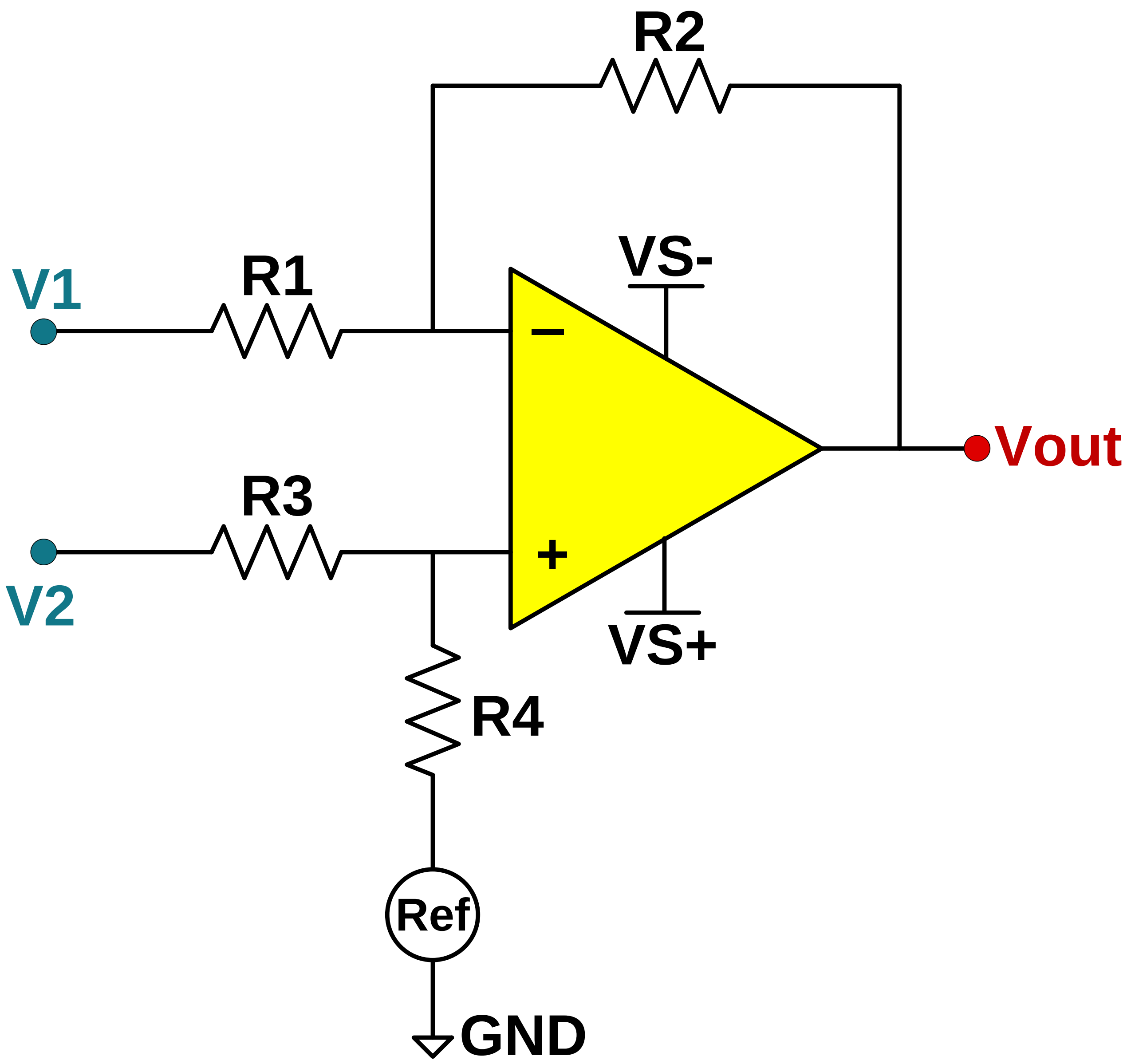
Instrumentation amplifier (IA) topologies: three-amp

TI Precision Labs – Instrumentation Amplifiers

Presented by Tamara Alani

Prepared by Tamara Alani

IA topologies – One amp recap



Difference amplifier output equation:

$$Vout = Vd \times Ad + Ref$$

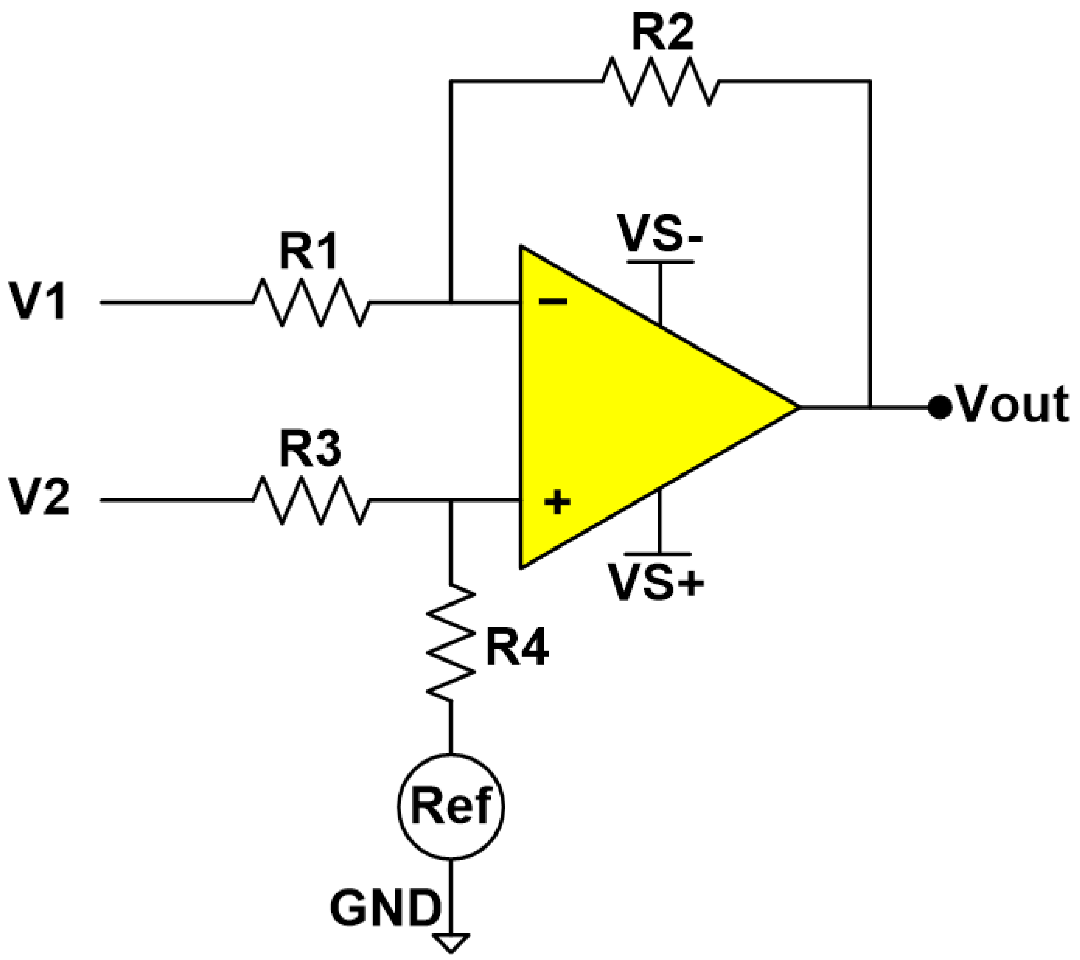
Where Ad is the gain of the circuit

If $R1 = R3$, and $R2 = R4$, then Ad $= \frac{R2}{R1}$

Challenges:

1. Precision relies on matched resistors
2. Low input impedance

Difference amplifier recap – Input impedance

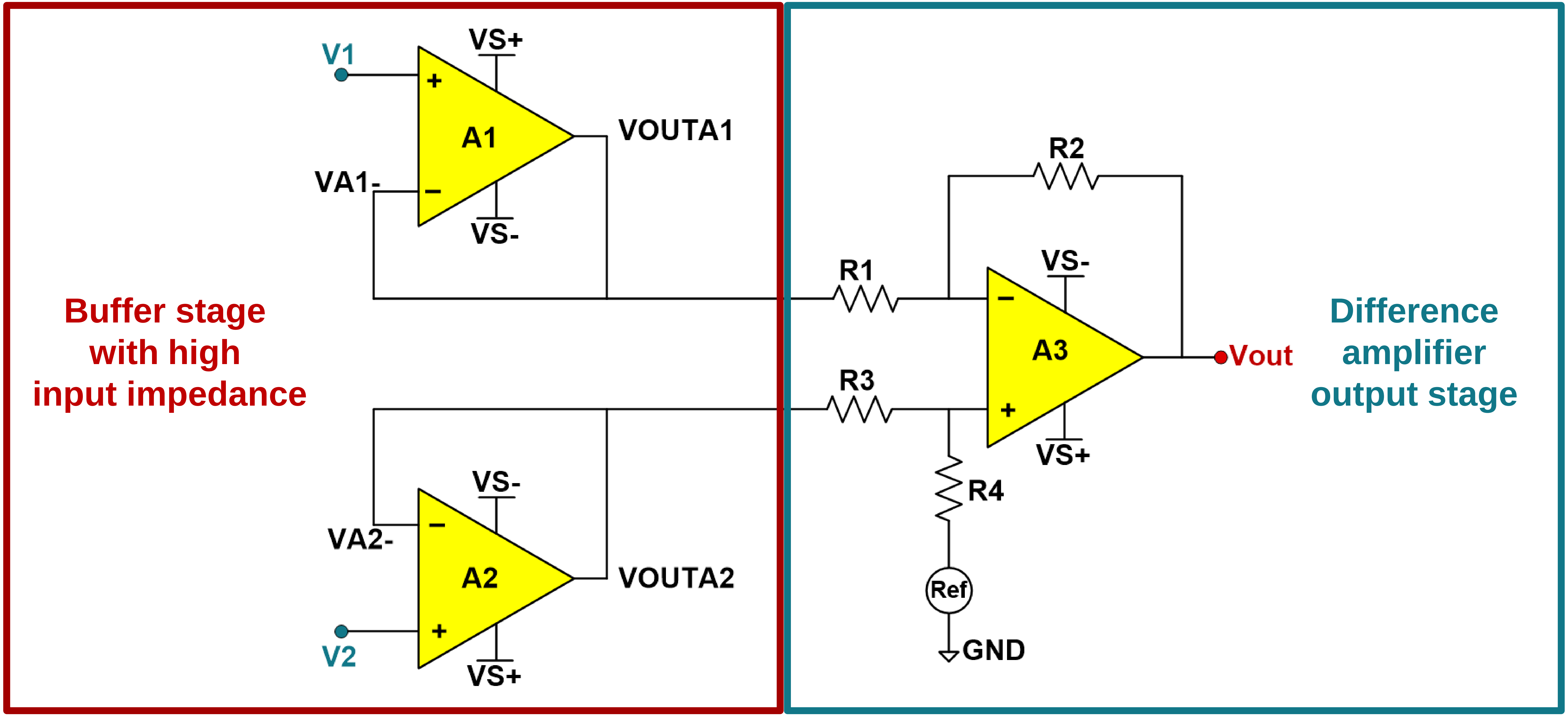


Design challenges:

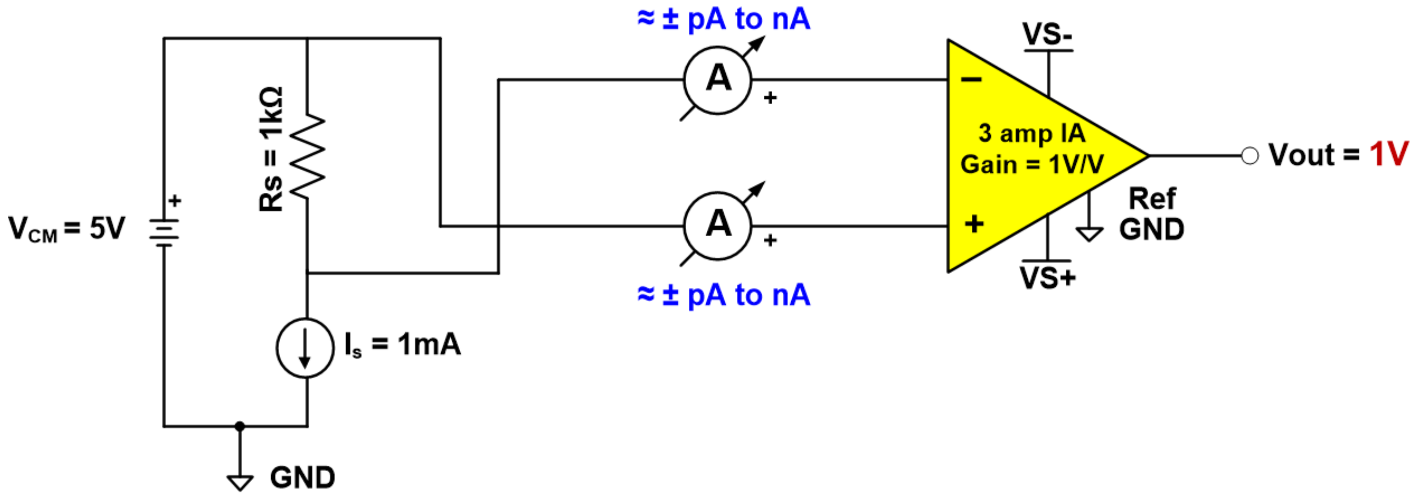
- ► **Low input impedance**
- ► Precisely matched resistances

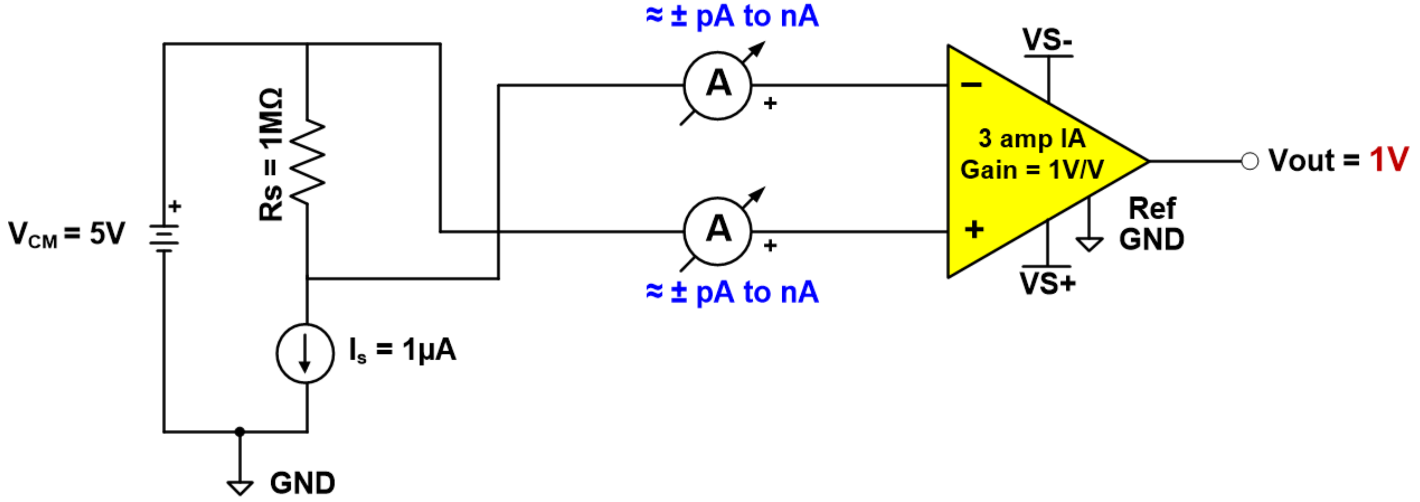
- ►This circuit will draw current from the signal source, and if the source's output impedance is not zero, it will degrade accuracy.

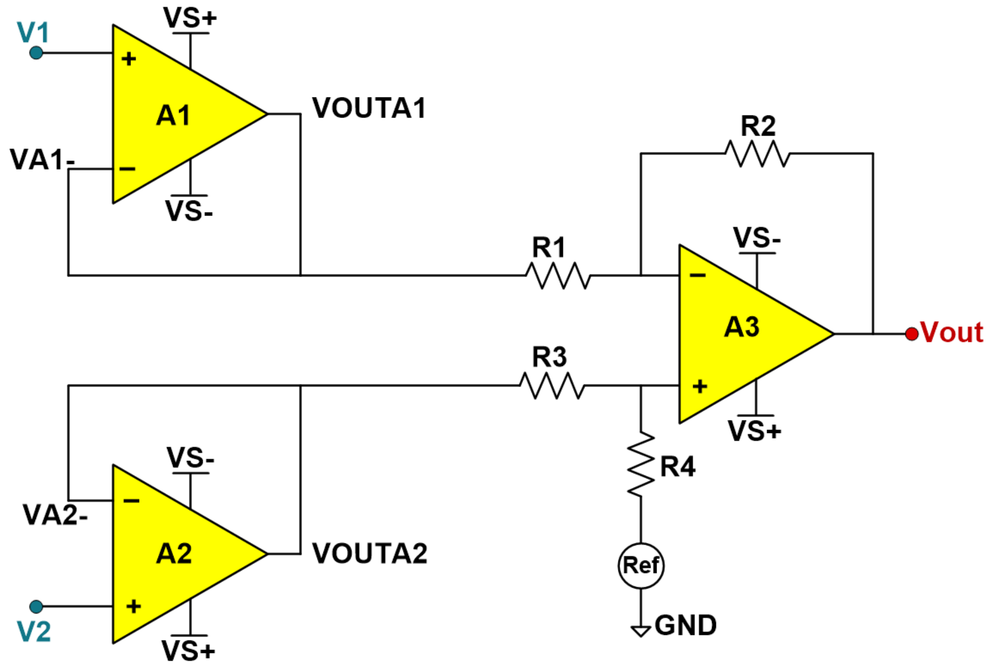
IA topologies – Three amp configuration



3 amp IA input impedance – Current sensing

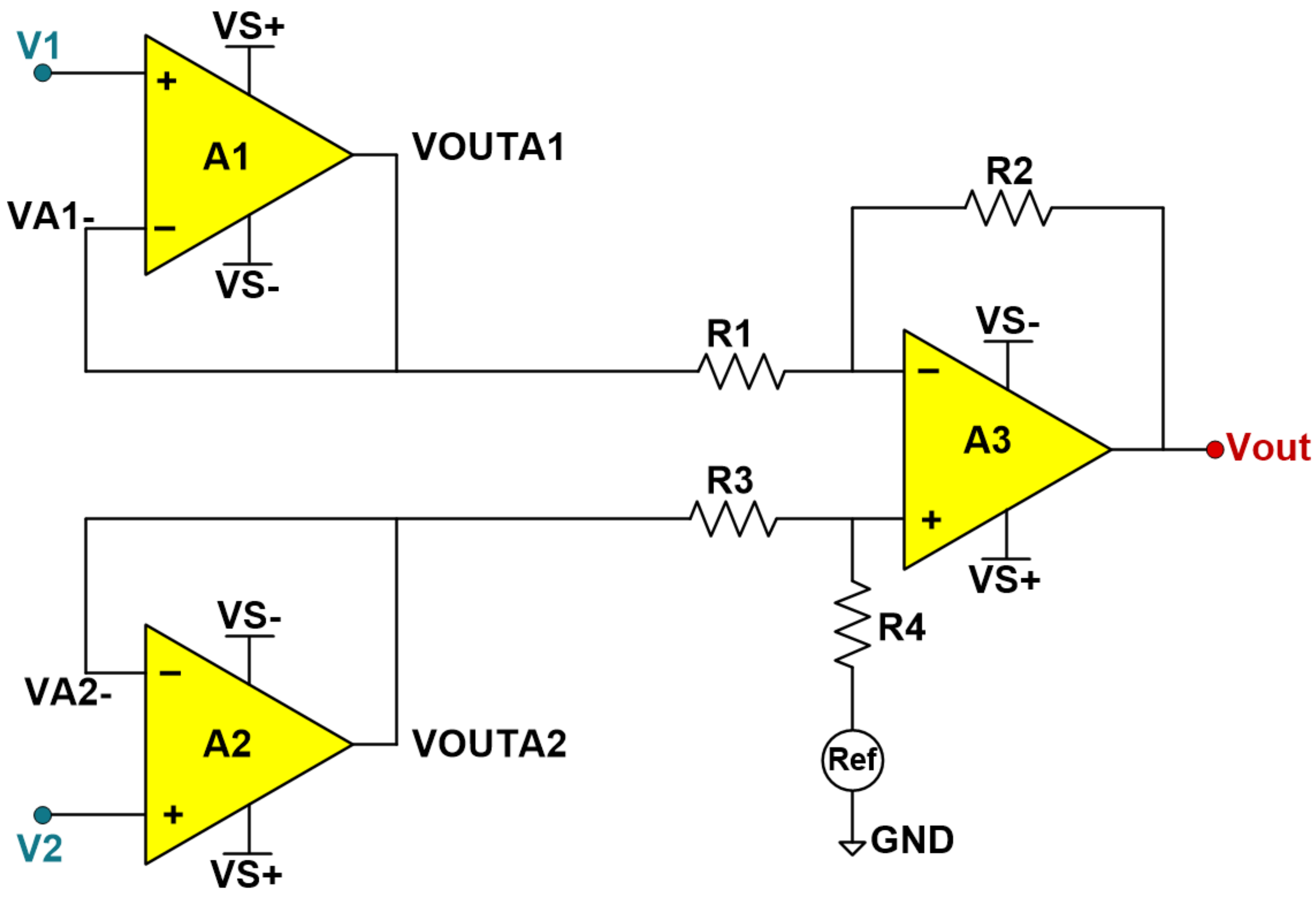






- Input impedance from 10^9 to 10^{12} Ω are typical, due to A1 and A2
- This high input impedance limits the current flowing through the inputs to levels ranging from pA to nA.
- Current draw is still dependent on technology, temperature, common mode voltage, and more.

3 amp IA – Gain control



Signal gain, $Ad = \frac{R2}{R1}$

This is assuming:

R1 = R3 and R2 = R4

If gain needs to be adjusted, 4 resistors need to be changed and matched for optimal precision.

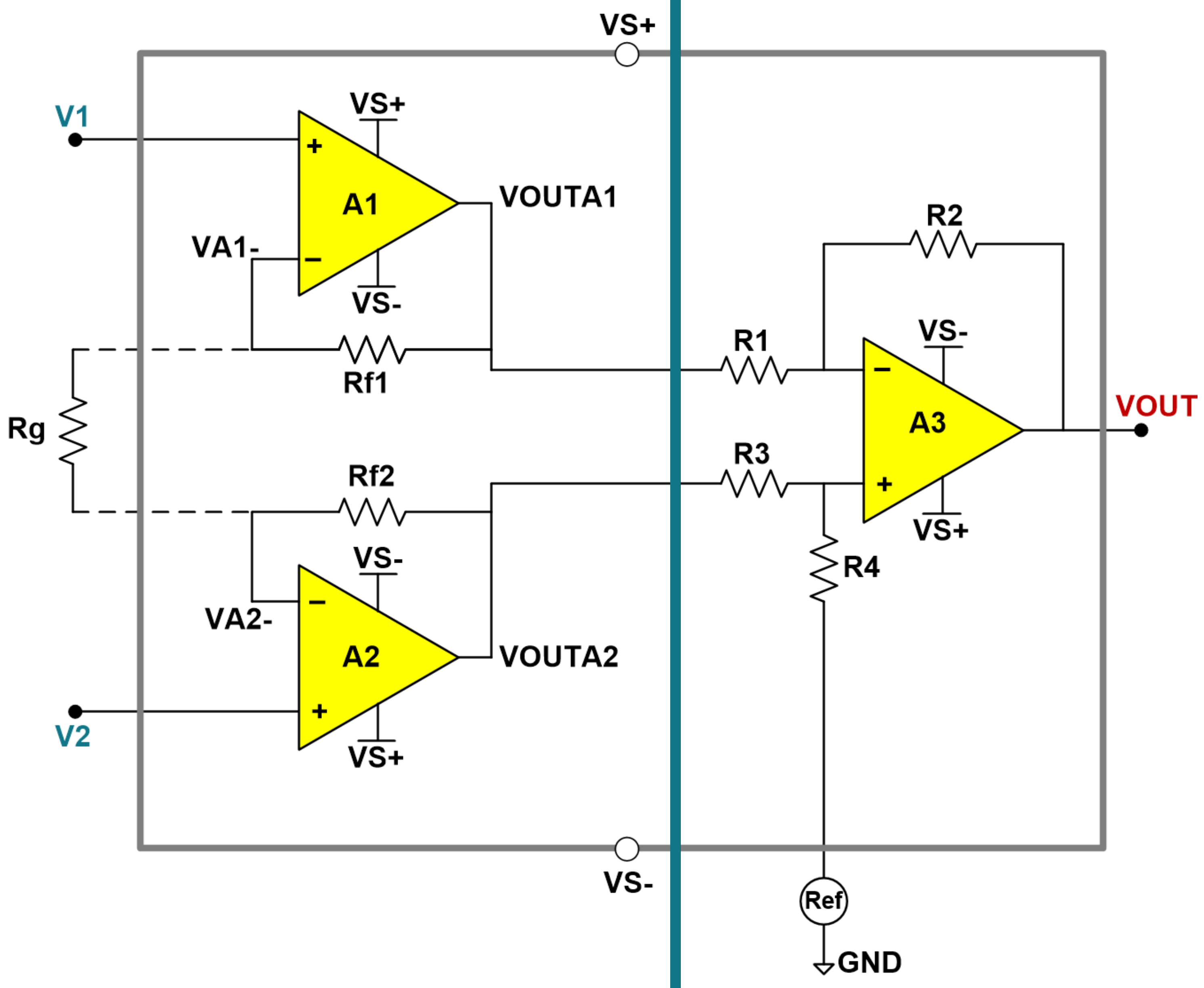
Want: Easy gain control

Solution: Pull into first stage

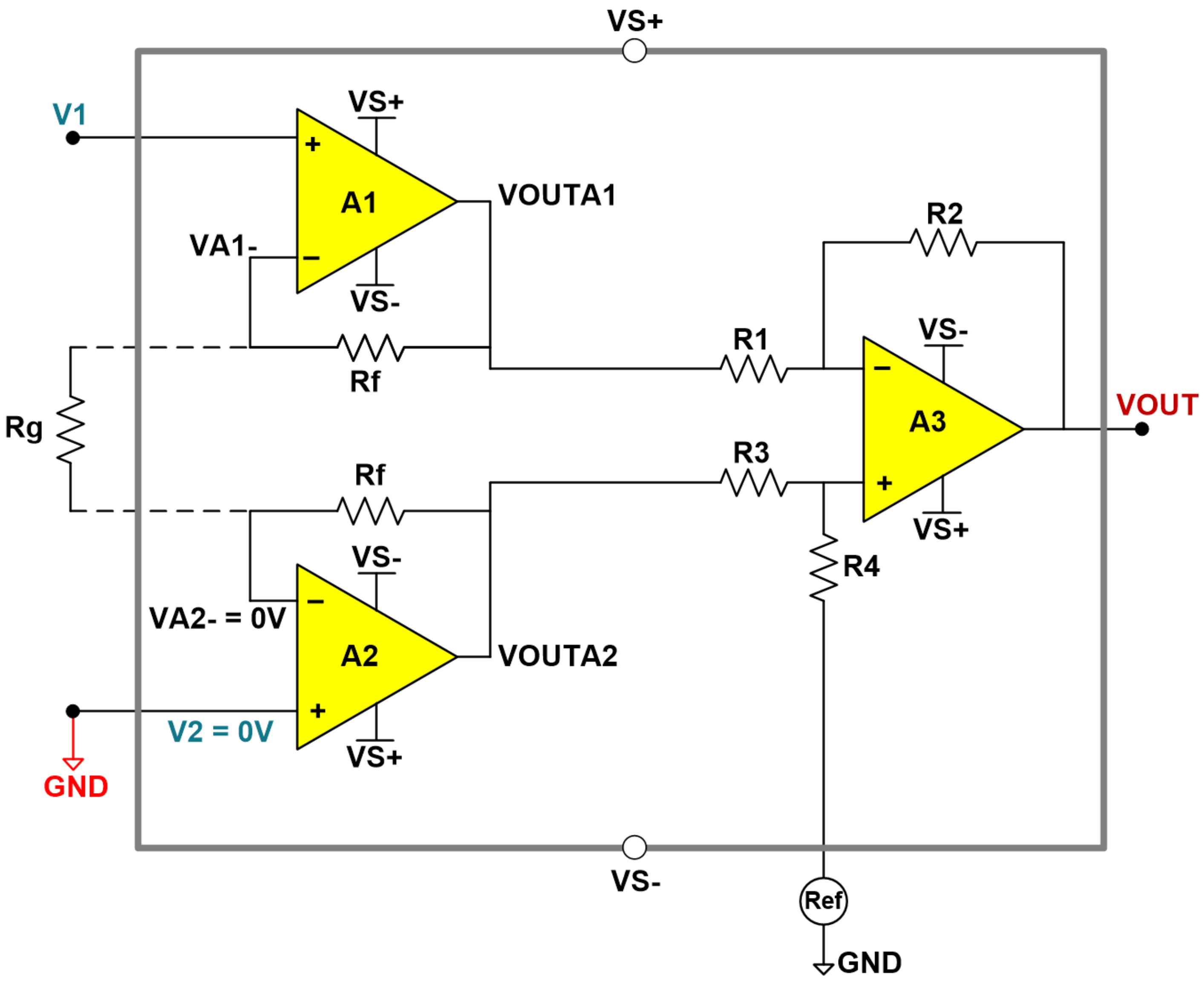
3 amp IA – Two stage breakdown

Buffer stage with gain and high input impedance

Difference amplifier output stage



3 amp IA derivation – First stage



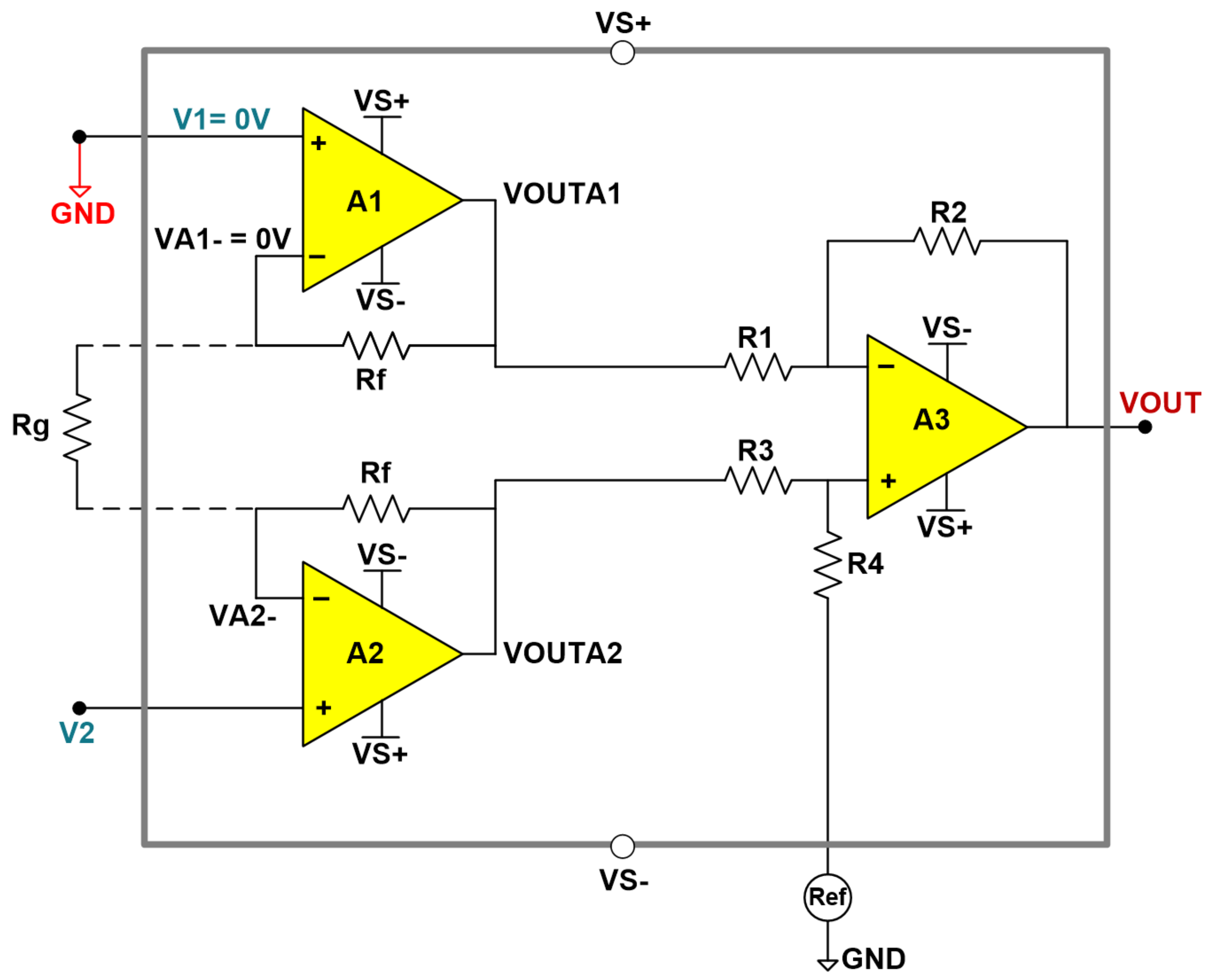
- VOUTA1 consists of two components: voltage due to V1 and V2
- If V2 = 0V, then VA2- = 0V
- A1 looks like a non-inverting amplifier:

$$Ad = 1 + \frac{Rf}{Rg}, \text{ and}$$

$$\boldsymbol{VoutA1 = V1 \times \left(1 + \frac{Rf}{Rg}\right)}$$

Equation 1

3 amp IA derivation – Frist stage cont'd



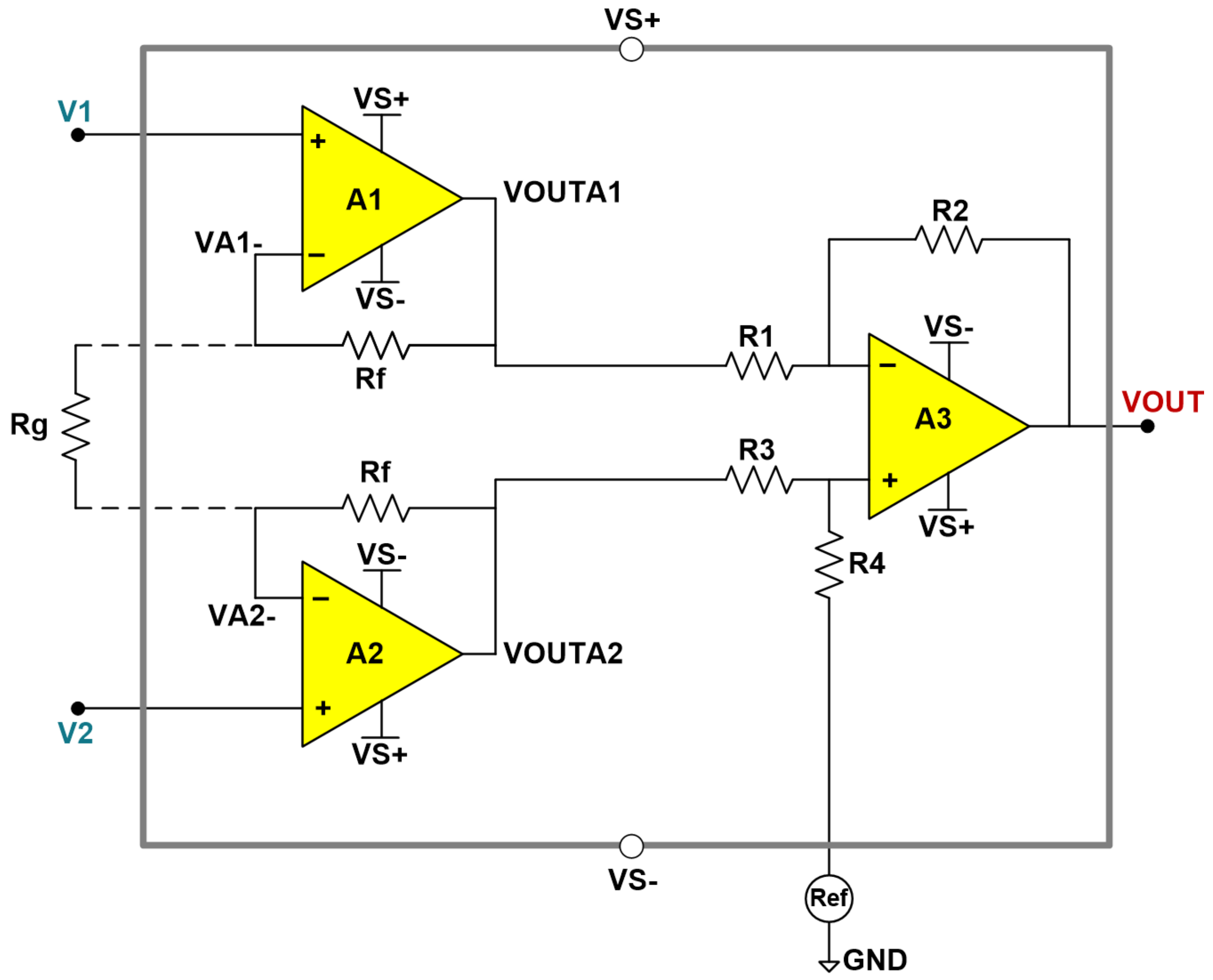
- If V1 = 0V, then VA1- = 0V
- A1 looks like an inverting amplifier:

$$Ad = -\frac{Rf}{Rg}, \text{ and}$$

$$\boldsymbol{VOUTA1 = \mathrm{V2} \times \left(\frac{-Rf}{Rg}\right)}$$

Equation 2

3 amp IA derivation – Combined



Equation 1: $\boldsymbol{VOUTA1} = \boldsymbol{V1} \times \left(\mathbf{1} + \frac{\boldsymbol{Rf}}{\boldsymbol{Rg}}\right)$

Equation 2: $\boldsymbol{VOUTA1} = \mathbf{V2} \times \left(\frac{\boldsymbol{-Rf}}{\boldsymbol{Rg}}\right)$

Combing Equations 1 and 2:

$$VOUTA1 = \left(1 + \frac{Rf}{Rg}\right) \times \mathrm{V1} - \left(\frac{Rf}{Rg}\right) \times \mathrm{V2}$$

$$= \left(\frac{\boldsymbol{Rf}}{\boldsymbol{Rg}}\right) \times \mathbf{(V1 - V2) + V1}$$

...Do the same to A2

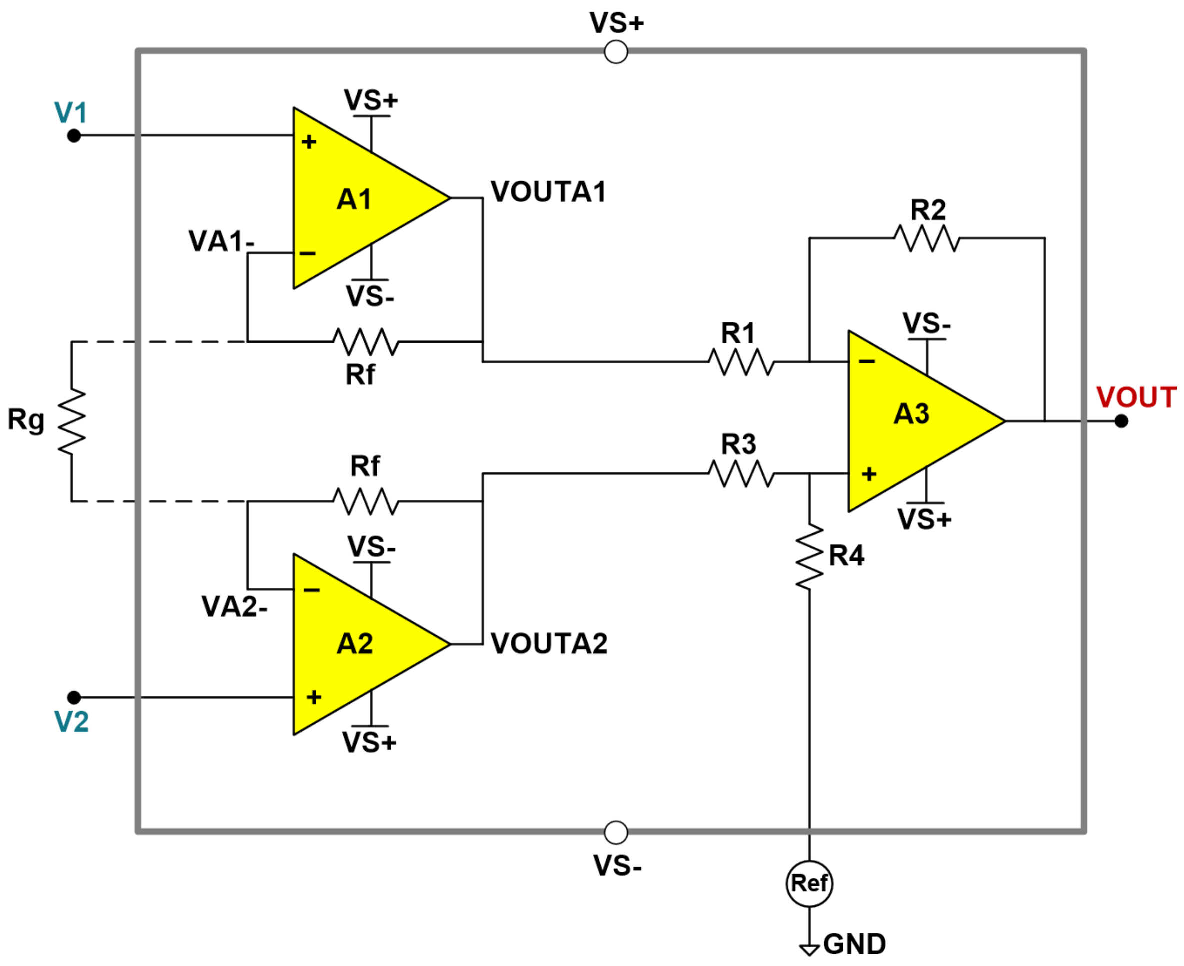
$$\boldsymbol{VOUTA2} = \left(\frac{\boldsymbol{Rf}}{\boldsymbol{Rg}}\right) \times \mathbf{(V2 - V1) + V2}$$

VOUTA1 and VOUTA2 feed into A3 (difference amplifier)

Assume R1=R3 and R2=R4, then

$$\boldsymbol{VOUTA3} = \left(\frac{\boldsymbol{R2}}{\boldsymbol{R1}}\right) \times \mathbf{(VOUTA2 - VOUTA1) + Ref}$$

3 amp IA derivation – Combined



$$VOUTA1 = \frac{Rf}{Rg} \times (V1 - V2) + V1$$

$$VOUTA2 = \frac{Rf}{Rg} \times (V2 - V1) + V2$$

$$VOUTA3 = \frac{R2}{R1} \times (VOUTA2 - VOUTA1) + Ref$$

Substitute the equations for VOUTA1 and VOUTA2 into VOUTA3:

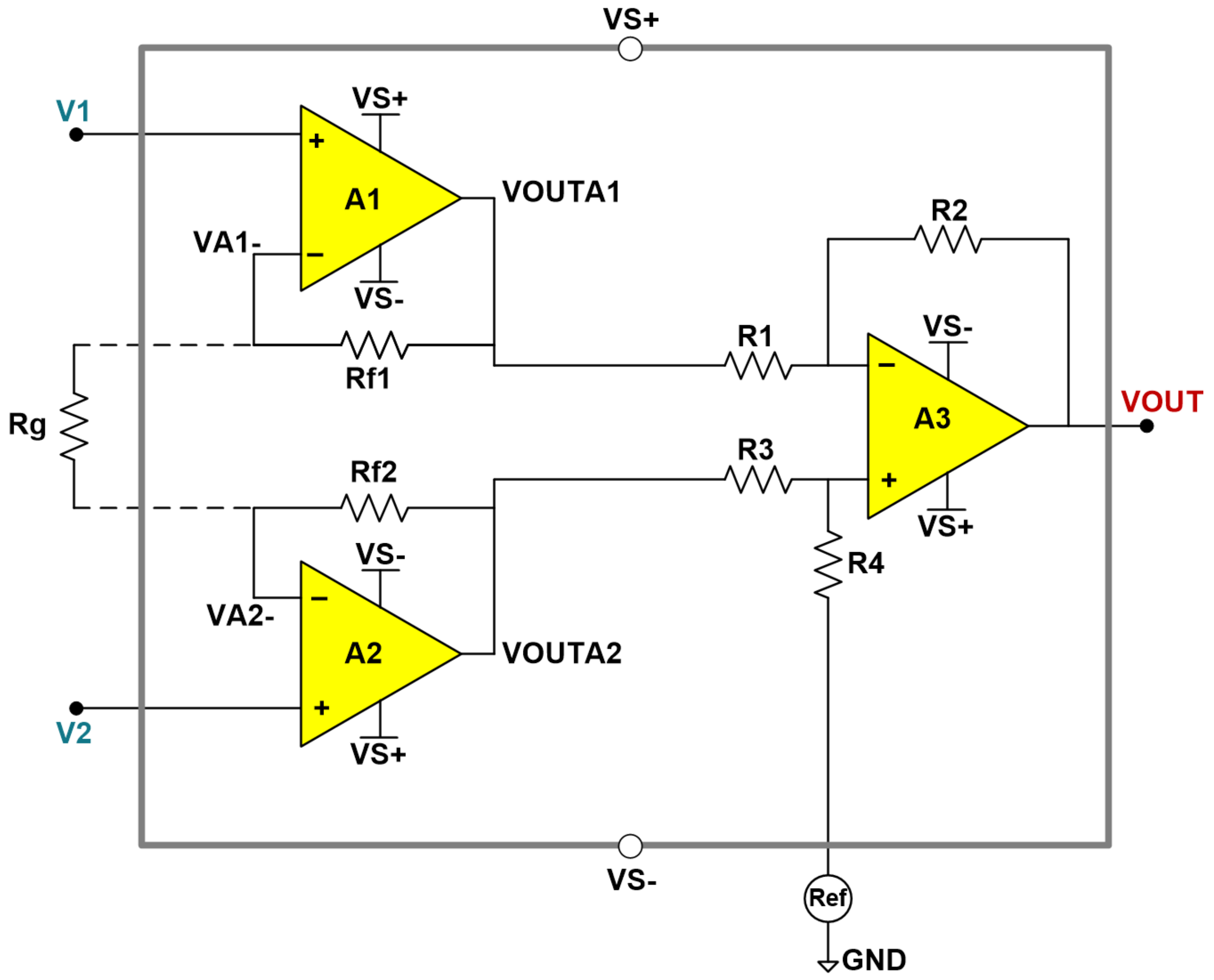
$$VOUT = \frac{R2}{R2} \times \left(\left(\frac{Rf}{Rg} \times (V1 - V2) + V1 \right) - \left(\frac{Rf}{Rg} \times (V2 - V1) + V2 \right) \right) + Ref$$

Simplifying…

$$VOUT = (V2 - V1) \times \frac{R2}{R1} \times \left(1 + \frac{2Rf}{Rg}\right) + Ref$$

Where the differential gain, Ad is $\frac{R2}{R1} \times \left(1 + \frac{2Rf}{Rg}\right)$

3 amp IA – Circuit goal



Circuit component goal:

Match R1 to R2, R3 and R4 to form a unity gain difference amplifier

Match Rf1 and Rf2; feedback resistors which interact with Rg to alter the gain of the input signal (Vd)

Transfer function recap:

$$Ad = \frac{R2}{R1} \times \left(1 + \frac{2Rf}{Rg}\right)$$

$$Vout = Ad \times Vd + Ref, \text{ where } Vd = V2 - V1$$

Amplifier roles:

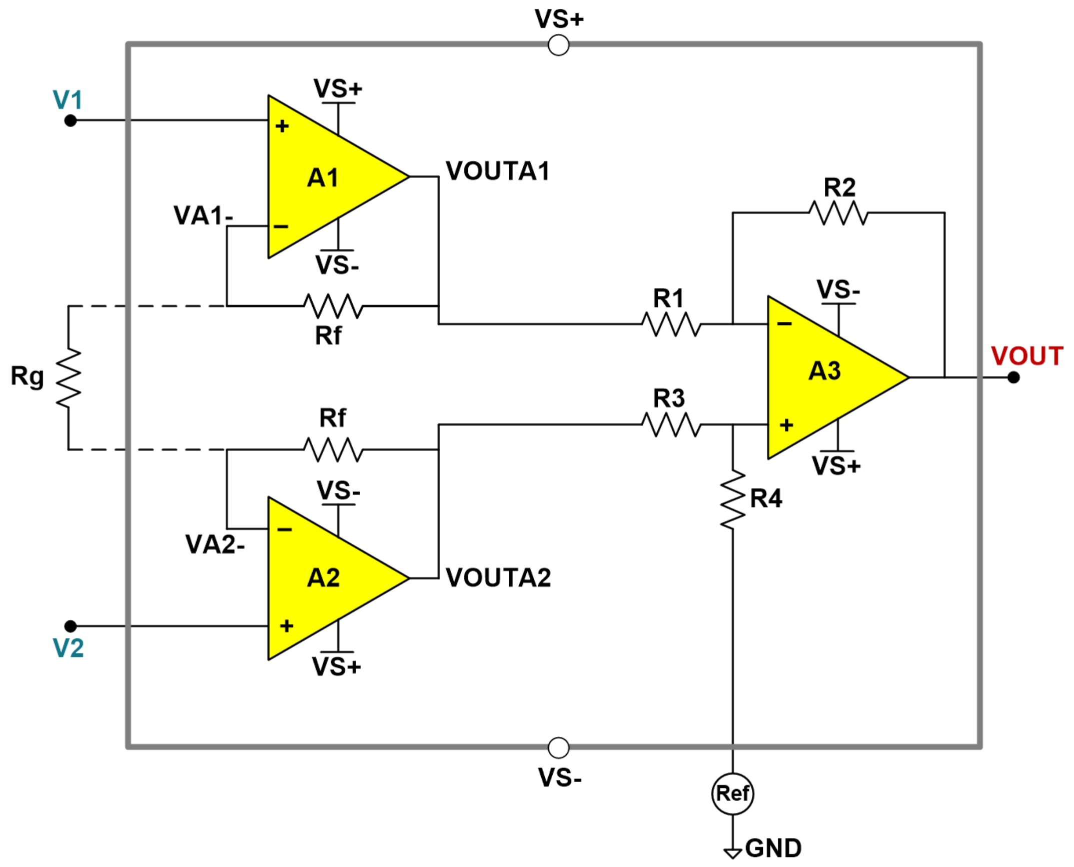
A1 & A2 operate with differential gain to amplify the signal

A3 unity gain difference amplifier

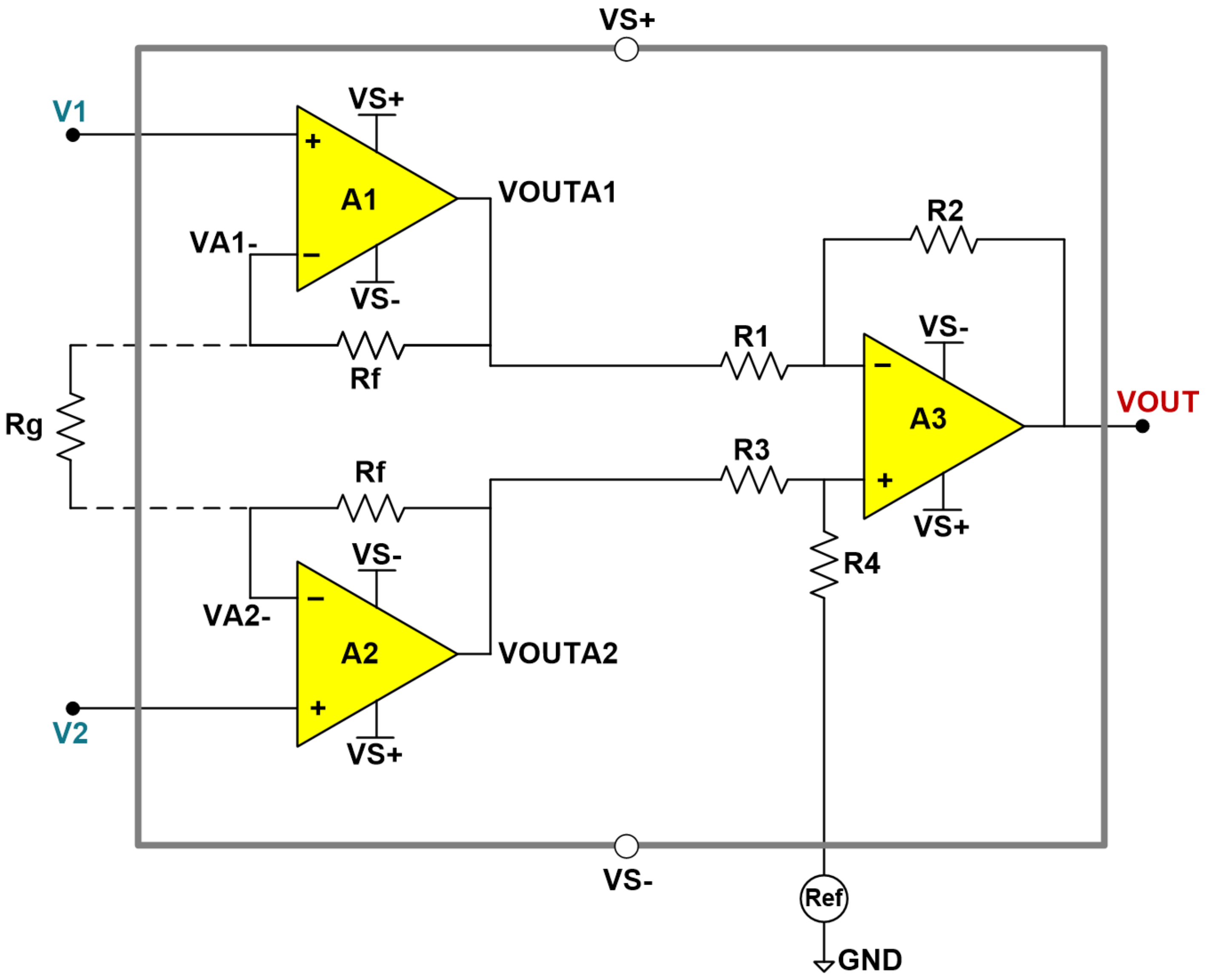
Instrumentation amplifier – Idealized model

Two main characteristics of an instrumentation amplifier:

1. Amplifies the signals that differ between the two inputs
2. Rejects the signals that are the same (common) to both inputs



Idealized model – Common mode voltage analysis



Apply a common mode voltage:

When a common-mode voltage is applied to inputs of A1 and A2, either side of Rg will be equal.

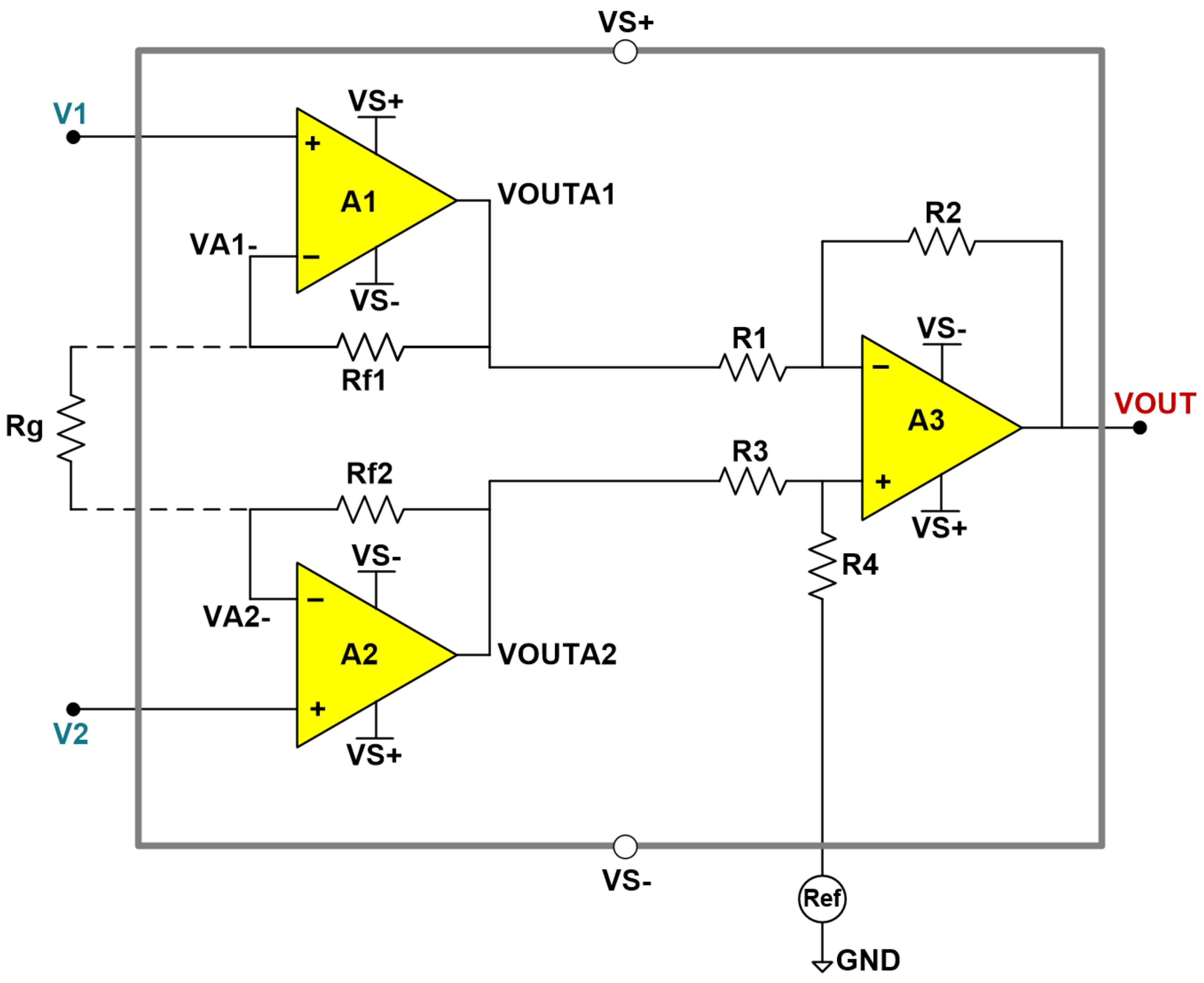
$$\boldsymbol{IRg = IRf1 = IRf2 = 0A}$$

Common mode signals will be passed through input buffers A1 and A2 at unity gain, but differential voltages will be amplified by:

$$1 + \frac{2Rf}{Rg}$$

The second stage difference amplifier rejects this common mode voltage and passes only the differential voltage.

CMRR – How gain effects CMRR



$$CMRR\left(\frac{V}{V}\right) = \frac{differential\ gain}{common\ mode\ gain} = \frac{A_d}{A_{CM}}$$

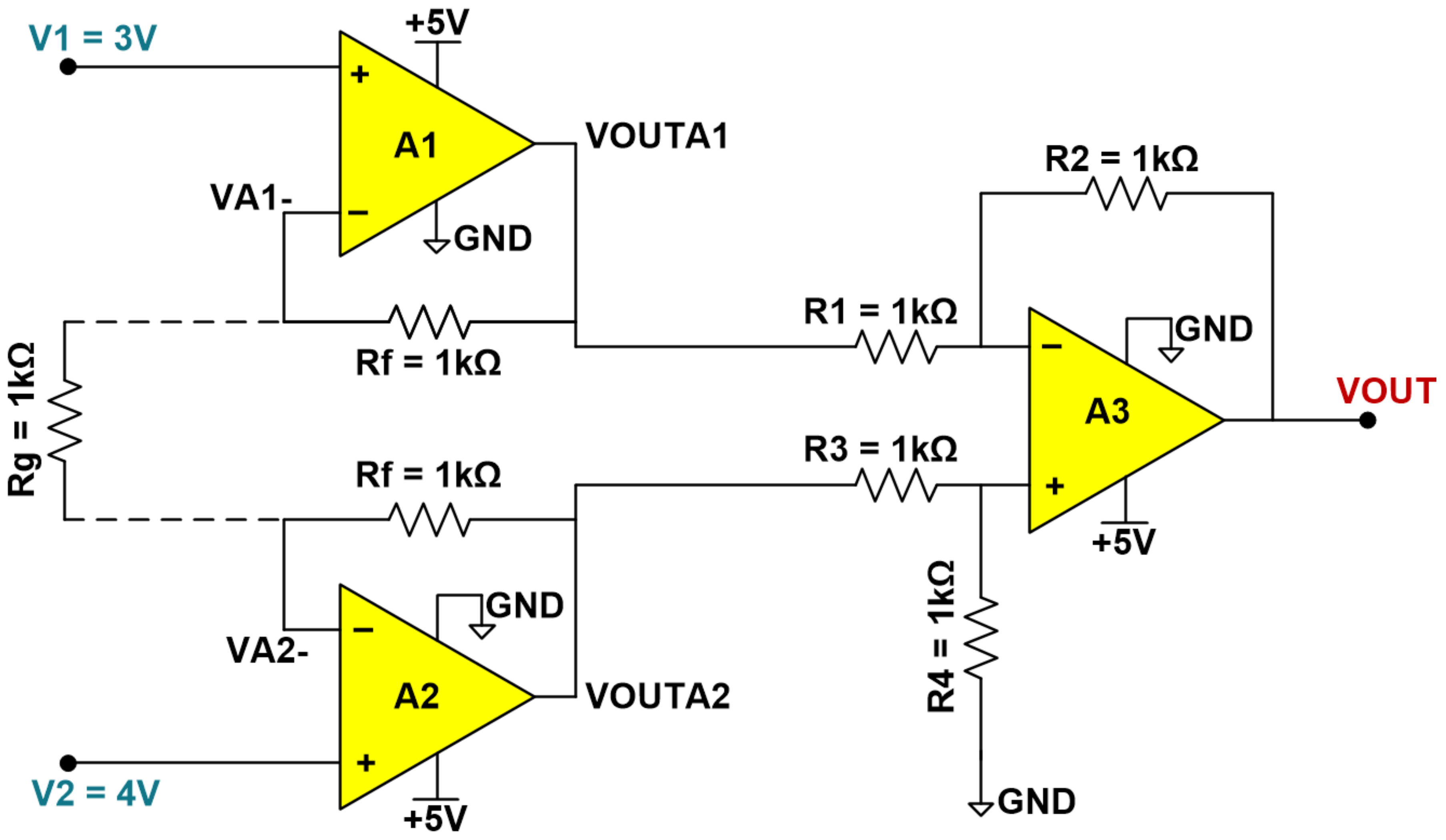
When gain is increased by Rg:

– the differential signal will be increased

– but the common-mode error will not

$\frac{A_d}{A_{CM}}$ will increase so CMRR will theoretically increase in direct proportion to gain

3 amp IA – Linear behavior analysis



3 amp IA with RRIO amps
Vs = 5V single supply
V2 = 4V, V1 = 3V

$$Vd = V2 - V1 = 1V$$

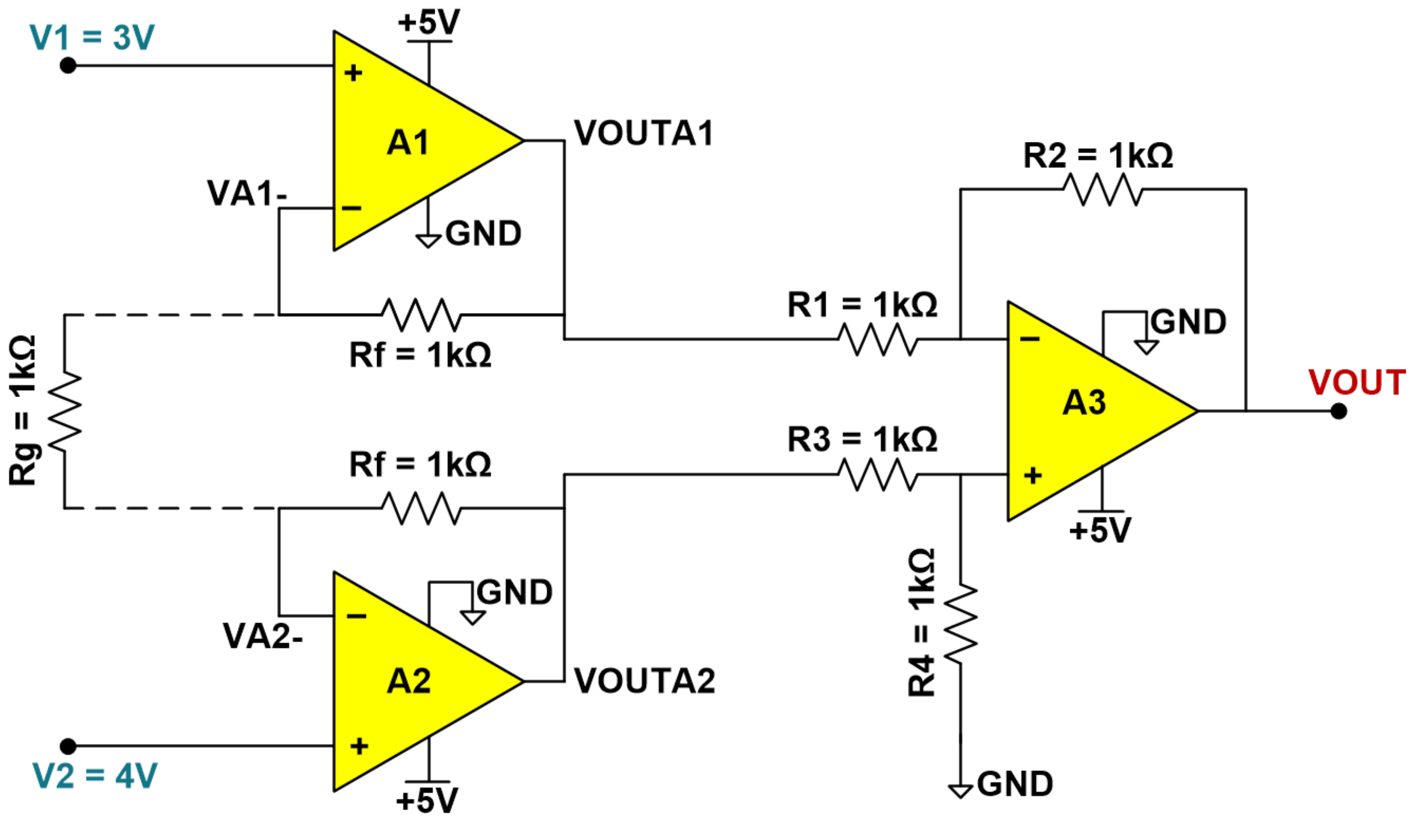
$$Ad = \frac{R2}{R1} \times \left(1 + \frac{2Rf}{Rg}\right) = \frac{3V}{V}$$

$$Ref = 0V$$

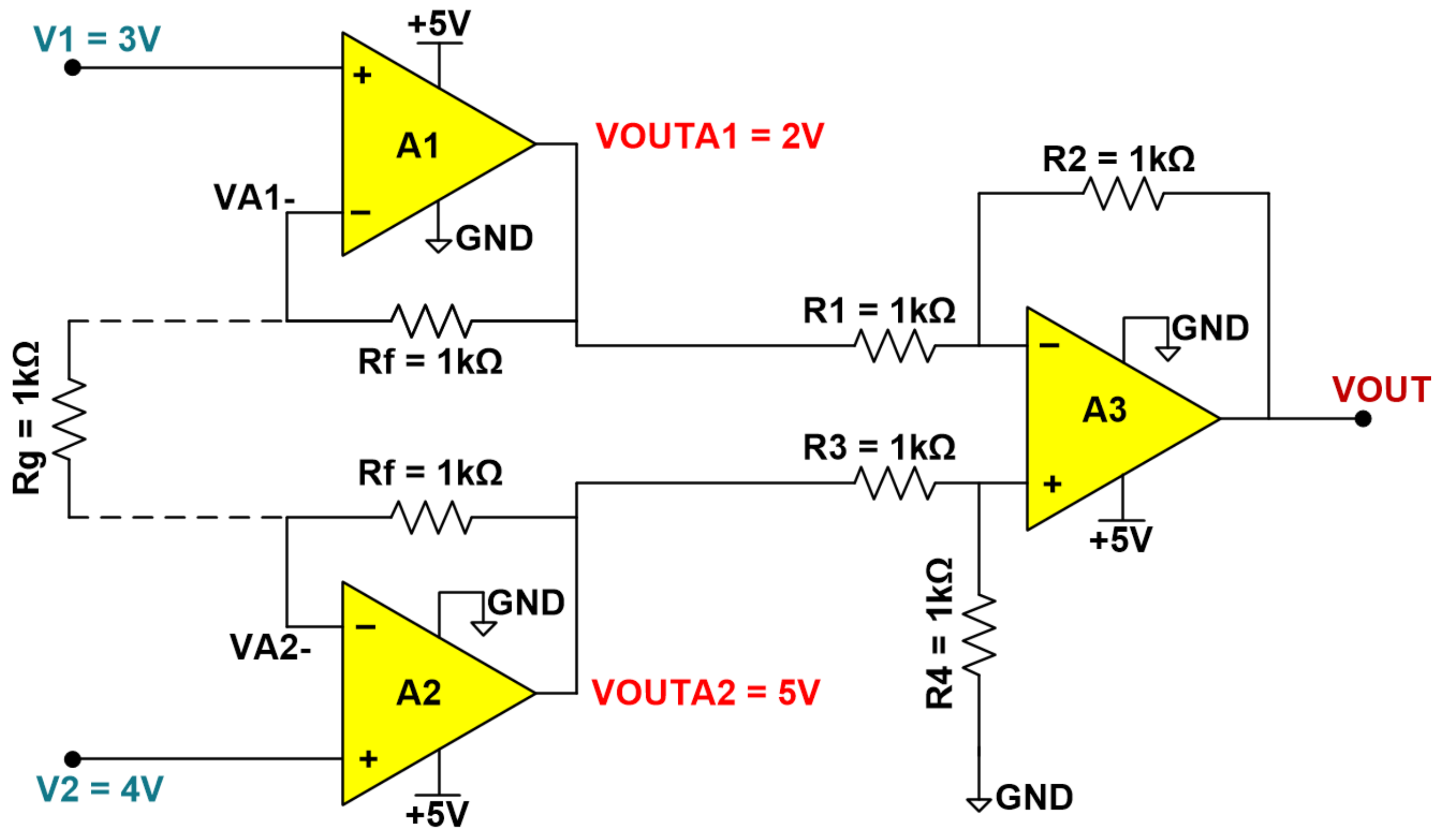
$$\mathrm{Vout} = \mathrm{Vd} \times \mathrm{Ad} + \mathrm{Ref} = 3\mathrm{V}$$

Input and output – RRIO

- **Rail-to-Rail input and output amplifiers**
  - Rail-to-Rail input (RRI) amplifiers have input ranges which extend *to* and sometimes *beyond* the rail
  - Rail-to-Rail output (RRO) amplifiers have output swings *near* the rails



3 amp IA – Linear behavior analysis



$$VOUTA1 = \frac{Rf}{Rg} \times (V1 - V2) + V1$$

$$VOUTA2 = \frac{Rf}{Rg} \times (V2 - V1) + V2$$

$$VOUTA3 = \frac{R2}{R1} \times (VOUTA2 - VOUTA1) + Ref$$

RRI: to and beyond the rail: 0V ≤ Vin ≤ 5V
RRO: *near* the rail: 0.1V ≤ Vout ≤ 4.9V

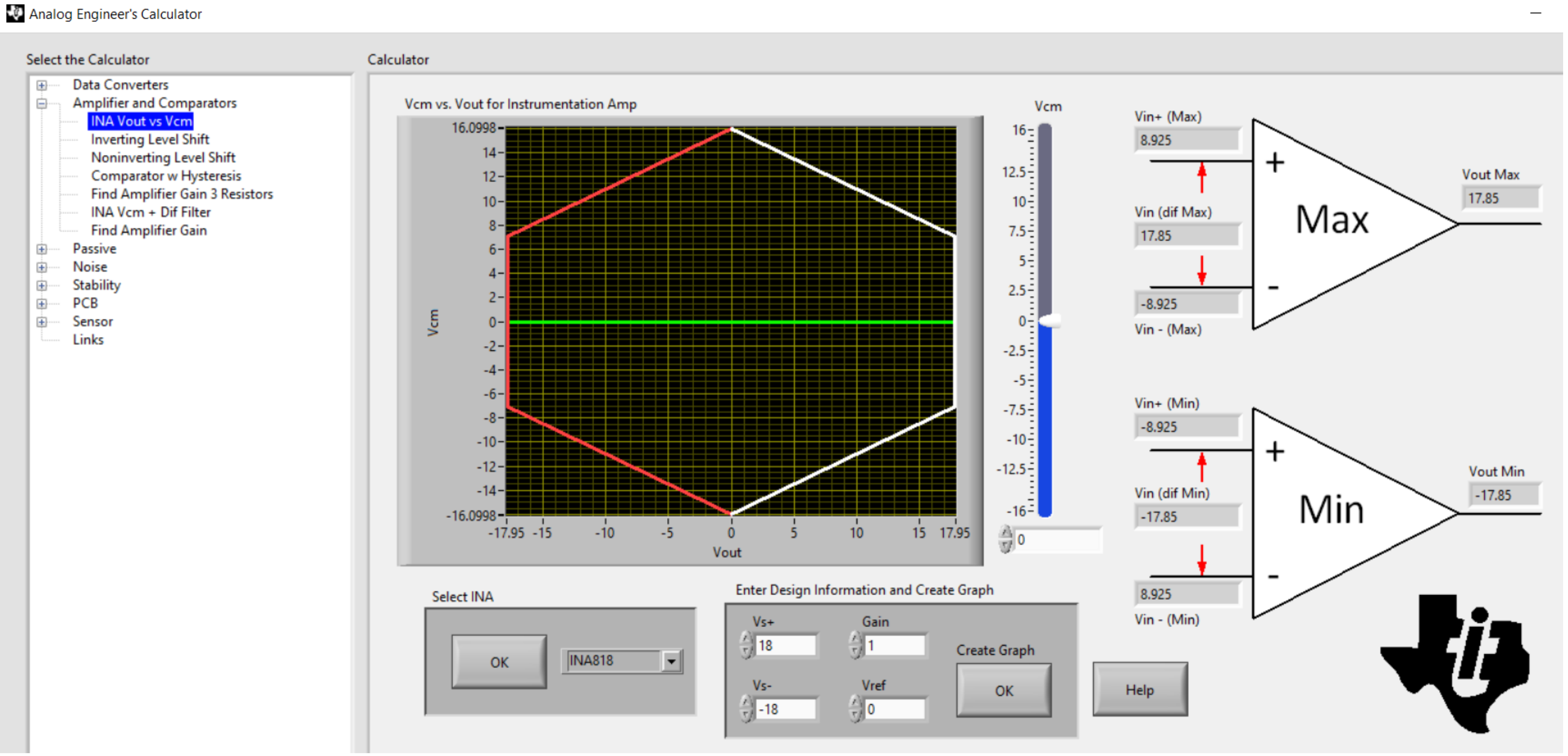
Let us analyze each amplifier individually:

A1:
- **Input = 3V, this is within** 0V ≤ Vin ≤ 5V
- **Output = 2V, this is within** 0.1V ≤ Vout ≤ 4.9V

A2:
- **Input = 4V, this is within** 0V ≤ Vin ≤ 5V
- **Output = 5V, this is NOT within** 0.1V ≤ Vout ≤ 4.9V

3 amp IA – Boundary plot

Boundary plots graphically show a designer the usable range of an IA by analyzing the internal nodes.



Analog engineer's calculator → INA VCM vs Vout

3 amp IA with gain – Example

Assume the following conditions:

- Power supply = ±5V
- Reference voltage = 0V
- Vd = 10mV, VCM = 1V
- Expected Vout is 3V

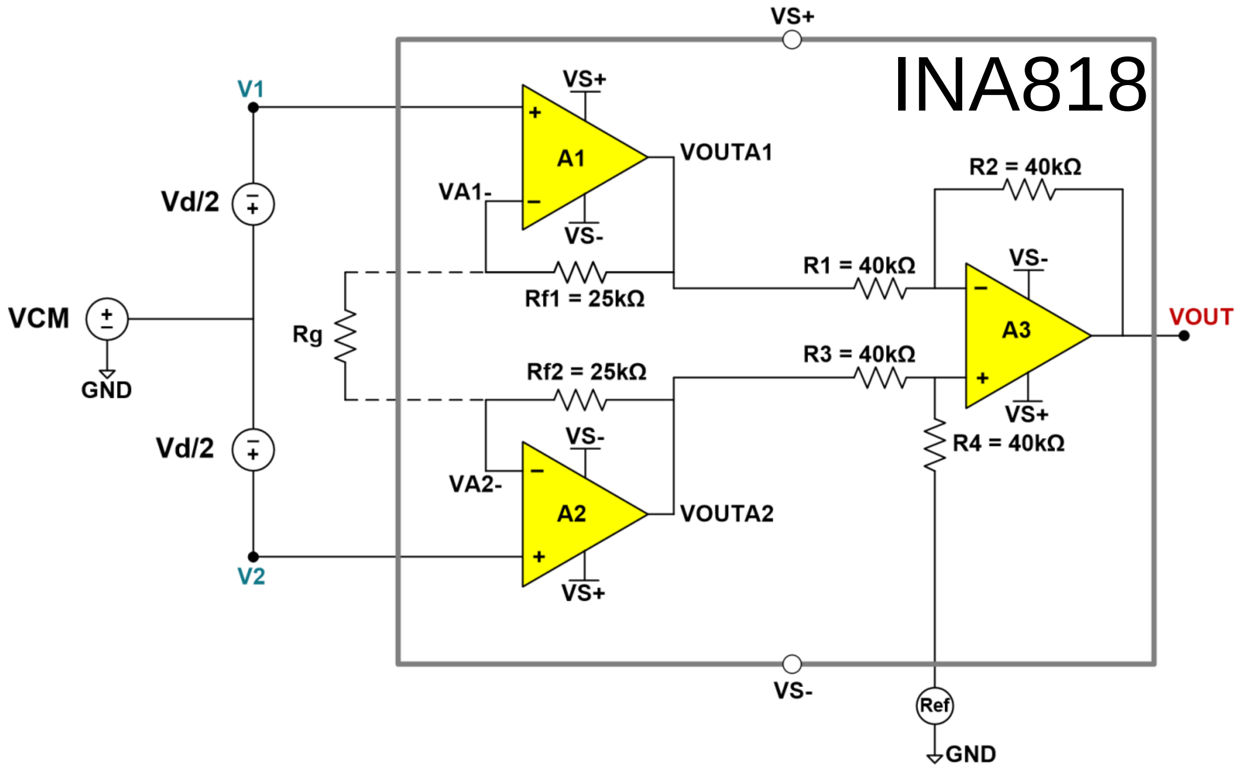
Calculate gain: $\frac{\Delta Vout}{\Delta Vin} = \frac{3V}{10mV} = 300V/V$

Ad for a 3 amp IA:

$$Ad = \frac{R2}{R1} \times \left(1 + \frac{2Rf}{Rg}\right)$$

$$300 = \frac{40k}{40k} \times \left(1 + \frac{2 \times 25k}{Rg}\right)$$

Solve for **Rg = 167.2Ω**



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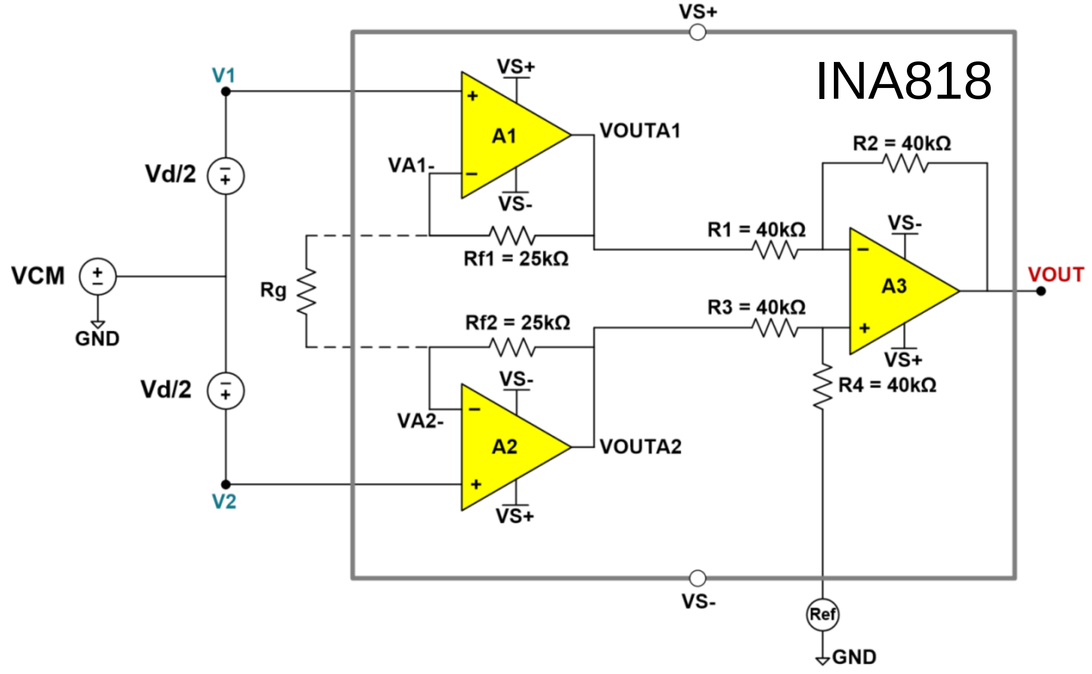
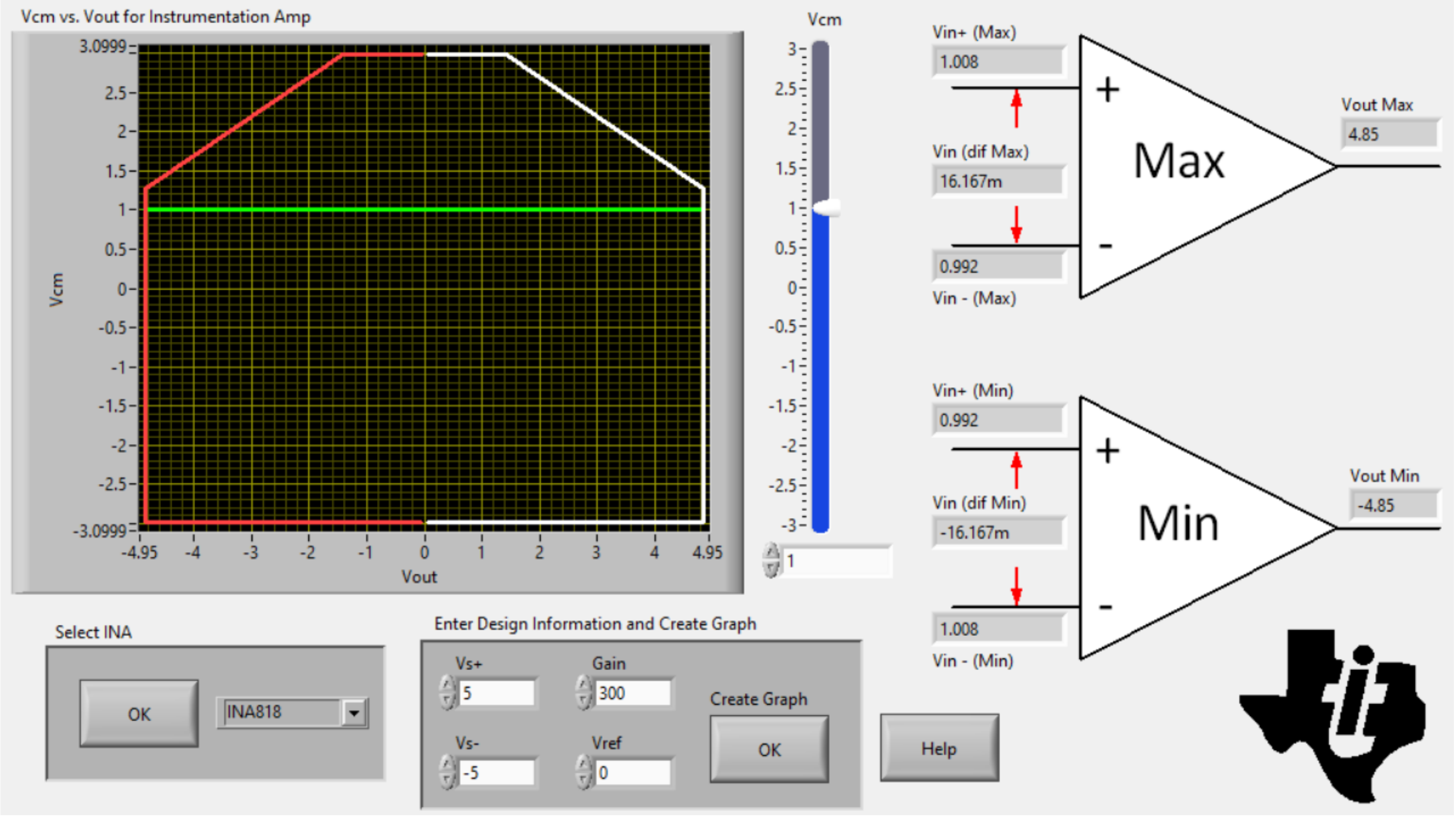
3 amp IA with gain – Example

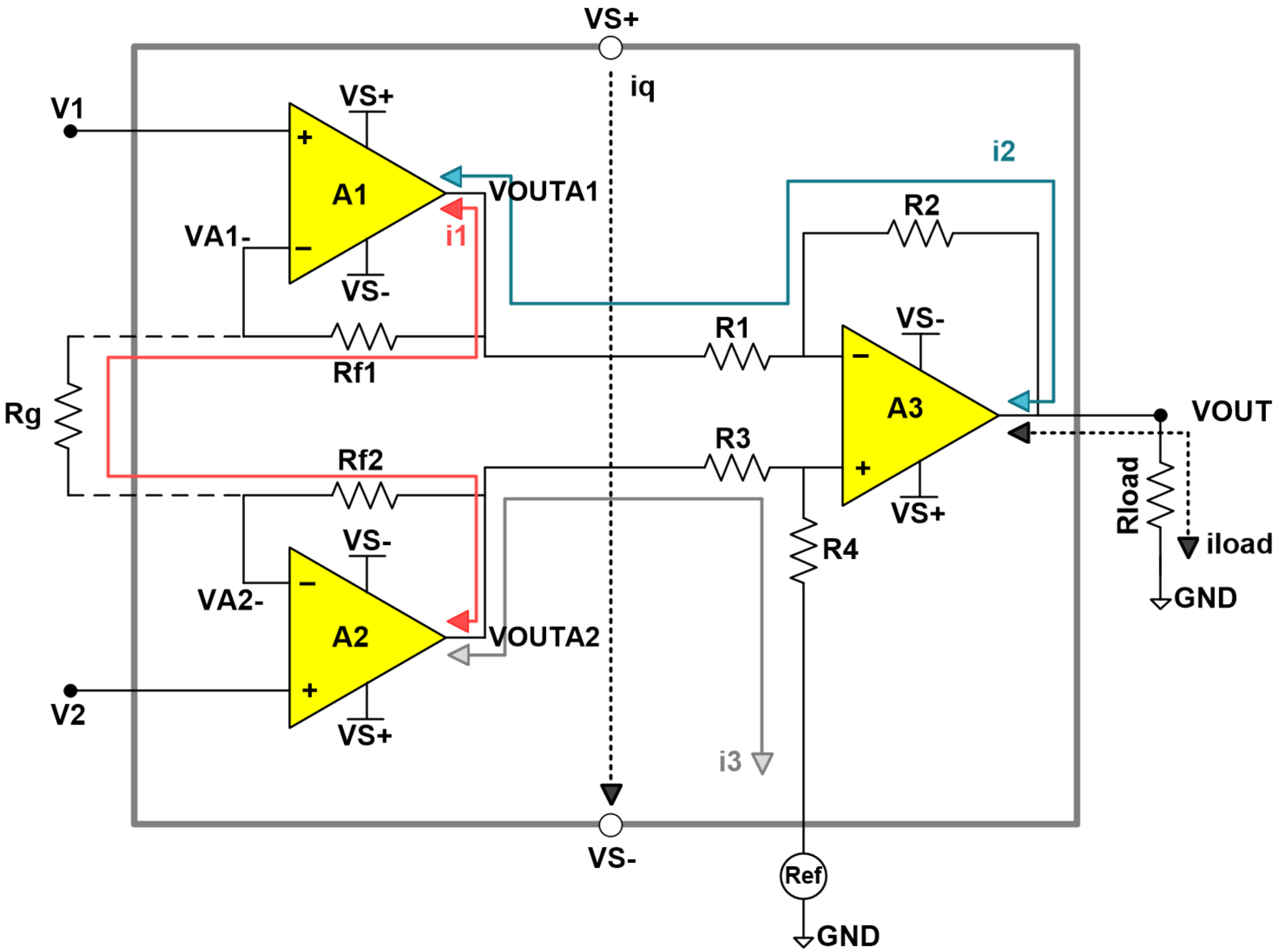
Assume the following conditions:

- Power supply = ±5V
- Reference voltage = 0V
- Vd = 10mV, VCM = 1V
- Expected Vout is 3V
- Gain = 300V/V, Rg = 167.2Ω





Common mistakes – Current consumption

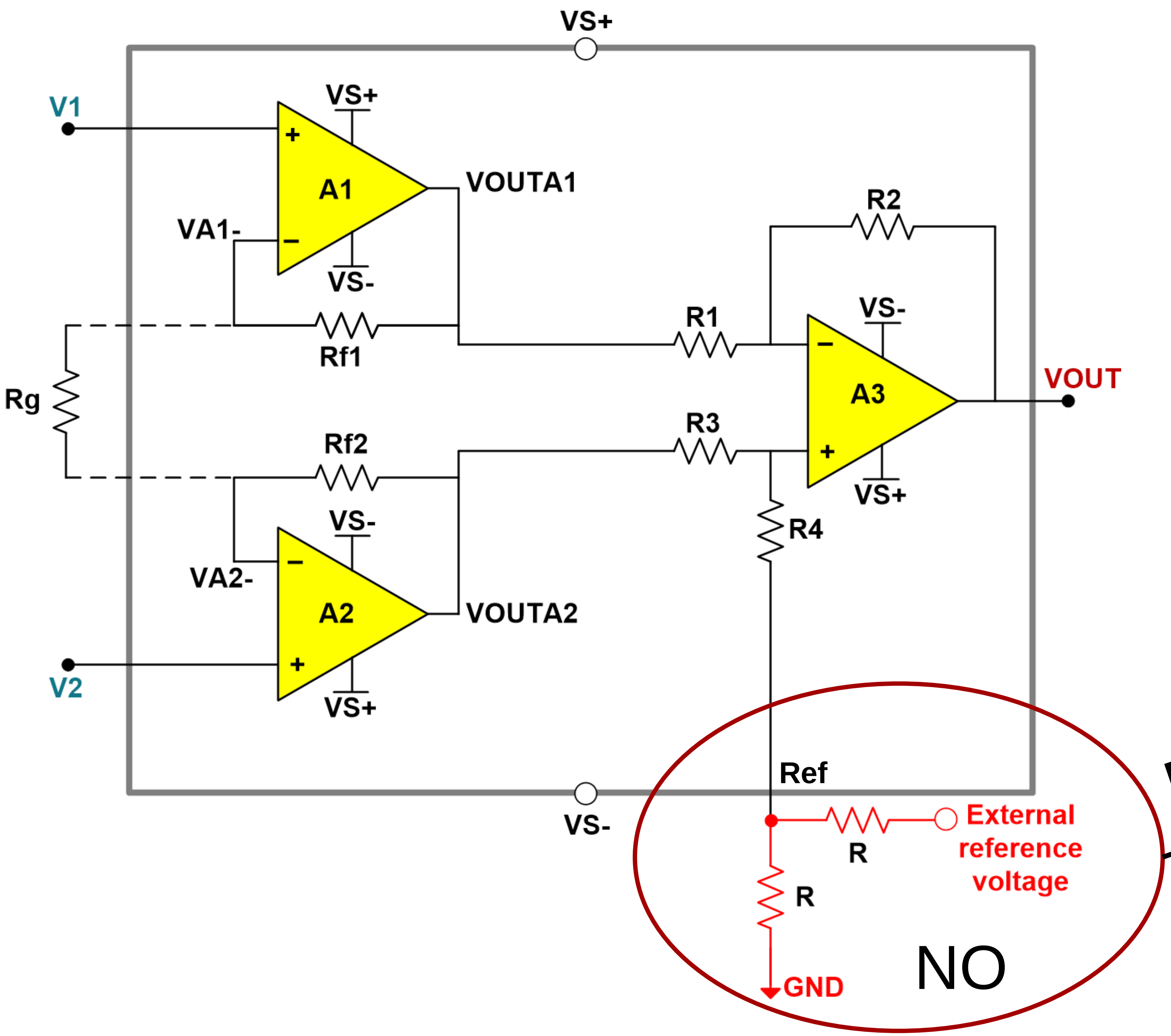


Current consumption of an IA is the sum of all load currents (i1, I2, and i3) in addition to the quiescent current and any loading on Vout.

- **i1:** between VOUTA1 and VOUTA2 through Rf1, Rg, and Rf2 and back through the power supplies.
- **i2:** between VOUT and VOUTA1 through R2 & R1, back through the power supplies.
- **i3:**between VOUTA2 and Ref through R3 & R4 and back through the power supplies.

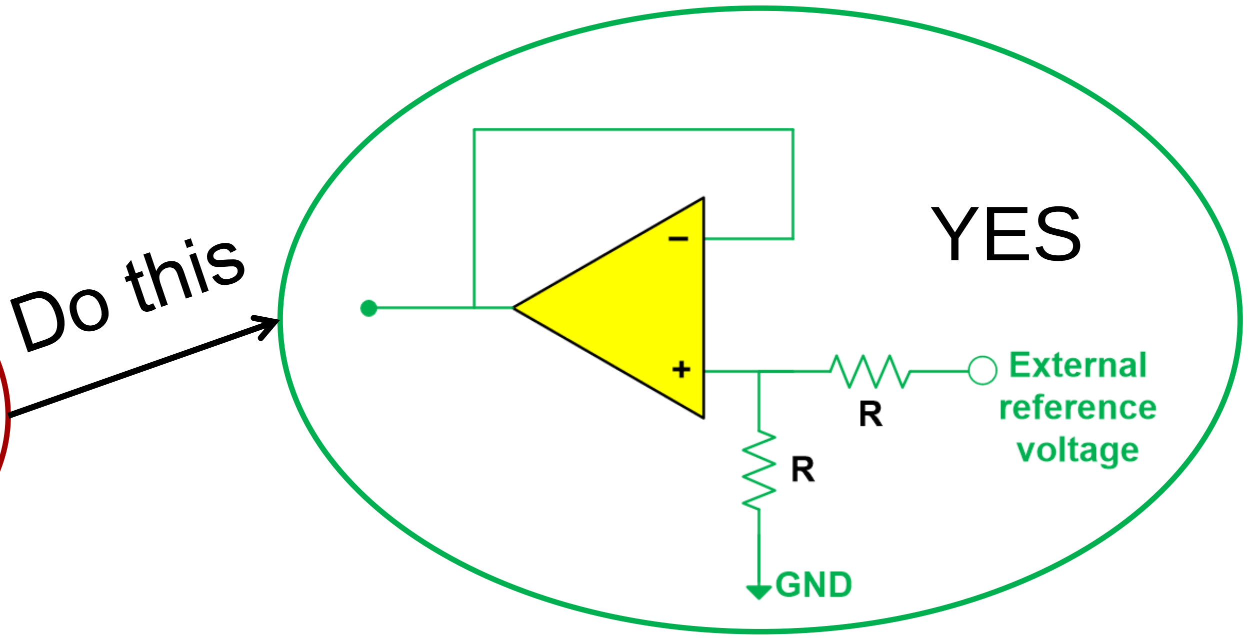
Analog engineer's calculator → IA Current Consumption

Common mistakes – Driving the Ref pin

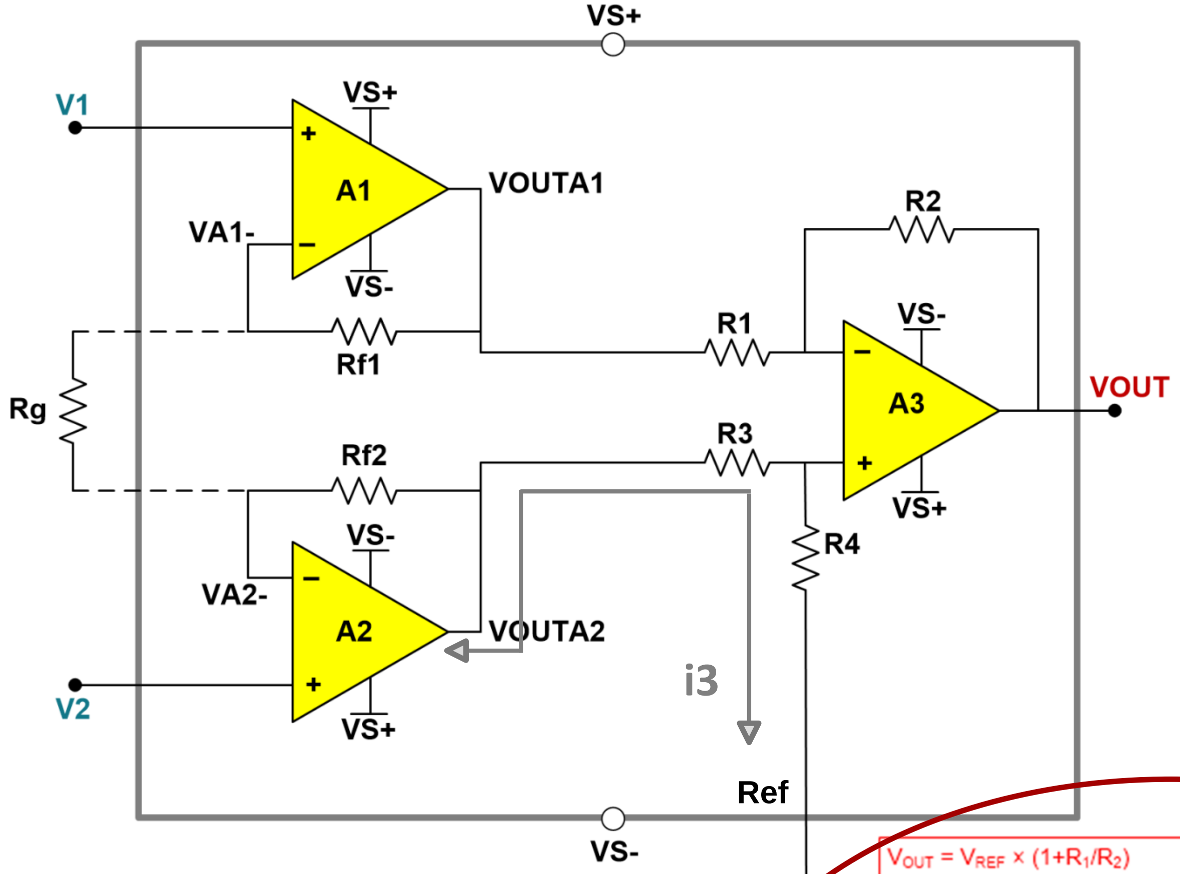


Do **NOT** drive with resistor divider

Assuming A3 is in unity gain (R1 = R2 = R3 = R4), if we add a resistor divider to the Ref pin, this additional resistance combines with R4 creating a mismatch to R1, R2 and R3 so A3 is no longer in unity gain! → **CMRR degradation**



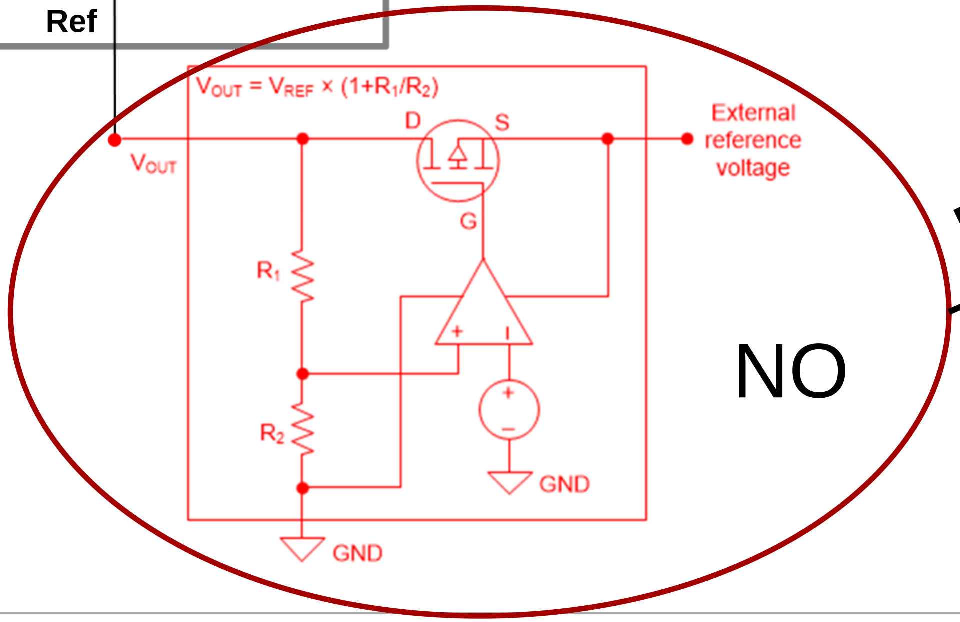
Common mistakes – Driving the Ref pin cont'd

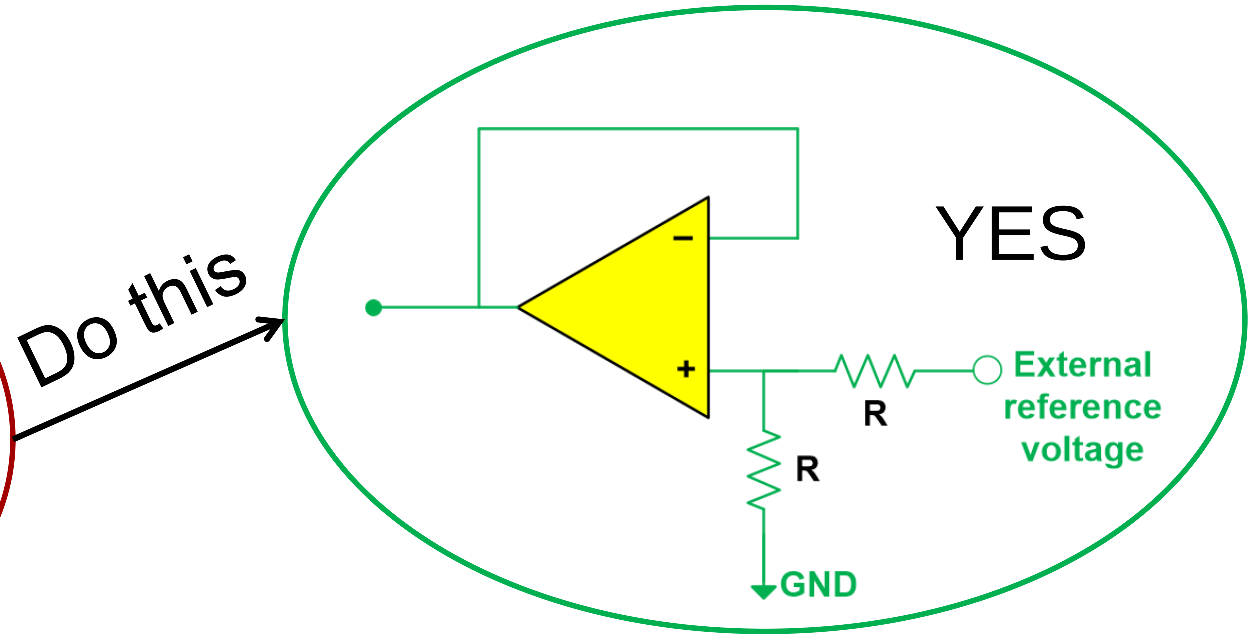


Do **NOT** drive with an LDO

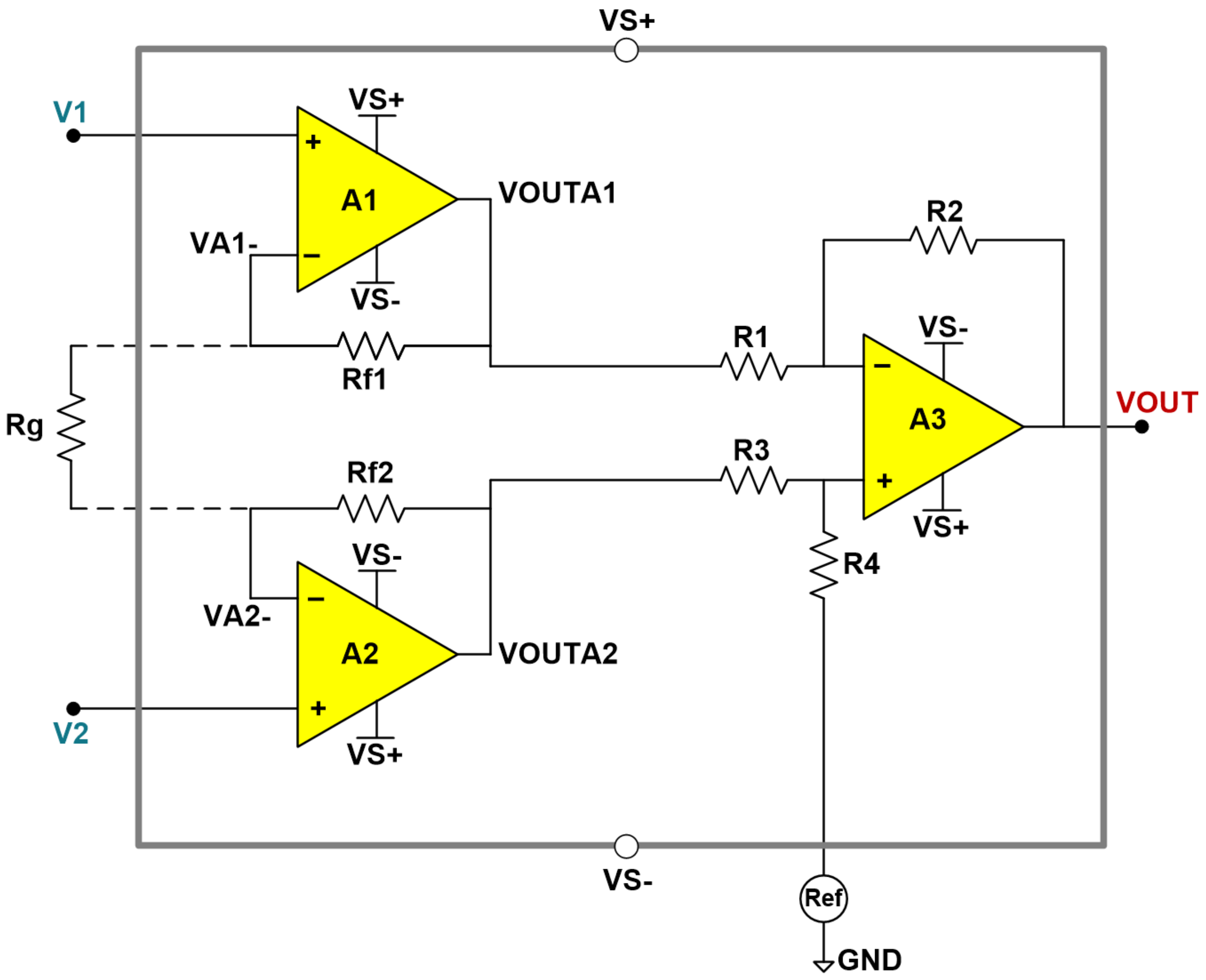
i3: current between VOUTA2 and Ref through R3 & R4 and back through the power supplies.

Ref should be able to **sink or source** current depending on the direction of i3





Instrumentation amplifier topologies – 3 amp summary



Amplifiers A1 and A2:

- balanced input – balanced output stage
- amplifies the differential signal put passes the common mode signal without amplification.
- Responsible for the high input impedance

Amplifier A3:

- forms the second stage of this design as a difference amplifier
- largely removes the common mode signal.

Summary:

If you have an application where you have high impedance sources and high common mode voltages, consider a three-amp IA topology.

Thanks for your time!

To find more Instrumentation Amplifier technical resources and search products, visit ti.com/inas

Quiz: Instrumentation Amplifier (IA) topologies: three-amp

TI Precision Labs – Instrumentation Amplifiers

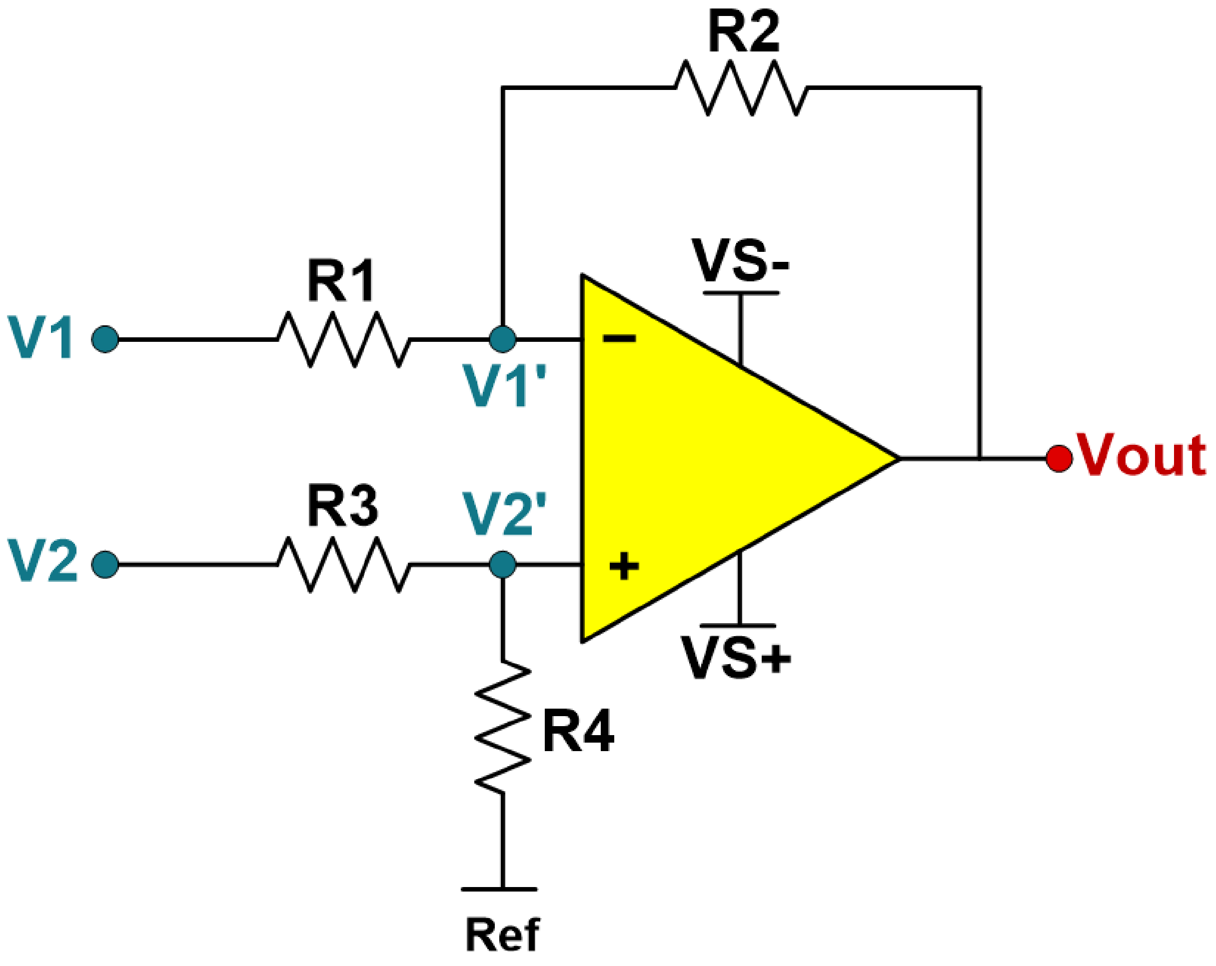
Presented by Tamara Alani

Prepared by Tamara Alani

Quiz: (IA) topologies: three-amp || Question

1. What are two challenges associated with the discrete one-amp IA topology?

   a) The one-amp IA consumes more power
   b) The one-amp IA has low input impedance
   c) The one-amp IA must have precision-matched resistors for high accuracy
   d) The one-amp IA has fixed gain
   e) The one-amp IA can only be used for mV-level input signals
   f) b & e
   g) c & a
   h) b & c



Quiz: (IA) topologies: three-amp || Answer

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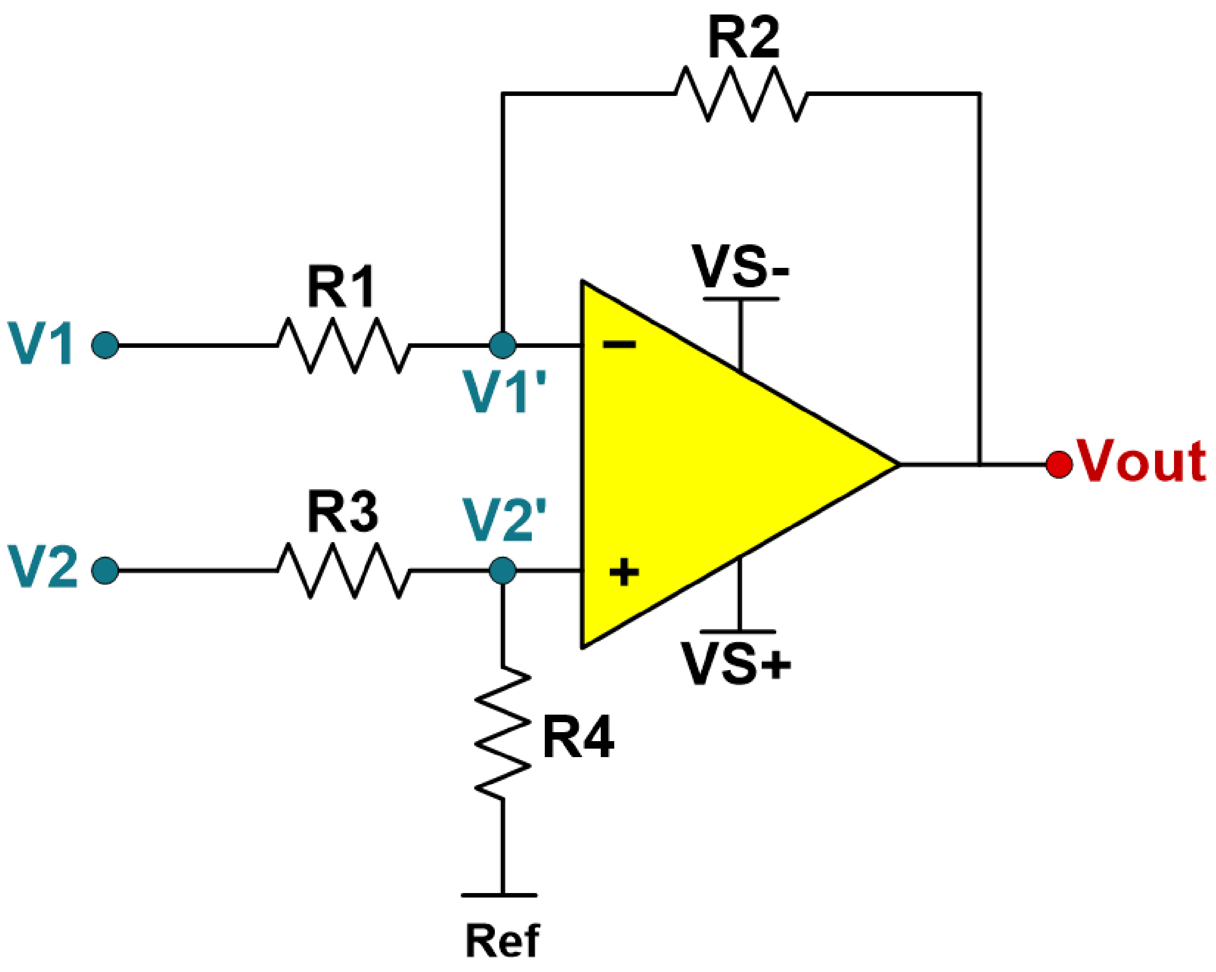
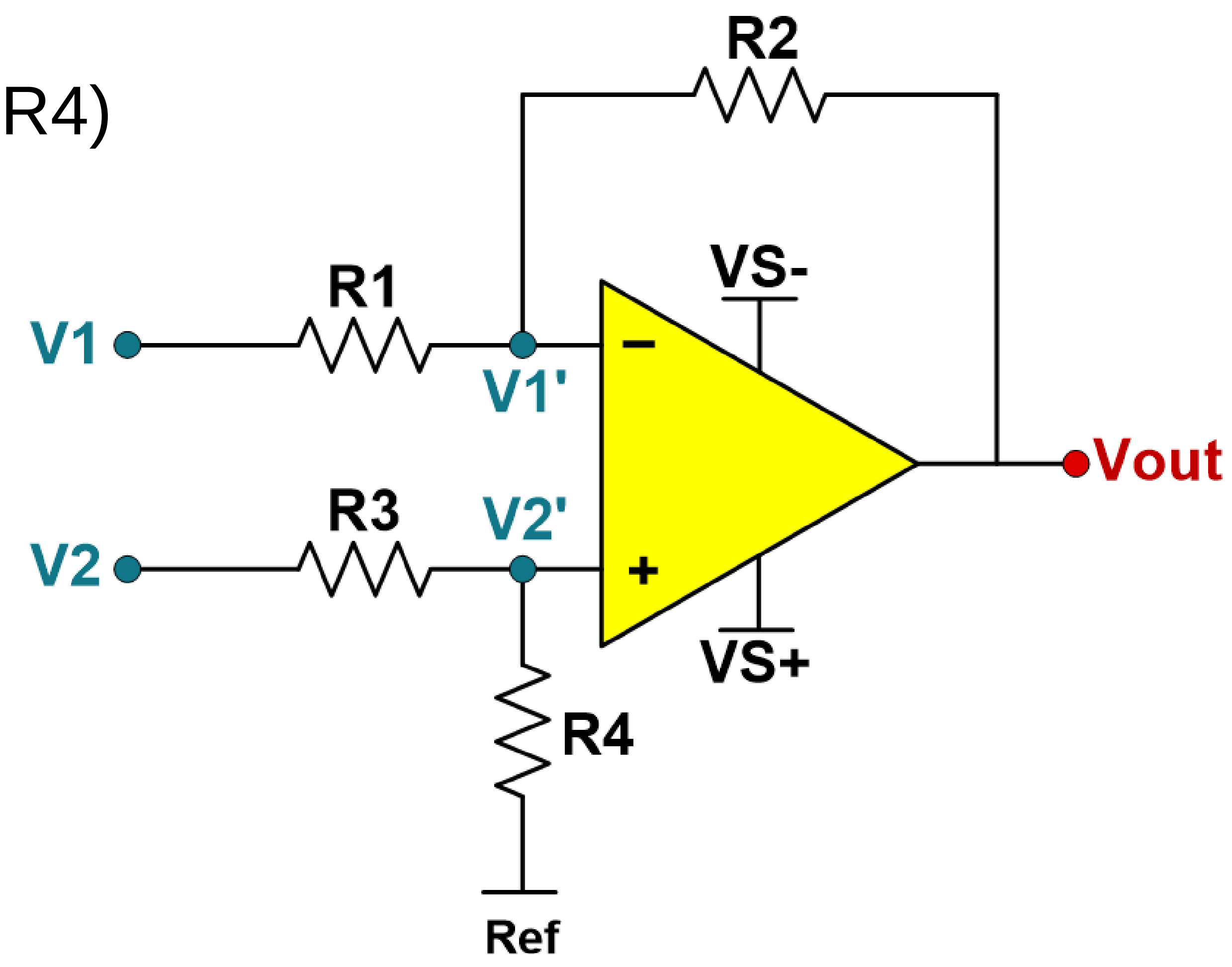
   g) c & a
   h) **b & c**



Quiz: (IA) topologies: three-amp || Question

2. A one-amp IA has low input impedance. What is best way to resolve this?

   a) Add really large input resistors (R1 through R4)
   b) Put the amplifier in high gain
   c) Add two buffers at the inputs (V1 and V2)
   d) Find an amplifier with high input impedance



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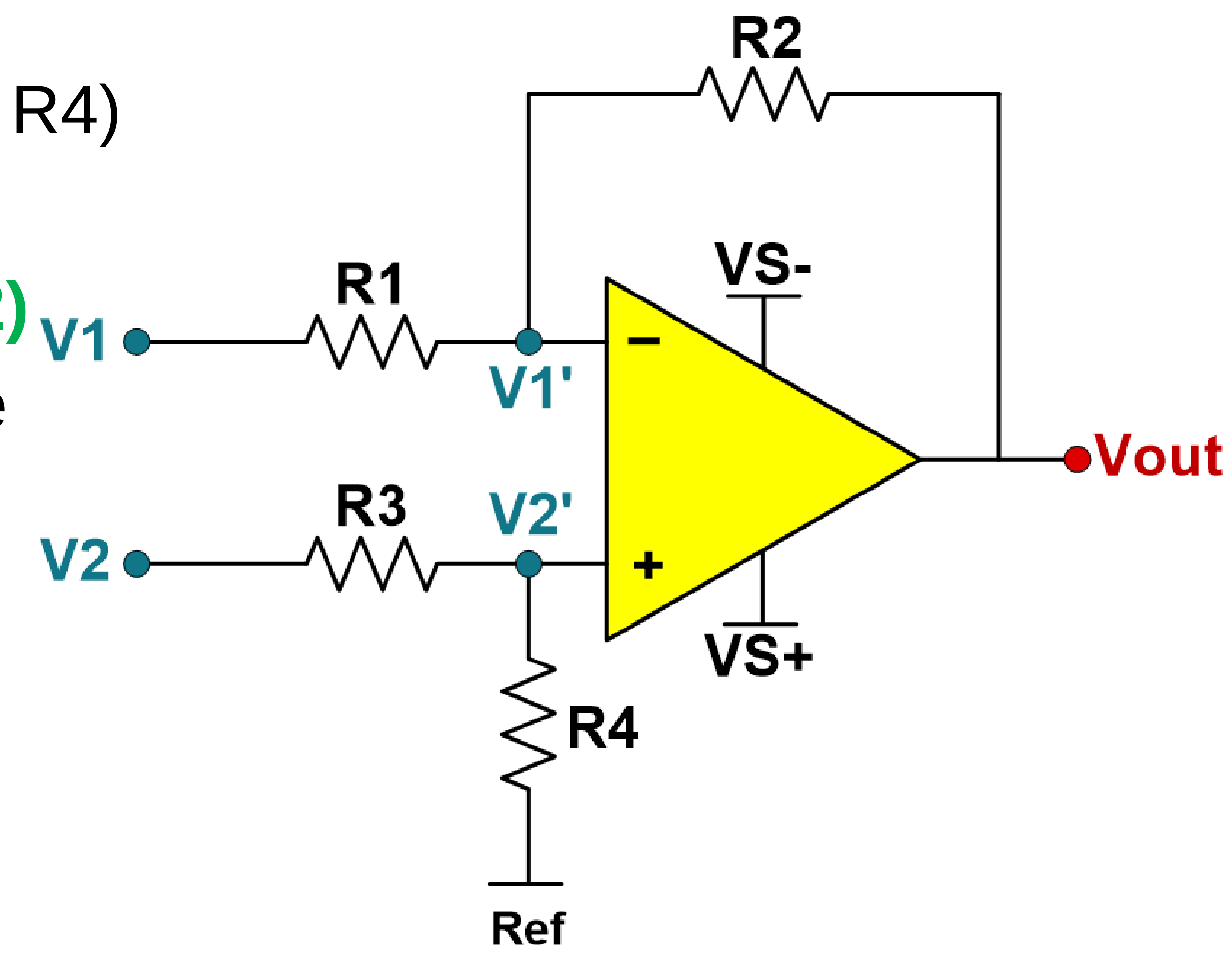


Quiz: (IA) topologies: three-amp || Question

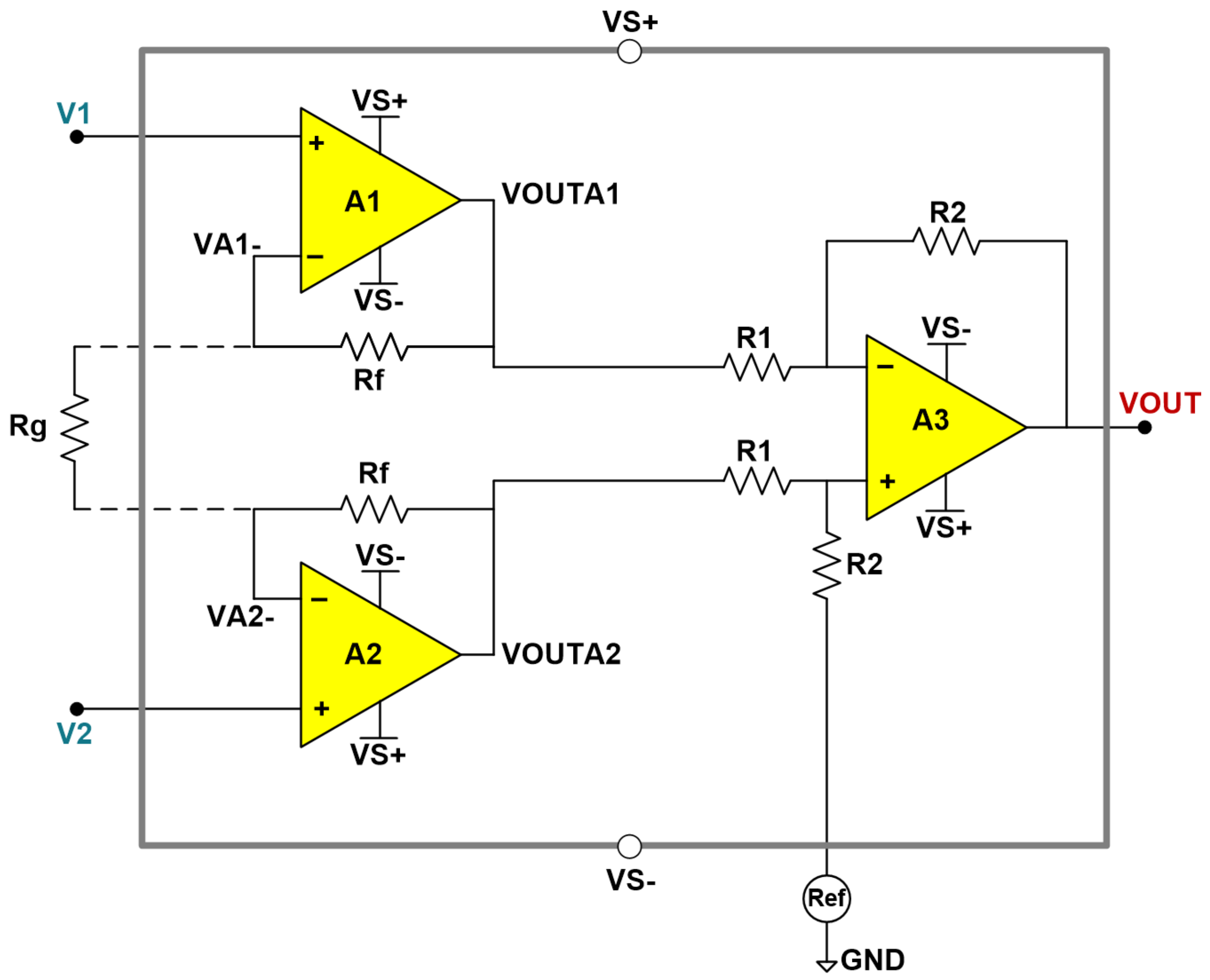
3. What is the gain equation for a three-amp IA?

a) $\text{Gain} = \frac{R2}{R1}$

b) $\text{Gain} = Rg$

c) $\text{Gain} = \frac{R2}{R1} \times (Rg + 2 \times Rf)$

d) $\text{Gain} = \frac{R2}{R1} \times \left(1 + \frac{2 \times Rf}{Rg}\right)$



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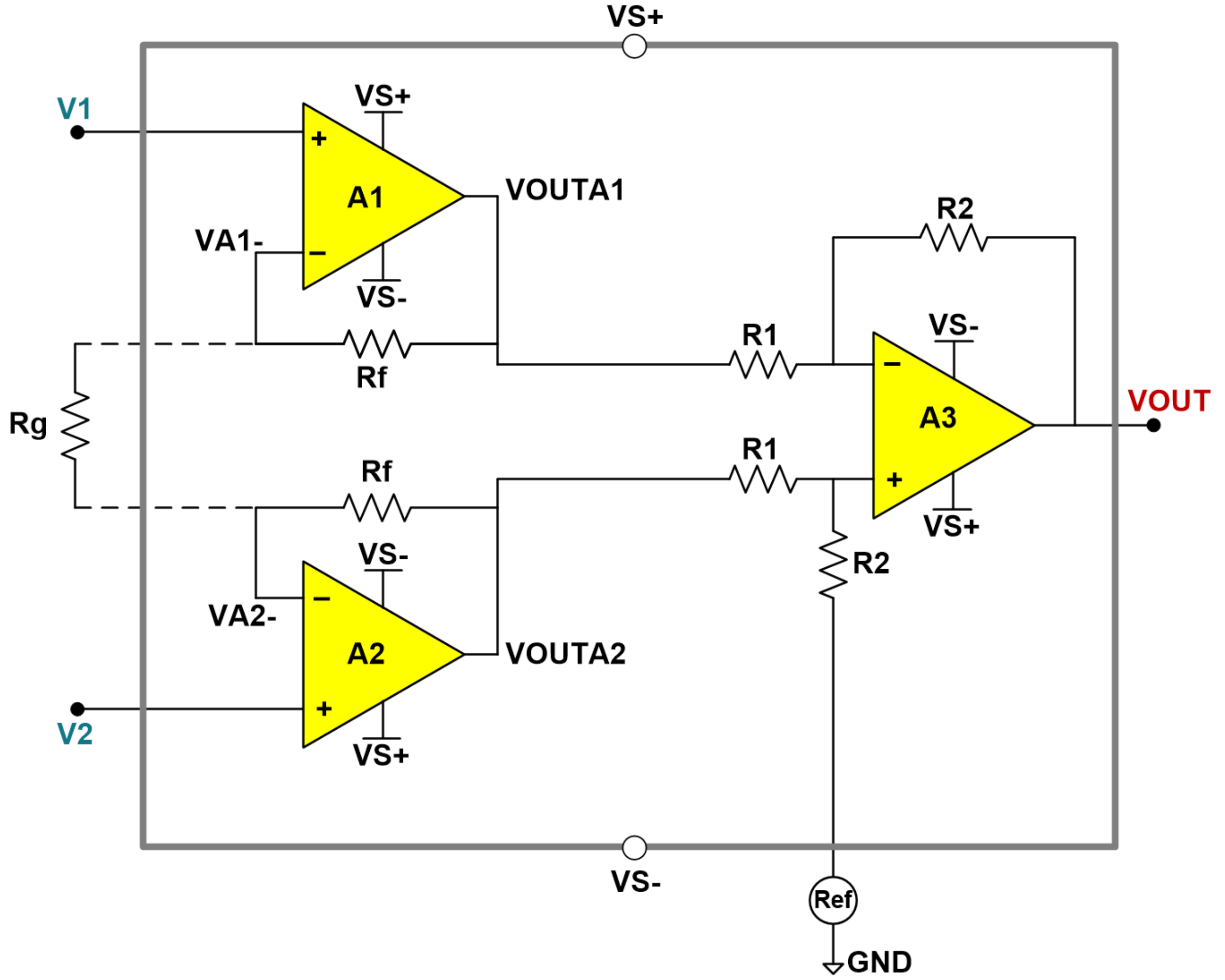

Quiz: (IA) topologies: three-amp || Question

4. Using the INA333-Q1 (TI's Automotive, Zero-drift, low power IA), what value of Rg do you need to achieve a signal gain of 501V/V?

   a) Rg = 100Ω
   b) Rg = 200Ω
   c) Rg = 200kΩ
   d) Rg = 501Ω

HINT:

Go to the product datasheet:
https://www.ti.com/lit/ds/symlink/ina333-q1.pdf

Quiz: (IA) topologies: three-amp || Answer

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c) Rg = 200kΩ
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HINT:

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$$\text{Gain} = \left(1 + \frac{100\text{k}\Omega}{\text{Rg}}\right)$$

Quiz: (IA) topologies: three-amp || Question

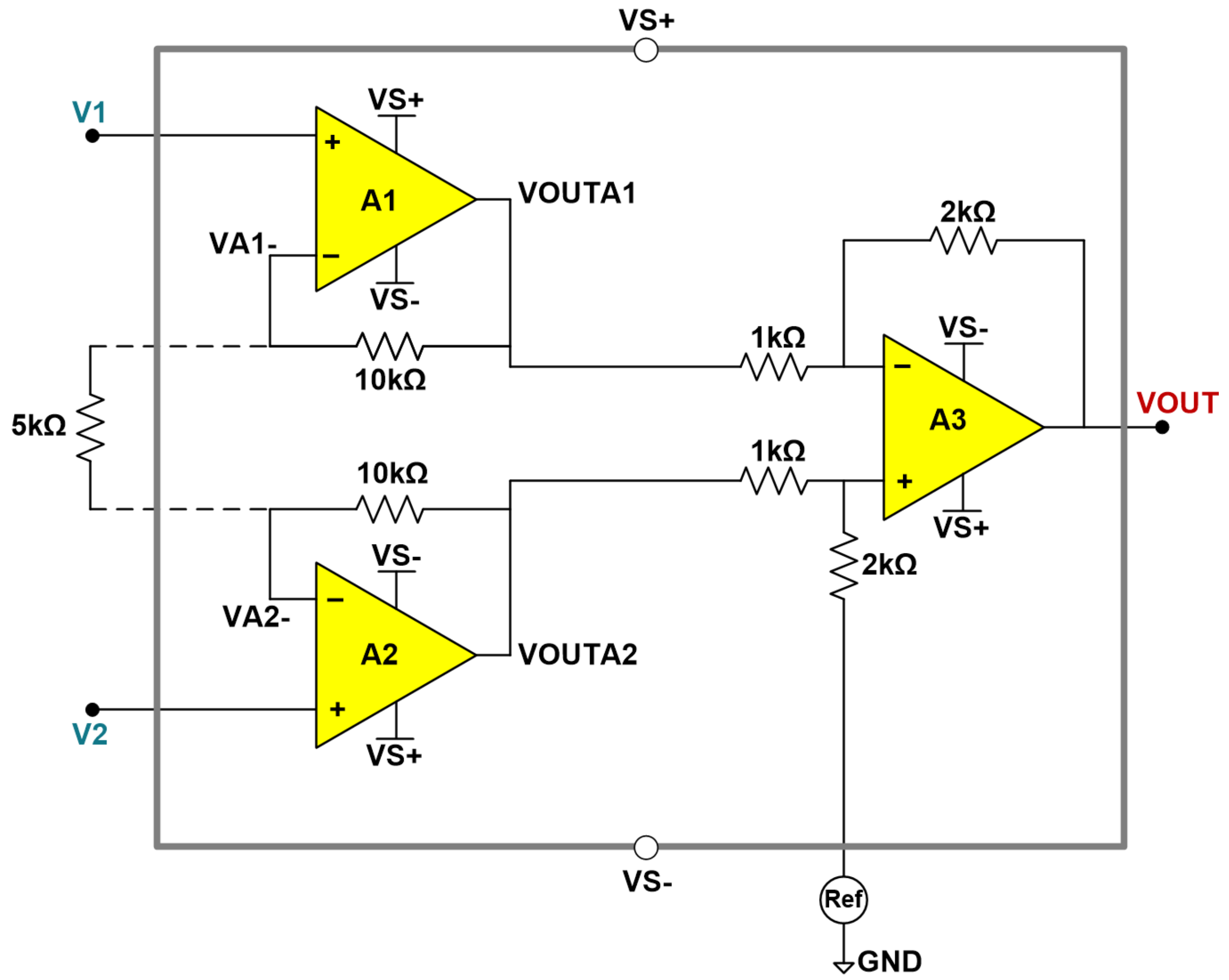
5. What is the differential gain of the following circuit?

a) Gain = 5V/V

b) Gain = 2V/V

c) Gain = 4V/V

d) Gain = 10V/V



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5. What is the differential gain of the following circuit?

a) Gain = 5V/V

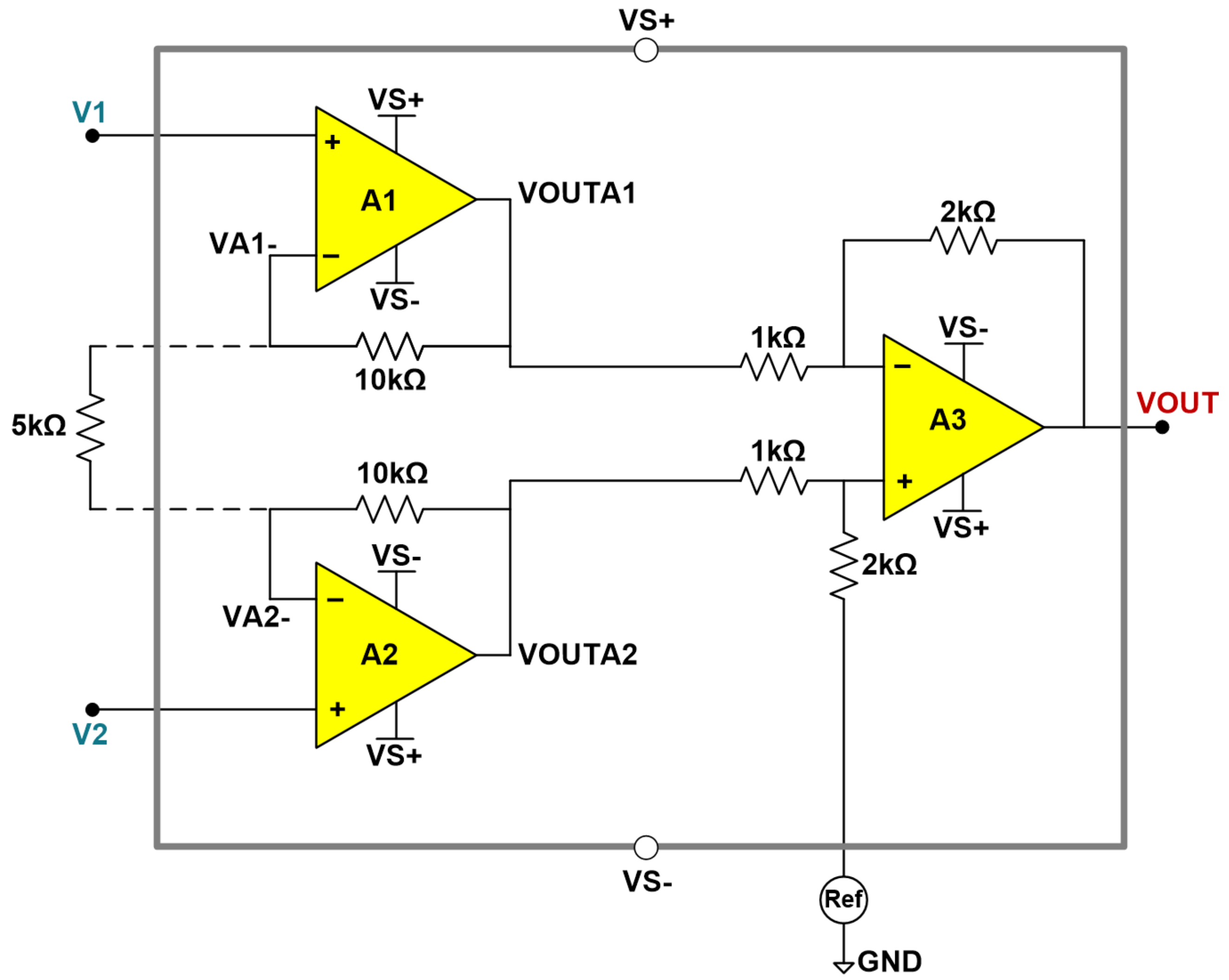
b) Gain = 2V/V

c) Gain = 4V/V

d) Gain = 10V/V

HINT:

$$Ad = \frac{R2}{R1} \times \left(1 + \frac{2Rf}{Rg}\right)$$



Quiz: (IA) topologies: three-amp || Question

6. Using the INA818 (TI's high-precision, low-power IA with over-voltage protection), create a boundary plot for the following conditions:
   - Voltage supply = ±15V
   - Gain = 100V/V
   - Reference = 0V
   - Common mode voltage = 8V

HINT:

Use the INA Boundary Plot calculator in the **Analog Engineer's Calculator**: https://www.ti.com/tool/ANALOG-ENGINEER-CALC

Quiz: (IA) topologies: three-amp || Answer

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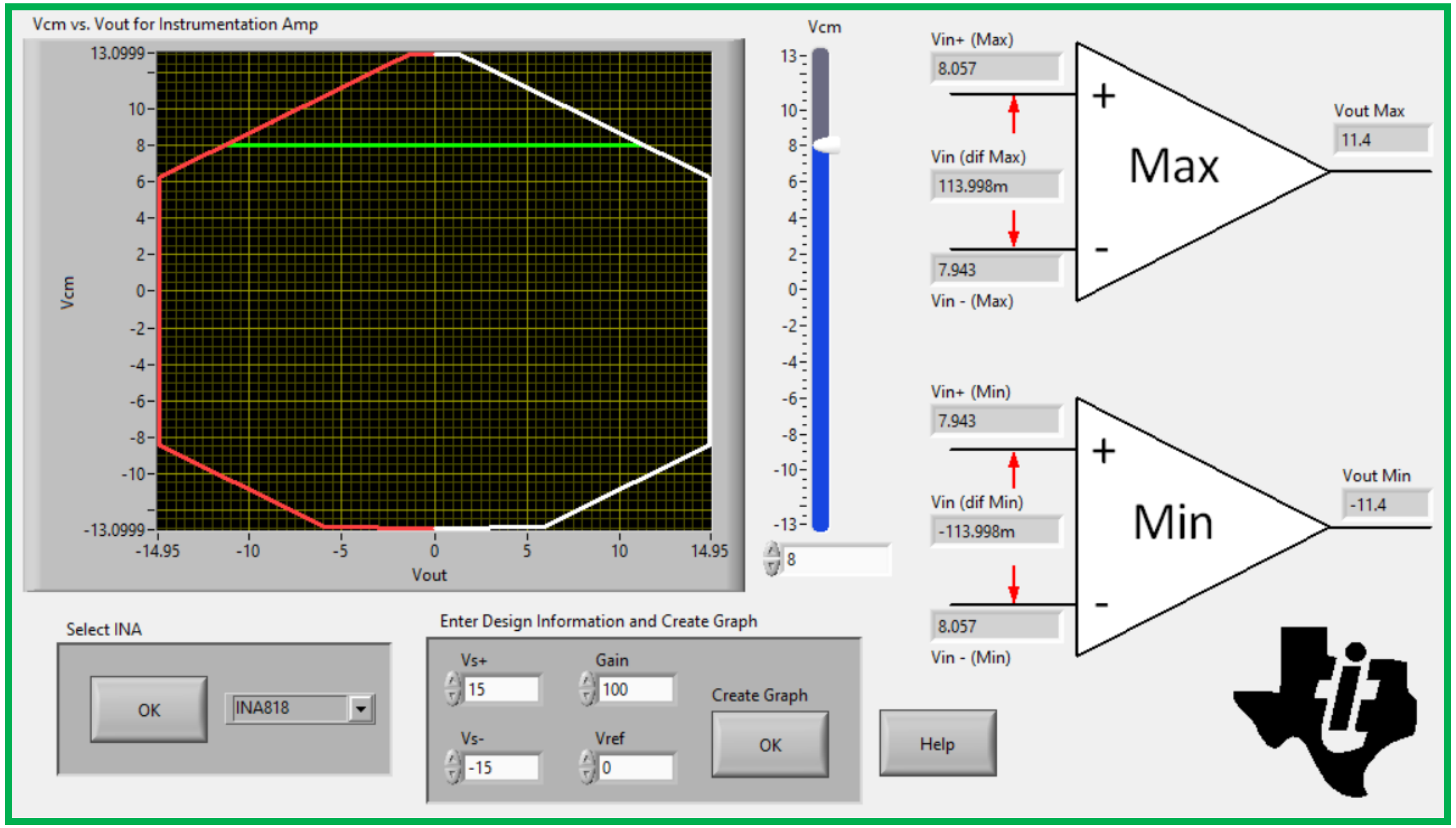

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Quiz: (IA) topologies: three-amp || Question

7. In theory, how does CMRR change with signal differential gain

   a) When signal gain is increased, ACM / Ad will increase so CMRR will double
   b) When signal gain is decreased, ACM / Ad will increase so CMRR will increase in direct proportion to gain
   c) When signal gain is increased, Ad / ACM will increase so CMRR will increase by a factor of 1/2
   d) When signal gain is increased, Ad / ACM will increase so CMRR will increase in direction proportion to gain

Quiz: (IA) topologies: three-amp || Answer

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HINT:

$$CMRR\left(\frac{V}{V}\right) = \frac{differential\ gain}{common\ mode\ gain} = \frac{A_d}{A_{CM}}$$

Quiz: (IA) topologies: three-amp || Question

8. What are the typical magnitudes of input impedance for a 3 op amp IA?

   a) 1 Ω to 1k Ω
   b) 1k Ω to 100k Ω
   c) 100k Ω to 10M Ω
   d) 10^9 Ω to 10^{12} Ω

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Quiz: (IA) topologies: three-amp || Question

9. How do you determine the total current consumption of a 3 op amp IA?

   a) Look for the quiescent current specified in the datasheet and multiply it by 3
   b) (Load currents (i1, I2, and i3) + quiescent current) multiplied by 3
   c) Load currents (i1, I2, and i3) + quiescent current + any loading on Vout
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Quiz: (IA) topologies: three-amp || Answer

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