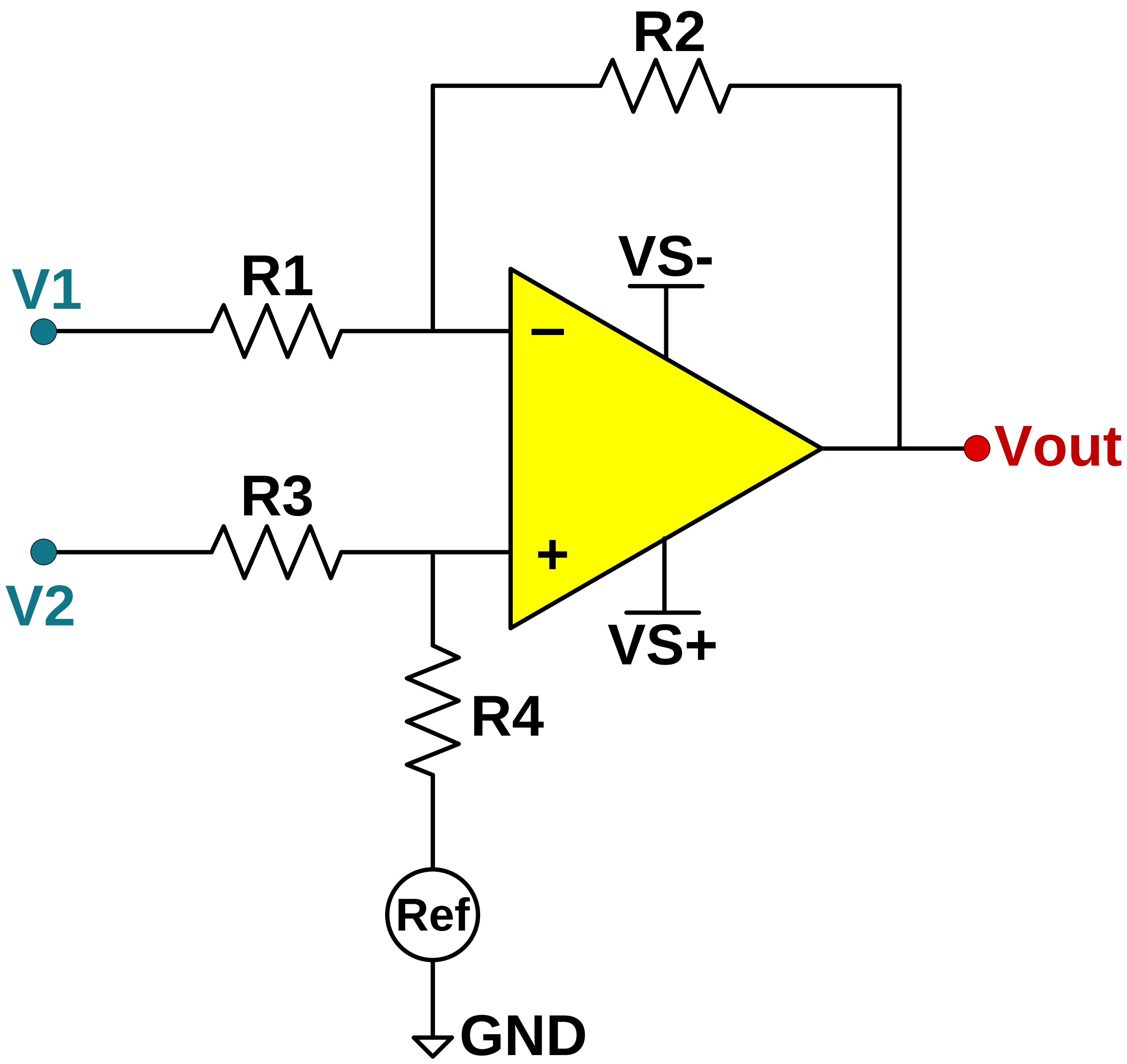
# Instrumentation Amplifier (IA) topologies: two-amp

## 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

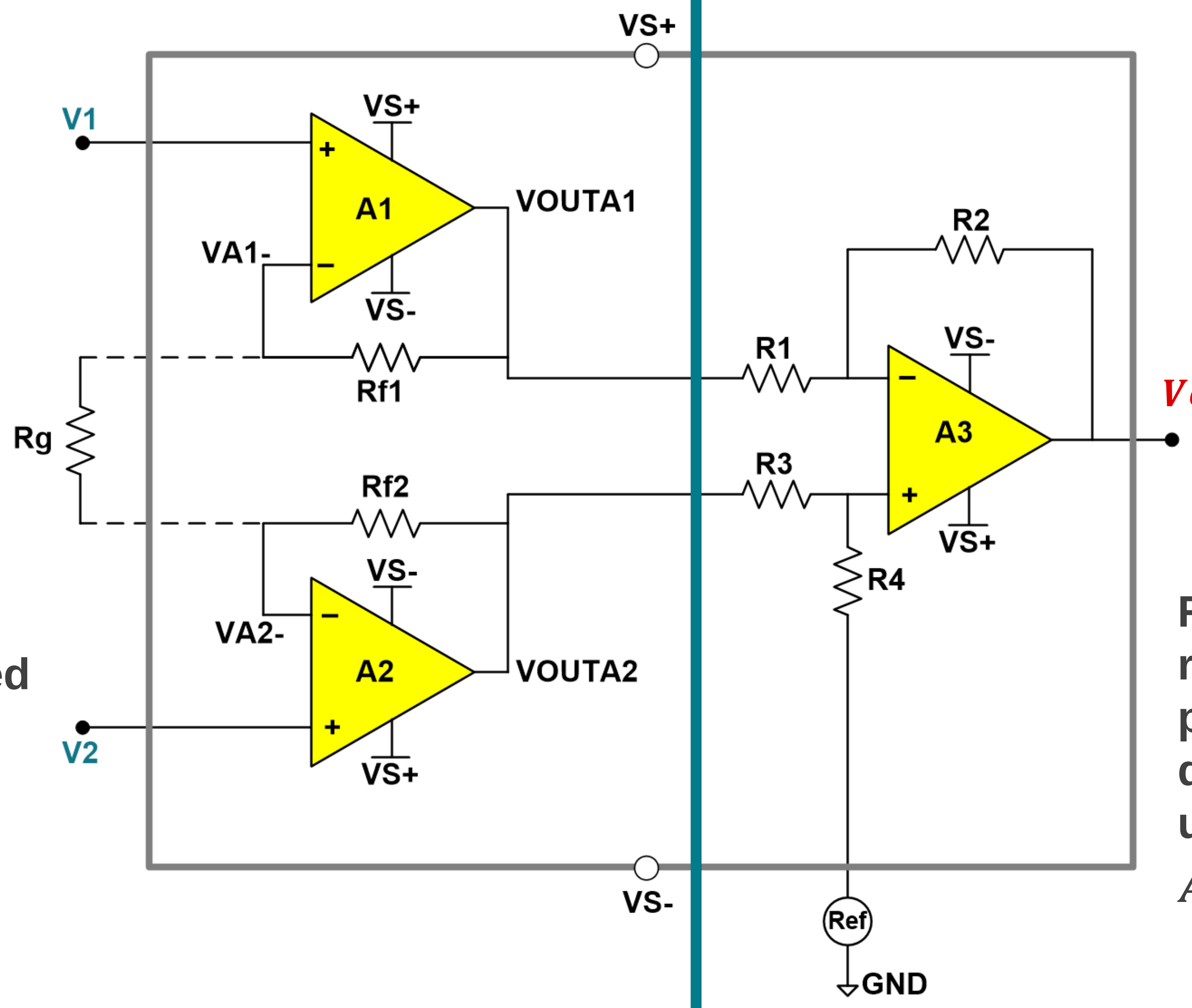
If $R1 = R3$, and $R2 = R4$, then Ad $= \frac{R2}{R1}$

**Challenges:**

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

# IA topologies – Three amp recap

**Buffer stage with gain and high input impedance**




**Difference amplifier output stage**

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

Rf1 and Rf2 are absolutely matched for precise gain calculation:

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

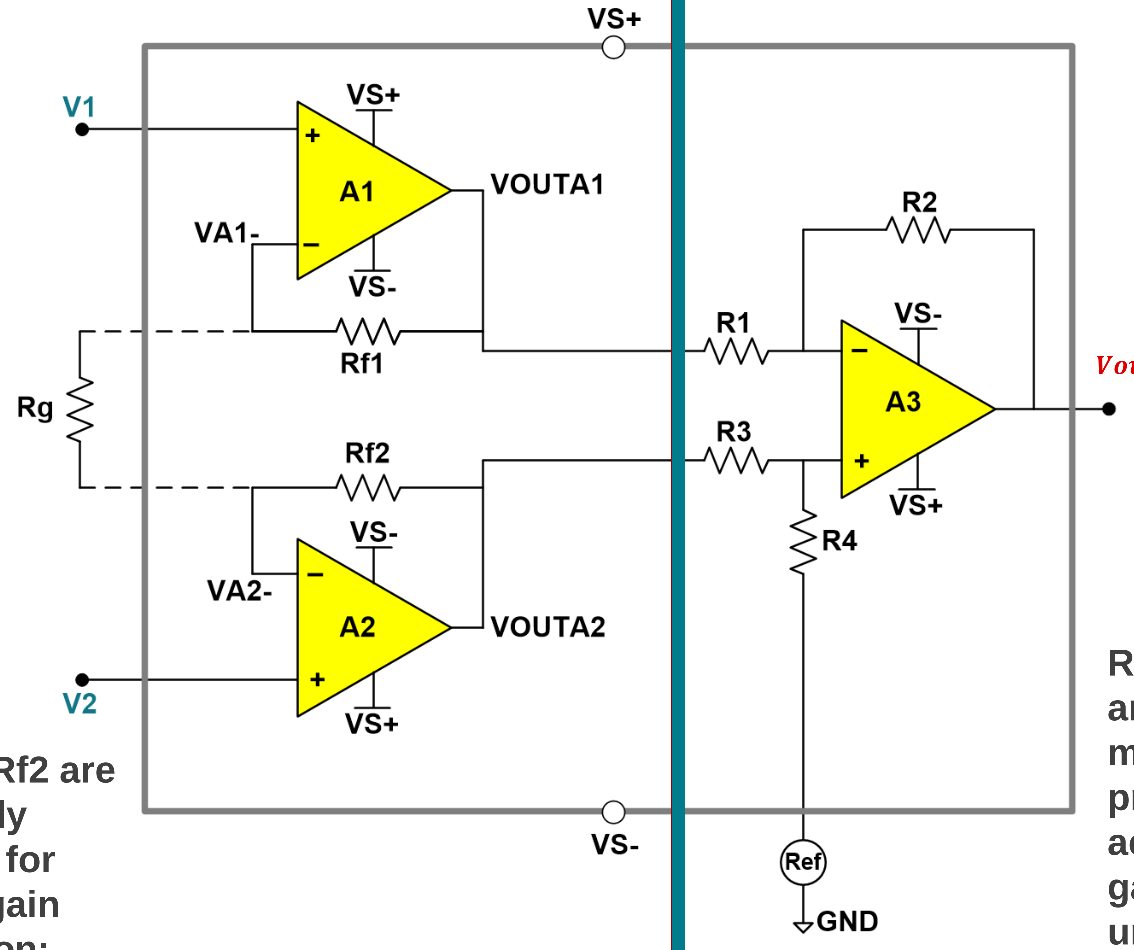
R1, R2, R3 and R4 are ratiometrically matched in production to achieve the desired gain, commonly unity

$Ad = \frac{R2}{R1}$ if R2=R4 and R1=R3

# IA topologies – Three amp recap cont'd

**Buffer stage with gain and high input impedance**

**Difference amplifier output stage**




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

**Rf1 and Rf2 are absolutely matched for precise gain calculation:**

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

**R1, R2, R3 and R4 are ratiometrically matched in production to achieve the desired gain, commonly unity**

$$Ad = \frac{R2}{R1}$$

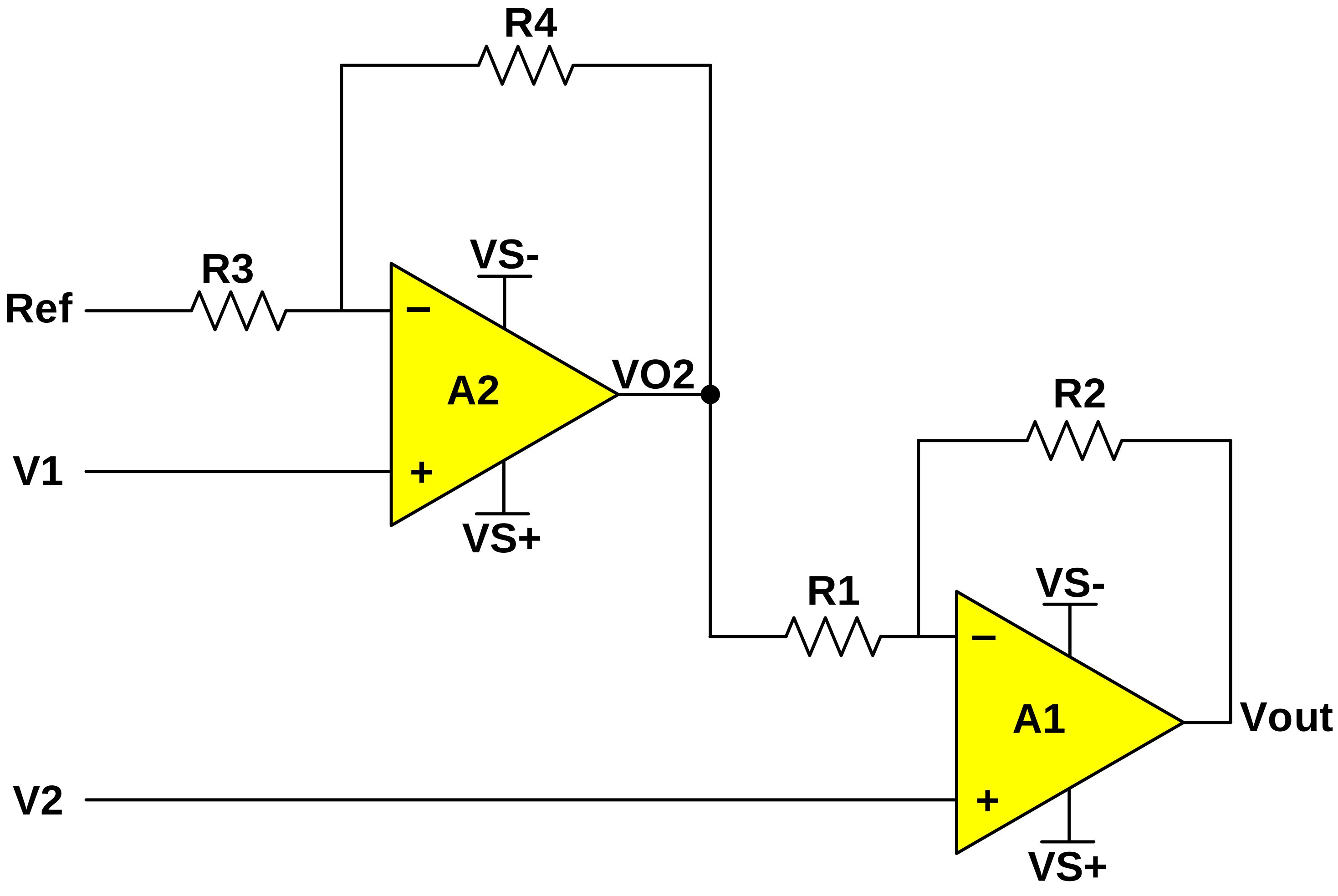
**if R2=R4 and R1=R3**

## Drawbacks:

Complex design: 3 amplifiers and 6 resistors.
This complexity may result in:

- larger die size,
- higher current consumption,
- higher manufacturing cost.

# IA topologies – Two amp IA introduction



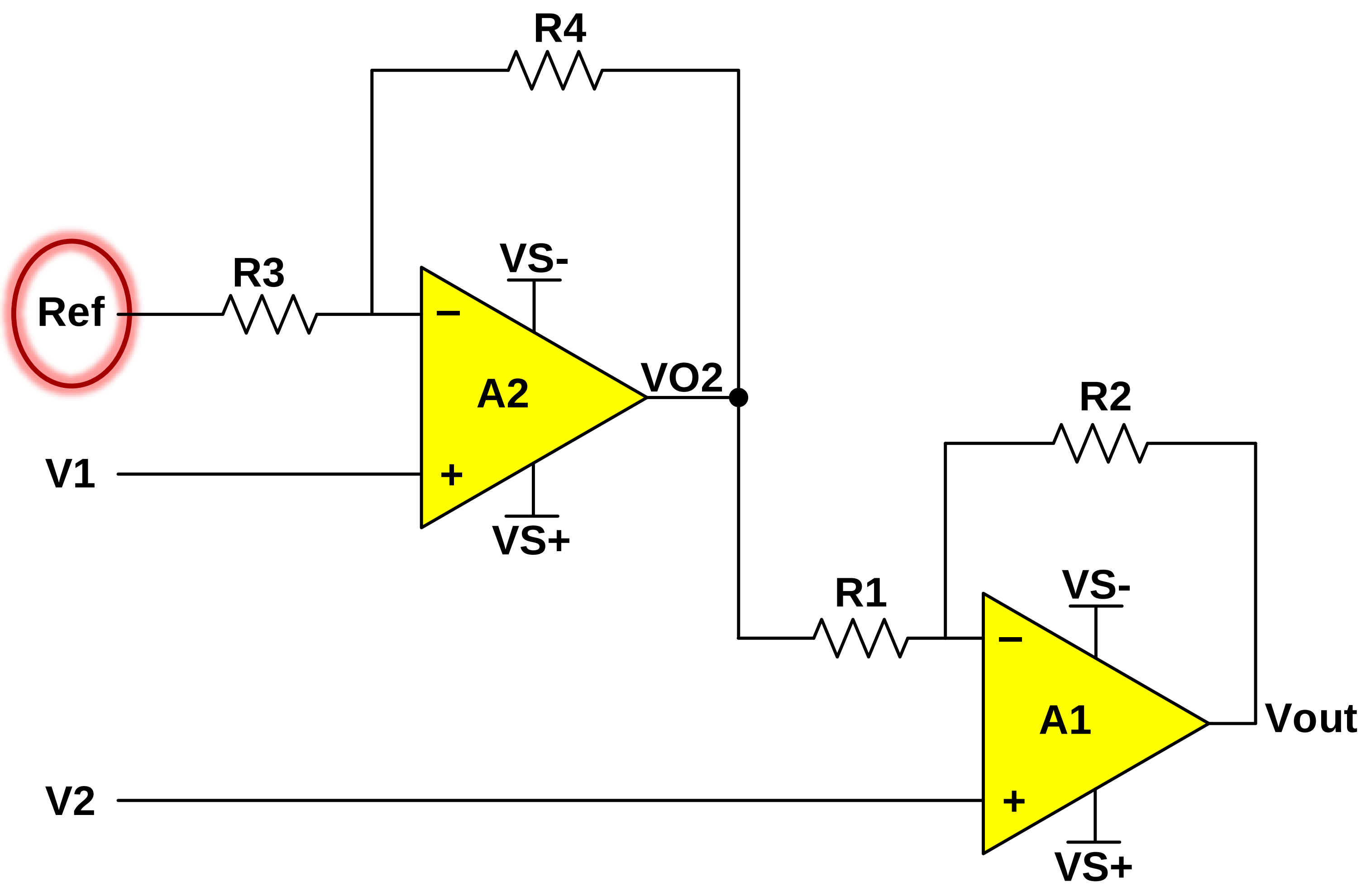

**Design simplicity:**

– 2 amps, 4 resistors →
  - smaller IC
  - lower current consumption
  - smaller manufacturing cost

**Input impedance:**

– High (typically $10^9$ Ω)

# IA topologies – 2 amp IA derivation; A2 derivation




Derive output of A2 using superposition theorem:

| Equation | V1 | Ref |
|---|---|---|
| V1* | Keep | Short |
| Ref* | Short | Keep |
| **VO2 = V2* + Ref*** | | |

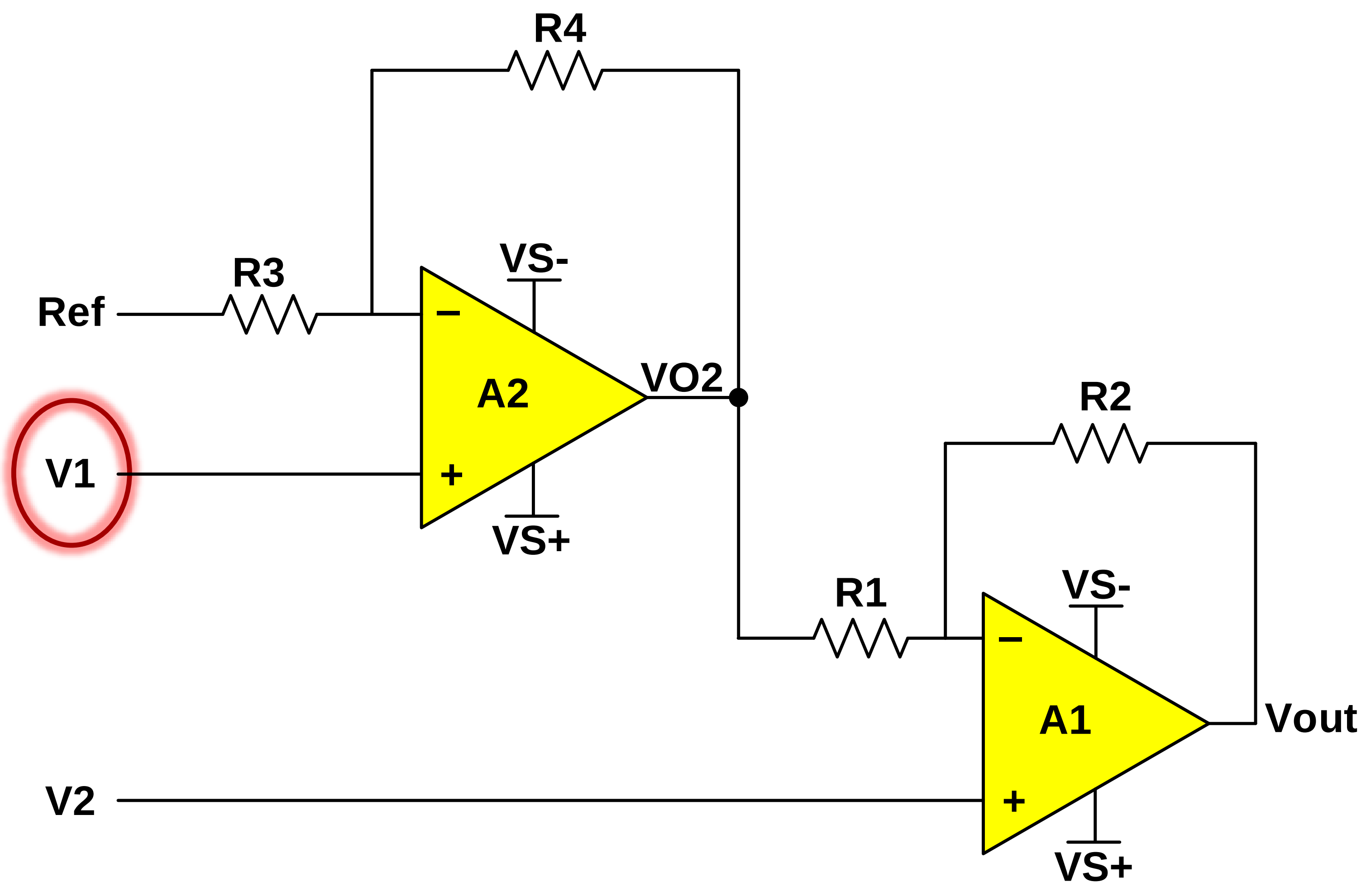
Ground Ref:

A2 looks like non-inverting configuration:

$$VO2 = \left(1 + \frac{R4}{R3}\right) \times V1$$

Equation V1*

# IA topologies – 2 amp IA derivation; A2 derivation




Derive output of A2 using superposition theorem:

| Equation | V1 | Ref |
|---|---|---|
| V1* | Keep | Short |
| Ref* | Short | Keep |
| VO2 = V2* + Ref* | | |

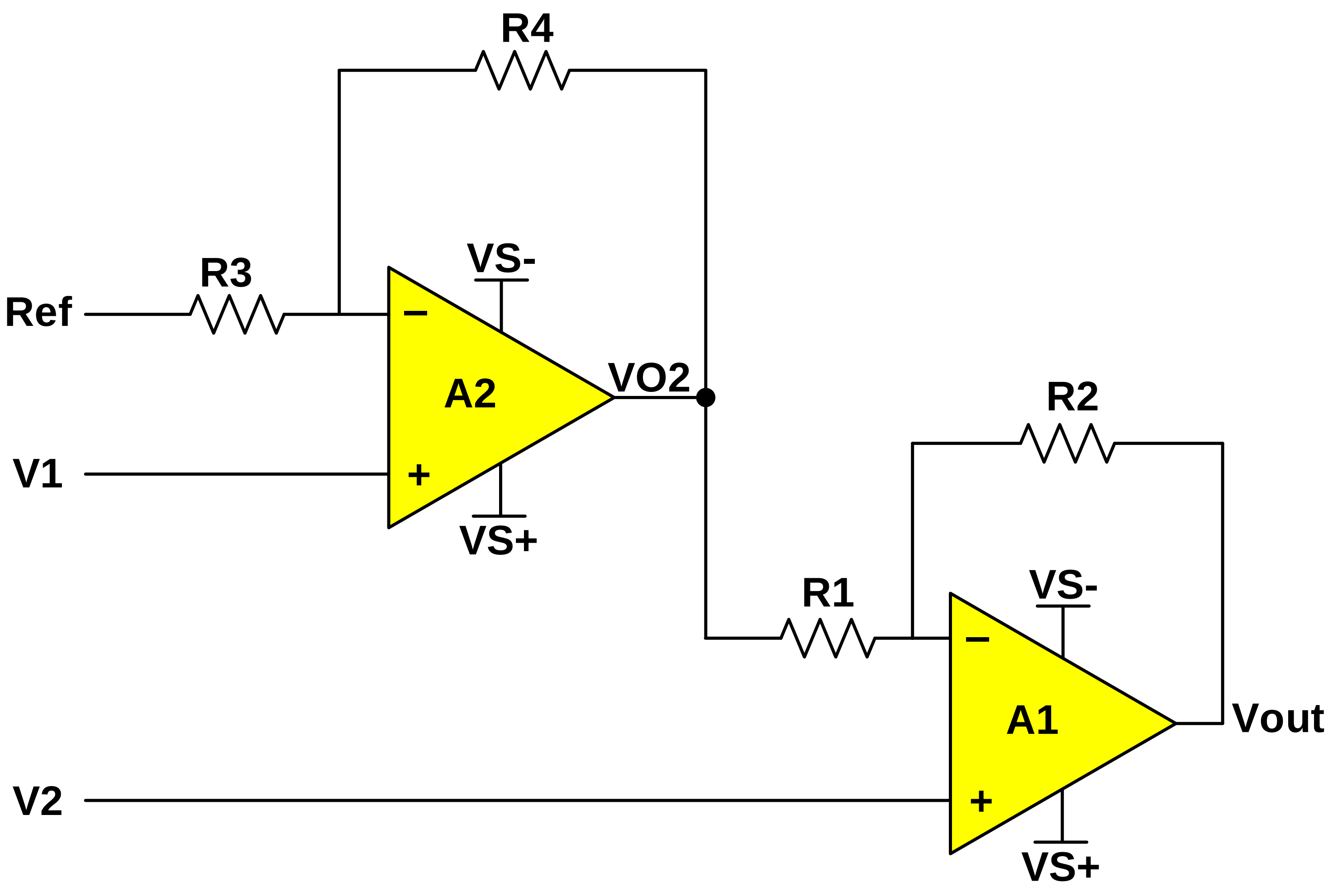
Ground V1:

A2 looks like inverting configuration:

$$VO2 = \left(-\frac{R4}{R3}\right) \times Ref$$

Equation Ref*

# IA topologies – 2 amp IA derivation; A2 derivation



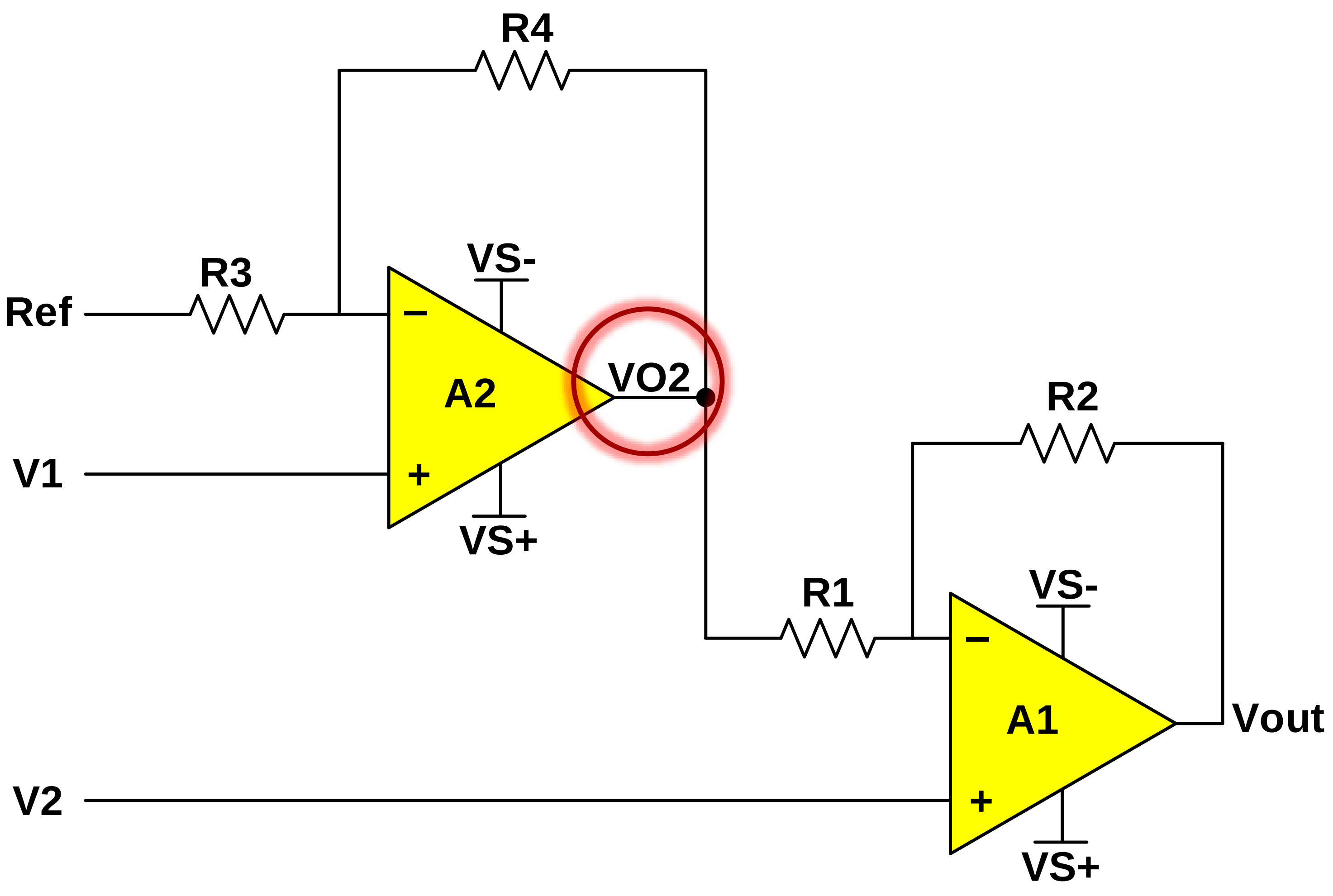

Derive output of A2 using superposition theorem:

| Equation | V1* | Ref | |
|---|---|---|---|
| V1* | Keep | Short | V1* = (1+R4/R3)×V1 |
| Ref* | Short | Keep | Ref* = (-R4/R3)×Ref |
| **VO2 = V1* + Ref*** | | | |

Combine equations V1* and Ref* to yield VO2:

$$VO2 = \frac{-R4}{R3} \times Ref + \left(1 + \frac{R4}{R3}\right) \times V1$$

# IA topologies – 2 amp IA derivation; A1 derivation




Derive output of A1 using superposition theorem:

| Equation | V2 | VO2 |
|---|---|---|
| V2* | Keep | Short |
| VO2* | Short | Keep |
| **Vout = V2* + VO2*** | | |

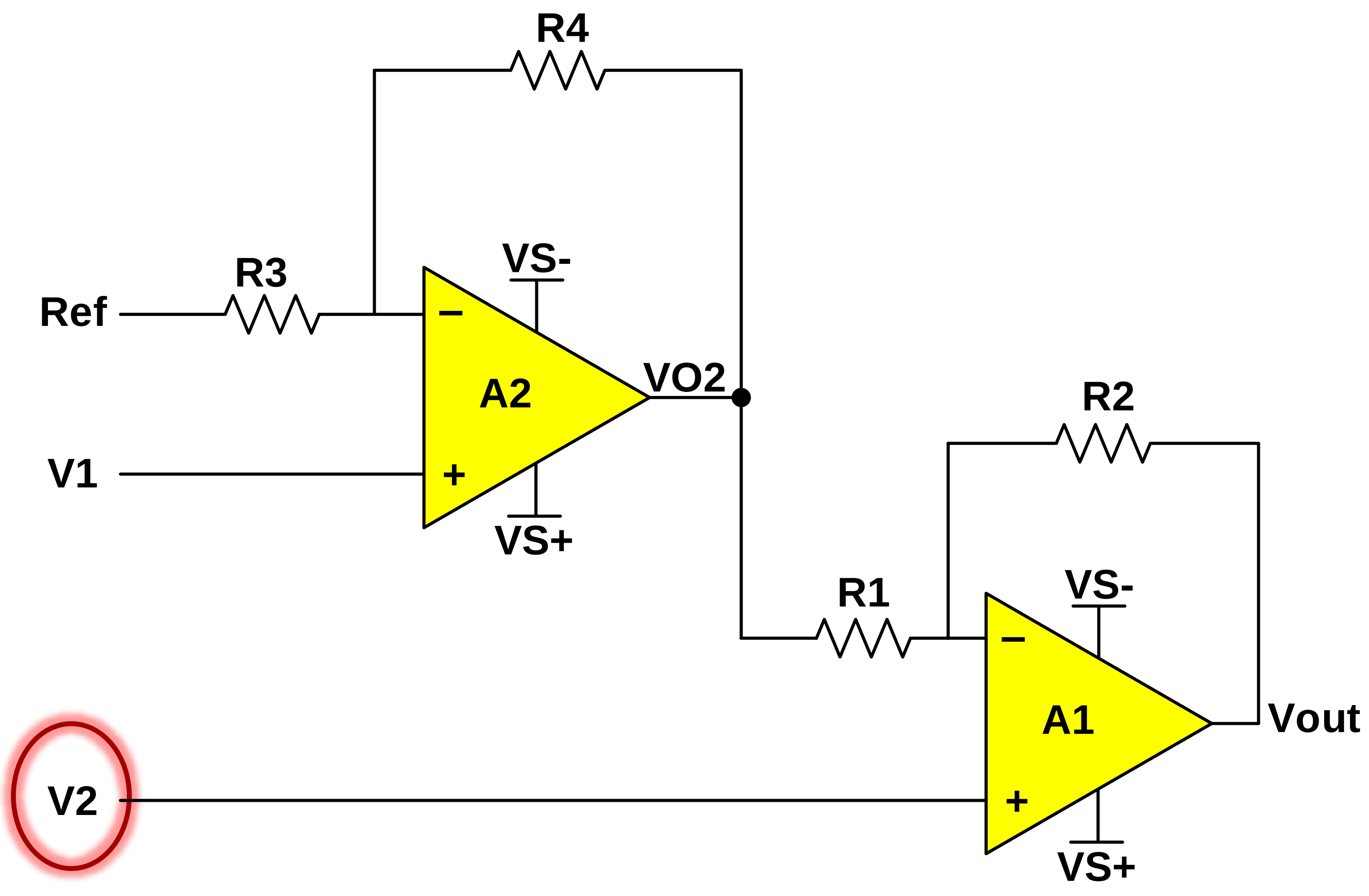
Ground VO2:

Looks like non-inverting configuration,

$$Vout = \left(1 + \frac{R2}{R1}\right) \times V2$$

Equation V2*

# IA topologies – 2 amp IA derivation; A1 derivation




Derive output of A1 using superposition theorem:

| Equation | V2 | VO2 |
|---|---|---|
| V2* | Keep | Short |
| VO2* | Short | Keep |
| **Vout = V2* + VO2*** | | |

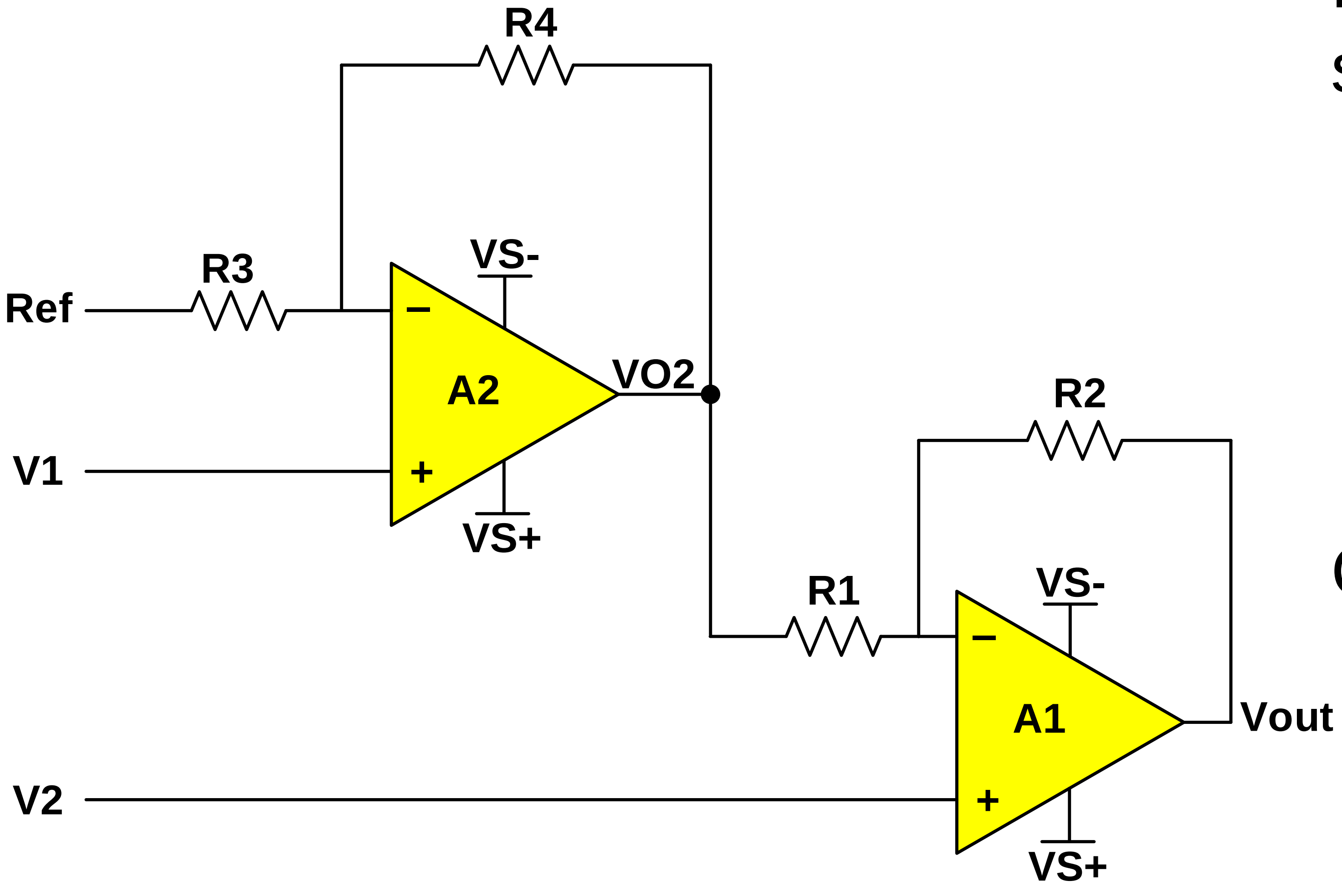
Ground V2:

Looks like an inverting configuration,

$$Vout = \frac{-R2}{R1} \times VO2$$

Equation VO2*

# IA topologies – 2 amp IA derivation; A1 derivation




Derive output of A1 using superposition:

| Equation | V2 | VO2 | |
|---|---|---|---|
| V2* | Keep | Short | V2* = $\left(1+\frac{R2}{R1}\right)\times V2$ |
| VO2* | Short | Keep | VO2* = $\frac{-R2}{R1}\times VO2$ |
| **Vout = V2* + VO2*** | | | |

Combine V2* and VO2* to yield Vout:

$$Vout = \left(1+\frac{R2}{R1}\right)\times V1 - \frac{R2}{R1}\times VO2 \text{ (eq1)}$$

$$VO2 = \frac{-R4}{R3}\times Ref + \left(1+\frac{R4}{R3}\right)\times V1 \text{ (eq2)}$$

$$Vout = \left(1+\frac{R2}{R1}\right)\times V2 - \frac{R2}{R1}\times\left[\frac{-R4}{R3}\times Ref + \left(1+\frac{R4}{R3}\right)\times V1\right]$$

# IA topologies – 2 amp IA derivation; simplified

$$Vout = \left(1 + \frac{R2}{R1}\right) \times V2 - \frac{R2}{R1} \times \left[\frac{-R4}{R3} \times Ref + \left(1 + \frac{R4}{R3}\right) \times V1\right]$$

Assuming R4 = R1 and R3 = R2:

$$Vout = \left(1 + \frac{R2}{R1}\right) \times V2 - \frac{R2}{R1} \times \left[\frac{-R1}{R2} \times Ref + \left(1 + \frac{R1}{R2}\right) \times V1\right]$$

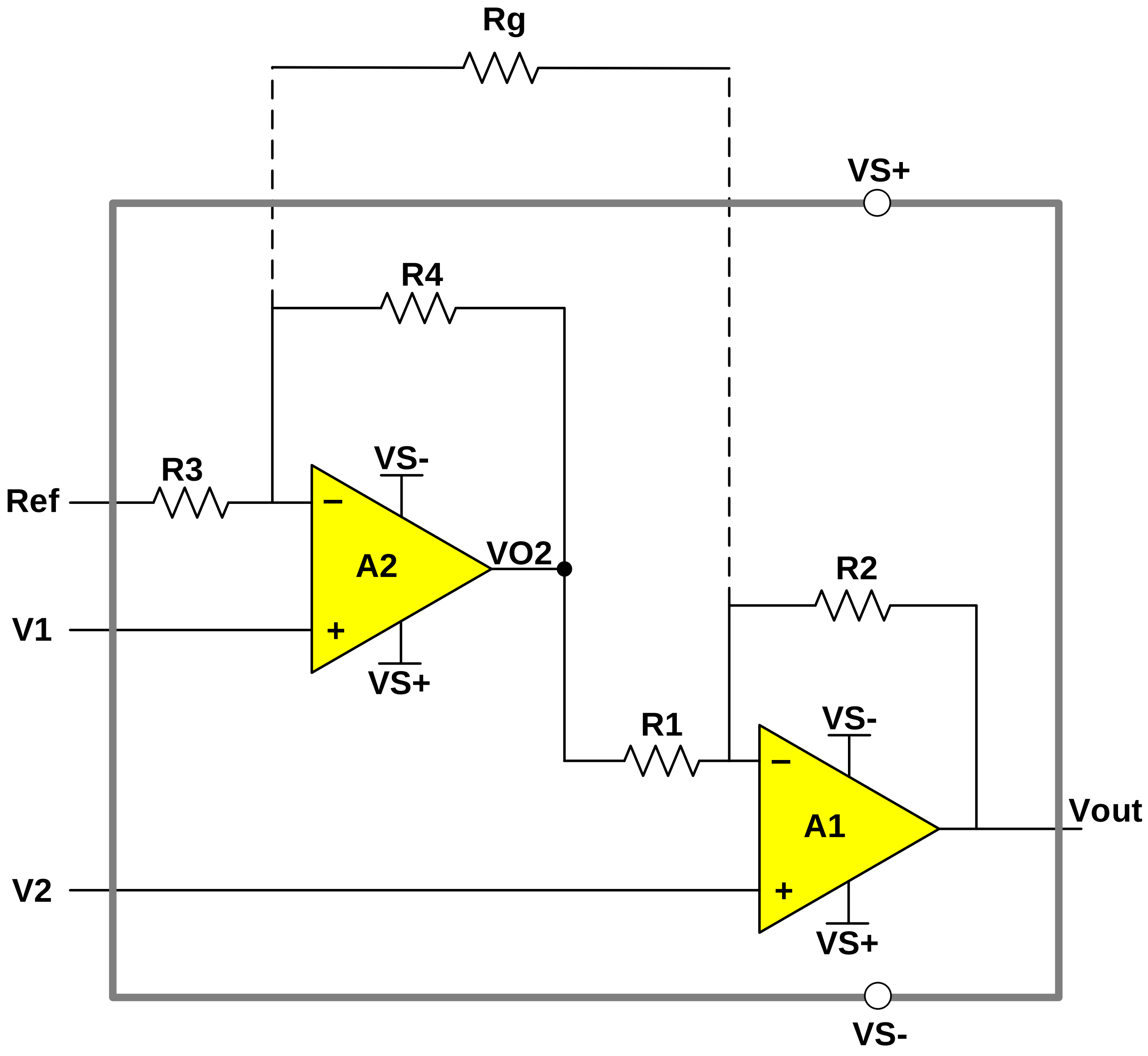
Simplify…

$$Vout = \left(1 + \frac{R2}{R1}\right) \times (V2 - V1) + Ref$$

Ad

Vd

# 2 amp IA – Gain control & driving the Ref pin




**Goal:** Set the gain of the entire circuit with one additional resistor

Adding resistor Rg yields the following output equation:

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

## Resistor matching recap:

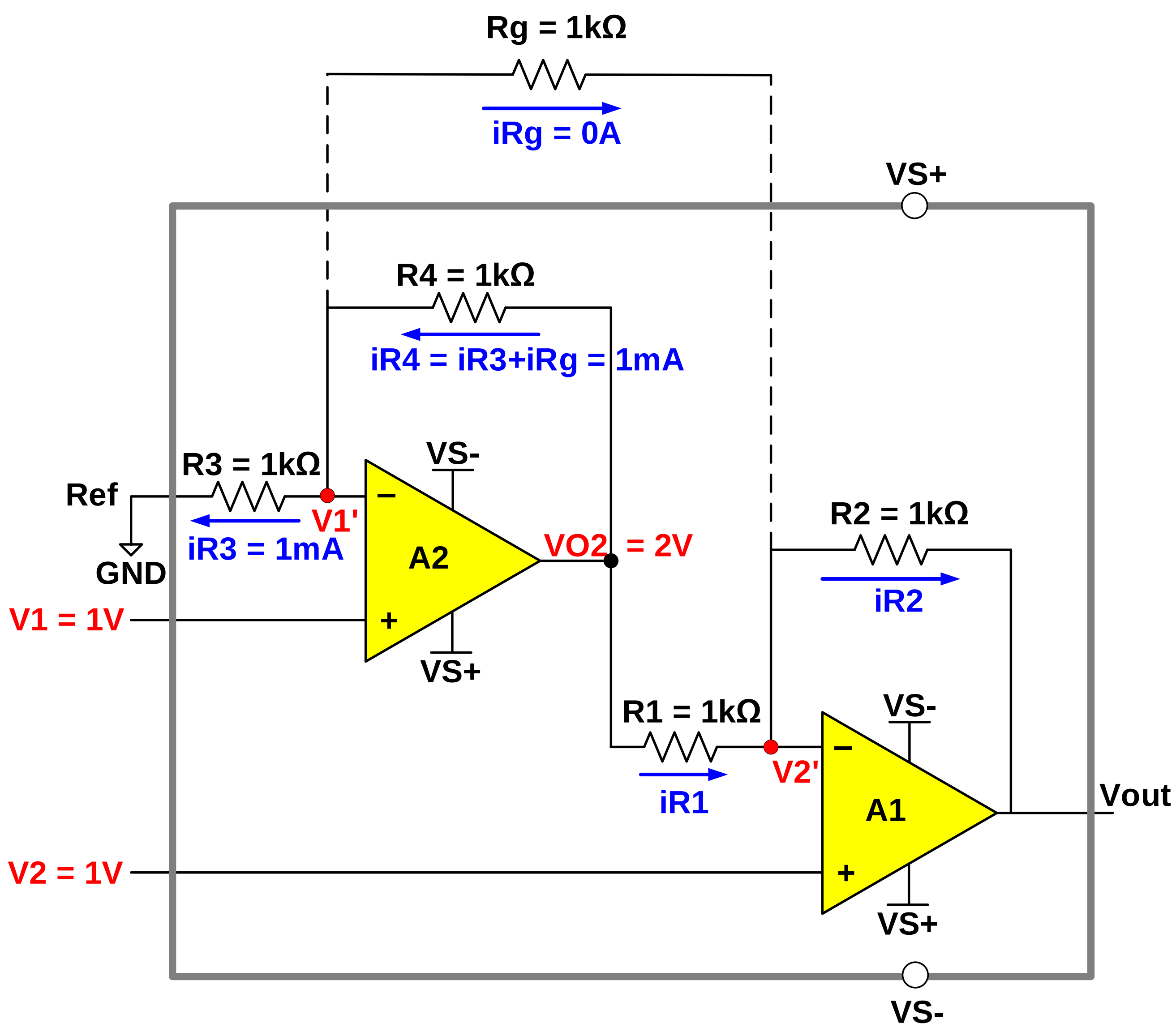
Aim for R4 = R1 and R3 = R2

In an integrated solution, R1, R2, R3, and R4 are absolutely matched in production.

## Reference voltage recap:

Drive with low-impedance source, such as a buffer or voltage reference

# 2 amp IA – ACM analysis and performance




**Common mode gain** $= A_{CM} = \frac{V_{OCM}}{V_{CM}} << 1$

Apply a 1V VCM (1V at V1 and V2)

Assume:

- Ref is grounded
- R1, R2, R3, R4 and Rg = 1kΩ

If V1 = 1V → V1' = 1V:

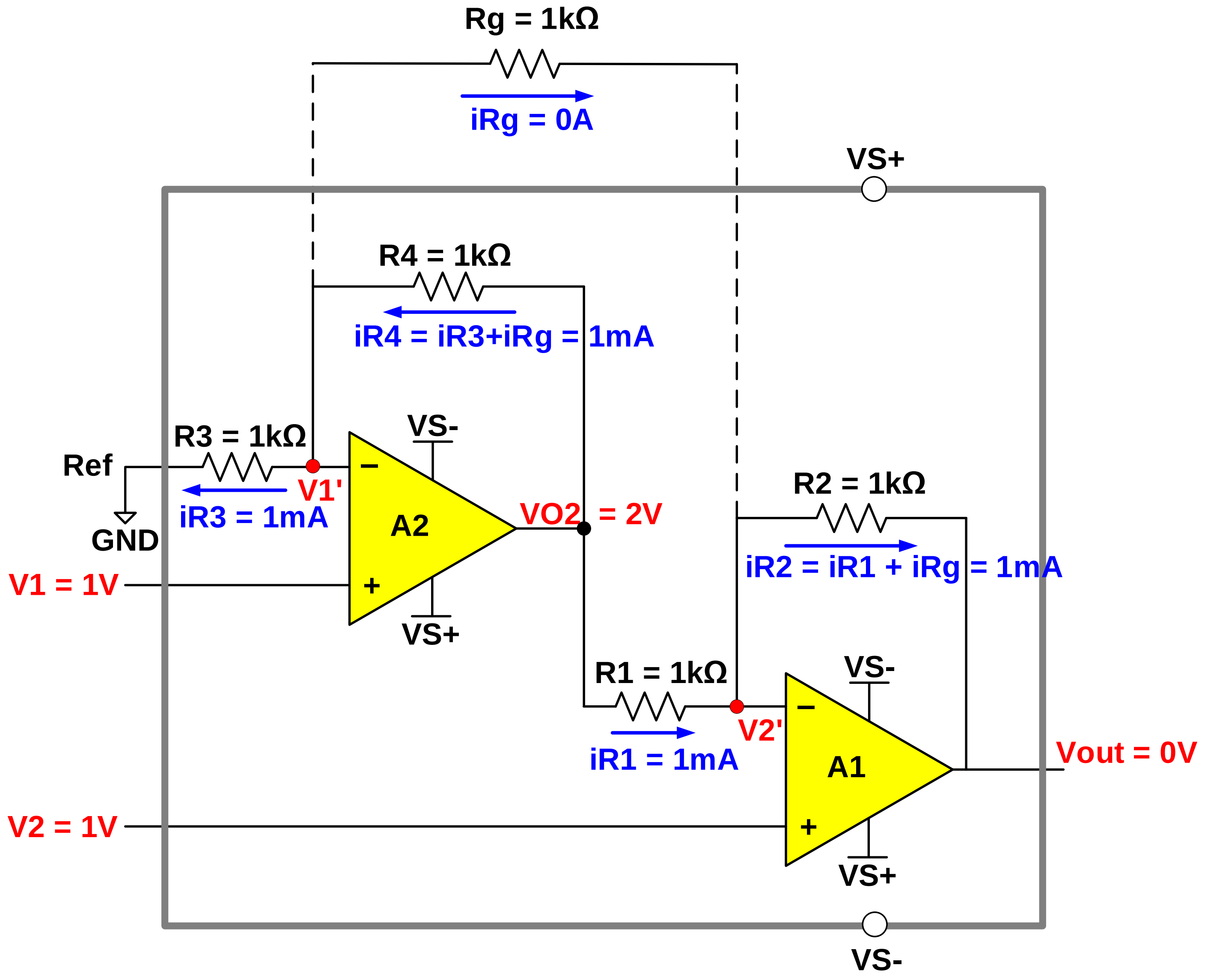
- Current flowing through R3 = 1V/1kΩ = 1mA

If V2 = 1V → V2' = 1V:

- V1'=V2'=1V, there is no current flowing through Rg, so iRg = 0A

- iR4 = iR3+iRg = 1mA,
  - Voltage drop across R4 is 1V, so VO2 = 2V

# 2 amp IA – ACM analysis and performance cont'd




VO2 = 2V and V2' = 1V:

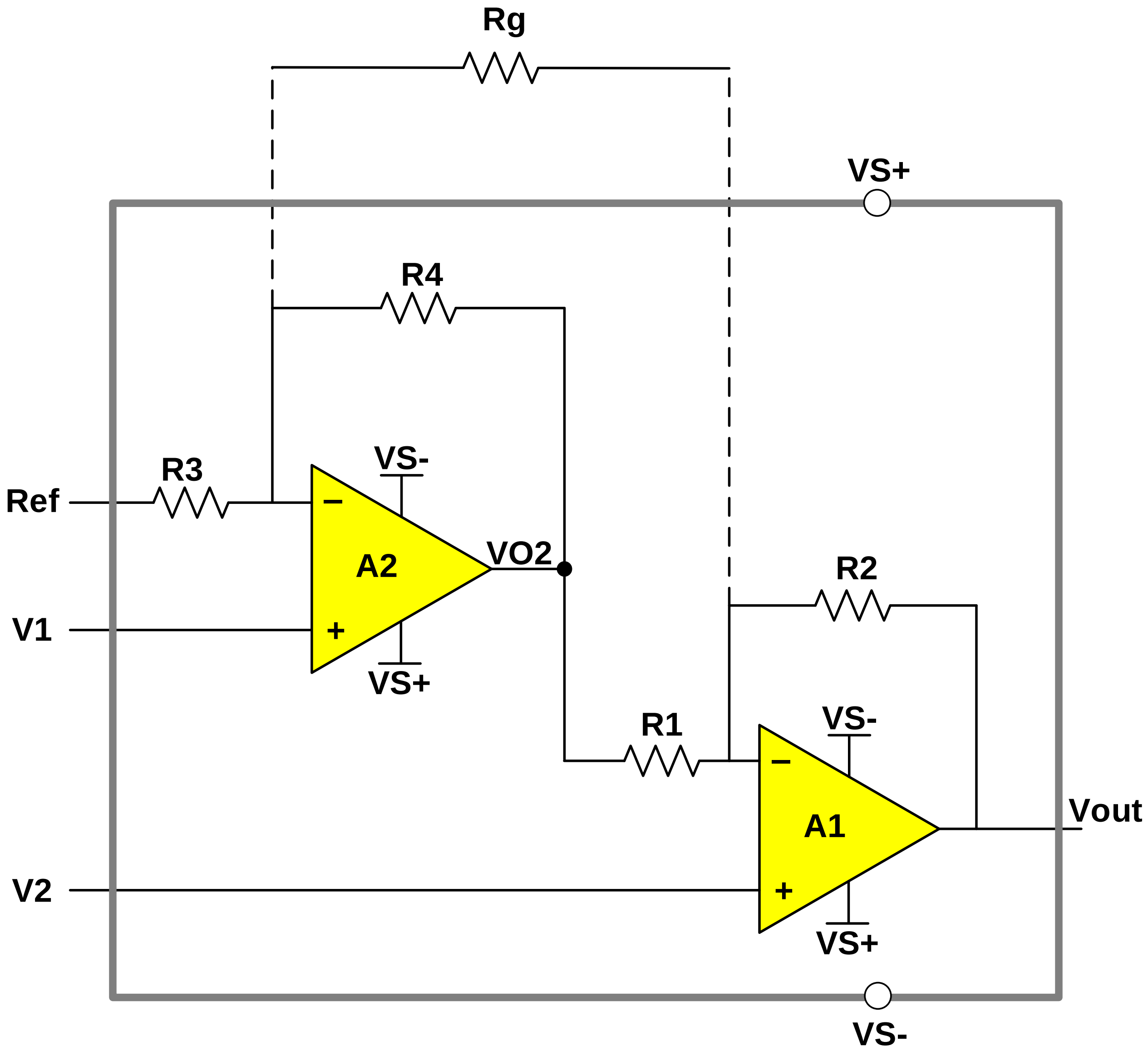
– current flowing through R1 is 1V/1kΩ = 1mA

iR2 = iRg + 1R1 = 1mA

Voltage drop across R2 is 1V, so Vout = 0V

**The two-amp IA was able to reject the common mode voltage (VCM)**

# 2 amp IA topology drawbacks – Gain




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

Ad = differential gain = $1 + \frac{R2}{R1} + \frac{2 \times R2}{Rg}$

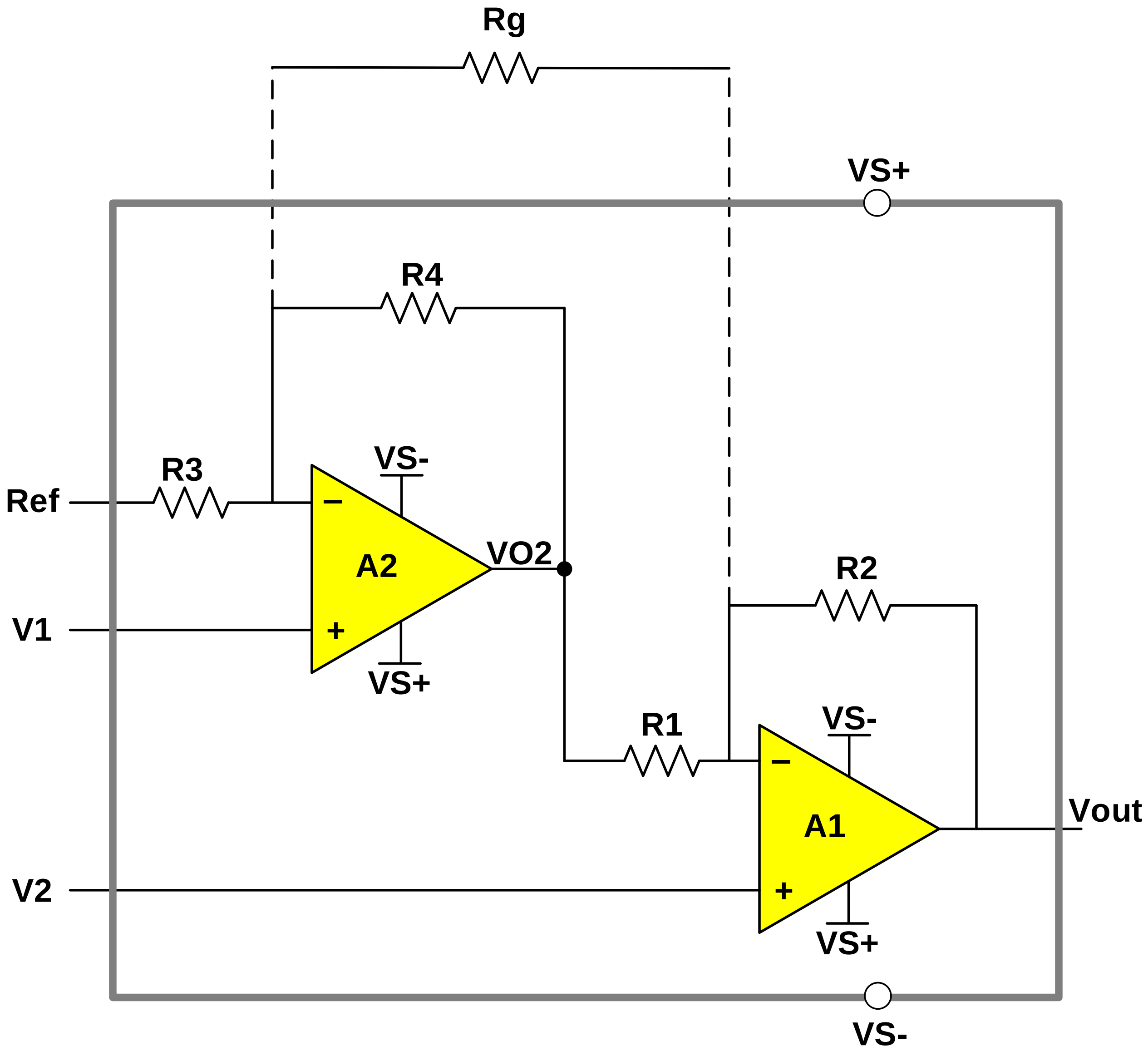
Vd = differential voltage = V2 – V1

Ref = reference voltage, level shifting term

**Drawback:**

- Ad cannot be 1V/V due to the addition of 1 in the gain equation: $\mathbf{1} + \frac{R2}{R1} + \frac{2 \times R2}{Rg}$

# 2 amp IA topology drawbacks – Headroom




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

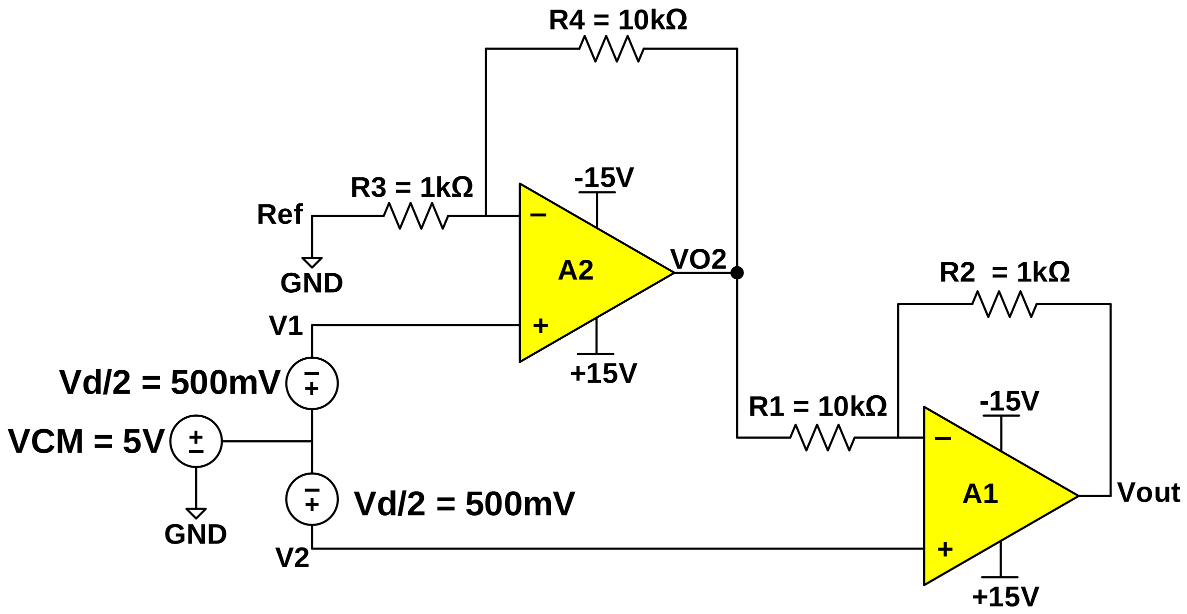
**Drawback:**

- Headroom:
  - Low gain: If R4 >> R3, A2 will saturate if V1 VCM is too high, leaving no headroom for A2 to amplify the wanted signal
  - High gain: If R4 << R3, there is more headroom at VO2, allowing for higher VCM

*Note: Ref = 0V

# 2 amp IA topology drawbacks – Headroom cont'd

$$Vout = \left(1 + \frac{R2}{R1} + \frac{2 \times R2}{Rg}\right) \times (Vd) + \text{Ref}$$



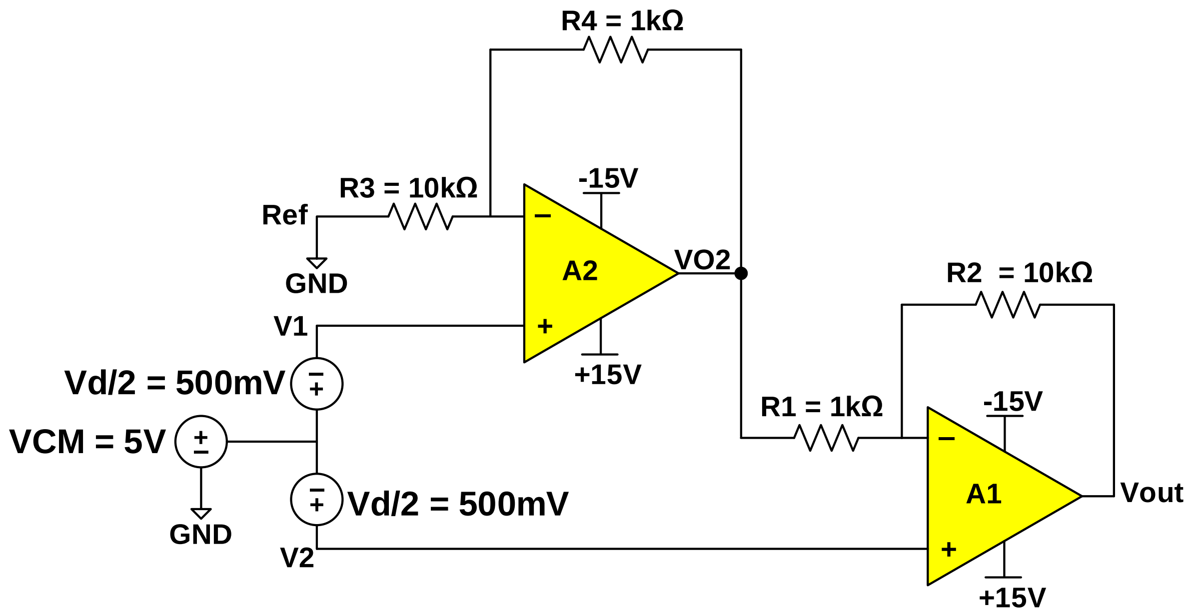

**Low gain example: R4 >> R3**

Assume A1 and A2 are powered by ±15V supplies

Ad = 1.1 V/V, Vd = 1V

VCM = 5 V, Ref = 0V

Expected output Vout = Ad × Vd + Ref = 1.1 V




**High gain example: R4 << R3**

Assume A1 and A2 are powered by ±15V supplies

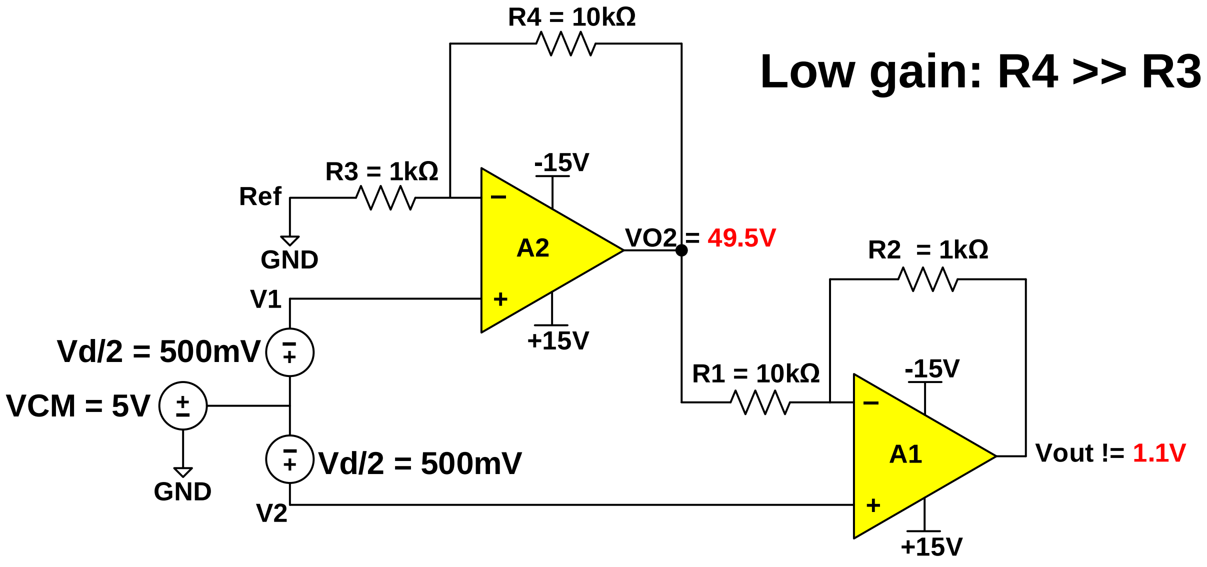
Ad = 11 V/V, Vd = 1V

VCM = 5 V, Ref = 0V

Expected output Vout= Ad × Vd + Ref = 11 V

# 2 amp IA topology drawbacks – Headroom cont'd

$$Vout = \left(1 + \frac{R2}{R1} + \frac{2 \times R2}{Rg}\right) \times (Vd) + \text{Ref}$$




**Low gain: R4 >> R3**

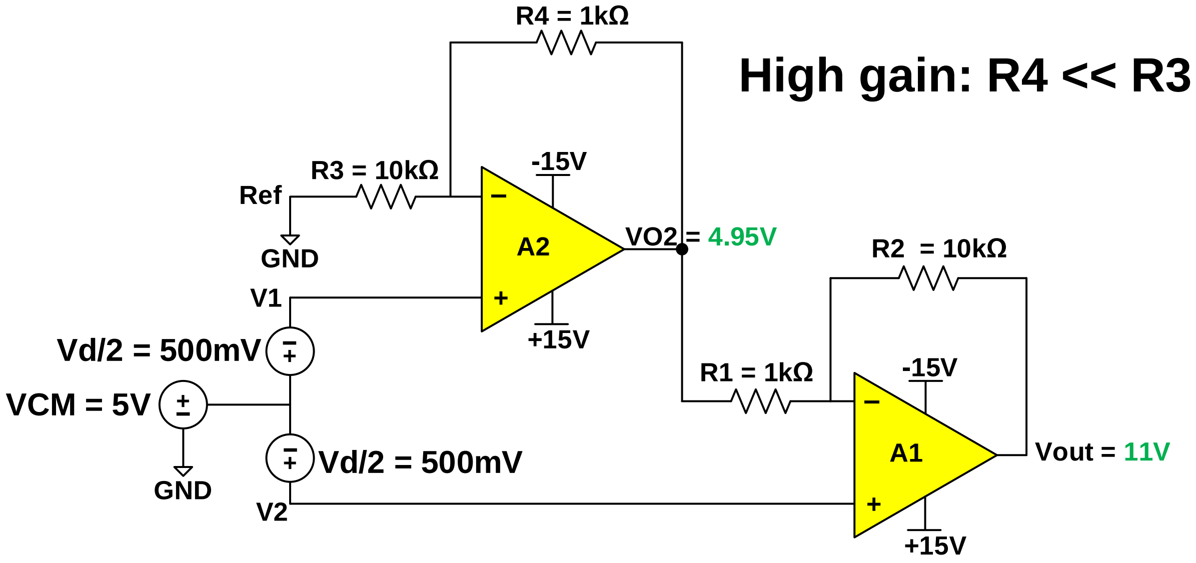
A1 and A2: ±15V supplies, RRIO

Ad = 1.1 V/V, Vd = 1V, VCM = 5V, Ref = 0V

Expected output Vout = Ad × Vd + Ref = 1.1 V

VO2 = **49.5V**

Vout != **1.1V**




**High gain: R4 << R3**

A1 and A2: ±15V supplies, RRIO

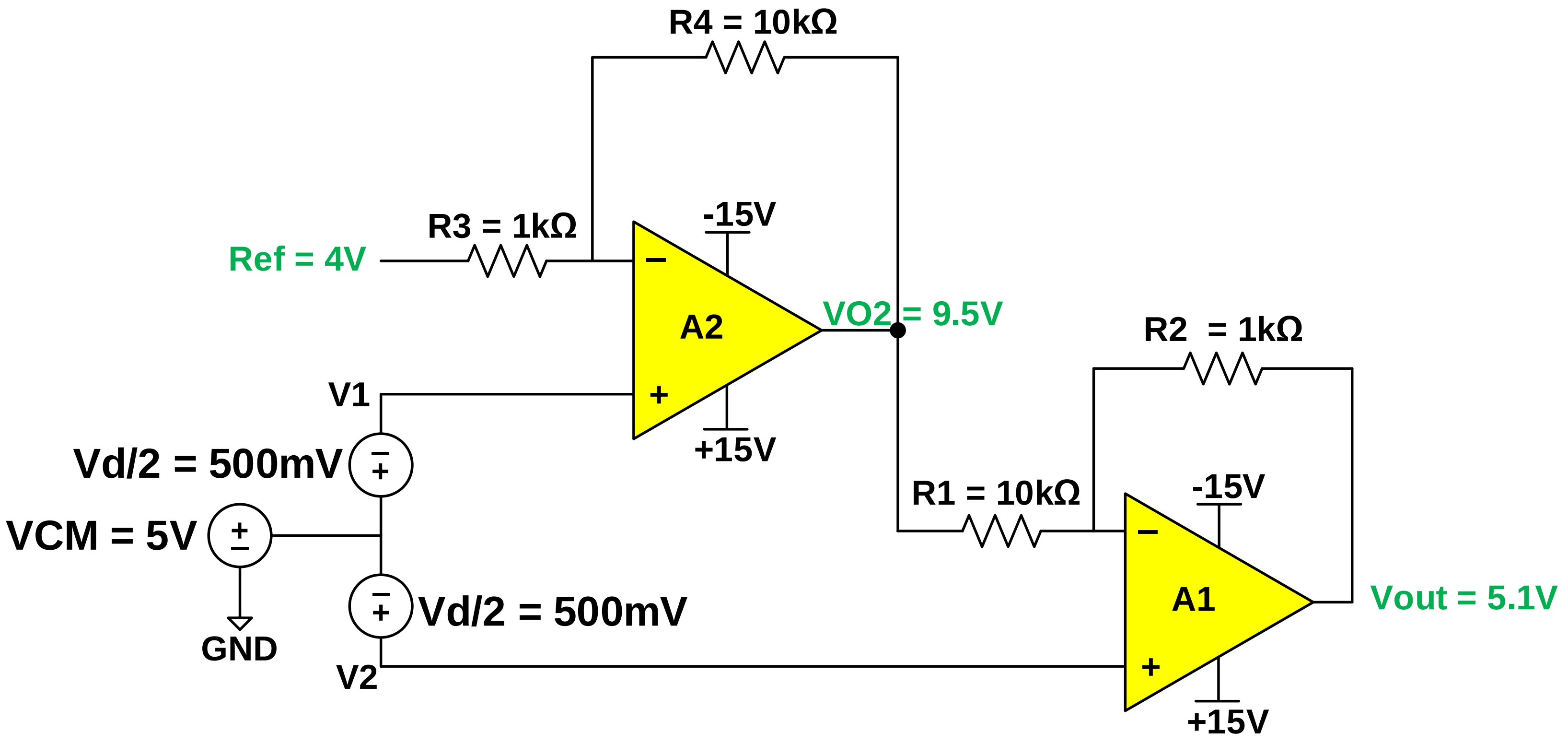
Ad = 11 V/V, Vd = 1V, VCM = 5V, Ref = 0V

Expected output Vout= Ad × Vd + Ref = 11 V

**VO2 = 4.95V**

**VOUT = 11V**

# 2 amp IA topology drawbacks – Headroom cont'd




$$Vout = \left(1 + \frac{R2}{R1} + \frac{2 \times R2}{Rg}\right) \times (\mathrm{Vd}) + \mathrm{Ref}$$

**Low gain: R4 >> R3**

- A1 and A2: ±15V supplies, RRIO
- Differential gain (Ad) = 1.1 V/V
- Differential voltage (Vd) = 1V
- Common mode voltage (VCM) = 5V
- Reference voltage (Ref) = 4V

**Expected output:**

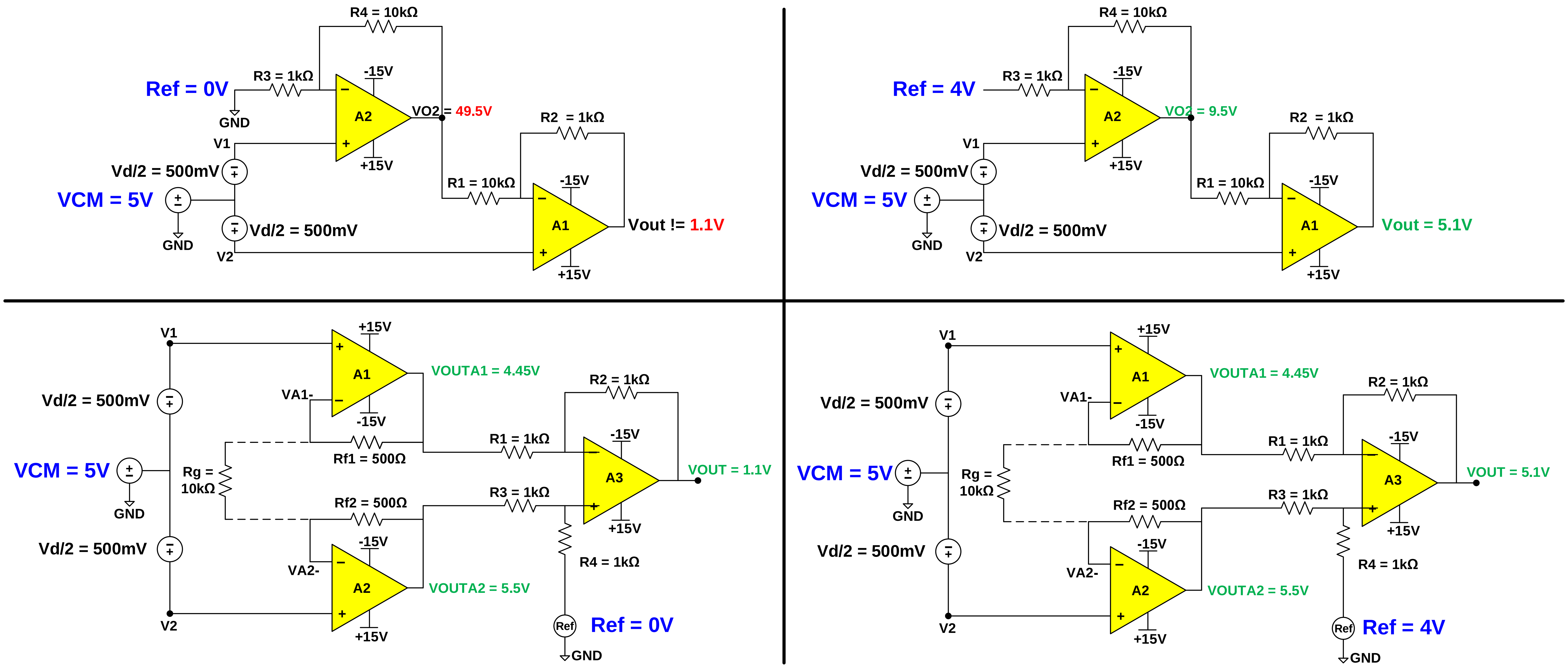
Vout = Ad × Vd + Ref = 5.1 V

VO2 = **9.5V**

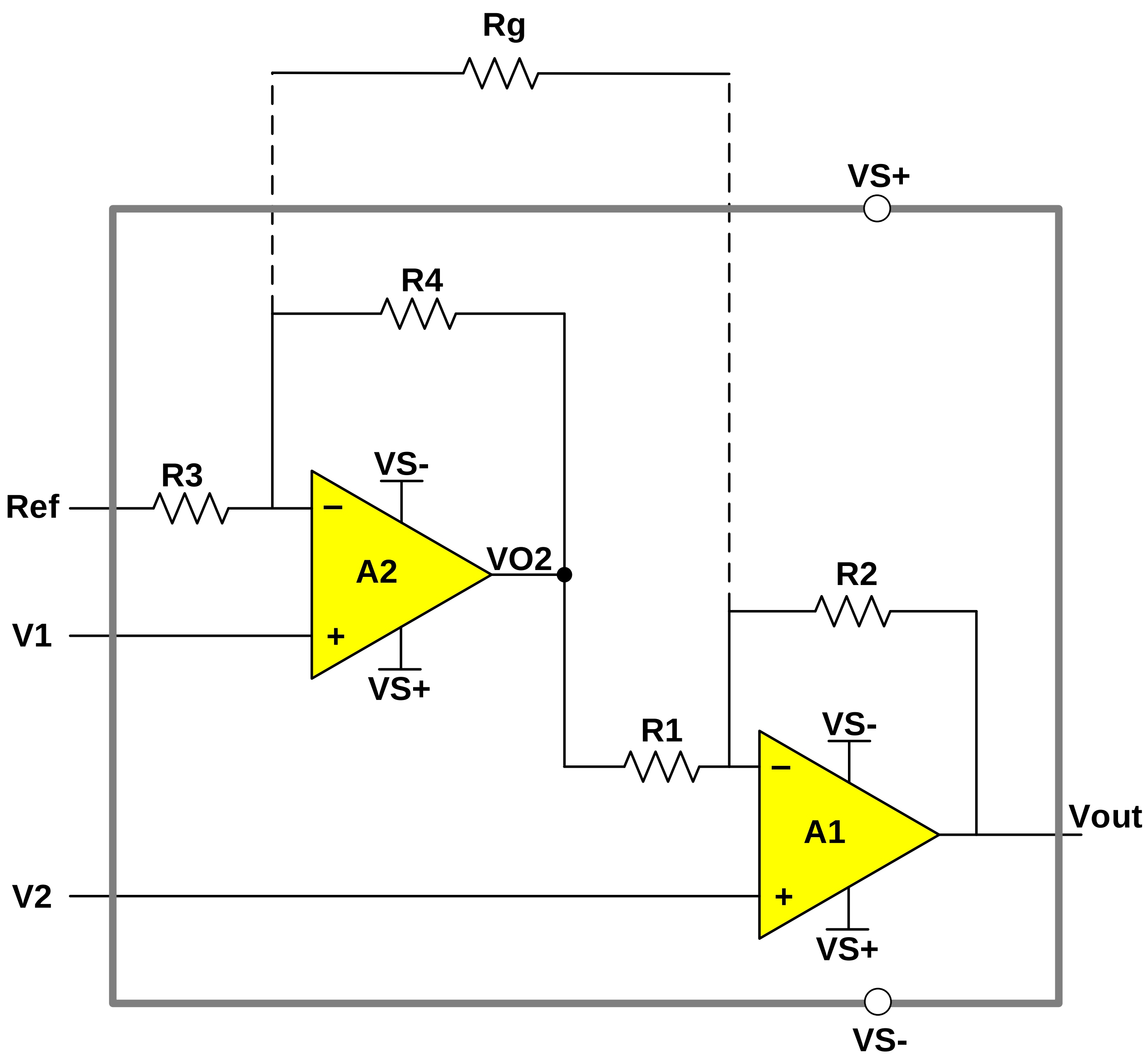
Vout = **5.1V**

# 2 amp IA vs 3 amp IA – Headroom

Ad = 1.1V/V, Vd = 1V, VCM = 5V
Ref = 0V or 4V
Expected Vout = 1.1V or 5.1 V



# 2 amp IA topology drawbacks – AC CMRR




**Drawback:**

- AC CMRR:
  - Path from V1 to Vout has an additional phase shift of A2

**Example:**

Assume we apply VCM at FCM to V1 and V2.

Expected common mode error = 0V which means A1 needs to see 0 difference between V2 and VO2.

Phase shift introduced by A2 causes the phase of VO2 to lag behind V2 → frequency-dependent common mode voltage error at Vout

# 2 amp IA – Example

Assume the following conditions:

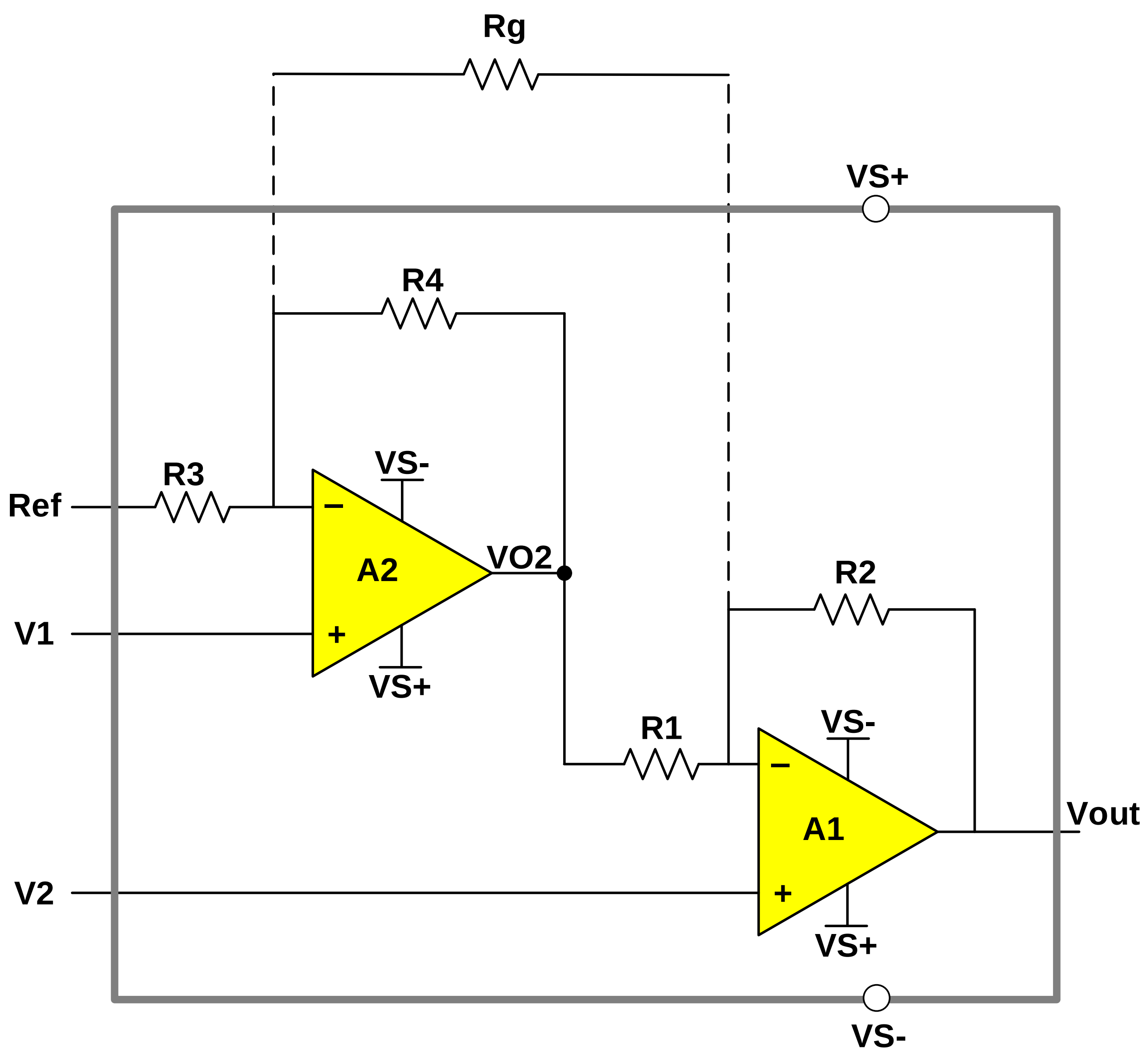
Voltage supplies = ±10V, Ref = 0V

Vd = 10mV, VCM = 2V

Expected Vout = 3V

**4 design steps:**

1. Determine gain required
2. Find IA & check boundary plot
3. Determine Rg required
4. Build and simulate with confidence



# 2 Amp IA – Example cont'd

## 1. Determine gain required

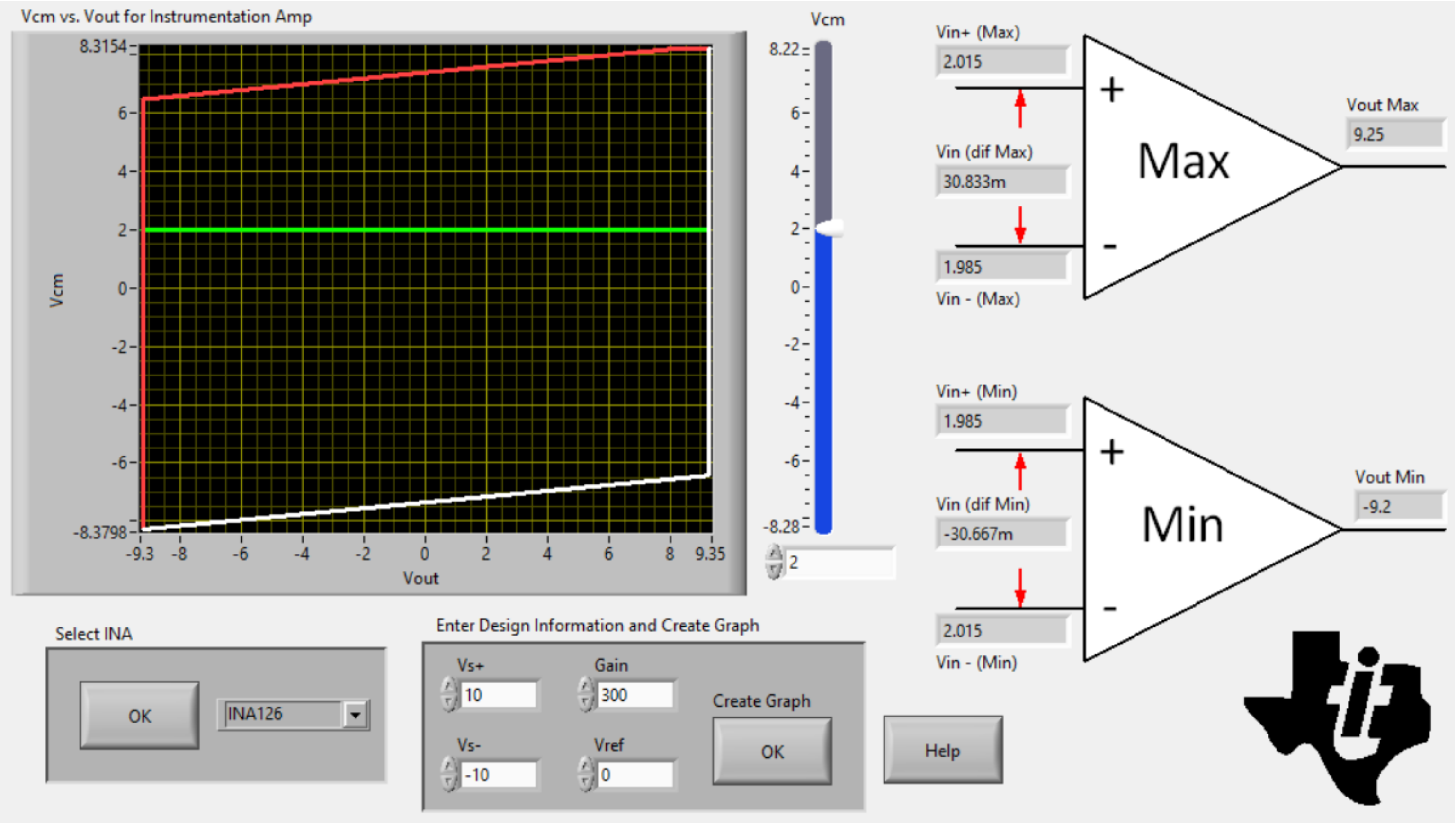
$$Gain = \frac{\Delta Vout}{\Delta Vin} = \frac{3V}{10mV} = 300V/V$$

## 2. Find IA & check boundary plot

IA selected: INA126

Plug in supply, gain, ref and VCM

Make sure our expected input & output voltages are within range



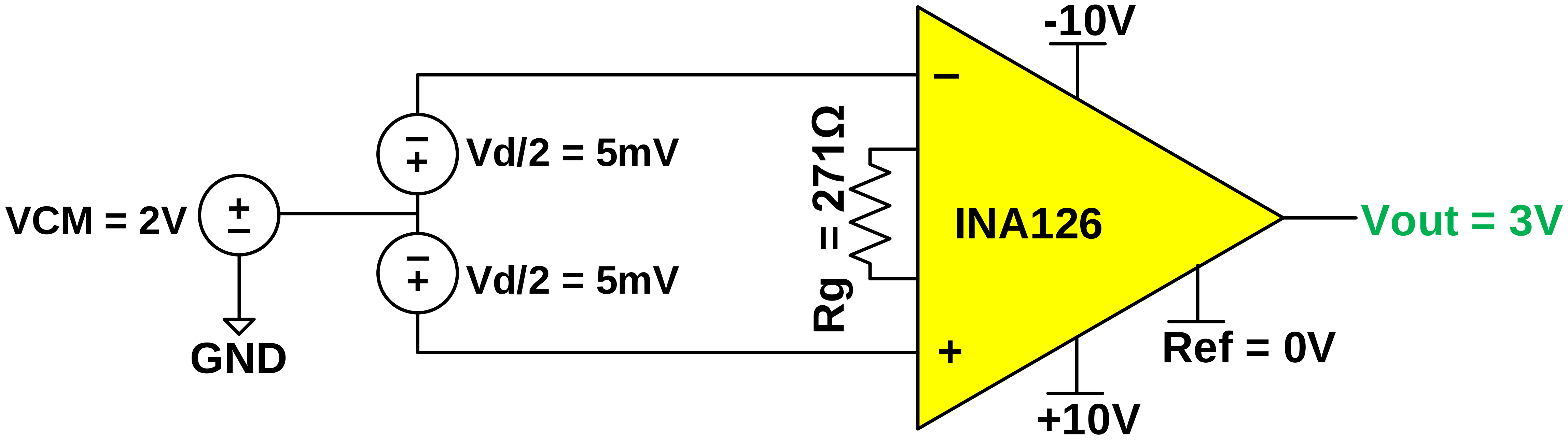

[Analog engineer's calculator → INA VCM vs Vout]

# 2 amp IA – Example cont'd

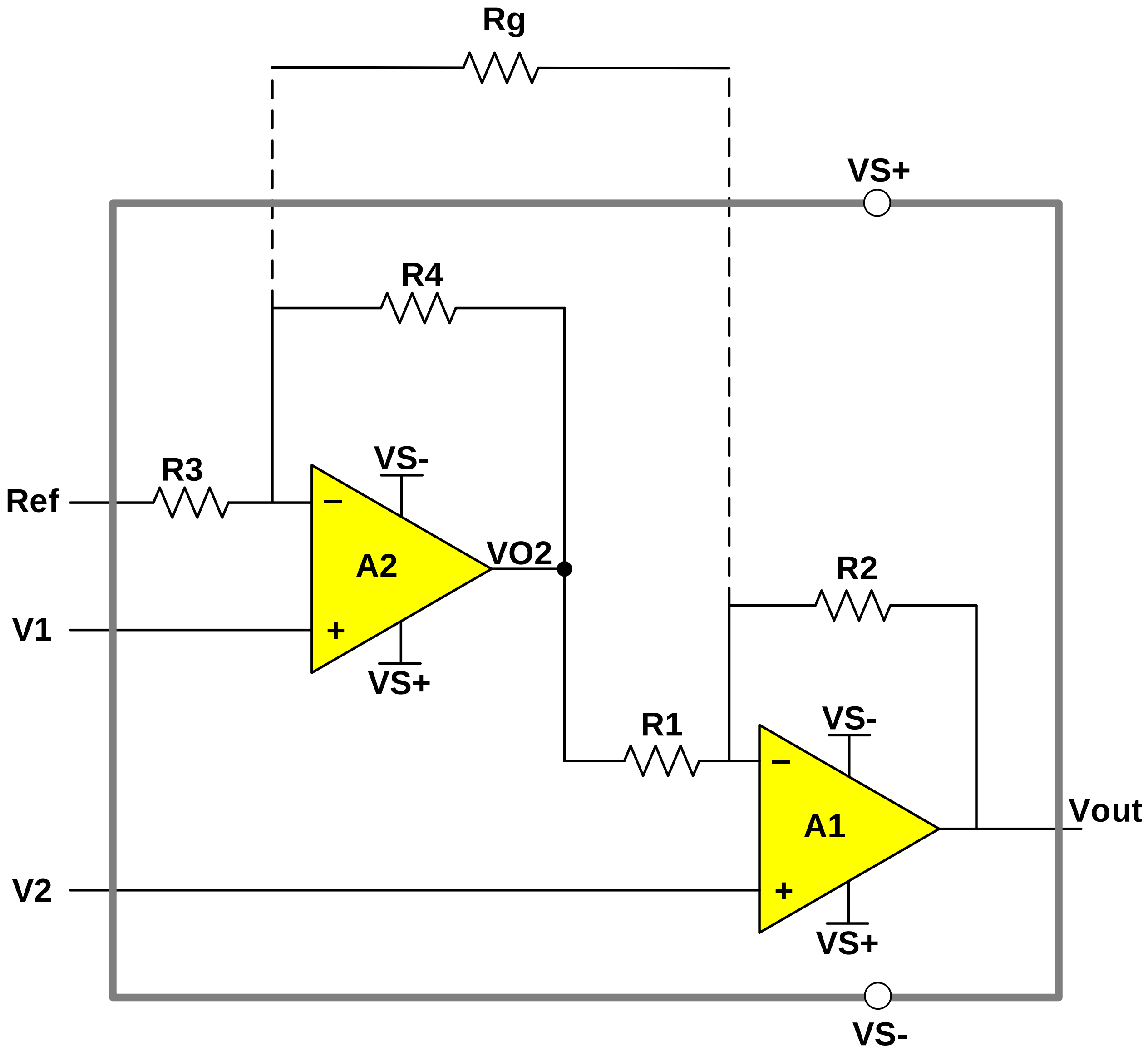
## 3. Determine Rg required

INA126 datasheet → $Gain = 5 + \frac{80k}{Rg} \rightarrow \text{Rg} = 271\Omega$

## 4. Build and simulate with confidence



# 2 amp IA – Summary of benefits and drawbacks




## Benefits:

- Fewer resistors, must need to be well matched → pick an integrated IA
- Fewer amplifiers → lower cost
- High input impedance

## Drawbacks:

- Minimum gain limitation (> 1V/V minimum)
- Gain vs headroom
- CMRR vs frequency
- Common mode voltage must be within the power supply rails

# Thanks for your time!
# Please try the quiz.

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

# Quiz: Instrumentation Amplifier (IA) topologies: two-amp

## TI Precision Labs – Instrumentation Amplifiers

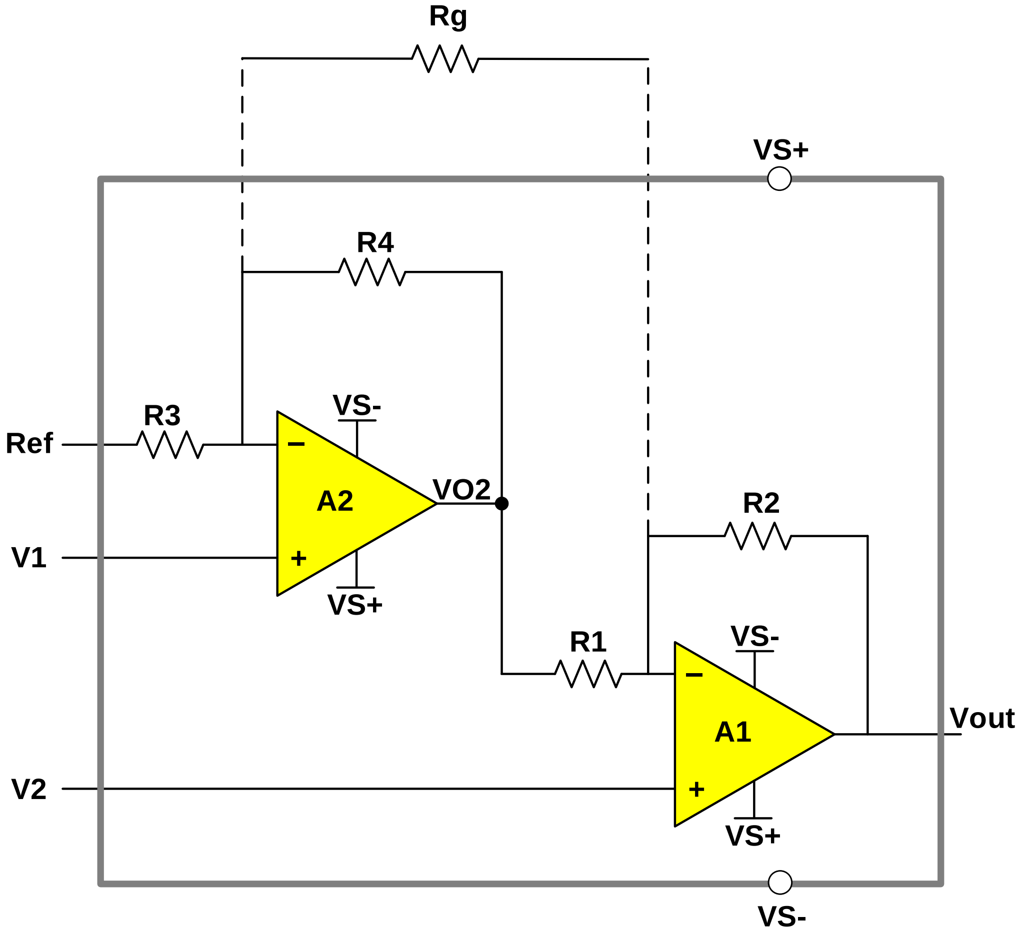
**Presented by Tamara Alani**

**Prepared by Tamara Alani**

# Quiz: (IA) topologies: two-amp || Question

1. What are some challenges associated with the two-amp IA topology? Select all that apply.

   a) The path from V1 to Vout has an additional phase shift of A2
   a) The two-amp IA must be configured in gains > 1 V/V
   a) The two-amp IA consumes more power
   b) There is trade-off between VCM and Ref to Gain



# Quiz: (IA) topologies: two-amp || Answer

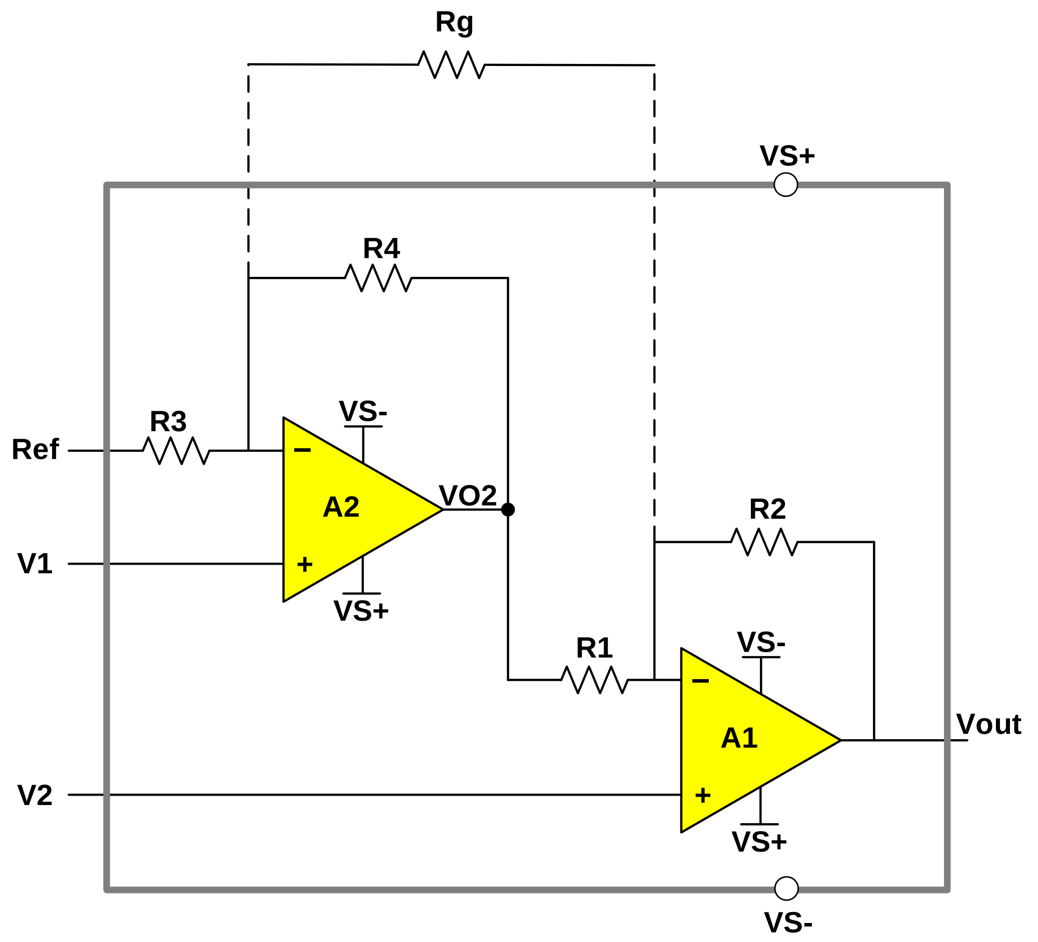
1. What are some challenges associated with the two-amp IA topology? Select all that apply.

   a) **The path from V1 to Vout has an additional phase shift of A2**

   a) **The two-amp IA must be configured in gains > 1 V/V**

   a) The two-amp IA consumes more power

   b) **There is trade-off between VCM and Ref to Gain**



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

2. Which of the following statements is false regarding the reference pin on a two-amp IA?

   a) The ref pin must be driven by a low-impedance source
   b) The ref pin is used to level-shift the output of the IA
   c) The ref pin should be able to source and sink current
   d) The ref pin may be driven by a resistor divider so long as the resistors are low tolerance

# Quiz: (IA) topologies: two-amp || Answer

2. Which of the following statements is false regarding the reference pin on a two-amp IA?

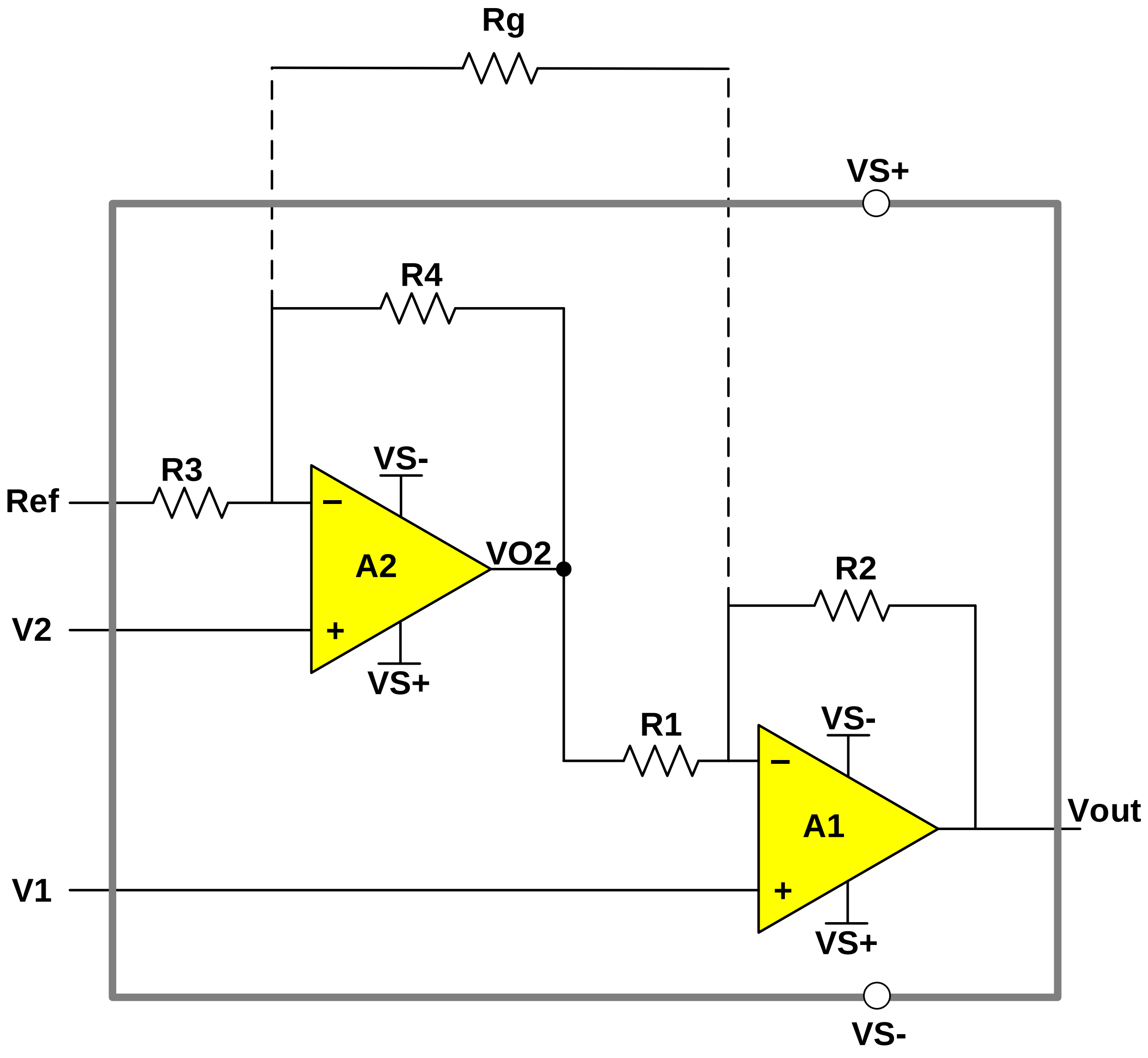
   a) The ref pin must be driven by a low-impedance source
   b) The ref pin is used to level-shift the output of the IA
   c) The ref pin should be able to source and sink current
   d) **The ref pin may be driven by a resistor divider so long as the resistors are low tolerance**

# Quiz: (IA) topologies: two-amp || Question

3. In a two-amp IA, which resistors do we aim to match?

   a) R4 = R1 and R2 = R3

   b) R4 = R3 and R2 = R1

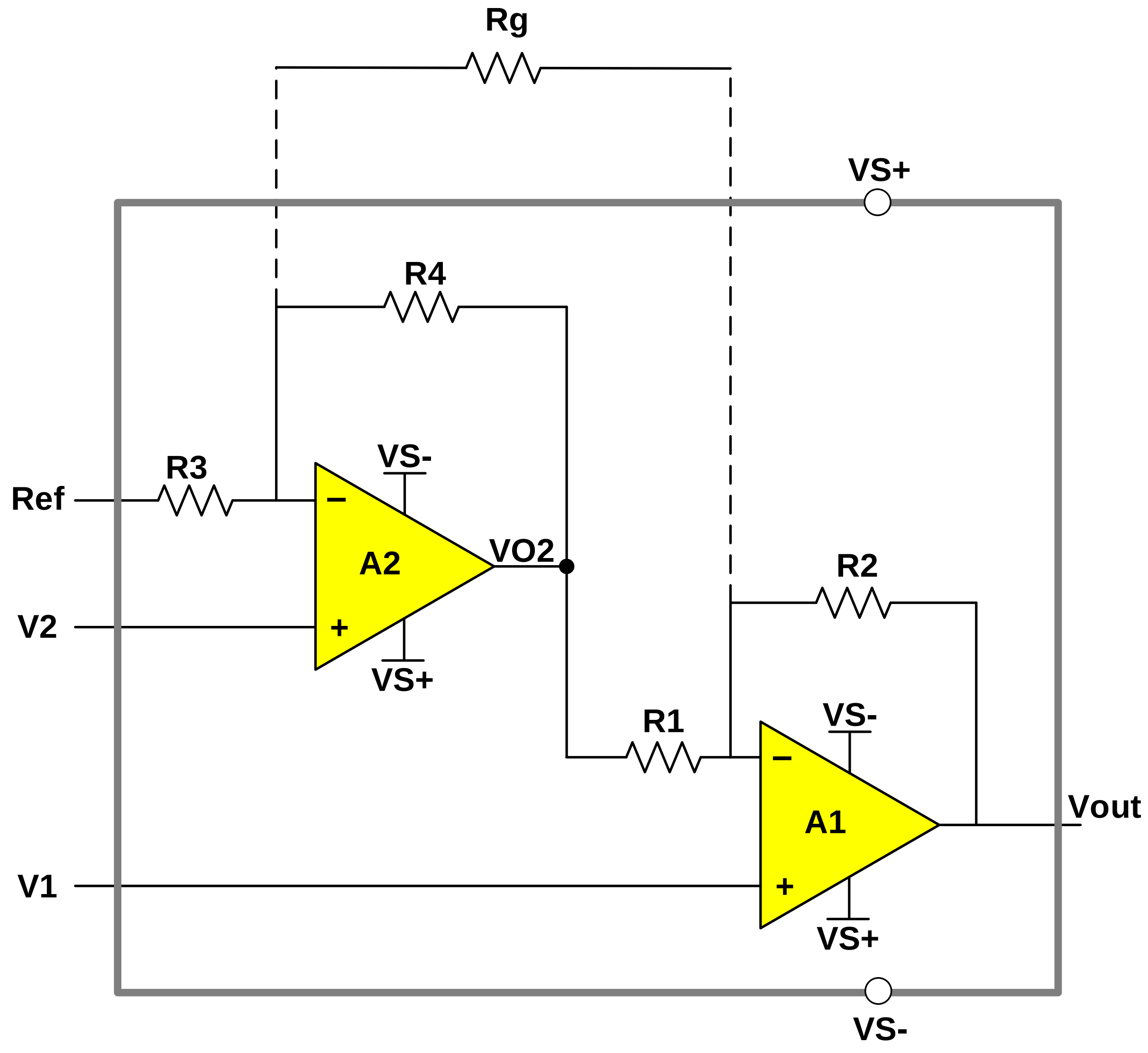


# Quiz: (IA) topologies: two-amp || Answer

3. In a two-amp IA, which resistors do we aim to match?

   a) **R4 = R1 and R2 = R3**

   b) R4 = R3 and R2 = R1



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

4. What is the gain equation of a two-amp IA, assuming we match R4 to R1 and R3 to R2?

   a) Gain = $1 + 2 \times R2$
   b) Gain = $1 + \frac{R1}{R2}$
   c) Gain = $1 + \frac{R2}{R1}$
   d) Gain = $2 \times (R1 + R2)$

HINT:

Go to the product datasheet: https://www.ti.com/lit/ds/symlink/ina126.pdf

# Quiz: (IA) topologies: two-amp || Answer

4. What is the gain equation of a two-amp IA, assuming we match R4 to R1 and R3 to R2?

   a) Gain = $1 + 2 \times R2$

   b) Gain = $1 + \frac{R1}{R2}$

   **c) Gain = $1 + \frac{R2}{R1}$**

   d) Gain = $2 \times (R1 + R2)$

**HINT:**

Go to the product datasheet: https://www.ti.com/lit/ds/symlink/ina126.pdf

# Quiz: (IA) topologies: two-amp || Question

5. Using the INA126 (TI's micro-power IA), what value of Rg do you need to achieve a signal gain of 105V/V?

a) Rg = 100Ω
b) Rg = 200Ω
c) Rg = 800kΩ
d) Rg = 800Ω

**HINT:**

Go to the product datasheet:
https://www.ti.com/lit/ds/symlink/ina126.pdf

# Quiz: (IA) topologies: two-amp || Answer

5. Using the INA126 (TI's micro-power IA), what value of Rg do you need to achieve a signal gain of 105V/V?

a) Rg = 100Ω
b) Rg = 200Ω
c) Rg = 800kΩ
**d) Rg = 800Ω**

HINT:

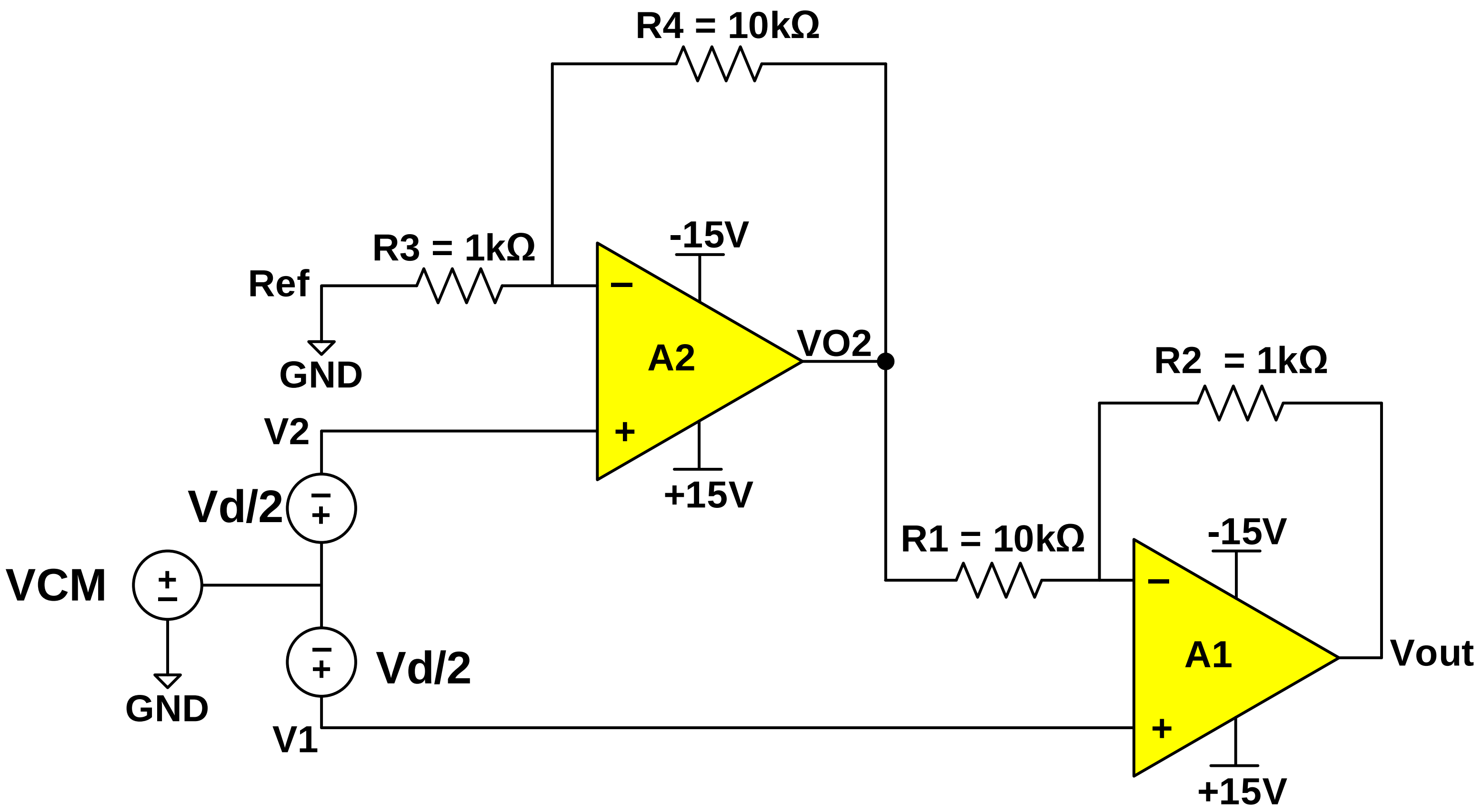
Go to the product datasheet:
https://www.ti.com/lit/ds/symlink/ina126.pdf

$$\text{Gain} = \left(5 + \frac{80\text{k}\Omega}{\text{Rg}}\right)$$

# Quiz: (IA) topologies: two-amp || Question

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

a) Gain = 1.1V/V
b) Gain = 2V/V
c) Gain = 0.1V/V
d) Gain = 10V/V



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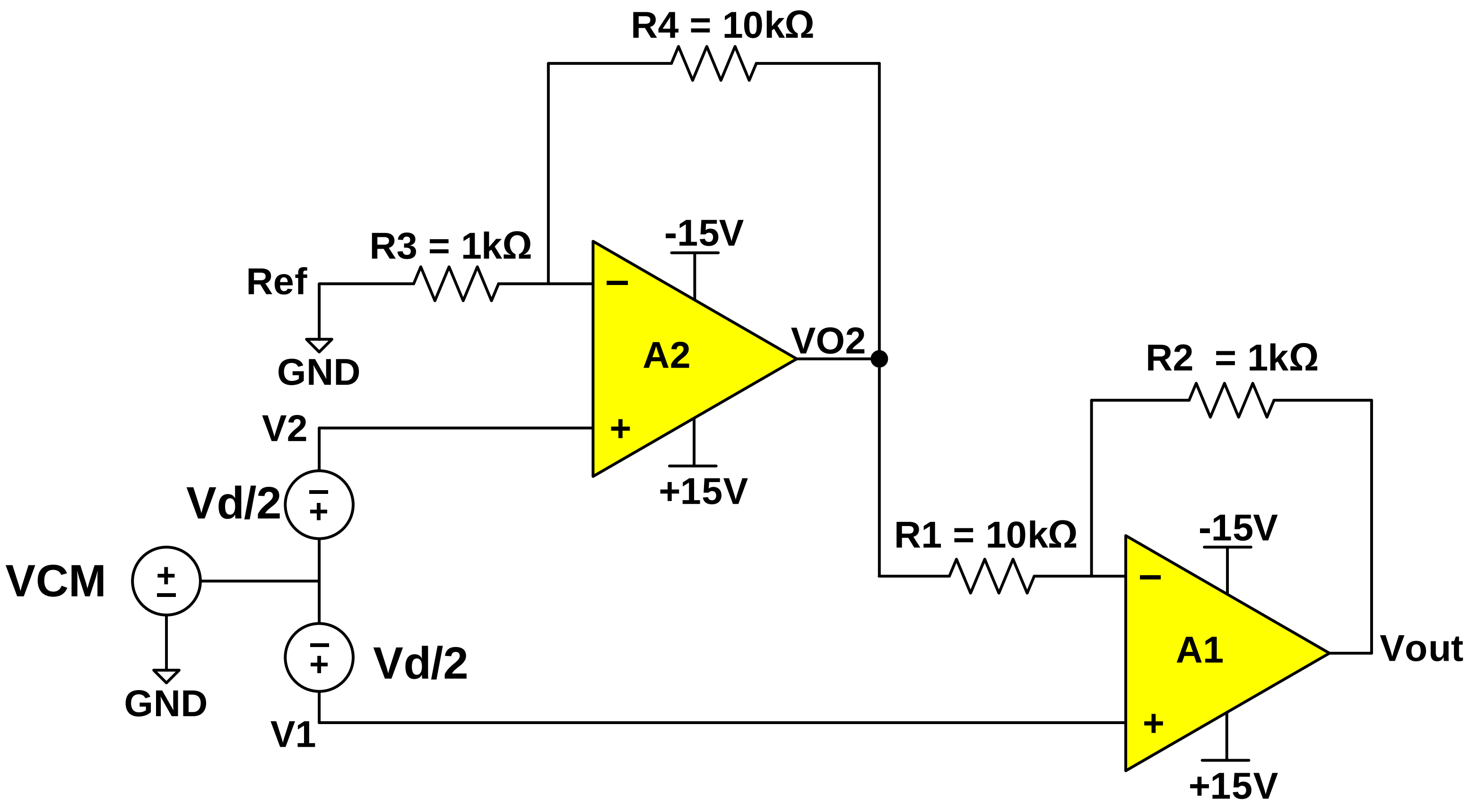

# Quiz: (IA) topologies: two-amp || Question

7. Using the INA156 (TI’s rail-to-rail output swing IA optimized for low-voltage, single-supply operation), create a boundary plot for the following conditions:

- Voltage supply = 5V single supply
- Gain = 10V/V
- Reference = 2.5V
- Common mode voltage = 2V

**HINT:**

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

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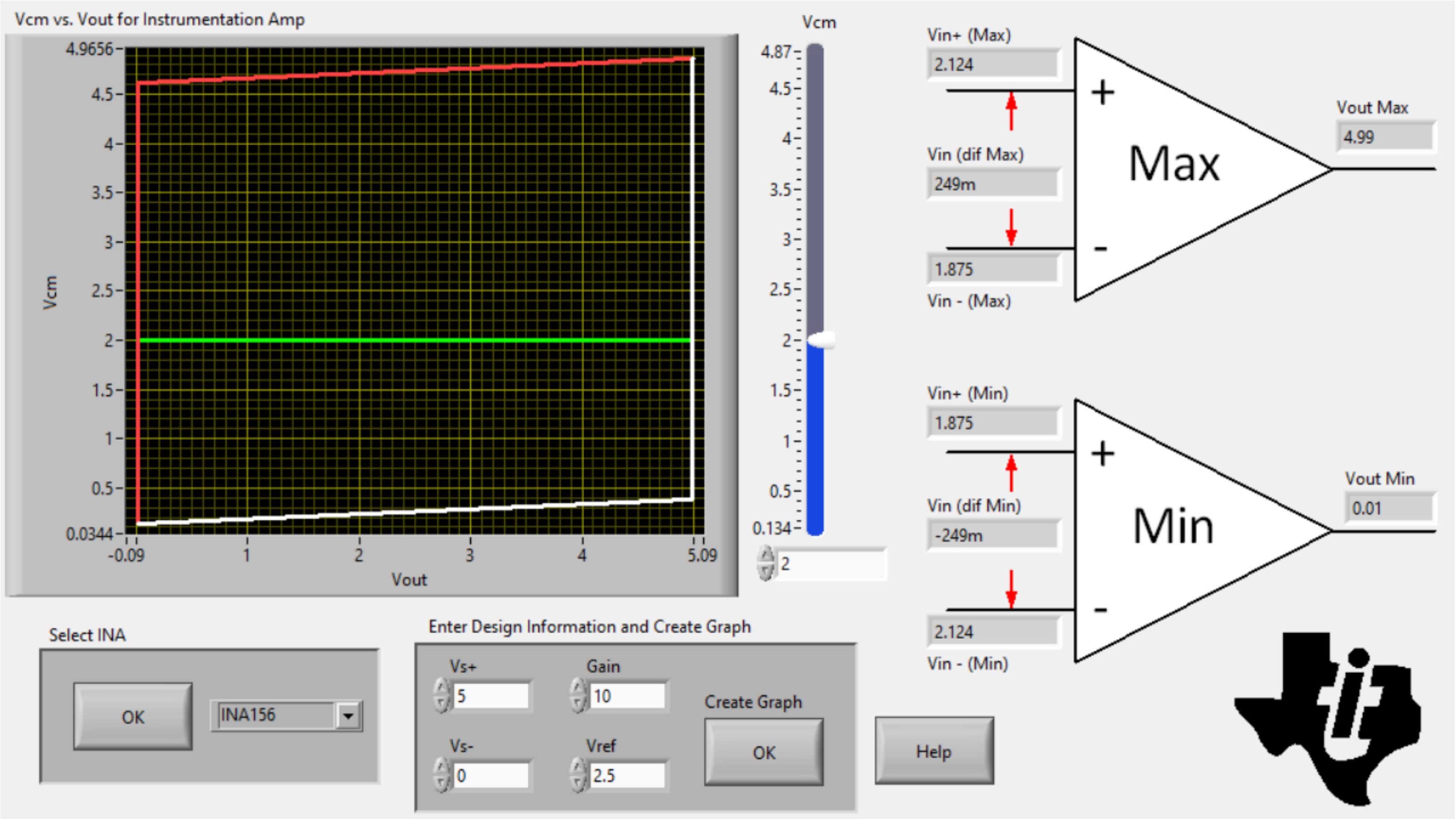


HINT:

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# Quiz: (IA) topologies: two-amp || Question

8. True or false: In an integrated two-amp IA, all resistors are absolutely matched in production

# Quiz: (IA) topologies: two-amp || Answer

8. True or false: In an integrated two-amp IA, all resistors are absolutely matched in production

**TRUE**

# Quiz: (IA) topologies: two-amp || Question

9. Which of the following statements is true regarding the relationship between Ref and VCM to Gain?

a) The further apart Ref is to VCM, lower gains can be achieved
b) The closer Ref is to VCM, lower gains can be achieved
c) If Ref = VCM, gain < 1 V/V can be achieved
d) If Ref << VCM, any gain can be achieved

# Quiz: (IA) topologies: two-amp || Answer

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