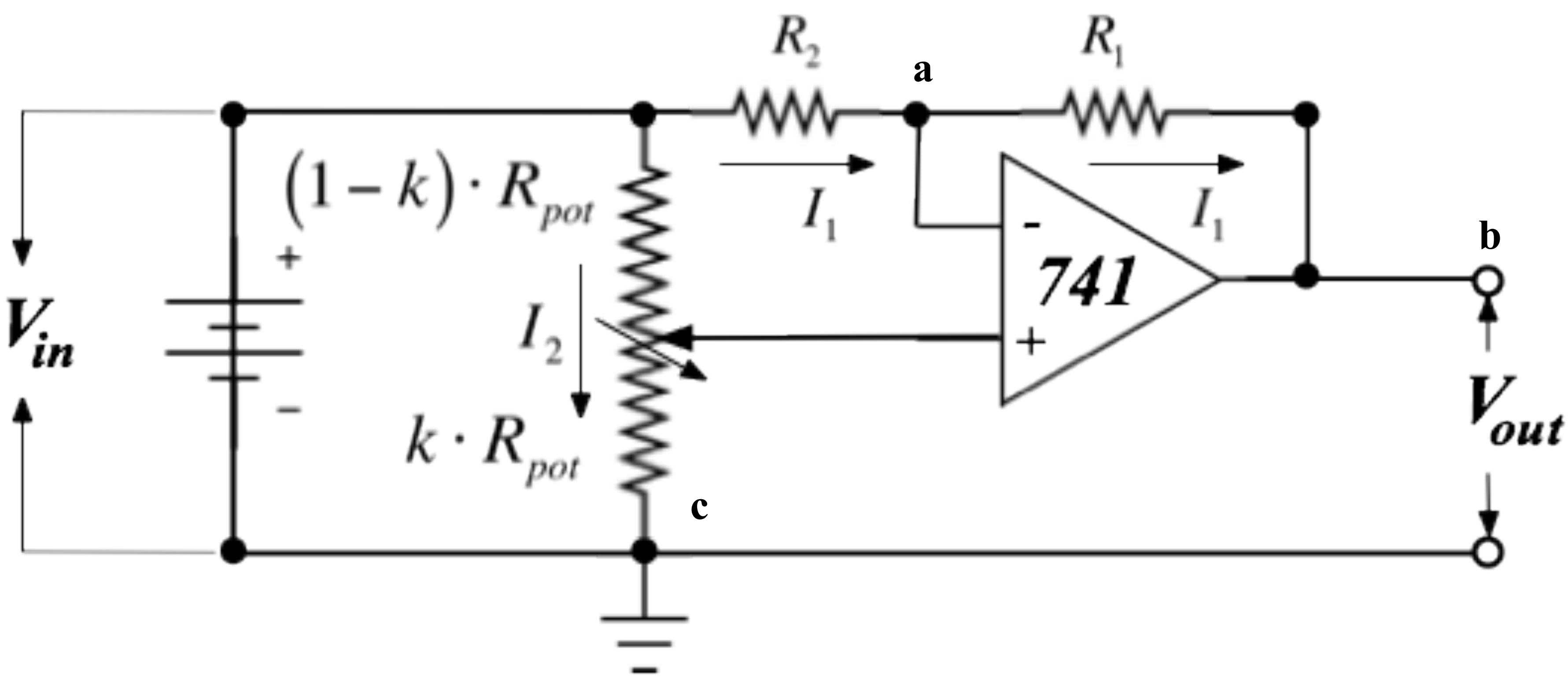
  -- Understand Op-Amp Properties

  -- Understand Potentiometers and Variable Resistances

  -- Build a Variable Gain Inverting Amplifier

  -- Understand "Virtual Ground" Concept … and Associated Grounding Issues

You Will Build This Amplifier Circuit



National Semiconductor 741 Op-Amp (1)

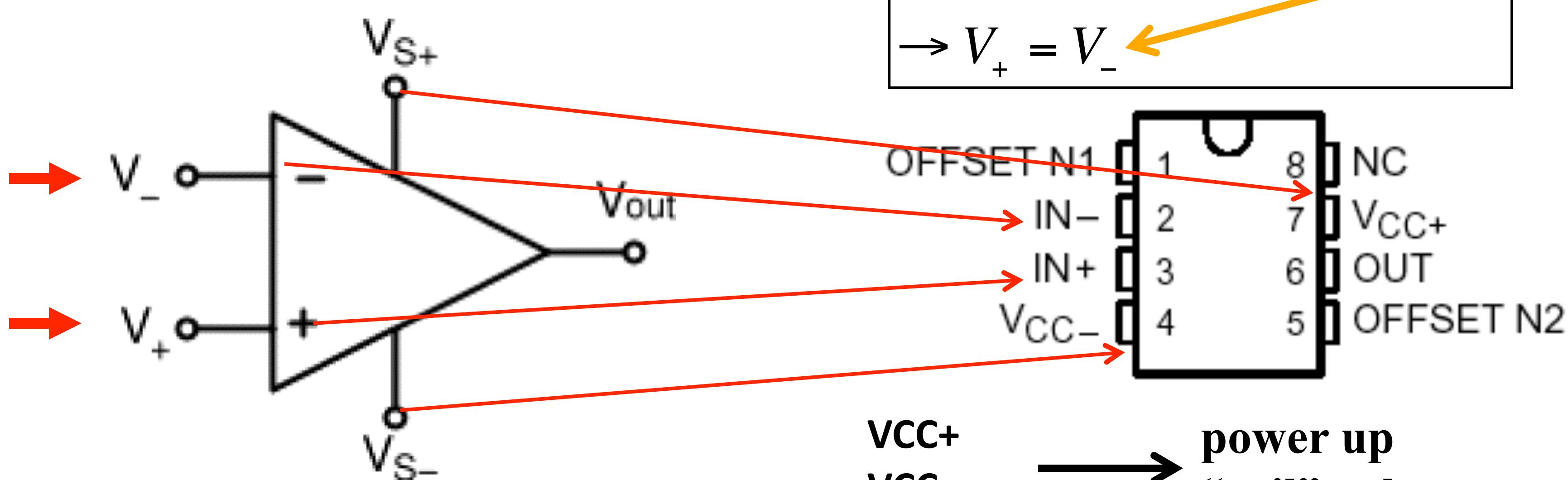
- The 741 is the godfather of all Op-Amps.
- Although many other designs beat it for speed, low noise, etc, it works well as a general purpose device.
- One of its advantages is that it is *compensated* to ensure that under most circumstances it won't produce unwanted spurious oscillations.
- This property makes 741 easy to use, but the down-side is the poor speed/gain performance compared to more modern op-amps.

NS Operational Amplifier (3)

Very common, available as a chip and has the following characteristics:

1) High input impedance (won't draw current)
2) Low output impedance (will deliver current w/o affecting voltage)
3) High internal gain ($A > 10^5$)

$$V_{out} = A\left[V_+ - V_-\right] \ldots\ldots A \to \infty$$
$$\to V_+ = V_-$$



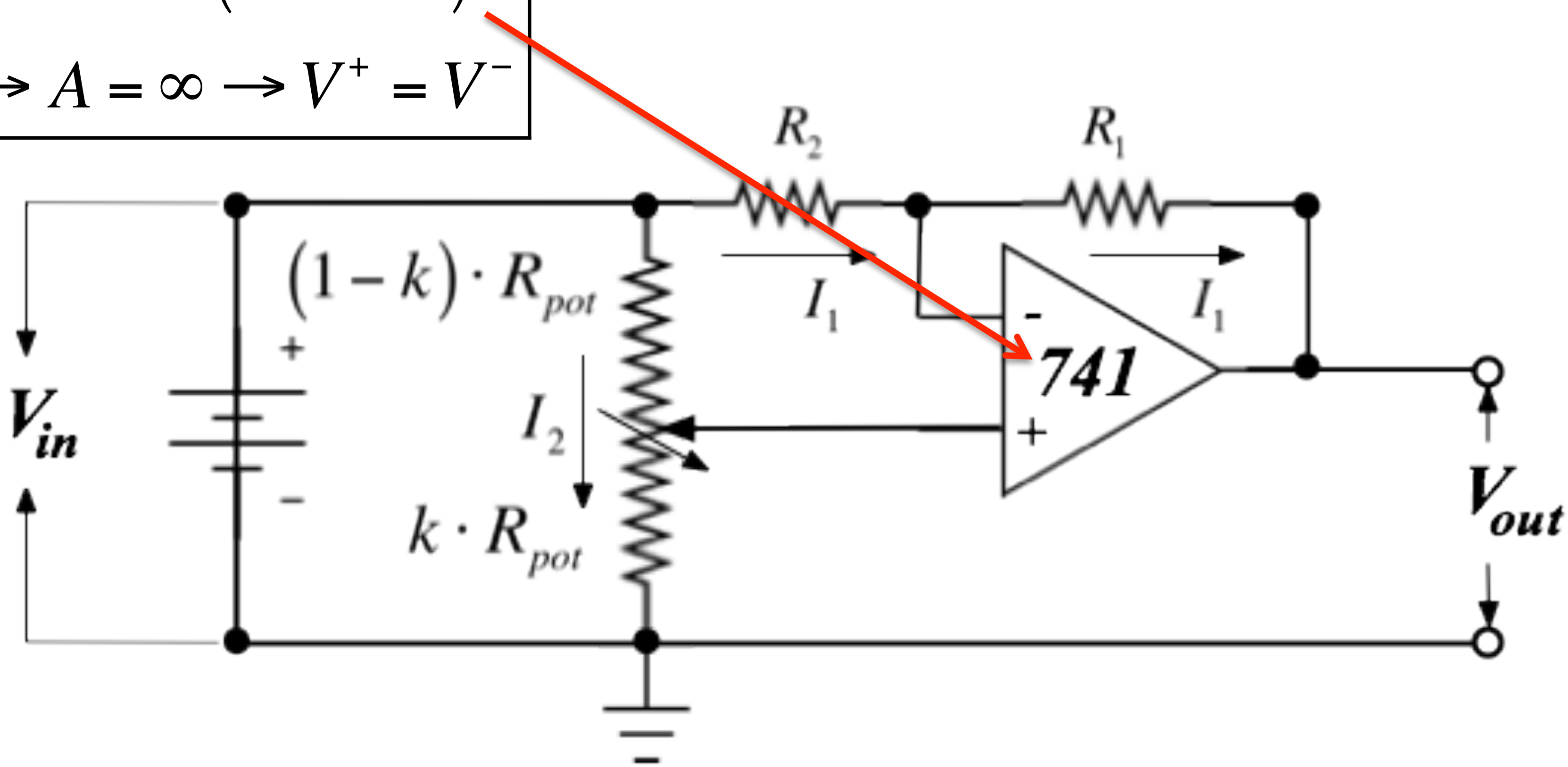
VCC+
VCC- → **power up "rail" voltage**

Circuit Analysis (1)

Idealized OpAmp

$$V_{out} = A \cdot \left(V^+ - V^-\right)$$

$$\rightarrow A = \infty \rightarrow V^+ = V^-$$



Circuit Analysis (2)

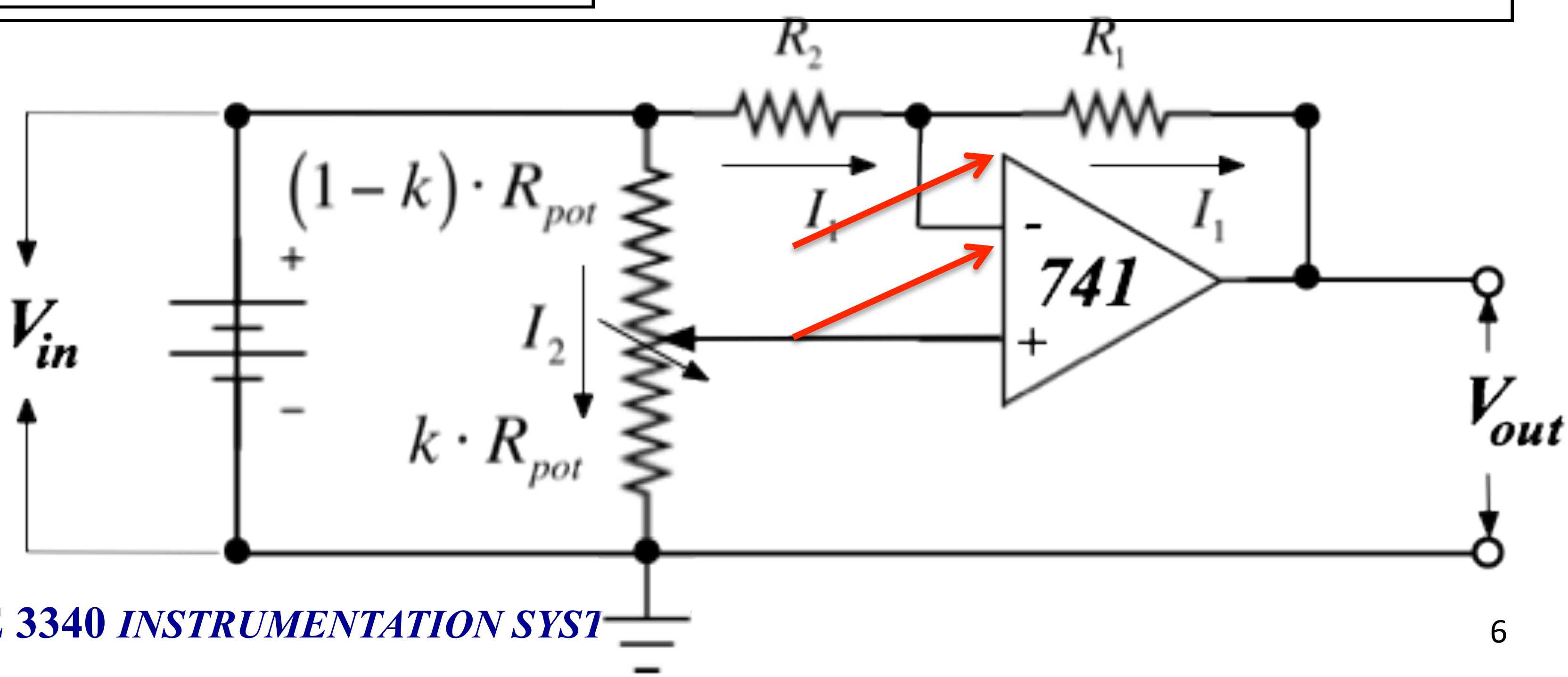
Across OpAmp Terminals :

$$V^- - V_{out} = R_1 I_1$$

$$V_{in} - V^+ = (1-k)\cdot R_{pot} \cdot I_2$$

$$V^- = V^+$$

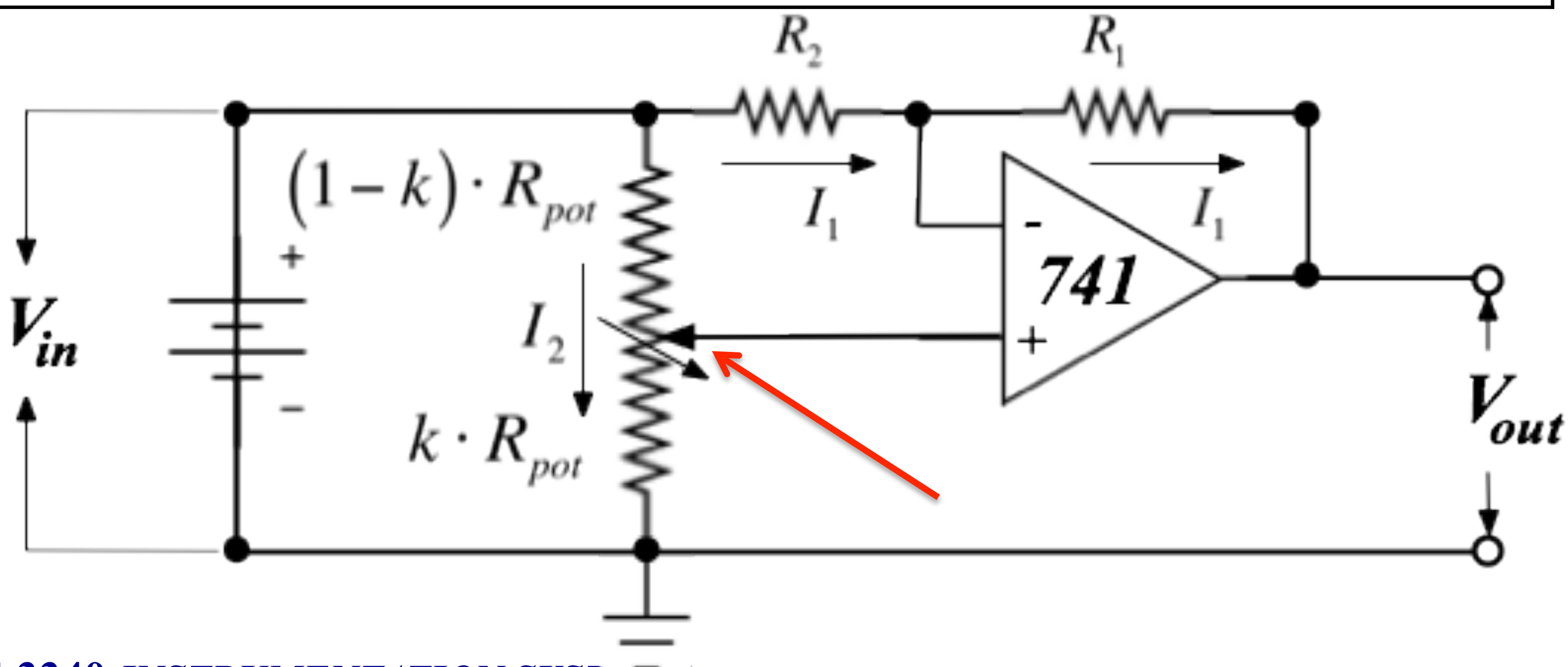
$$\rightarrow \boxed{V_{out} + R_1 I_1 = V_{in} - (1-k)\cdot R_{pot}\cdot I_2}$$



Circuit Analysis $_{(3)}$

Across Potentiometer :

$$V_{in} = (1-k)\cdot R_{pot}\cdot I_1 + k\cdot R_{pot}\cdot I_2 = R_{pot}\cdot I_2 \rightarrow I_2 = \frac{V_{in}}{R_{pot}}$$

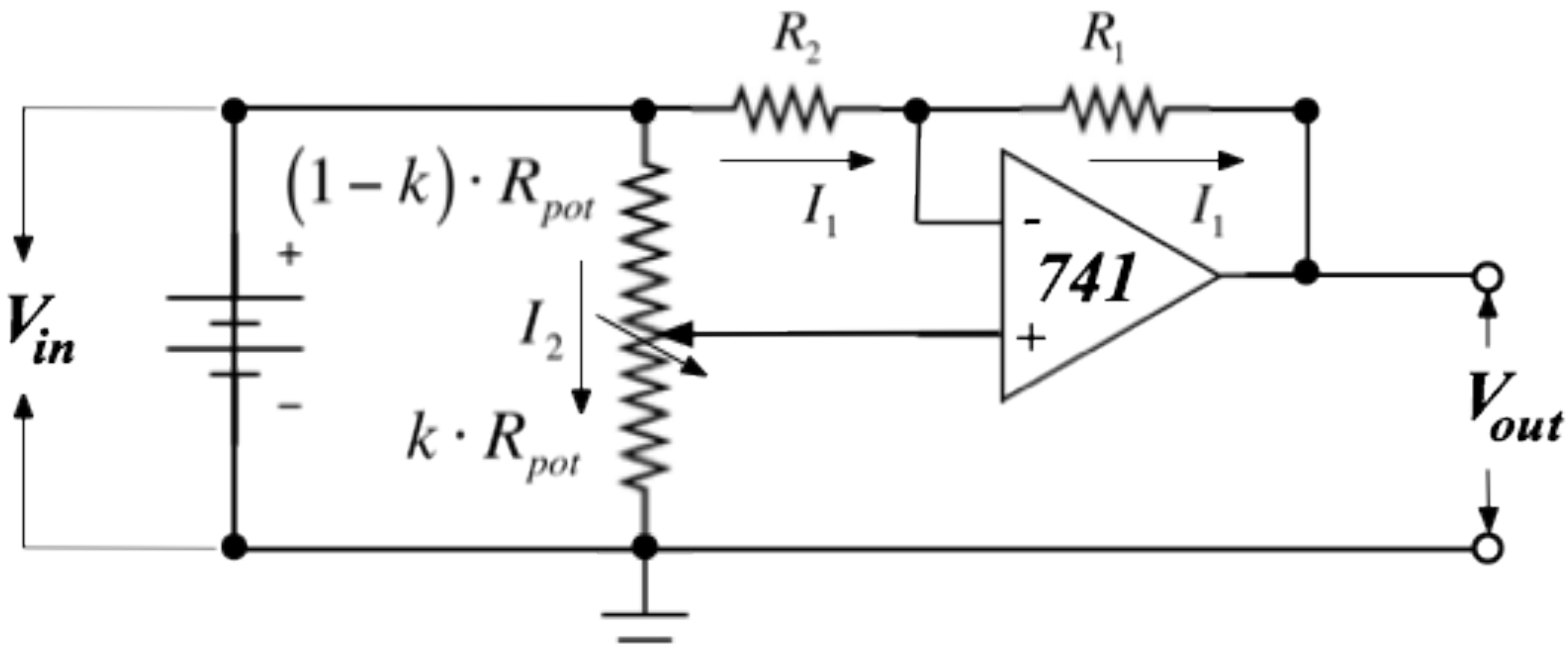


Circuit Analysis (4)

$$Substitute: V_{in} = \underline{R_{pot} \cdot I_2} \rightarrow V_{out} + I_1 \cdot R_1 = V_{in} - (1-k) \cdot \underline{R_{pot} \cdot I_2}$$

$$V_{out} + I_1 \cdot R_1 = V_{in} - (1-k) \cdot V_{in}$$

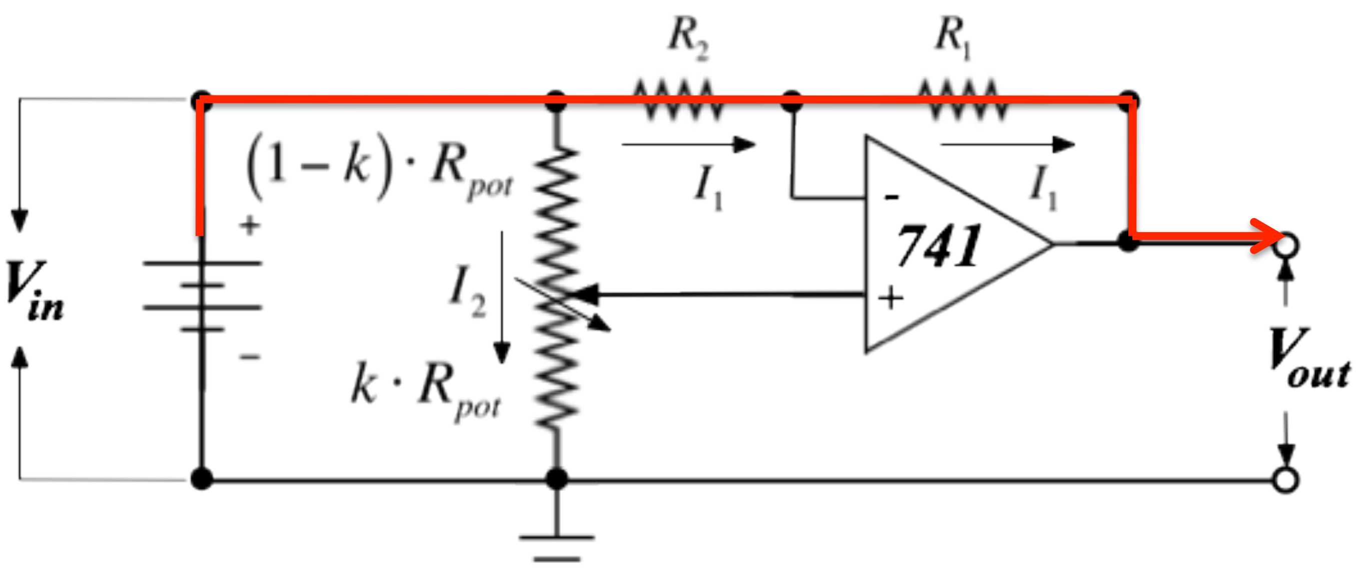
$$\boxed{V_{out} = k \cdot V_{in} - I_1 \cdot R_1}$$



Circuit Analysis (5)

From Input to Output Across Top Loop :

$$\boxed{V_{in} - V_{out} = (R_2 + R_1) \cdot I_1} \rightarrow \underline{I_1 = \frac{V_{in} - V_{out}}{(R_2 + R_1)}}$$



Circuit Analysis (6)

Collected Equations :

$$V_{out} = V_{in} - (R_2 + R_1) \cdot I_1$$

$$V_{out} = k \cdot V_{in} - R_1 \cdot I_1$$

$$\rightarrow \frac{V_{out} - V_{in}}{(R_2 + R_1)} = I_1$$

Eliminate I_1

$$(R_2 + R_1) \cdot V_{out} = (R_2 + R_1) \cdot k \cdot V_{in} - R_1 \cdot (R_2 + R_1) I_1$$

$$-R_1 \cdot V_{out} = -R_1 \cdot V_{in} + R_1 \cdot (R_1 + R_2) \cdot I_1$$

$$R_2 \cdot V_{out} = \left[(R_1 + R_2) \cdot k - R_1 \right] \cdot V_{in}$$

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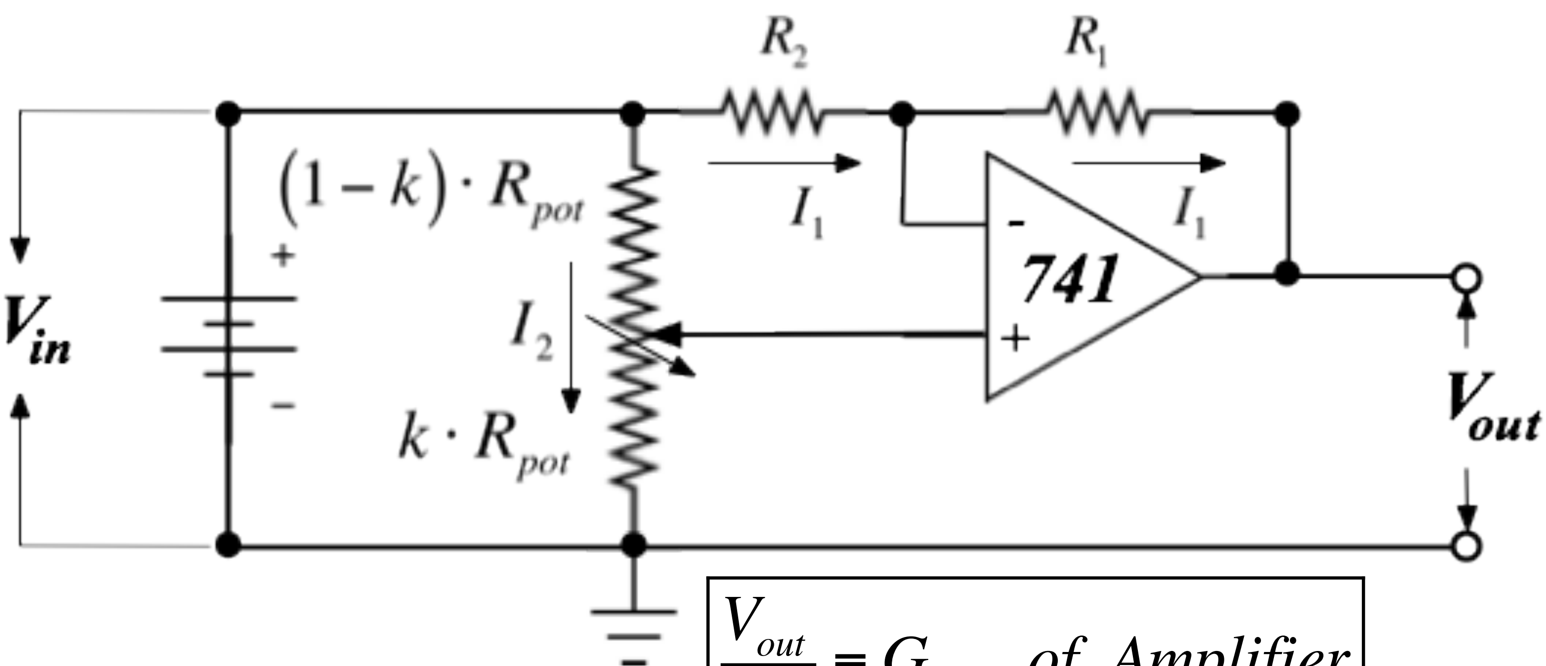
Circuit Analysis (7)

→ **Simplify**

$$\rightarrow \quad V_{out} = \left[\left(1+\frac{R_1}{R_2}\right)\cdot k - \frac{R_1}{R_2}\right]\cdot V_{in}$$

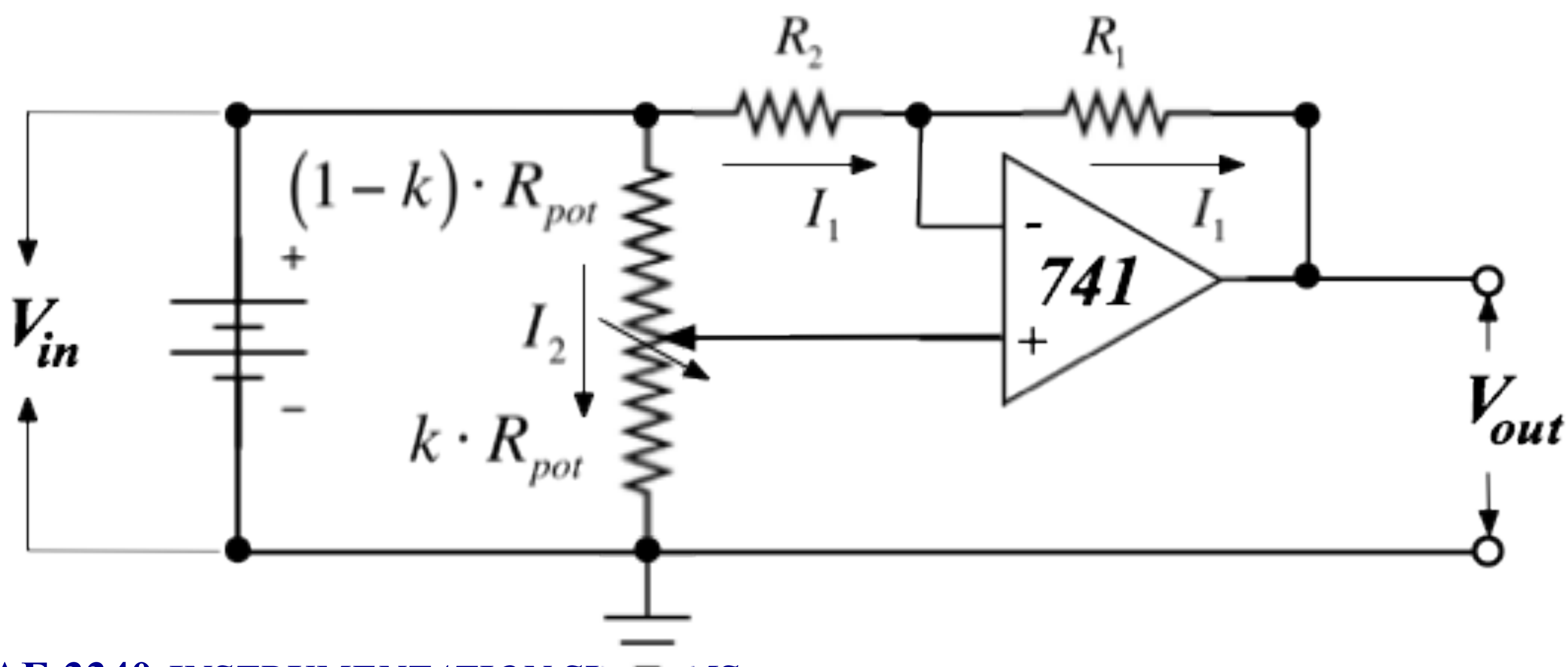


$$\frac{V_{out}}{V_{in}} \equiv G_{ain} \ldots of \;\; Amplifier$$

Circuit Power Dissipation (1)

Potentiometer:

$$I_2 = \frac{V_{in}}{R_{pot}} \rightarrow \boxed{P_{R_{pot}} = I_2 \cdot V_{in} = \frac{V_{in}^{\ 2}}{R_{pot}}} \text{...}(Slide\ 7)$$



Circuit Power Dissipation (2)

Current Through R_1, R_2:

$$from\ Slide\ 9 \rightarrow I_1 = \frac{V_{out} - V_{in}}{\left(R_2 + R_1\right)} = \frac{\left[\left(1 + \frac{R_1}{R_2}\right)\cdot k - \frac{R_1}{R_2}\right]V_{in} - V_{in}}{\left(R_2 + R_1\right)} =$$

$$\frac{\left[\left(1 + \frac{R_1}{R_2}\right)\cdot k - \frac{R_1}{R_2} - 1\right]}{\left(R_2 + R_1\right)}\cdot V_{in} = \frac{\left[\left(k - 1\right)\cdot \frac{\left(R_2 + R_1\right)}{R_2}\right]}{\left(R_2 + R_1\right)}\cdot V_{in} = \frac{\left(k - 1\right)}{R_2}V_{in}$$

Circuit Power Dissipation (3)

Power Dissipated by R_1, R_2:

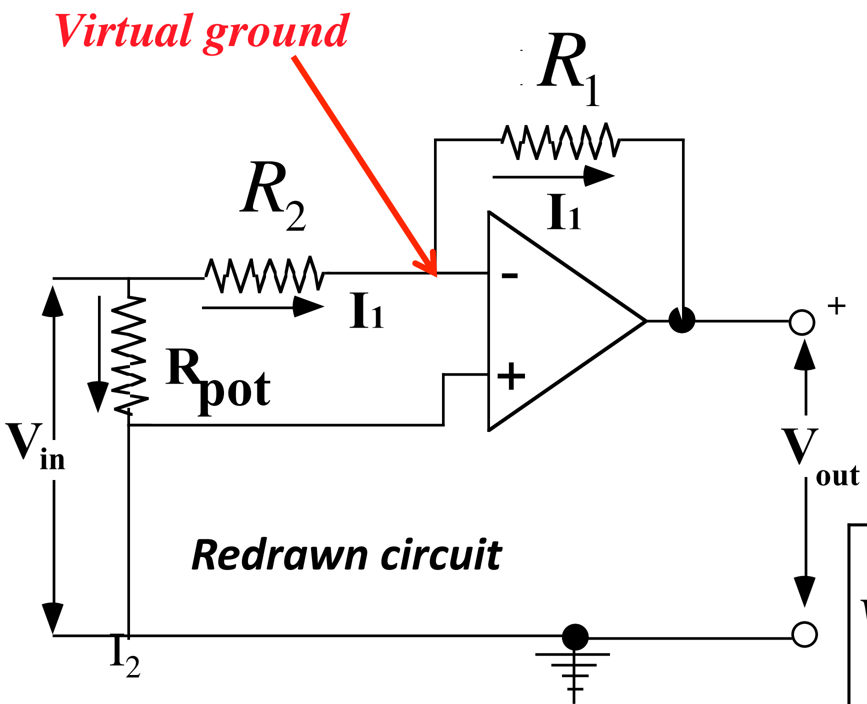
$$P_{R_2} = I_1^{\,2} \cdot R_2 = \left(\frac{(k-1)}{R_2} V_{in}\right)^2 \cdot R_2 = \frac{\left[(k-1)V_{in}\right]^2}{R_2}$$

$$P_{R_1} = I_1^{\,2} \cdot R_1 = \left(\frac{(k-1)}{R_2} V_{in}\right)^2 \cdot R_1 = \left(\frac{R_1}{R_2}\right) \cdot \frac{\left[(k-1)V_{in}\right]^2}{R_2}$$

R_1 is the critical resistor we have to watch for power dissipation

Circuit Properties (1)

$$Let \rightarrow \quad k = 0$$



$across\ OpAmp$ Terminals $\rightarrow V^+ = V^-$

$$\rightarrow \boxed{V^- = 0 = V^+} \rightarrow "virtual\ ground"$$

$$V_{in} = R_2 \cdot I_1 \rightarrow V_{out} = -R_1 \cdot I_1$$

$$\boxed{V_{out} = -\frac{R_1}{R_2} \cdot V_{in}}$$

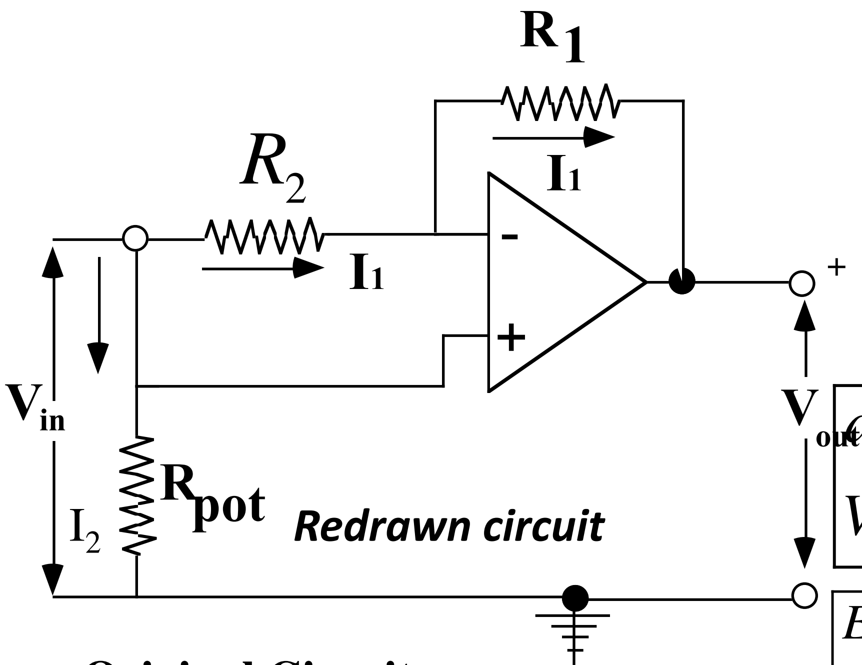
- **Original Circuit**

$$\boxed{V_{out} = \left[\left(1 + \frac{R_1}{R_2}\right) \cdot 0 - \frac{R_1}{R_2}\right] V_{in} = -\frac{R_1}{R_2} \cdot V_{in}}$$

Check! • **Voltage Polarity Inverter!**

Circuit Properties (2)

$$Let \rightarrow k = 1$$



- Check … let ***k=1***

$$across\ OpAmp\ Terminals:$$

$$V_{in} = V^{+} \rightarrow V^{-} = V_{out} + R_1 \cdot I_1$$

$$V^{+} = V \rightarrow V_{in} = V_{out} + R_1 \cdot I_1$$

$$across\ Top\ Loop\ from\ Input\ to\ Output:$$

$$V_{in} = V_{out} + \left(R_1 + R_2\right) \cdot I_1$$

$$Eliminate\ I_1:$$

$$\left(R_1 + R_2\right) \cdot V_{in} = \left(R_1 + R_2\right) \cdot V_{out} + \left(R_1 + R_2\right) \cdot R_1 \cdot I_1$$

$$- R_1 \cdot V_{in} = \quad - R_1 \cdot V_{out} - R_1 \cdot \left(R_1 + R_2\right) \cdot I_1$$

$$R_2 \cdot V_{in} = R_2 \cdot V_{out}$$

$$\rightarrow V_{in} = V_{out}$$

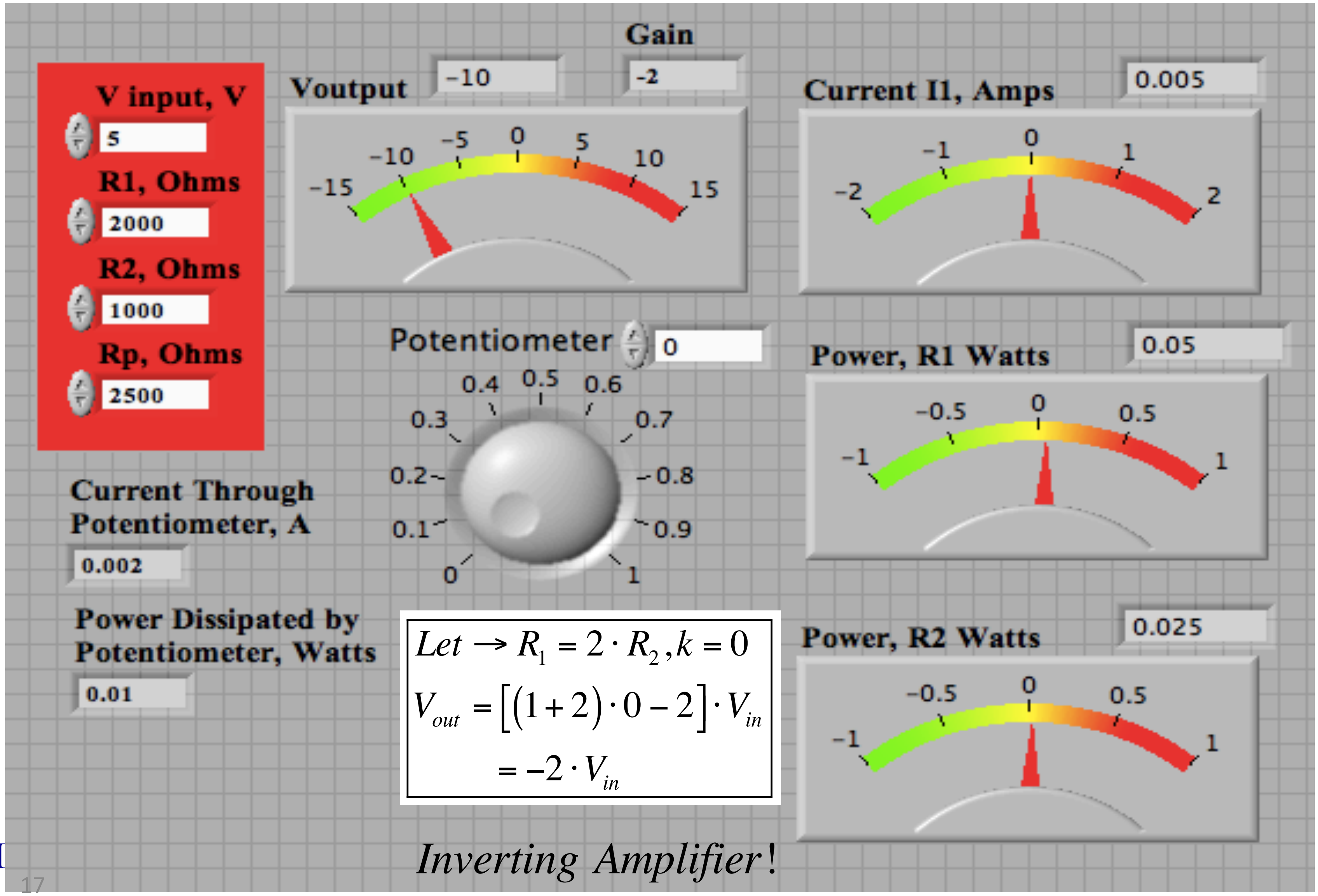
- **Original Circuit**

$$V_{out} = \left[\left(1 + \frac{R_1}{R_2}\right) \cdot 1 - \frac{R_1}{R_2}\right] V_{in} = V_{in}$$

- **Voltage Follower!**

Check 2!

Circuit Properties (3)

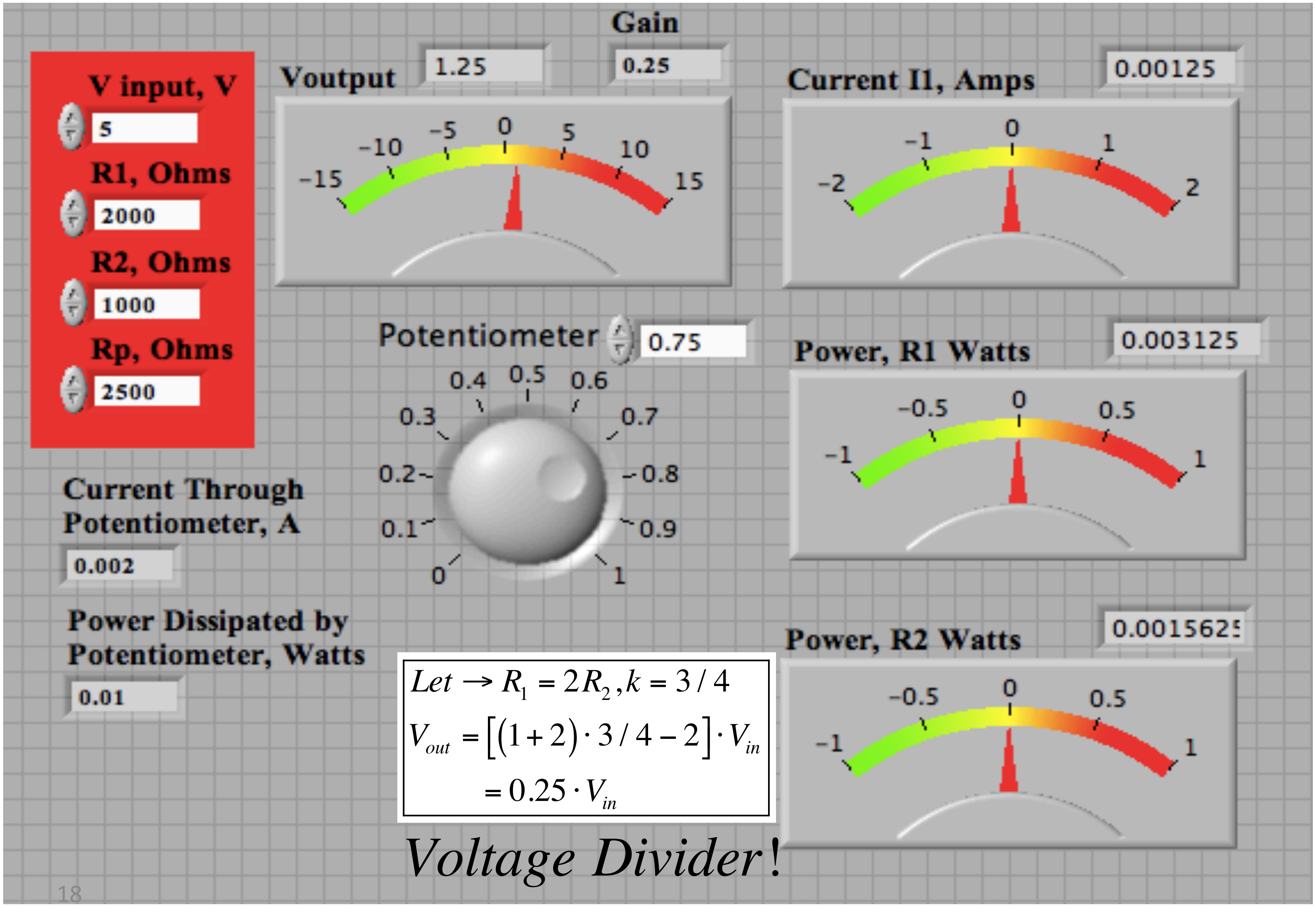


$$Let \rightarrow R_1 = 2 \cdot R_2, k = 0$$

$$V_{out} = \left[(1+2) \cdot 0 - 2 \right] \cdot V_{in} = -2 \cdot V_{in}$$

Inverting Amplifier!

Circuit Properties (4)



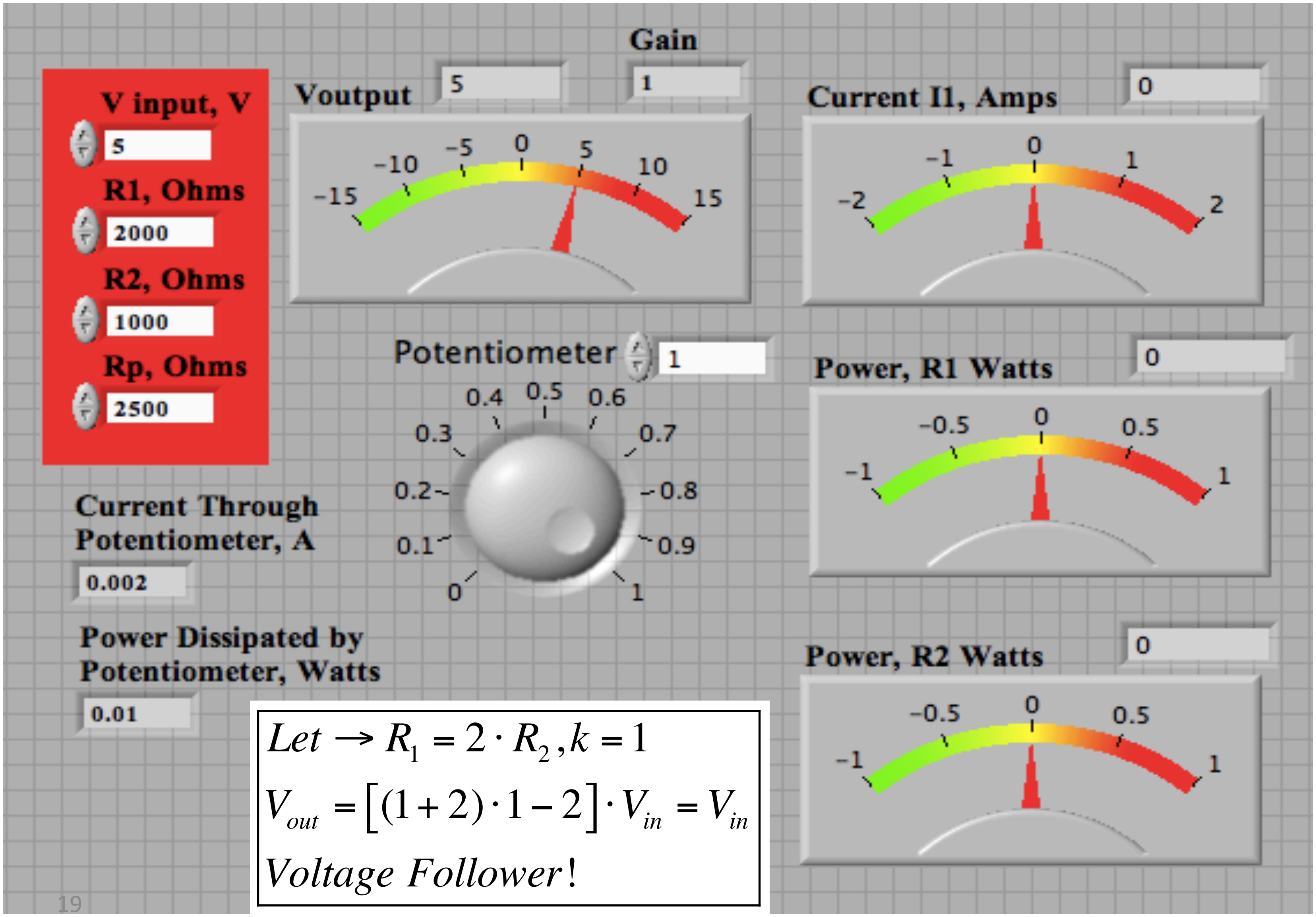
$$Let \rightarrow R_1 = 2R_2, k = 3/4$$

$$V_{out} = \left[(1+2)\cdot 3/4 - 2\right]\cdot V_{in}$$

$$= 0.25 \cdot V_{in}$$

Voltage Divider!

Circuit Properties (5)



$$Let \rightarrow R_1 = 2 \cdot R_2, k = 1$$

$$V_{out} = \left[(1+2)\cdot 1 - 2\right]\cdot V_{in} = V_{in}$$

Voltage Follower!

Lab Equipment

1. My DAQ Chassis and USB Cable
2. MyDAQ Red and Black Voltage Probes
3. MyDAQ BreadBoard
4. Honeywell 2.5 kΩ, 2 Watt Potentiometer
5. Breadboard Jumper Wires
6. 10 Assorted Resistors from *1000 Ω to 5000 kΩ*
7. *NS-742 OpAmp*

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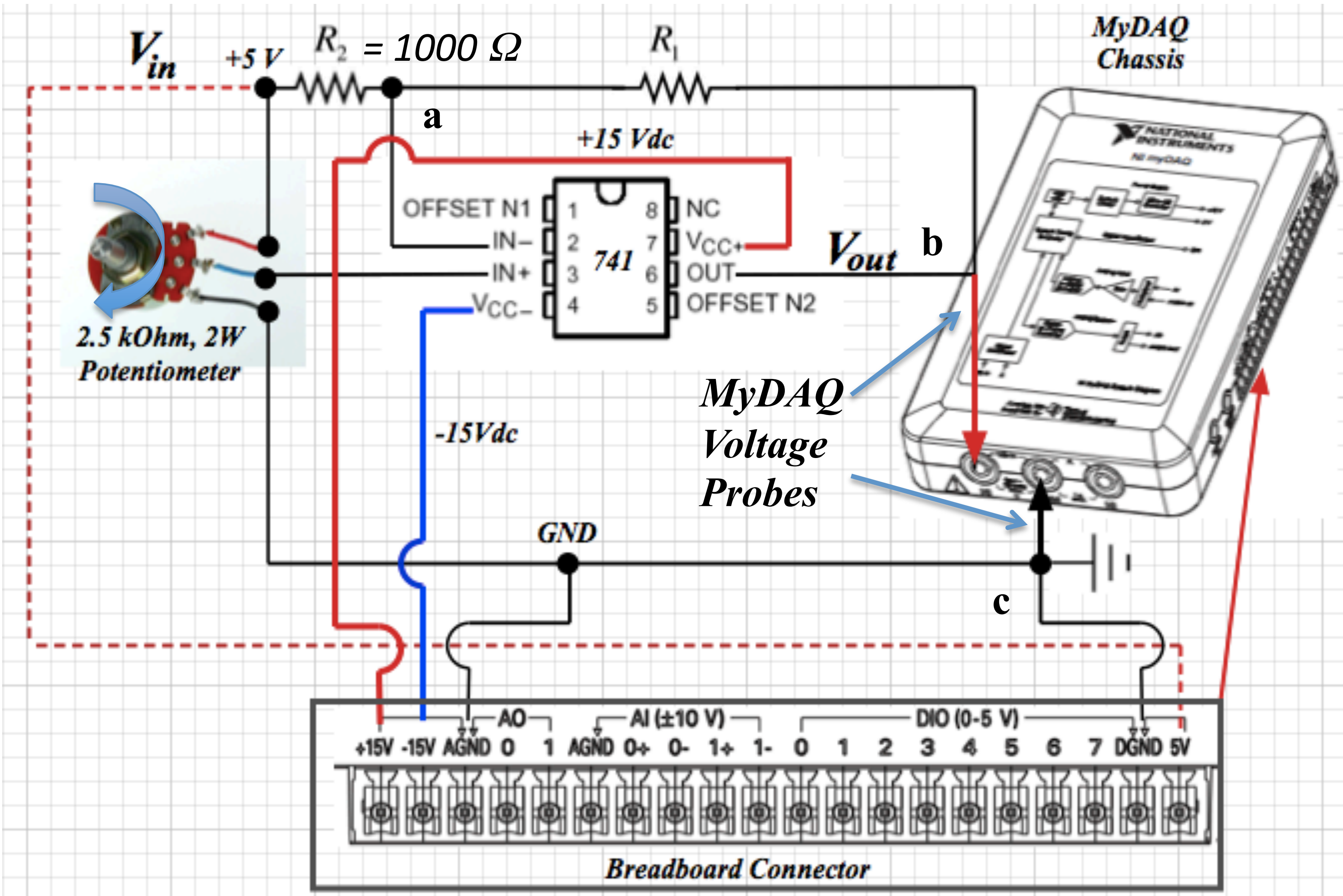
Hardware Configuration



Potentiometer Spec Sheet (1)

Honeywell

Potentiometer Type	Industrial
Element Type	Conductive Plastic
Terminal	Solder lug
Power Rating	2 W
Resistance Value	2.5 kOhm
Resistance Tolerance	± 10 %
Linearity	± 5 %
Bushing Thread	9,53 mm [0.375 in] x 32 NEF-2A
Bushing Length	9,53 mm [0.375 in]
Bushing Type	Standard
Shaft Diameter	6,35 mm [0.25 in]
Shaft Length	50,80 mm [2.0 in]

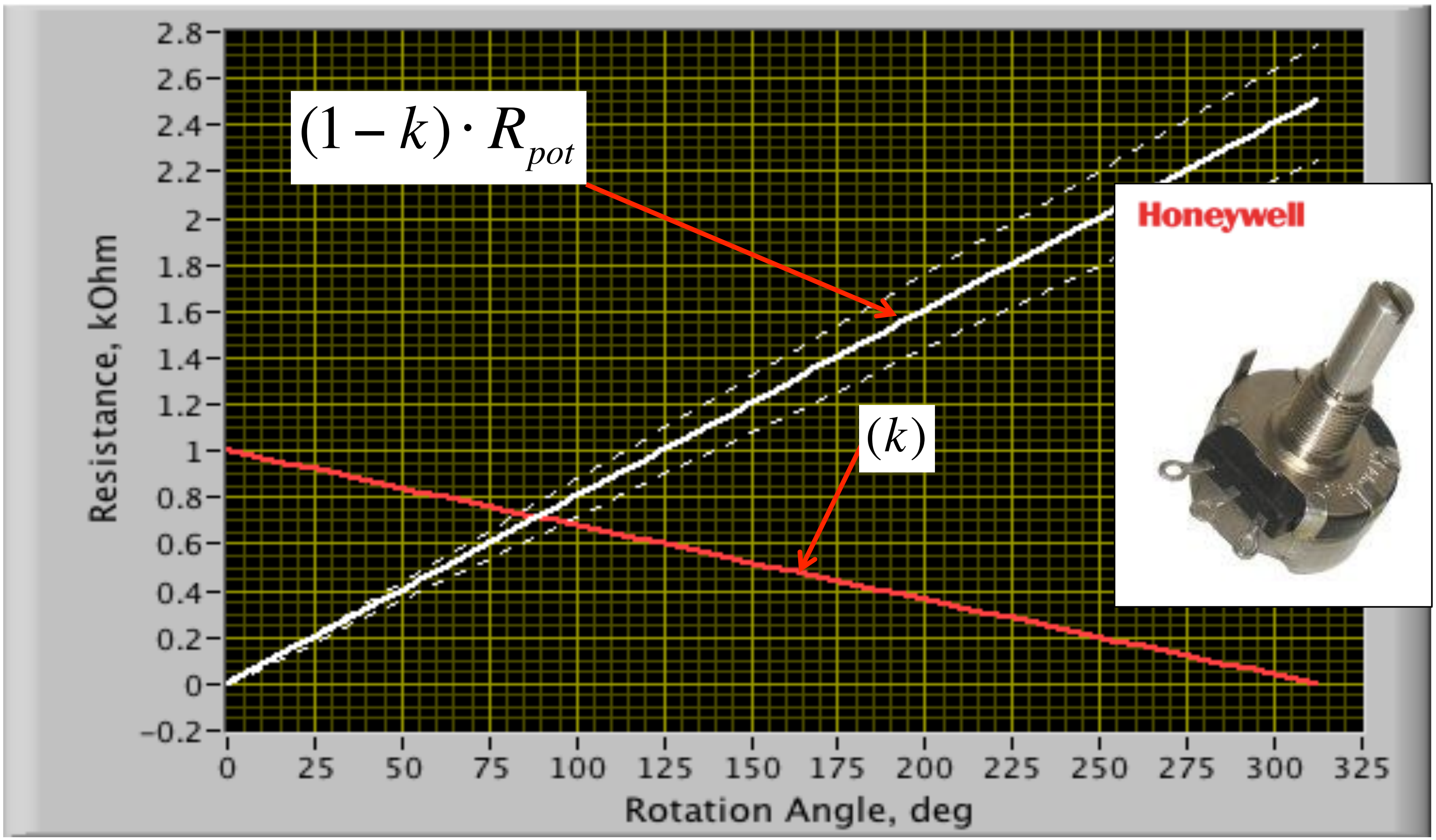
Potentiometer Spec Sheet (2)

Shaft Ending	Plain round
Body	27.8 mm [1.094 in] diameter max.
Electrical Taper	Linear
Operating Temperature	-55 °C to 120 °C [-67 °F to 248 °F]
Working Voltage (Max.)	500 V
Rotational Life	25000 cycles
Mechanical Rotation	312°
Availability	Global
Series Name	53
UNSPSC Code	4111363300
UNSPSC Commodity	4111363300 Potentiometers

Honeywell

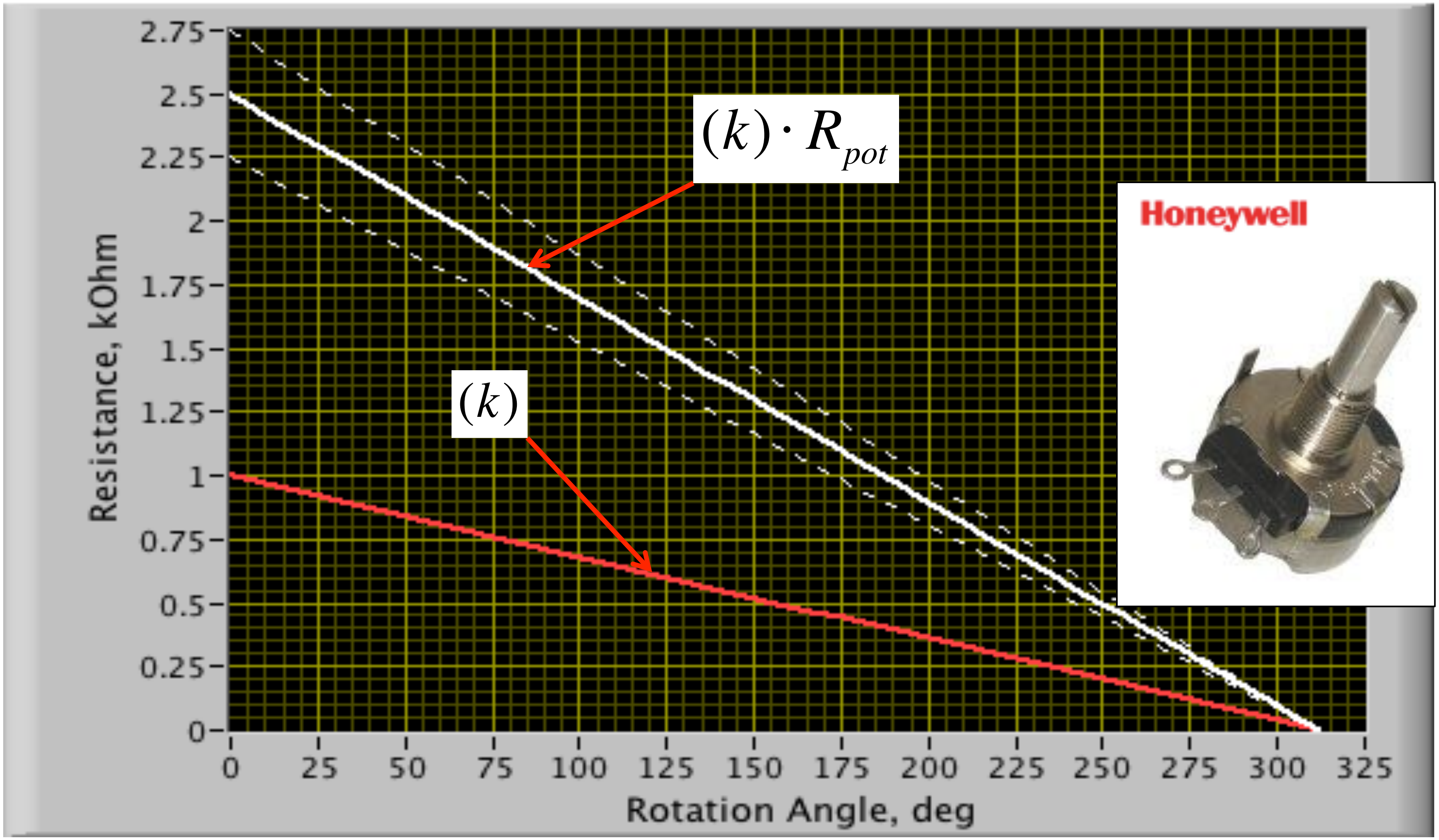
Potentiometer Spec Sheet (3)

Potentiometer Resistance, (1-k)*Rmax
Rotation Angle, deg.



Potentiometer Spec Sheet (3)

Potentiometer Resistance, (k)*Rmax
Rotation Angle, deg.



PreLab Calculations/Measurements

- Verify that All Resistances lie Between *1 kΩ and 5kΩ*
- Ensure that Two Resistors ~ *1000 Ω*
- Power Dissipated by Potentiometer @5Vdc V_{in}: ________________
- Maximum Power Dissipated in R_1 R_2 @5Vdc V_{in}: _______________
- Expected Range of Output Voltages: _________________________

  Based on Resistor Range from 1KΩ to 2 KΩ
- Actual Potentiometer Resistance (*k=1*):________ %Deviation________
- Actual Potentiometer Resistance (*k=0*): _______ %Deviation _______
- Find Rotation Point on Potentiometer where *k=0.5*, Mark with "Sharpie" Felt Tip Pen

-- Perform Calculation to Ensure that ¼ Watt Limit is not Exceeded for any Resistor with Any Potentiometer Setting at @5Vdc V_{in}

PreLab Uncertainty Analysis

• Calculate the Expected Uncertainty in the Amplifier Gain

***Gain* = V_{out}/V_{in}**

• Based on the Manufacturer's Specs for R_{pot}, R_1, and R_{2f}
For k ={0, ½, 1} Potentiometer Settings

• Use Chain Rule for Error Propagation

• Assume σ_k/k ~ linearity tolerance (See Slide 18)

• Plot Expected Gain Error as a function of R_1/R_2
• *Assume V_{in} V_{out} measurements are exact*

PreLab Uncertainty Analysis (2)

$$\frac{V_{out}}{V_{in}} \equiv G_{ain} \ldots U^2{}_{Gain} = \left(\frac{\partial G_{ain}}{\partial R_1}\right)^2 \cdot U^2{}_{R_1} + \left(\frac{\partial G_{ain}}{\partial R_2}\right)^2 \cdot U^2_{R_2} + \left(\frac{\partial G_{ain}}{\partial k}\right)^2 \cdot U^2_k$$

- **Calculate Partial Derivatives**

$$\frac{\partial G_{ain}}{\partial R_1} = \frac{\partial}{\partial R_1}\left[\left(1+\frac{R_1}{R_2}\right)\cdot k - \frac{R_1}{R_2}\right] = \frac{1}{R_2}\cdot k - \frac{1}{R_2} = \frac{1}{R_2}\cdot(k-1)$$

$$\frac{\partial G_{ain}}{\partial R_2} = \frac{\partial}{\partial R_2}\left[\left(1+\frac{R_1}{R_2}\right)\cdot k - \frac{R_1}{R_2}\right] = \frac{\partial}{\partial R_2}\left[\frac{R_1}{R_2}\cdot(k-1)+k\right] = -\frac{R_1}{R_2{}^2}\cdot(k-1)$$

$$\frac{\partial G_{ain}}{\partial k} = \frac{\partial}{\partial R_2}\left[\left(1+\frac{R_1}{R_2}\right)\cdot k - \frac{R_1}{R_2}\right] = \left(1+\frac{R_1}{R_2}\right)$$

PreLab Uncertainty Analysis (3)

Substitute Partial Derivatives

$$U^2{}_{Gain} = \left[\frac{1}{R_2}\cdot(k-1)\right]^2 U_{R_1}^2 + \left[\frac{R_1}{R_2{}^2}\cdot(k-1)\right]^2 U_{R_2}^2 + \left(1+\frac{R_1}{R_2}\right)^2 \cdot U_k^2$$

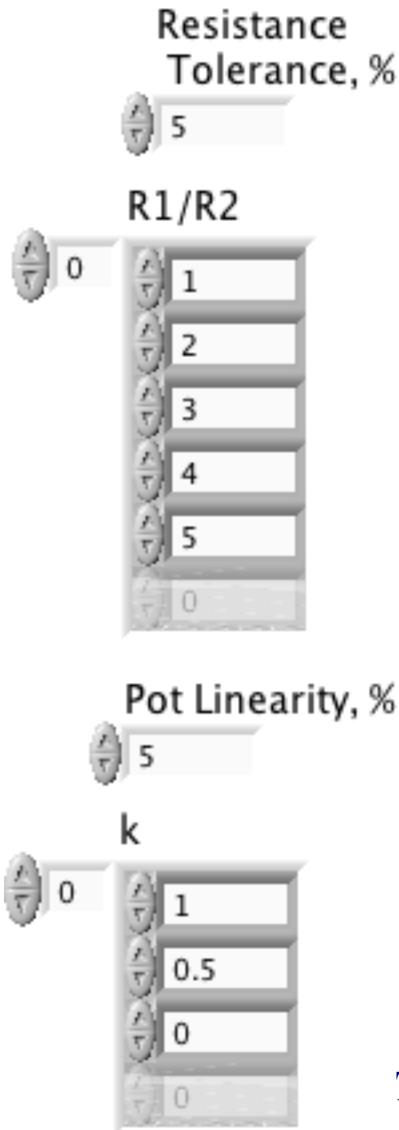
Normalize Independent Errors …

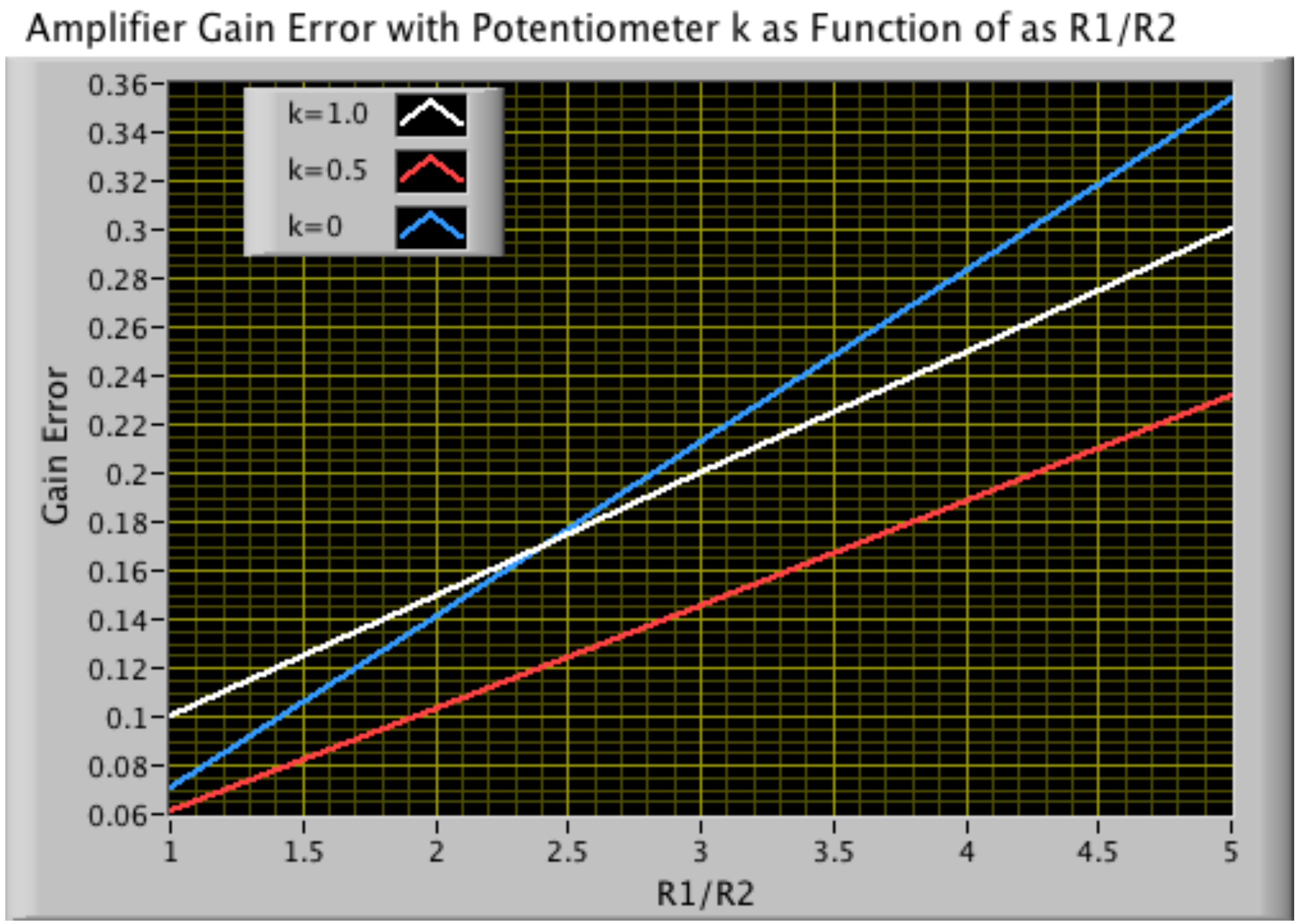
$$U^2{}_{Gain} = \left[\frac{R_1}{R_2}\cdot(k-1)\right]^2 \left(\frac{U_{R_1}}{R_1}\right)^2 + \left[\frac{R_1}{R_2}\cdot(k-1)\right]^2 \left(\frac{U_{R_2}}{R_2}\right)^2 + \left[k\left(1+\frac{R_1}{R_2}\right)\right]^2 \cdot \left(\frac{U_k}{k}\right)^2$$

$$\left\{\frac{U_{R_1}}{R_1},\frac{U_{R_1}}{R_1}\right\} \approx 5\%\ tolerance$$

$$\left(\frac{U_k}{k}\right) \approx 5\%\ linearity$$

PreLab Uncertainty Analysis (4)





Resistor Table

Resistor No.	Nom. Value kΩ	Tolerance, %	Measured Value, *k*Ω	% Deviation
1	1000 kΩ			
2	1000 kΩ			
3				
4				
5				
6				
7				
8				
9				
10				

Lab Procedure

1 Measure Resistance of Potentiometer *with {k=1, k=0}*.
   a. Log Data.
2 Read Nominal Values/Tolerances for Test Resistors.
   b) Log Data in Resistor Table.
3 Build and Test Circuit
   c) Start with $R_1 = R_2 \sim 1000\ \Omega$.
   d) Power Up Circuit
   e) Populate Voltage Tables for all R_1 Resistors, Keep $R_2 \sim 1000\ \Omega$.
   f) Measure Voltages across nodes *{a,c}* and *{b,c}* Using MyDAQ Voltage Probes. See Figure on Slide 17.
   g) Be sure to power down circuit when swapping out R_1
4 Repeat Part 3 for Potentiometer *k={0, ½, 1}*
5 Complete Error Analysis

Voltage Table I

R_1	**Measured Value, *kΩ*, *R_1***	V_{in}	$V_{\{b,c\}}$ "V_{out}"	V_{out}/V_{in}, *Gain*	$V_{\{a,c\}}$	*k*
1	1000 kΩ					0
2						0
3						0
4						0
5						0
6						0
7						0
8						0
9						0

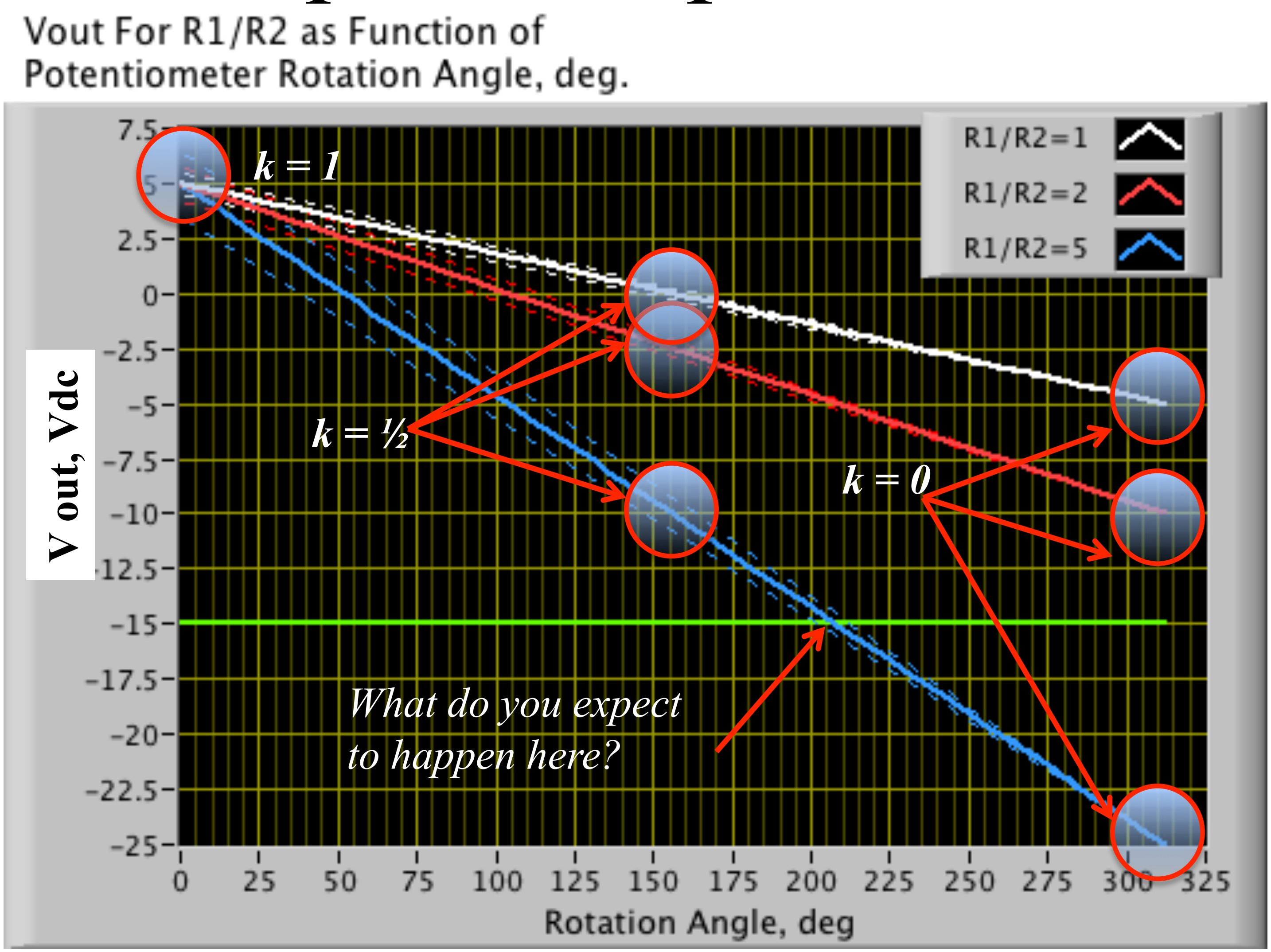
Voltage Table II

R_1	Measured Value, $k\Omega$, R_1	V_{in}	$V_{\{b,c\}}$ "V_{out}"	V_{out}/V_{in}, Gain	$V_{\{a,c\}}$	k
1	1000 kΩ					½
2						½
3						½
4						½
5						½
6						½
7						½
8						½
9						½

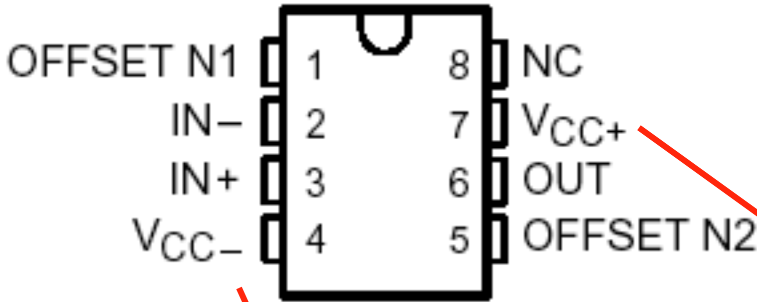
Voltage Table III

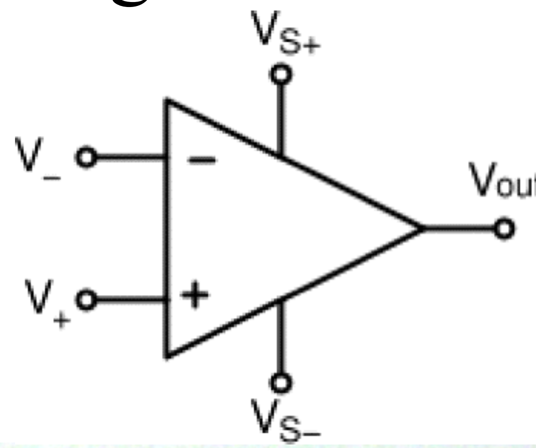
R_1	Measured Value, $k\Omega$, R_1	V_{in}	$V_{\{b,c\}}$ "V_{out}"	V_{out}/V_{in}, Gain	$V_{\{a,c\}}$	k
1	1000 kΩ					1
2						1
3						1
4						1
5						1
6						1
7						1
8						1
9						1

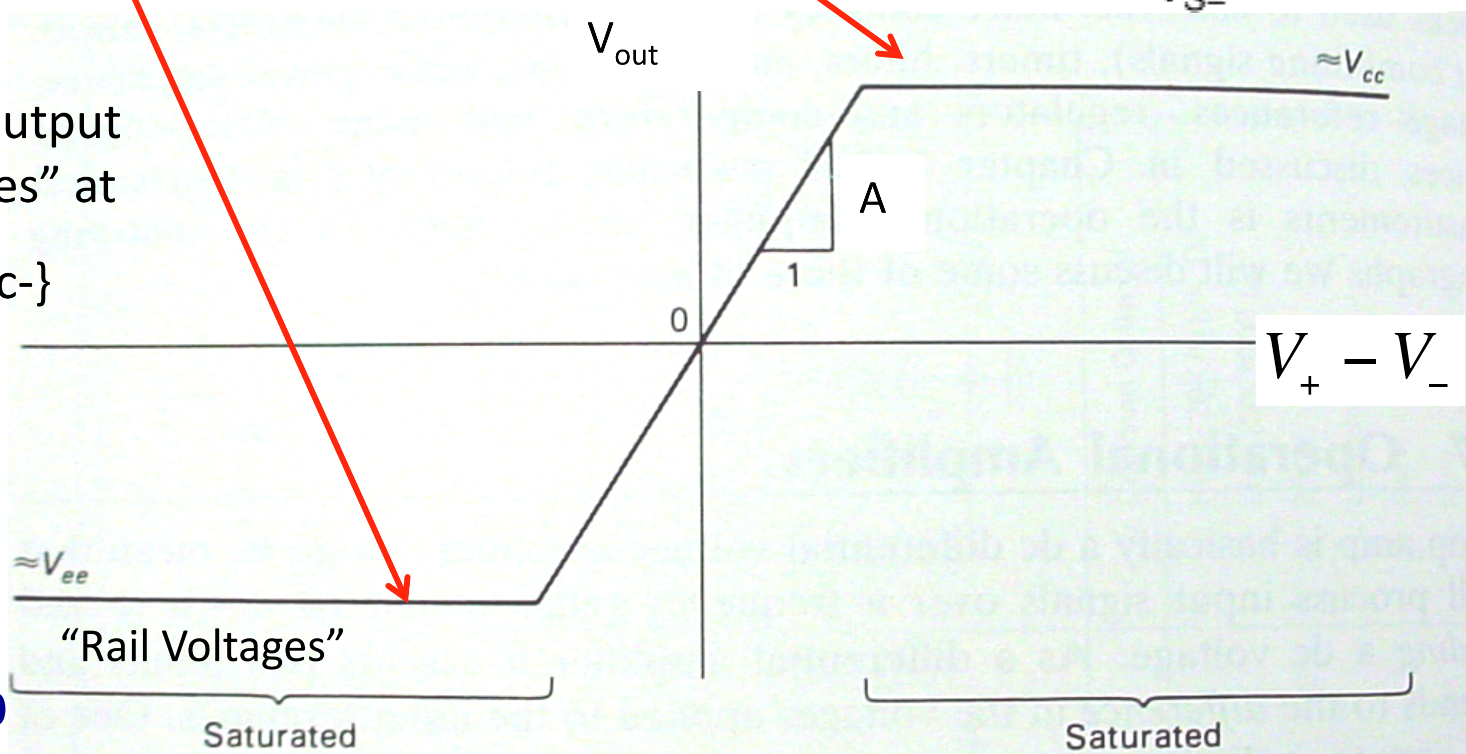
Example of Expected Results



OpAmp Saturation Voltage





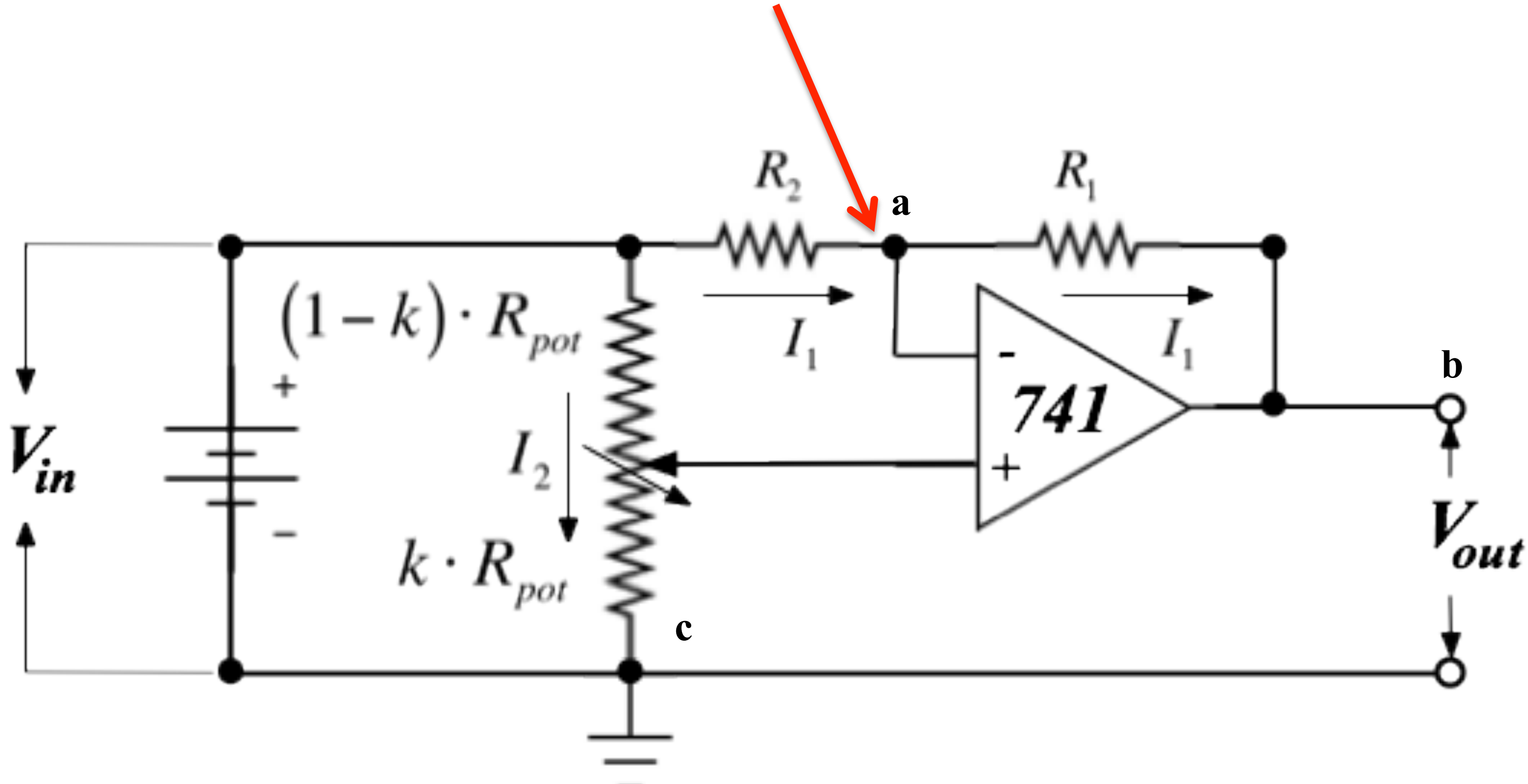


- Chip Output "saturates" at

{Vcc+,Vcc-}

Virtual Ground

Verify that Node *"a"* becomes Virtual ground as $k \rightarrow 0$



Error Analysis:

- **For each Potentiometer setting → *k={1, ½, 0} Calculate your mean Gain Value {V_{out}/V_{in}} and the Corresponding Standard Deviation***

- ***Assess the 95% confidence interval for this mean value***

- ***Based on the Normal (Gaussian) Distribution***

- ***Based on the Student-T Distribution with the appropriate degrees of freedom***