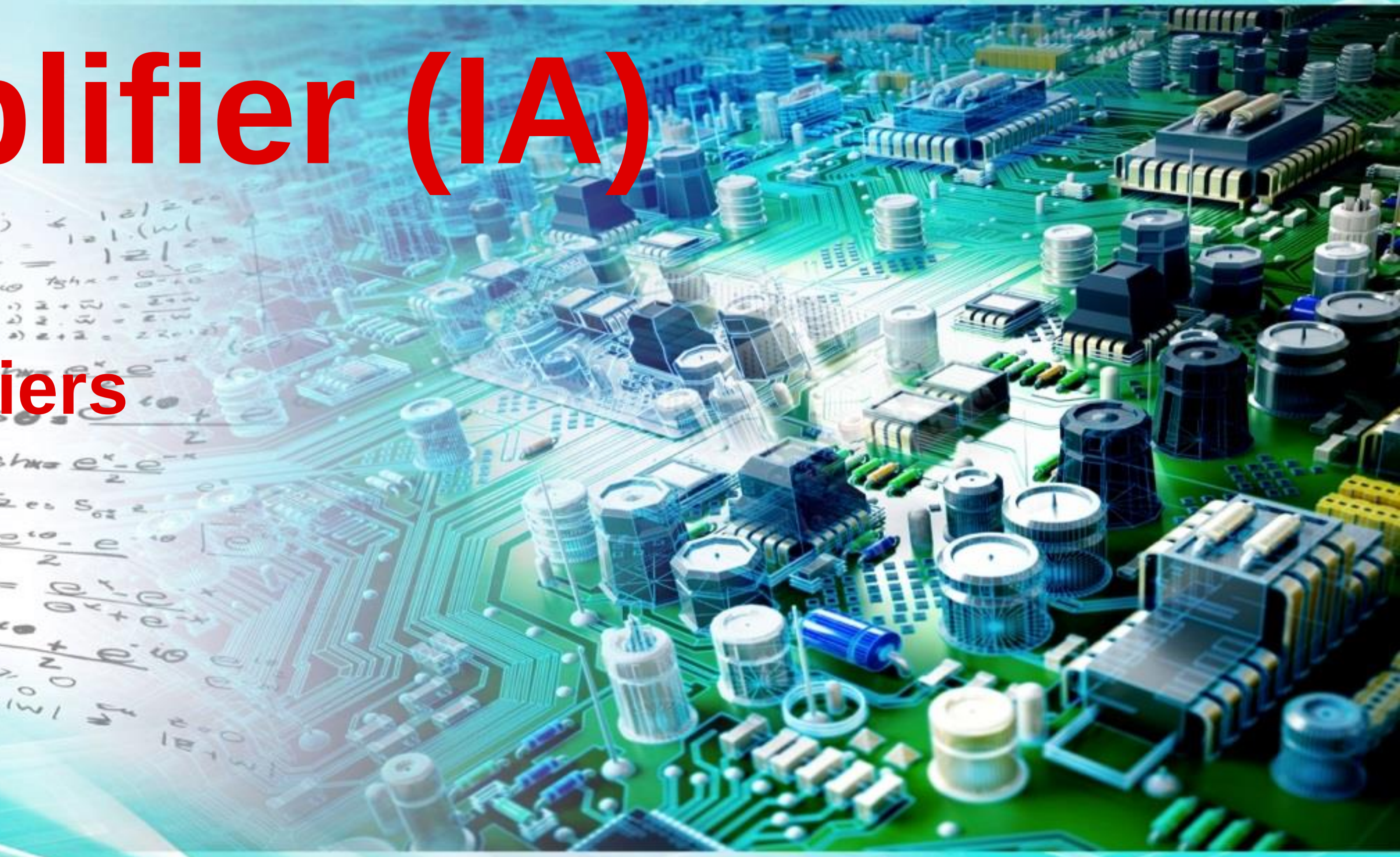
Instrumentation Amplifier (IA) topologies: two-amp

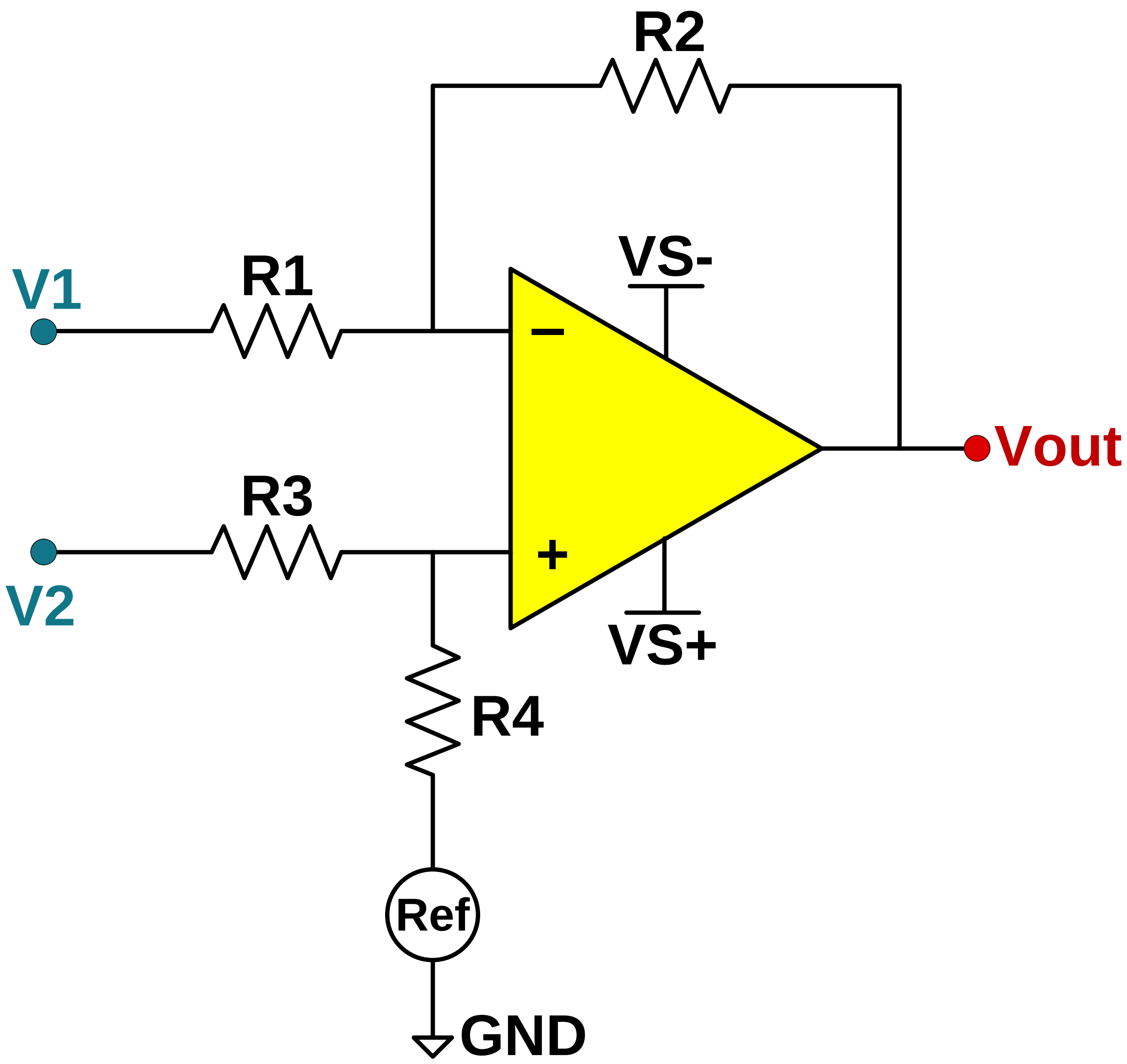
TI Precision Labs – Instrumentation Amplifiers



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

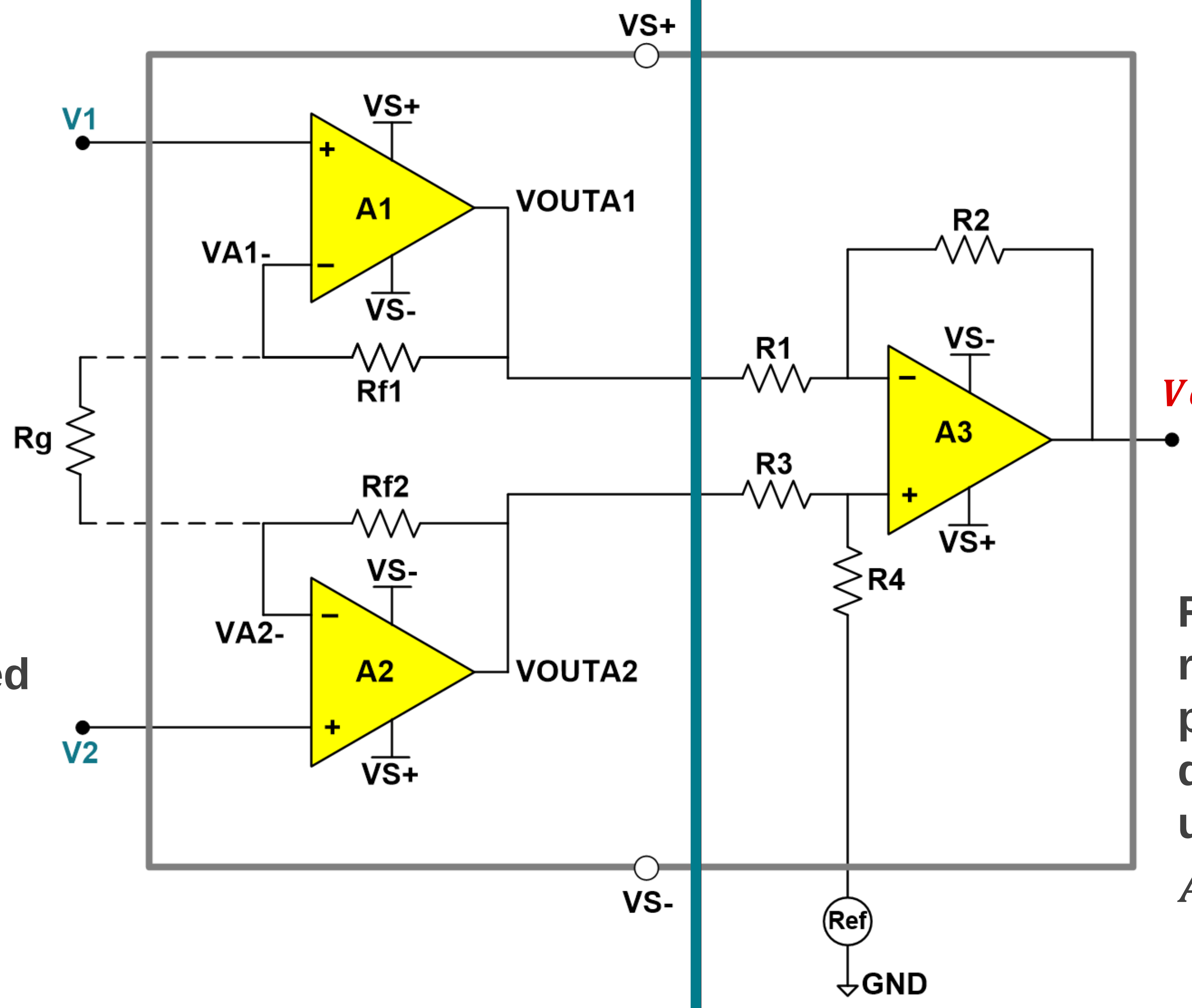
If $R1 = R3$, and $R2 = R4$, then Ad $= \frac{R2}{R1}$

Challenges:

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

IA topologies – Three amp recap

Buffer stage with gain and high input impedance



Rf1 and Rf2 are absolutely matched for precise gain calculation:

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

Difference amplifier output stage

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

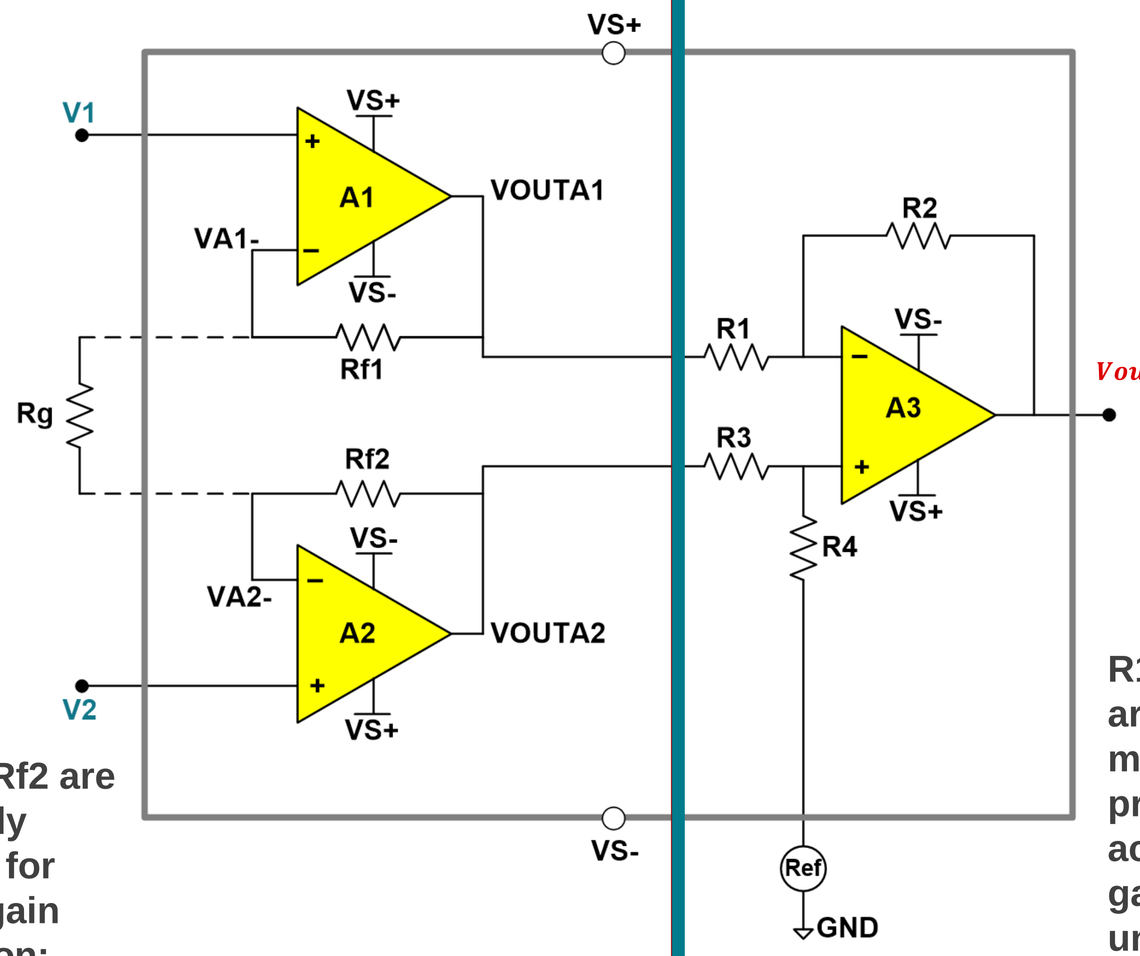
R1, R2, R3 and R4 are ratiometrically matched in production to achieve the desired gain, commonly unity

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

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

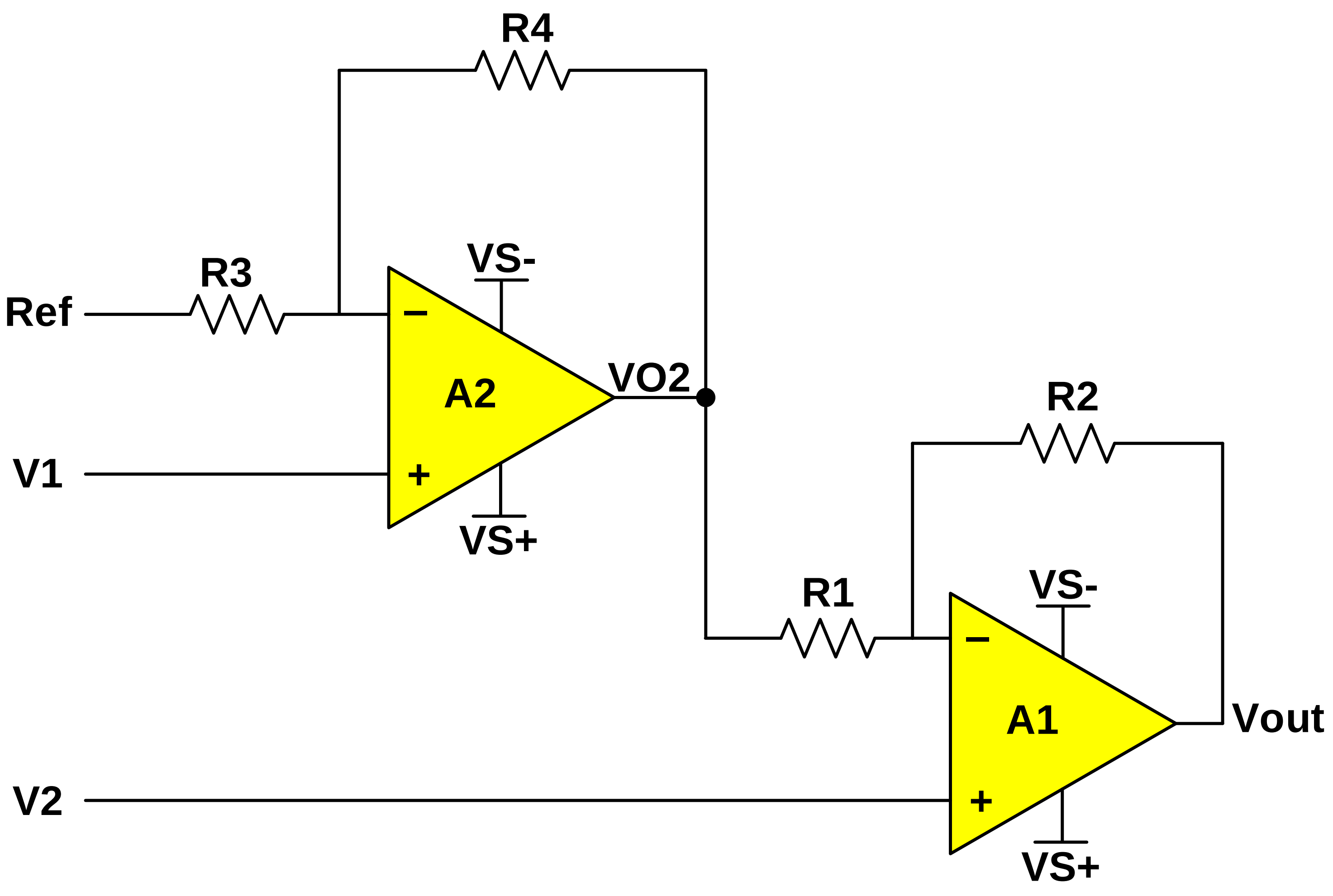
if R2=R4 and R1=R3

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



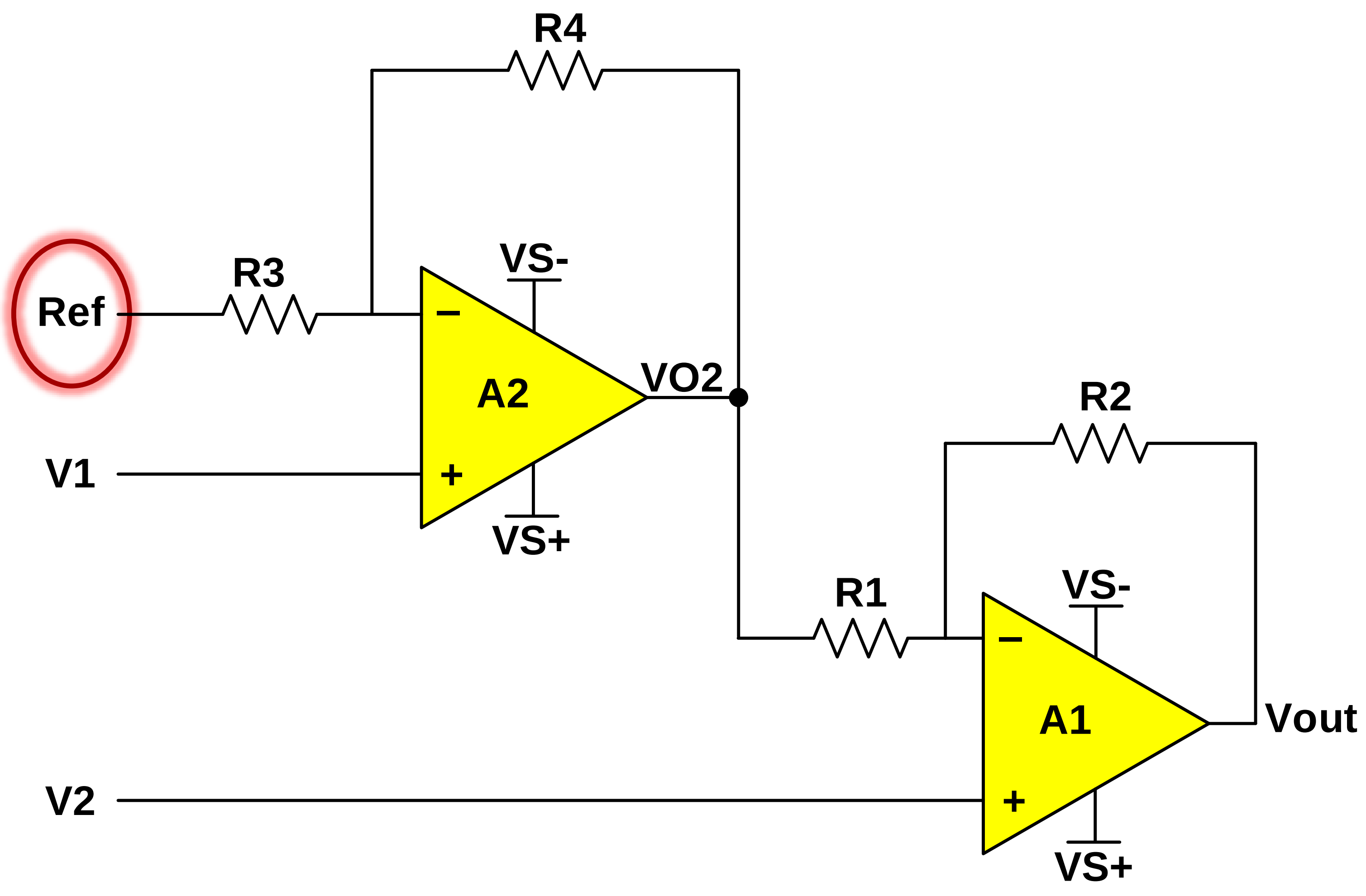
Design simplicity:

– 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*		

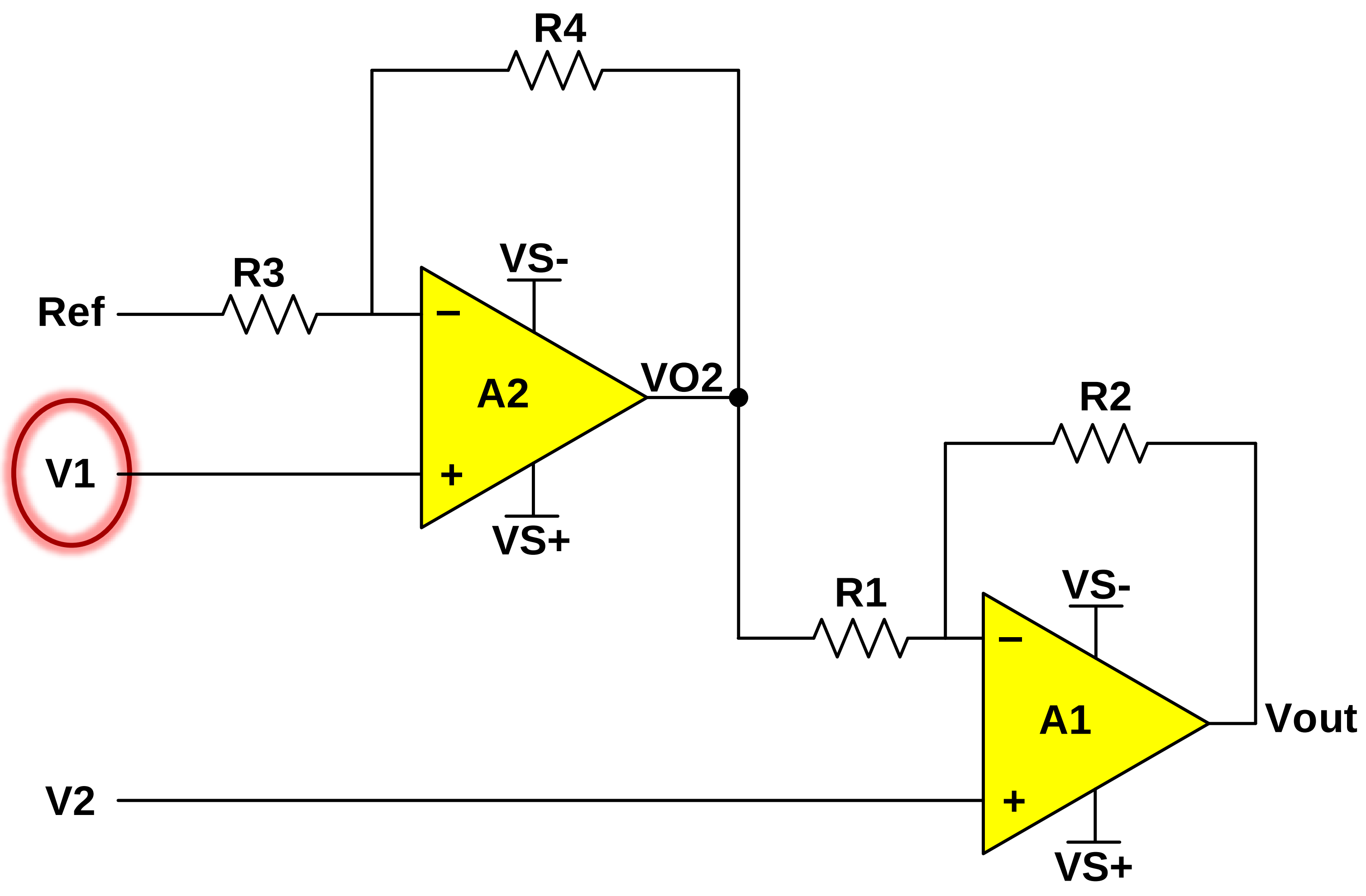
Ground Ref:

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*		

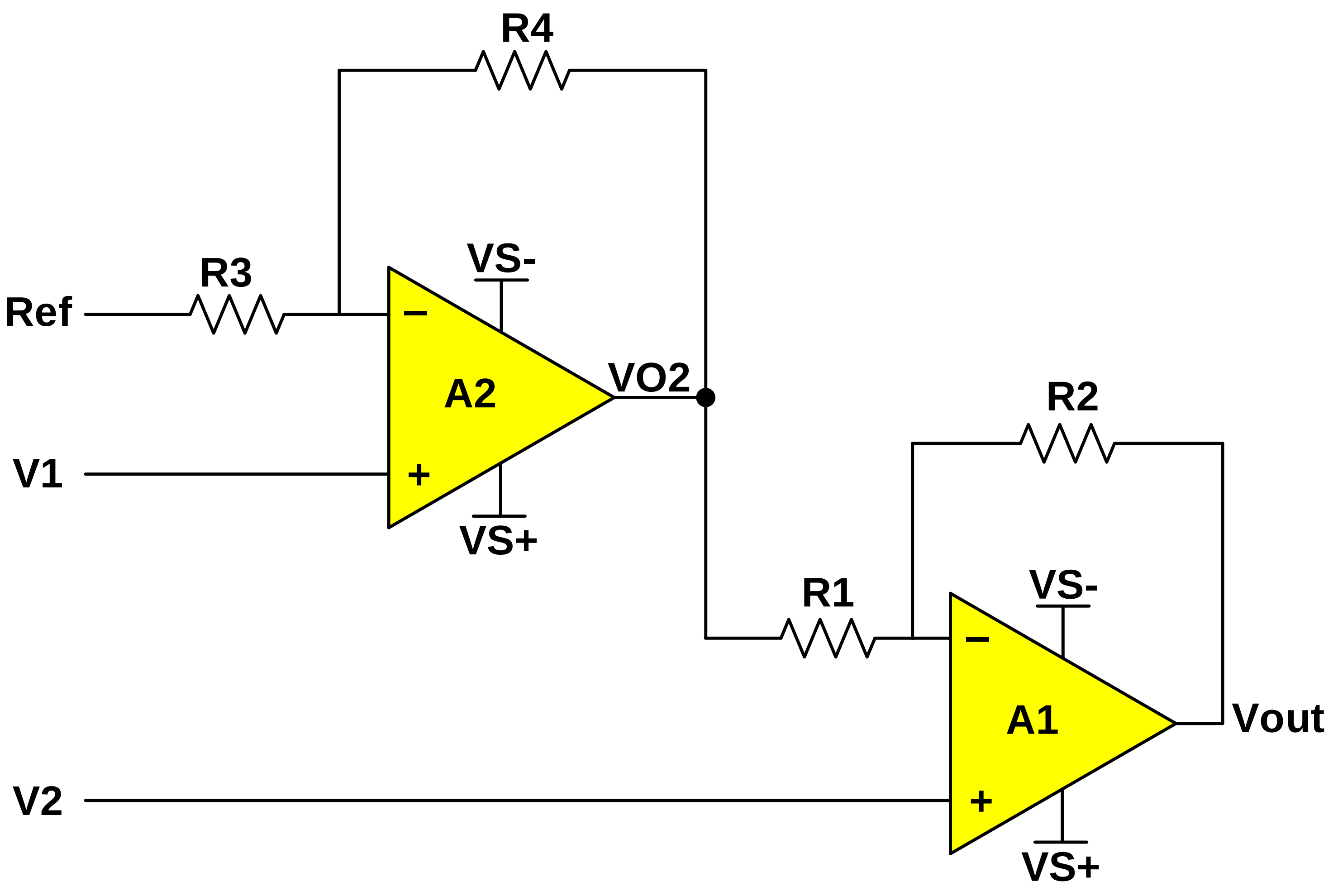
Ground V1:

A2 looks like inverting configuration:

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

Equation Ref*

IA topologies – 2 amp IA derivation; A2 derivation



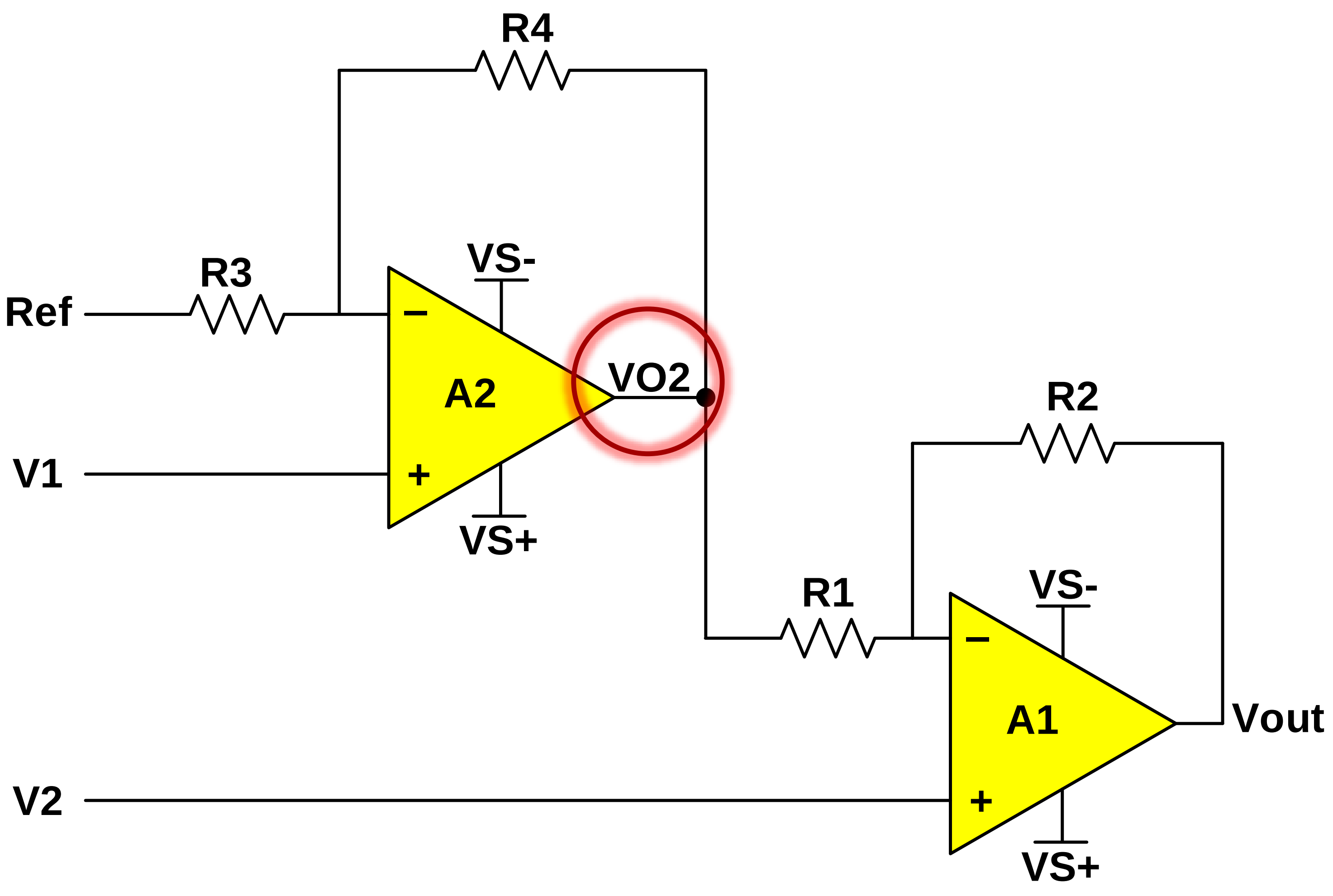
Derive output of A2 using superposition theorem:

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*		

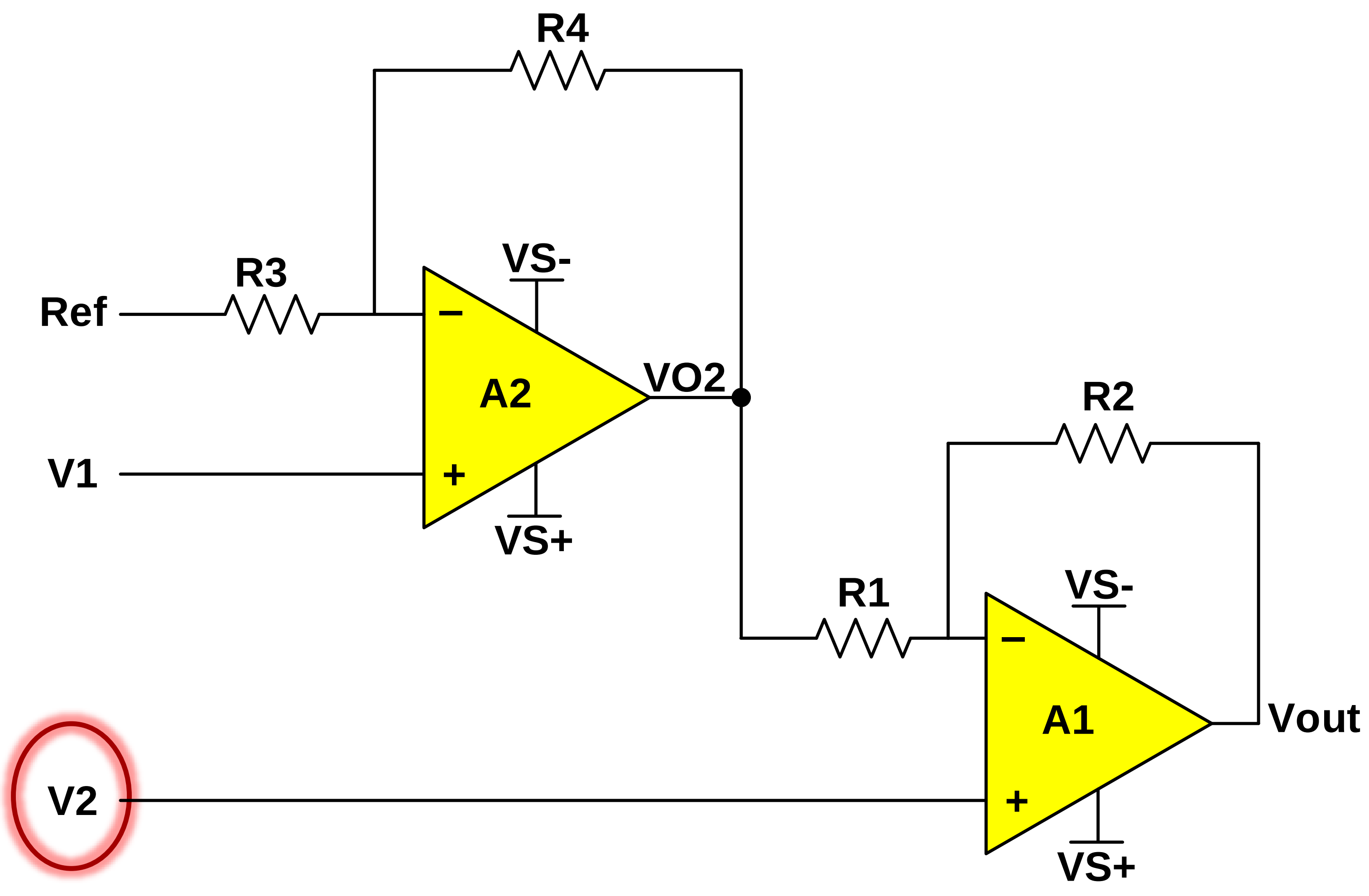
Ground VO2:

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*		

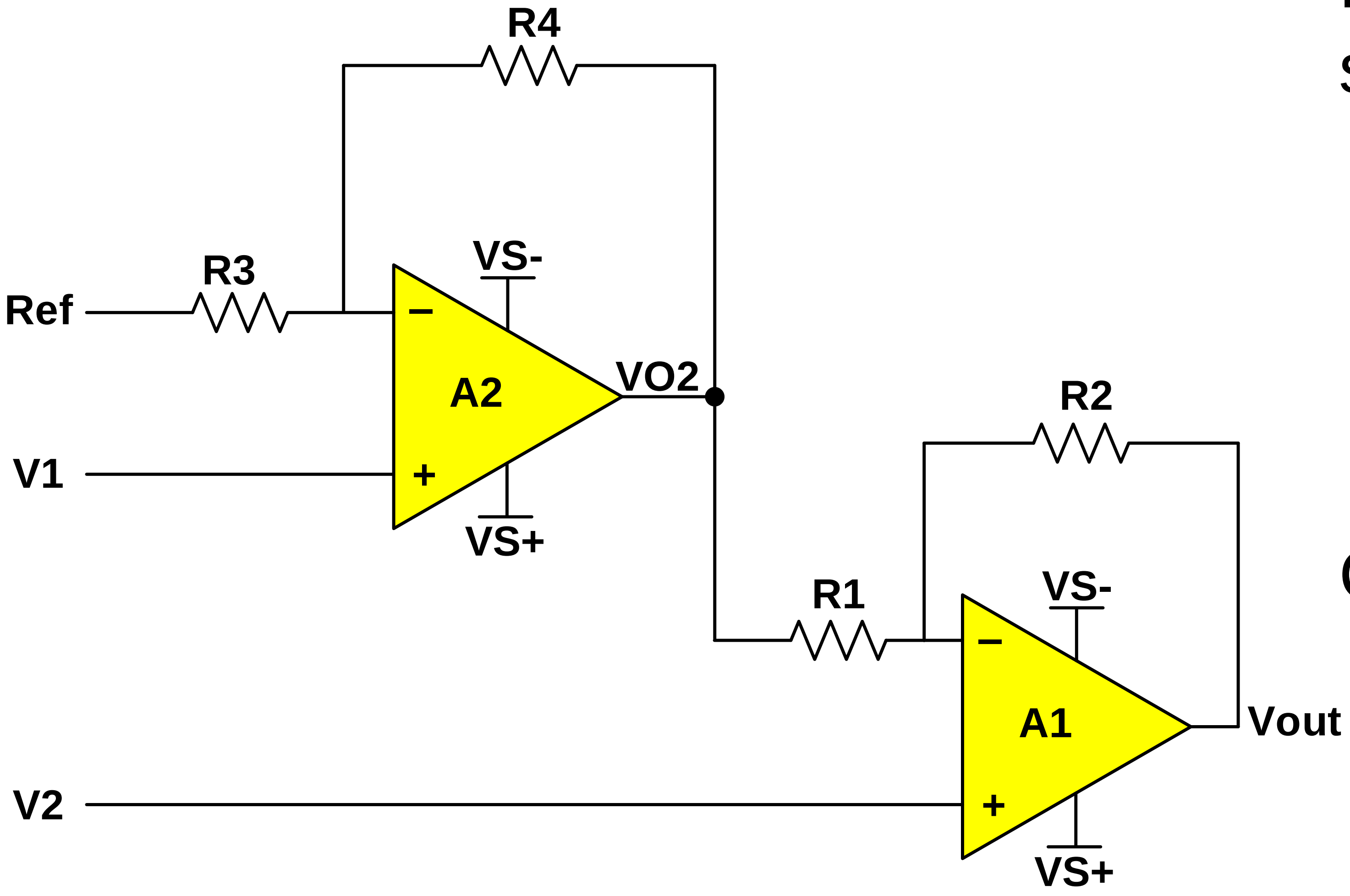
Ground V2:

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:

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

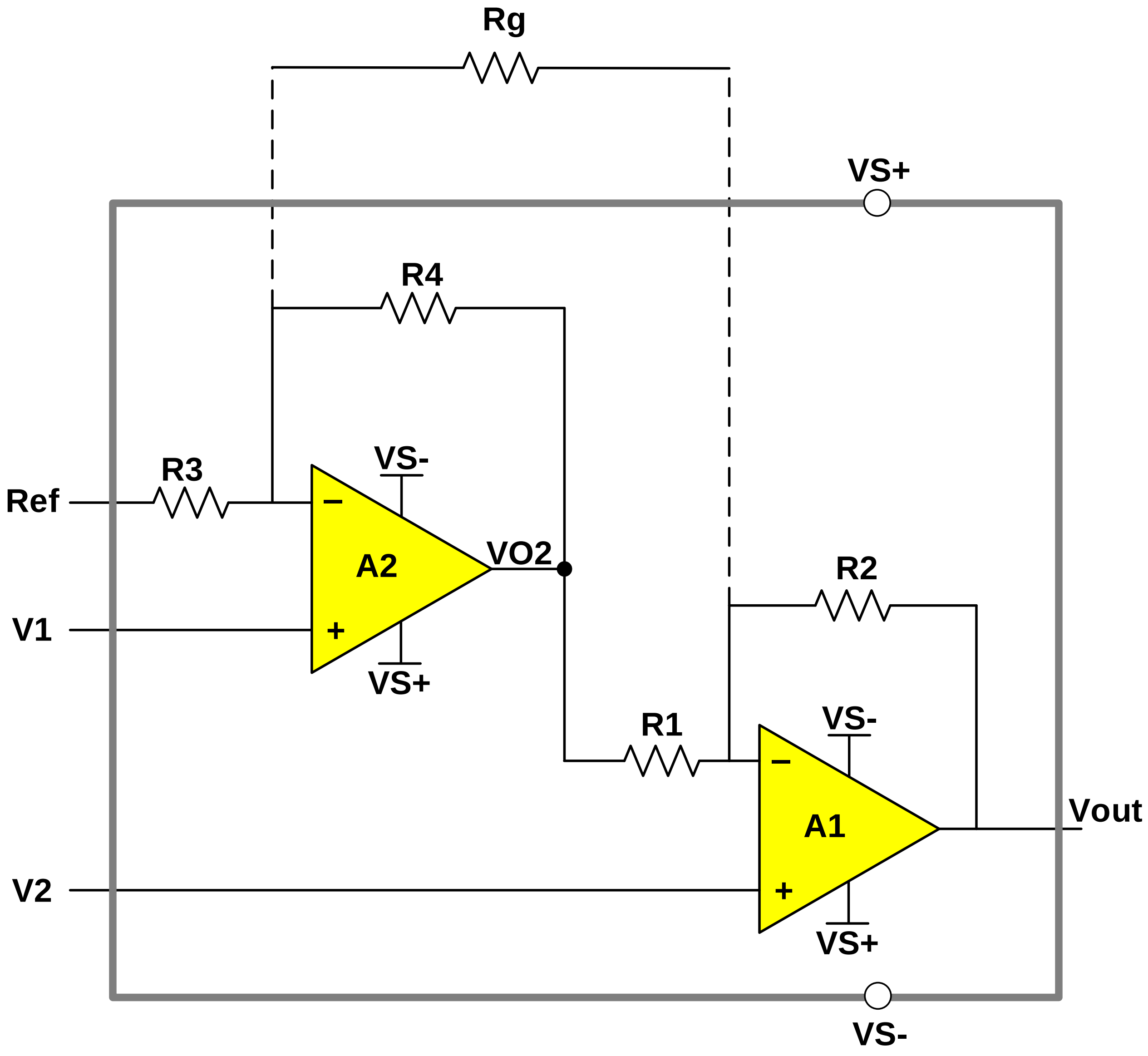
Simplify…

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

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:

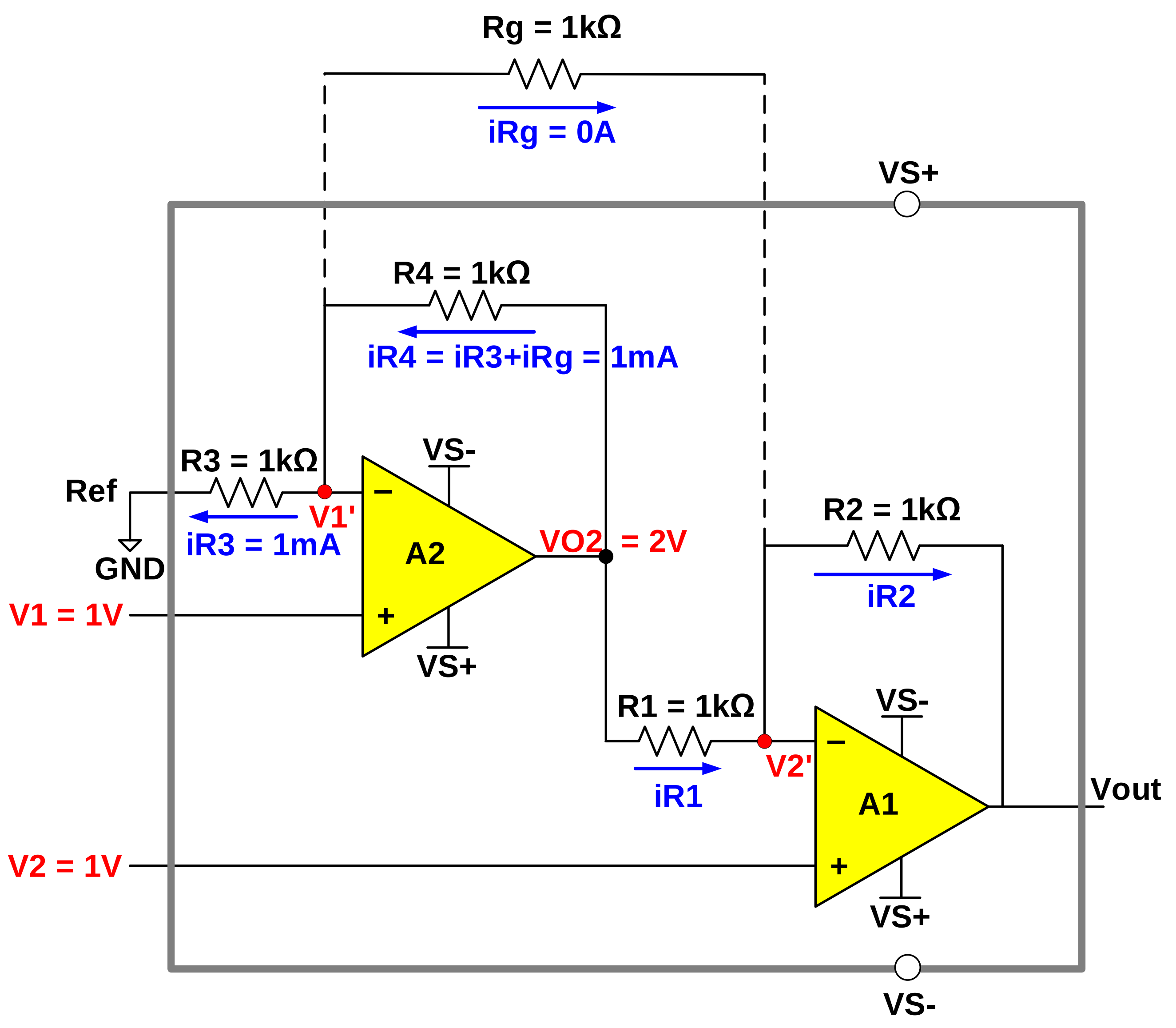
Aim for R4 = R1 and R3 = R2

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 $= A_{CM} = \frac{V_{OCM}}{V_{CM}} \ll 1$

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

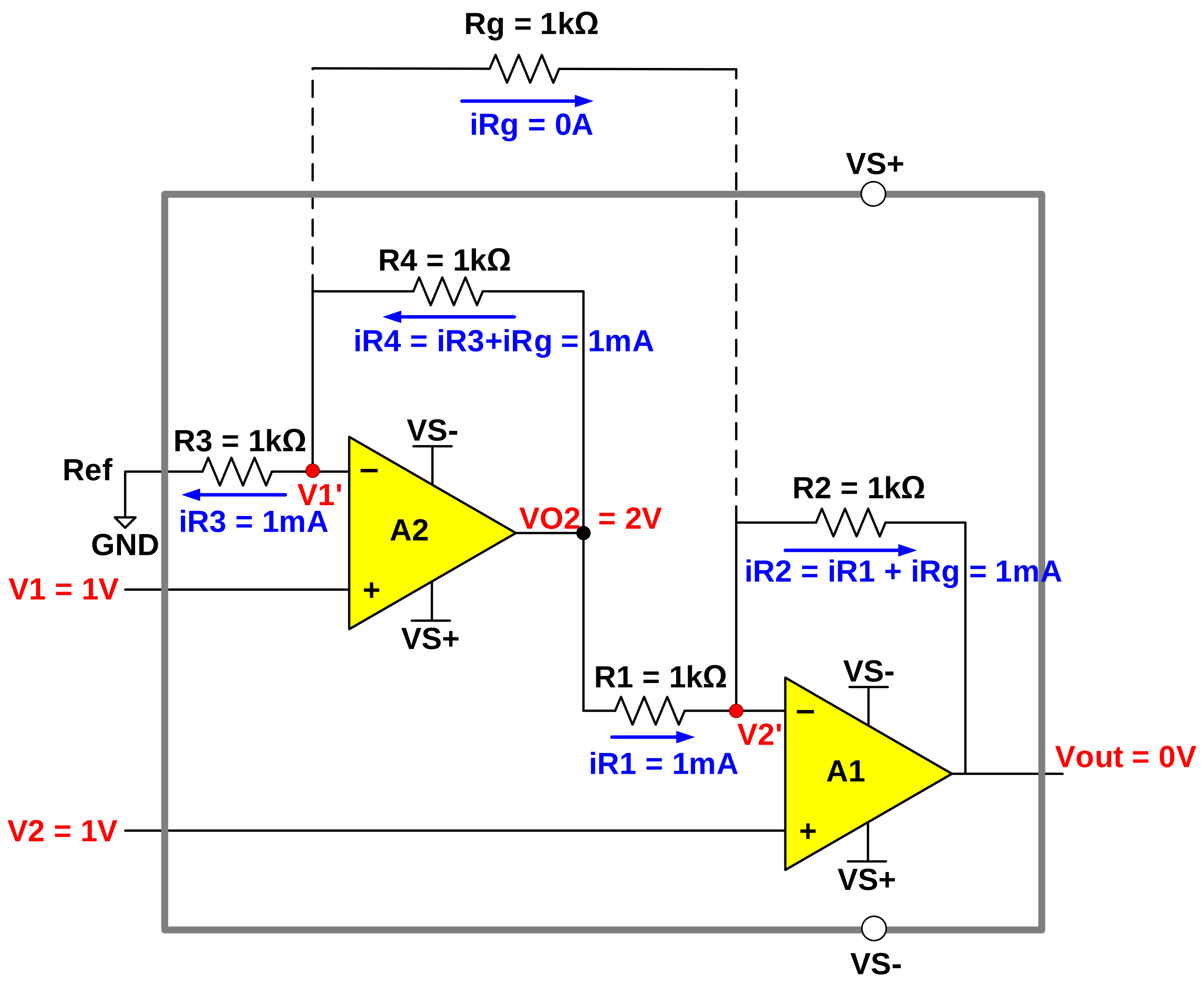
If V2 = 1V → V2' = 1V:

– 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:

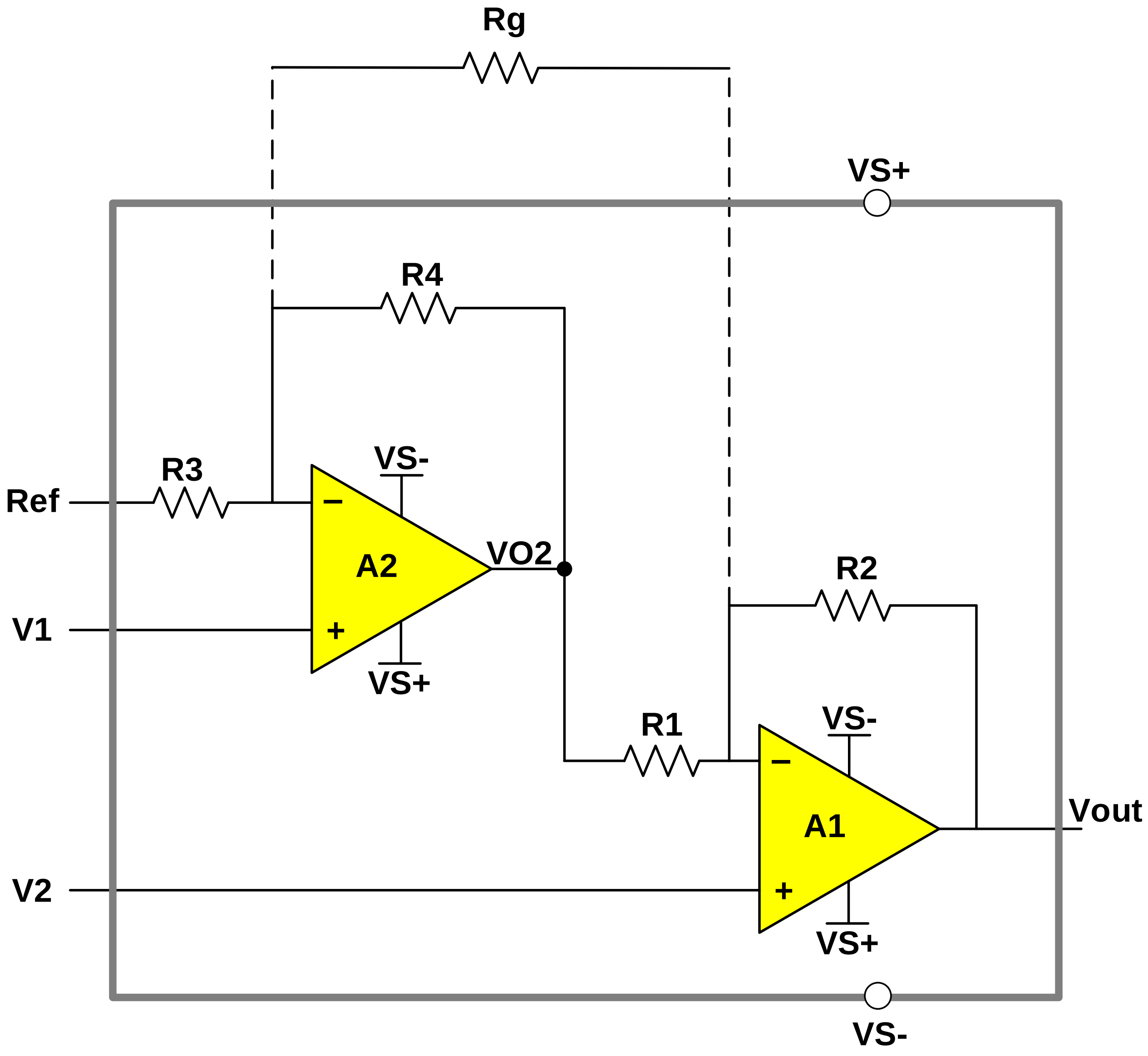
- current flowing through R1 is 1V/1kΩ = 1mA

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

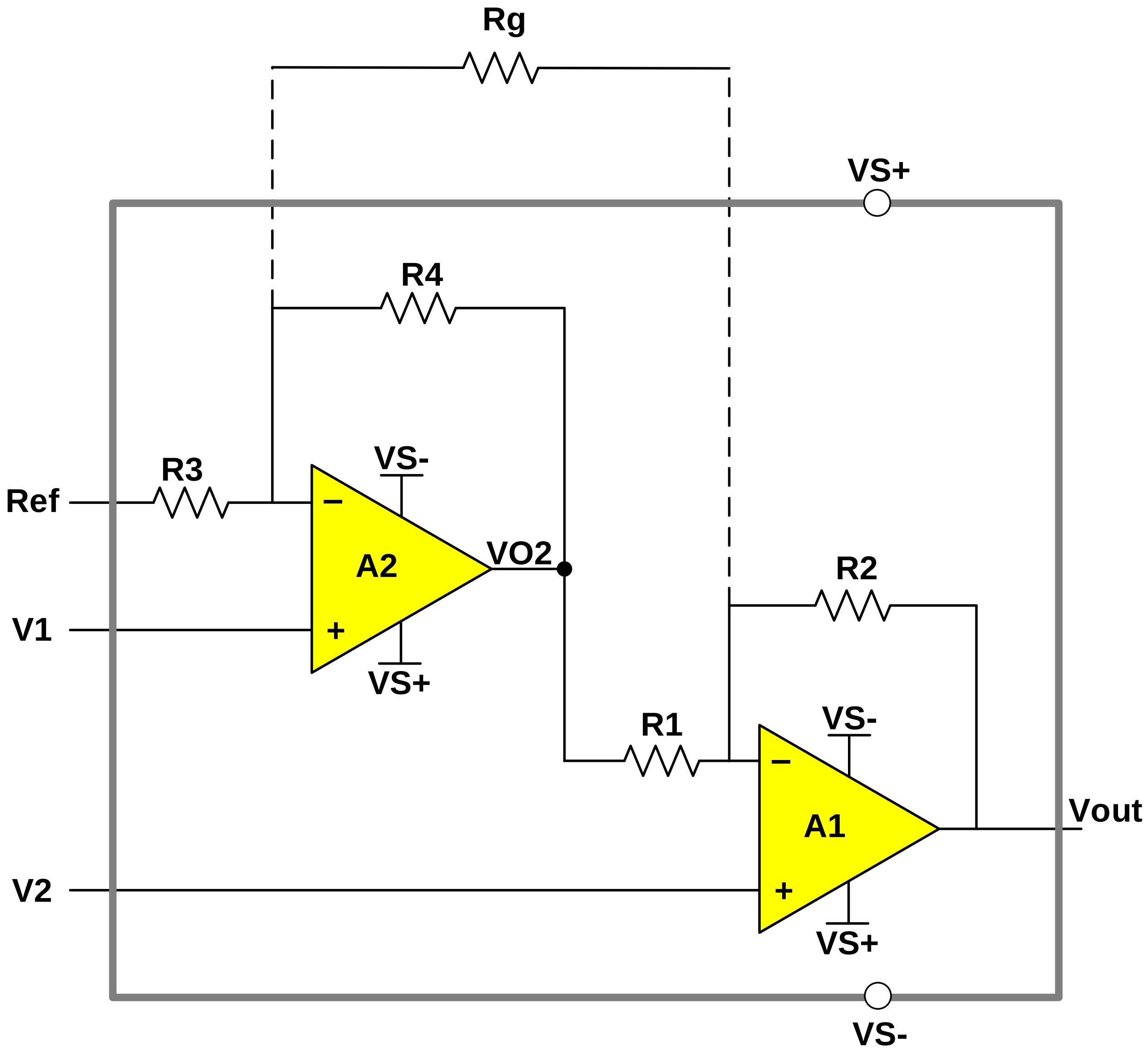
Vd = differential voltage = V2 – V1

Ref = reference voltage, level shifting term

Drawback:

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

2 amp IA topology drawbacks – Headroom



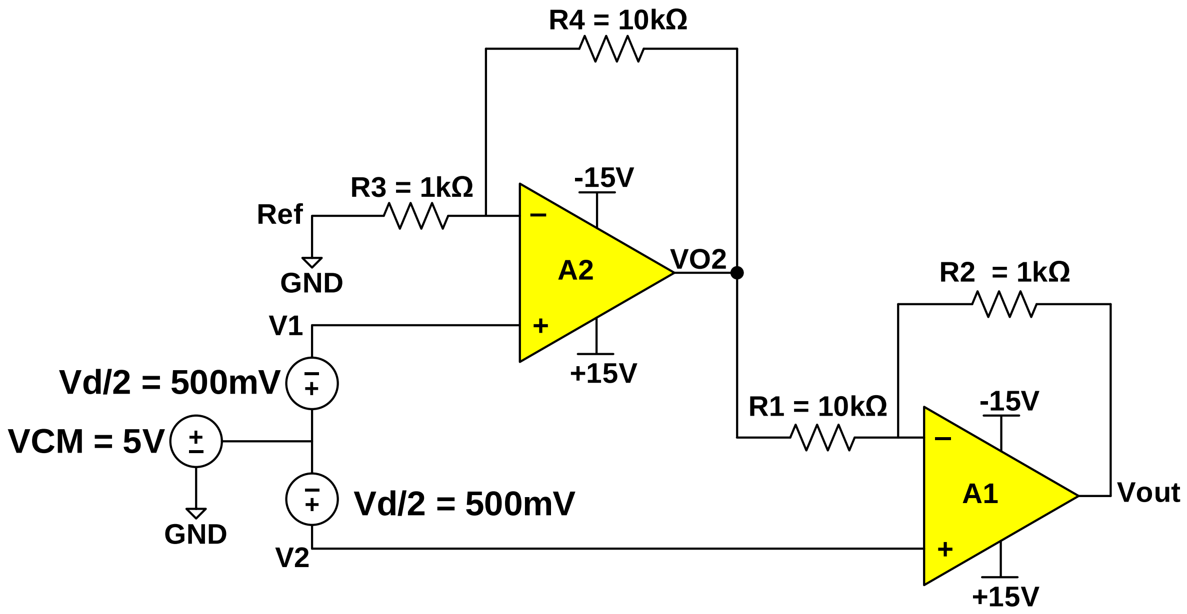
$$Vout = \left(1 + \frac{R2}{R1} + \frac{2 \times R2}{Rg}\right) \times (\mathrm{V1} - \mathrm{V2}) + \mathrm{Ref}$$

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



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

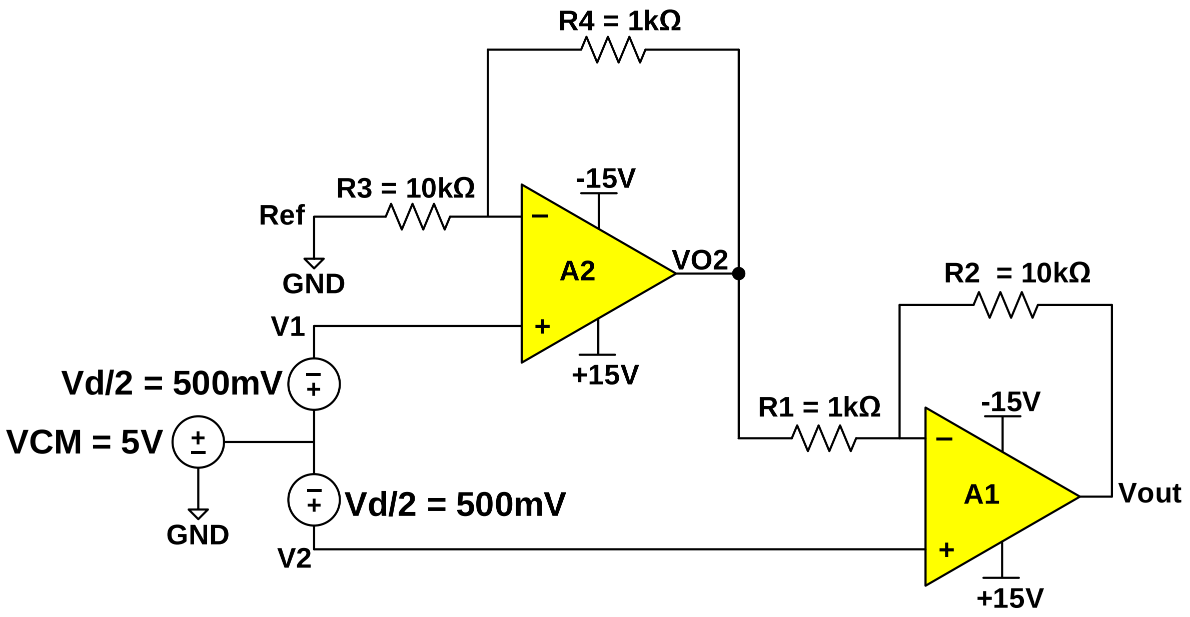
Low gain example: R4 >> R3

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

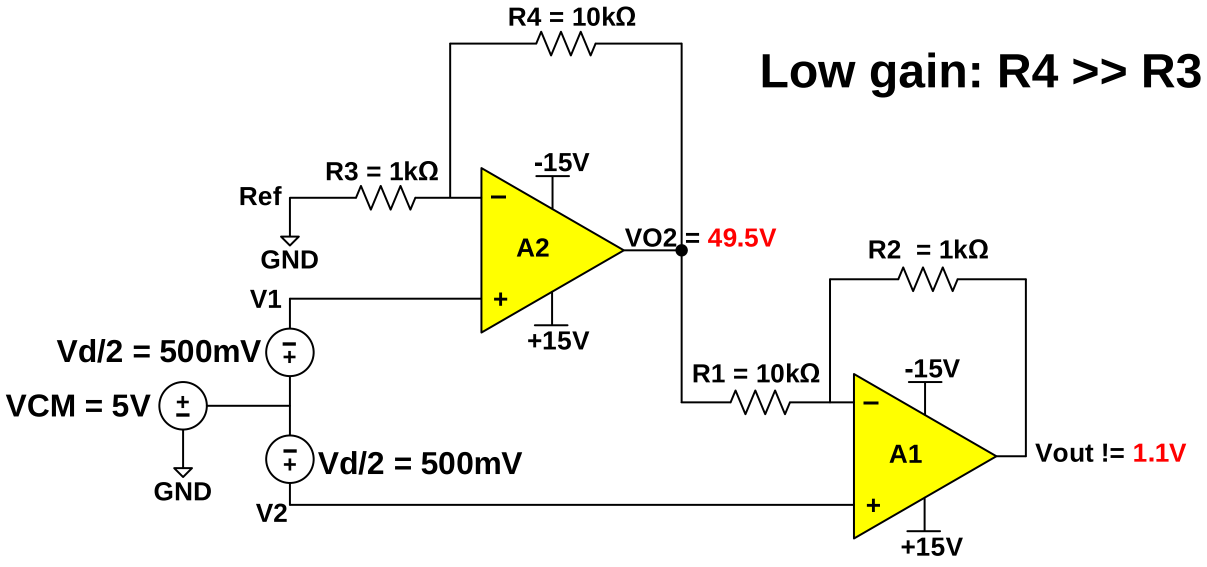
Ad = 11 V/V, Vd = 1V

VCM = 5 V, Ref = 0V

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

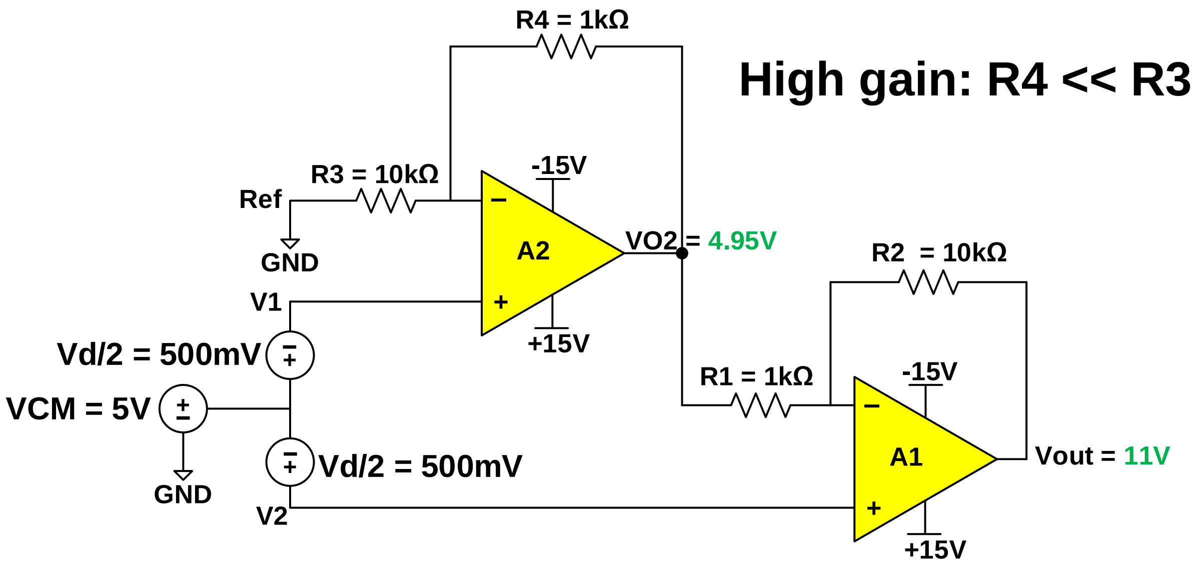
2 amp IA topology drawbacks – Headroom cont'd

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



Low gain: R4 >> R3

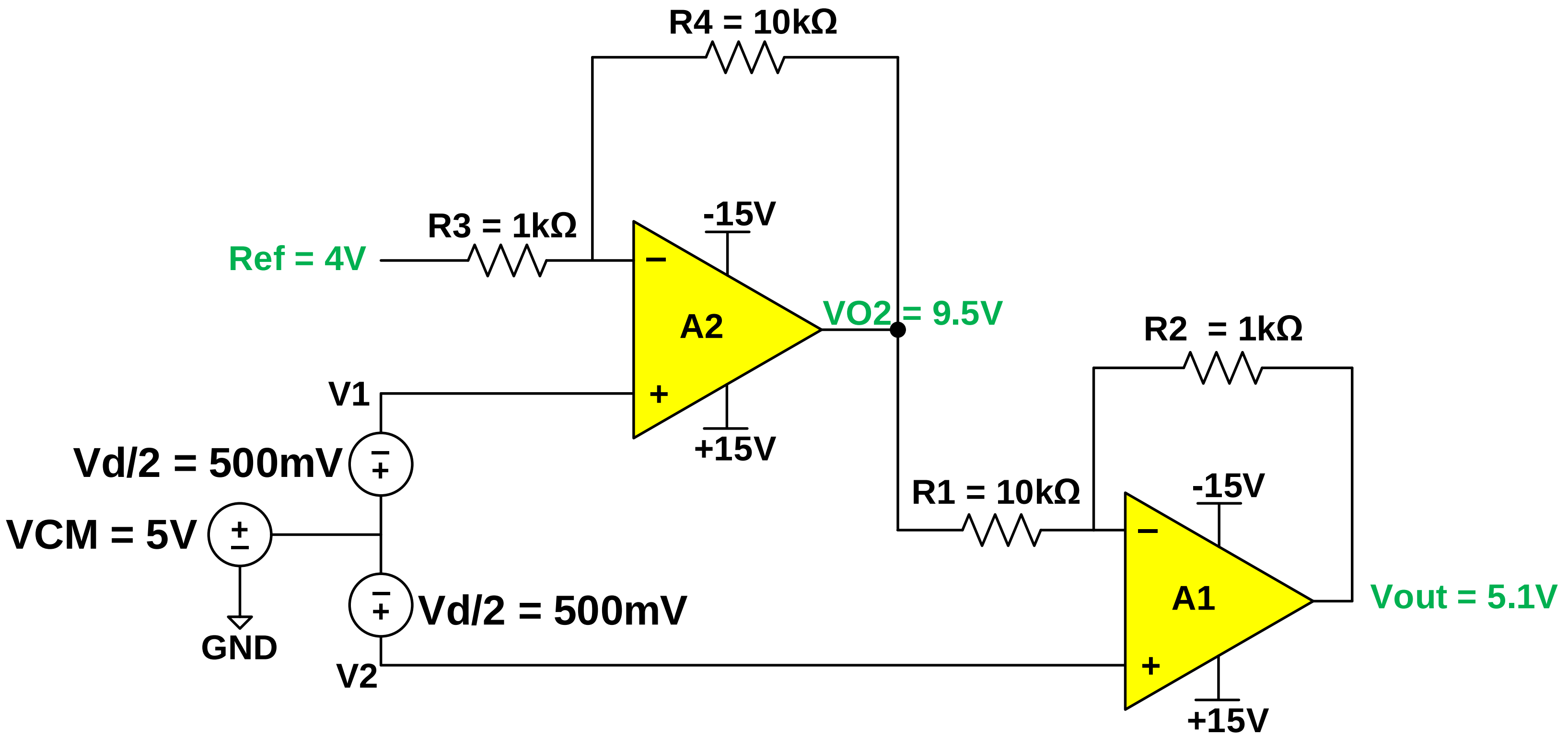
A1 and A2: ±15V supplies, RRIO
Ad = 1.1 V/V, Vd = 1V, VCM = 5V, Ref = 0V
Expected output Vout = Ad × Vd + Ref = 1.1 V
VO2 = **49.5V**
Vout != **1.1V**



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:

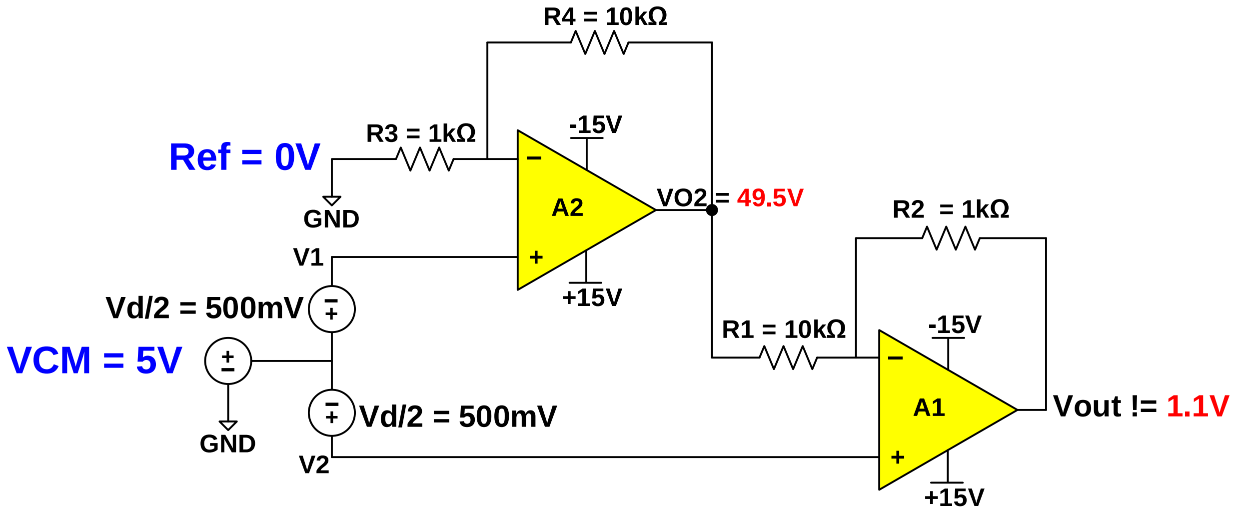
Vout = Ad × Vd + Ref = 5.1 V

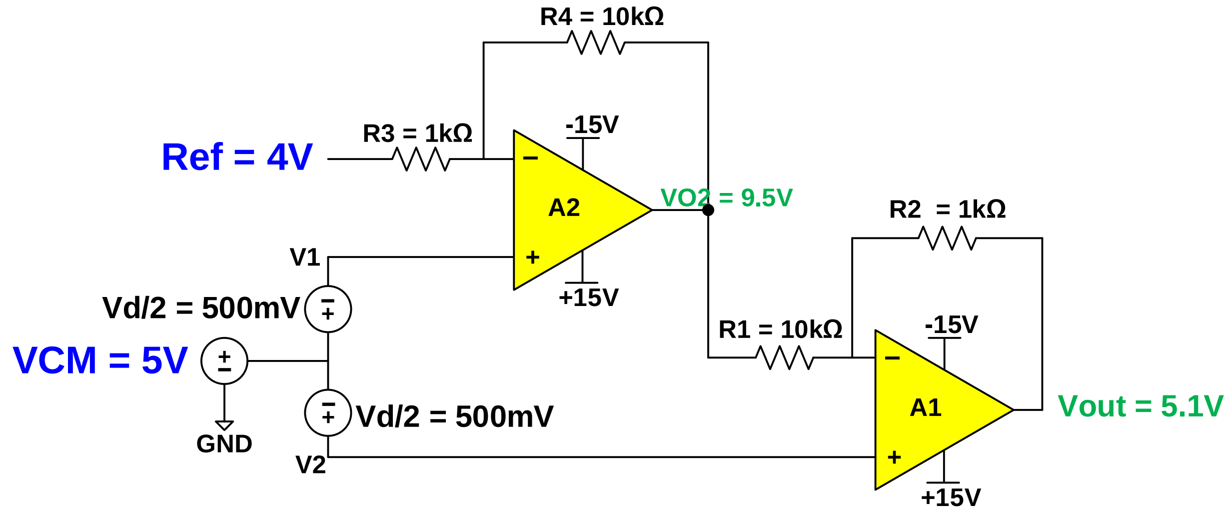
VO2 = **9.5V**

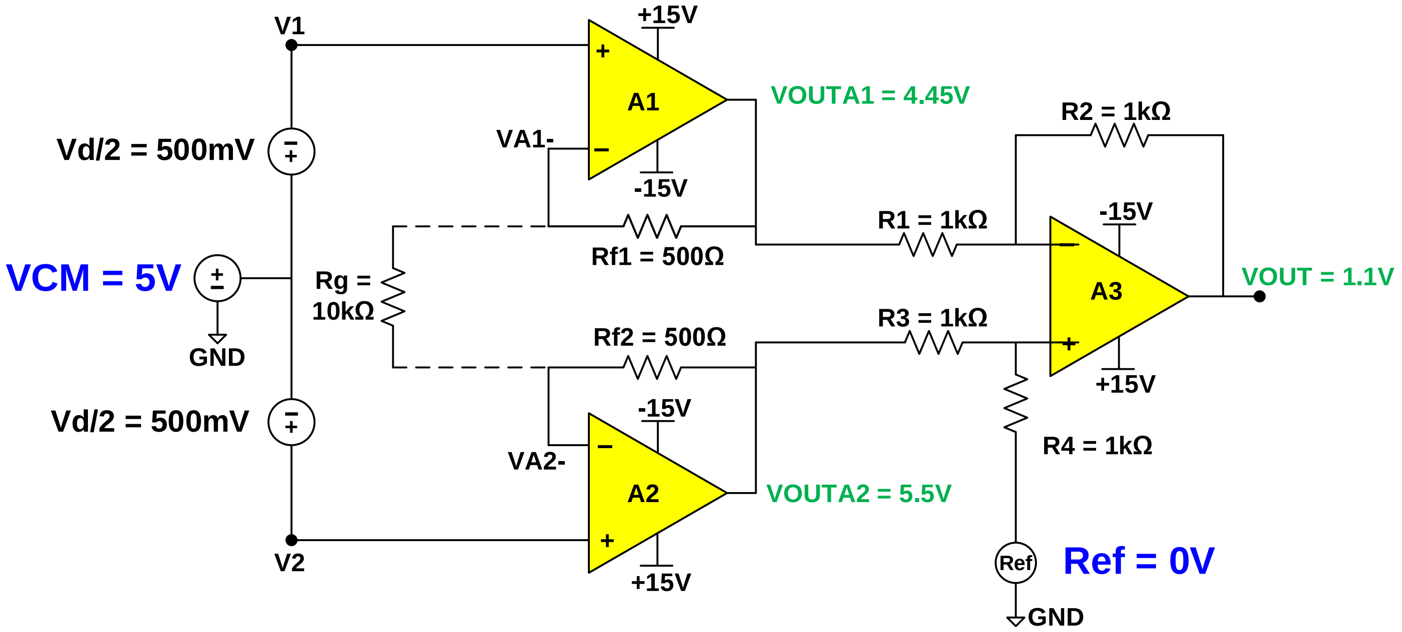
Vout = **5.1V**

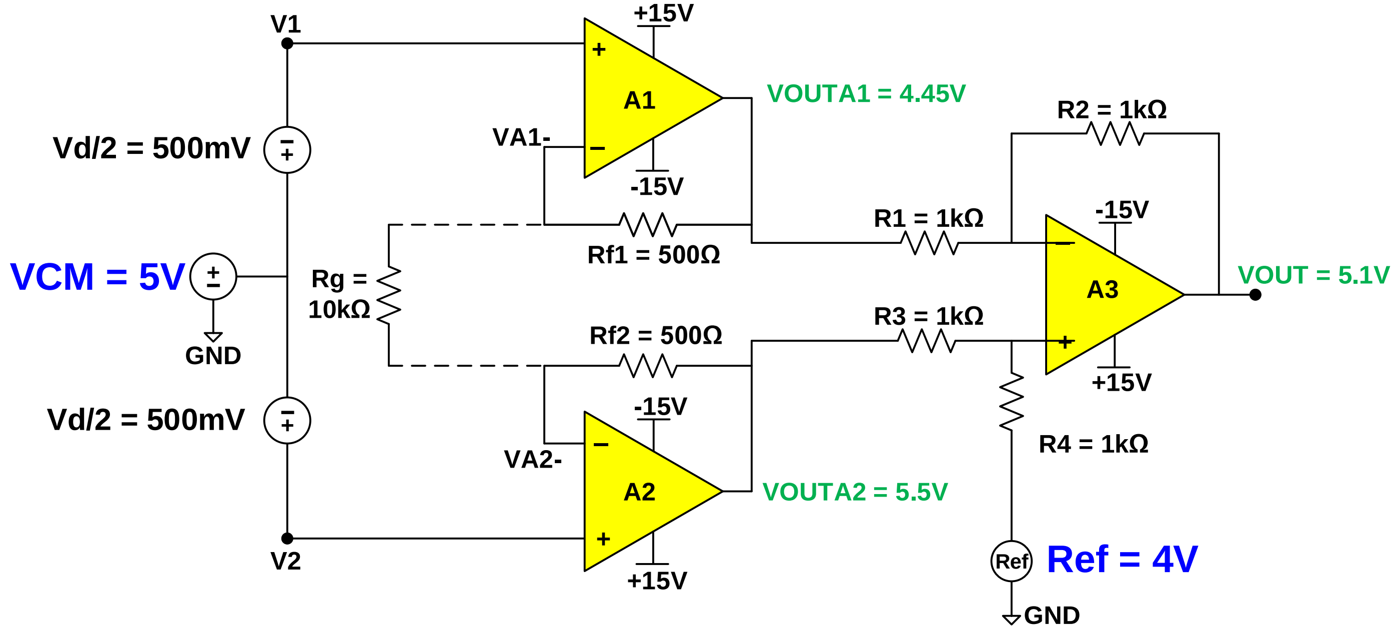
2 amp IA vs 3 amp IA – Headroom

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

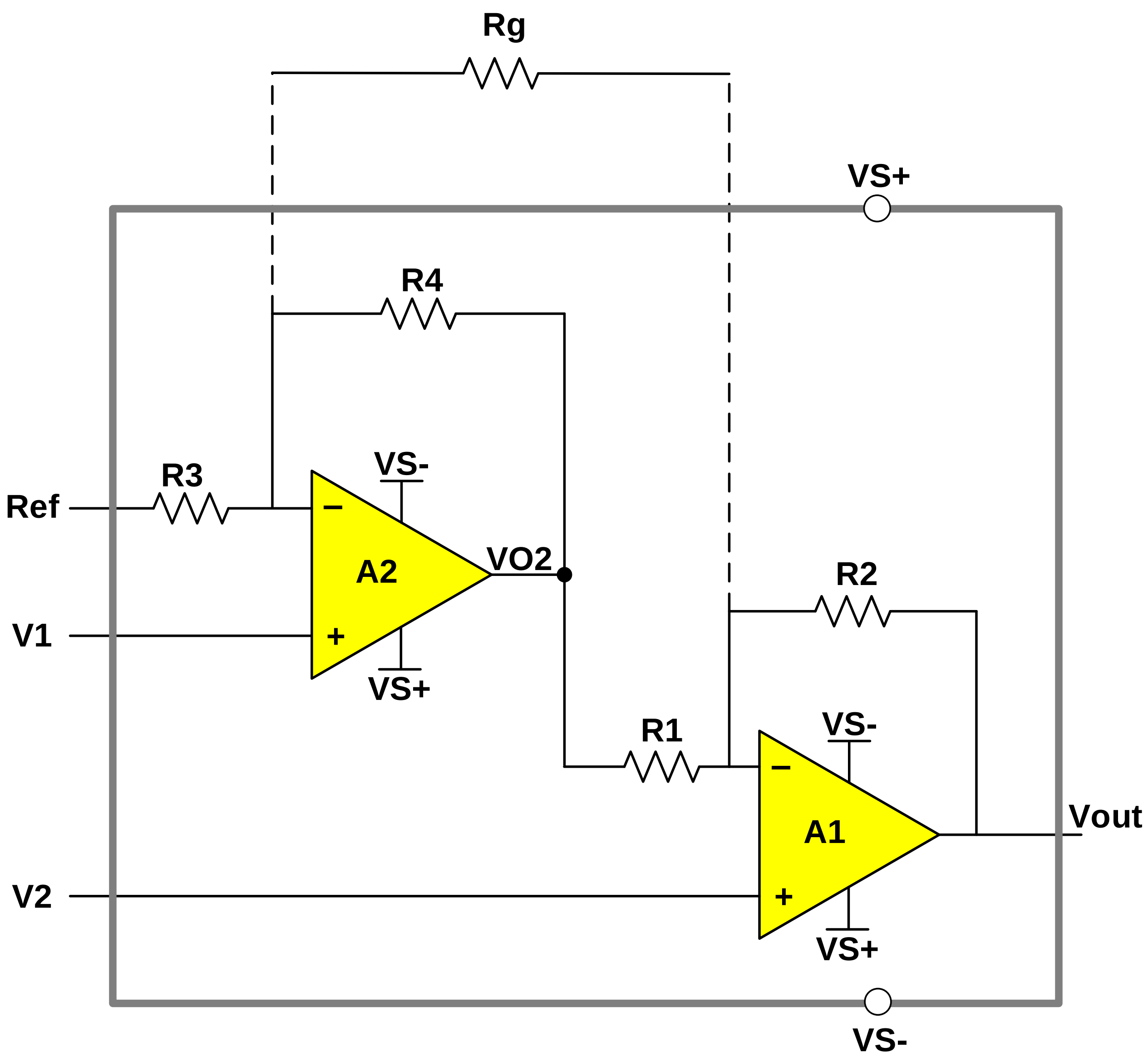








2 amp IA topology drawbacks – AC CMRR



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:

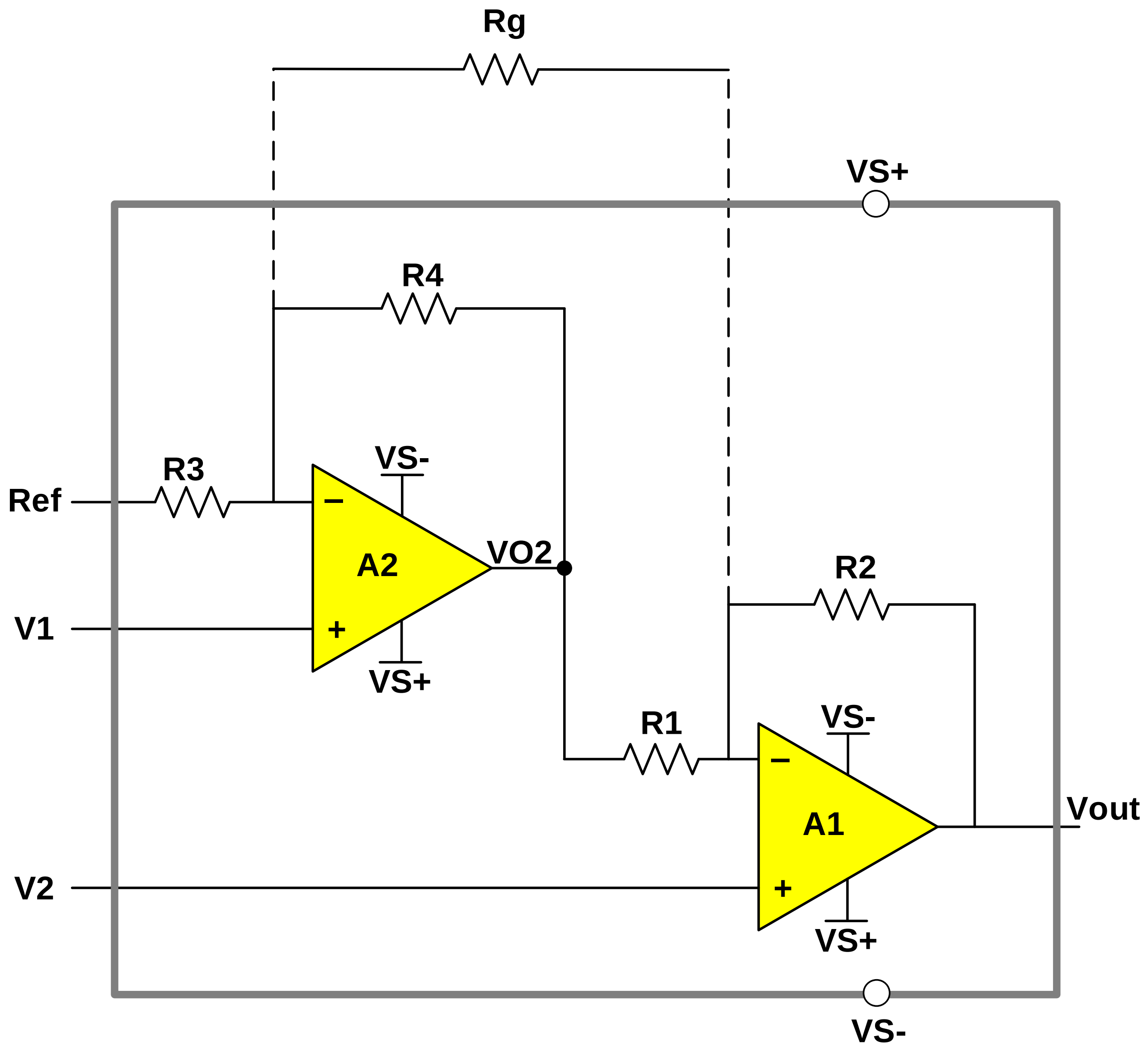
Voltage supplies = ±10V, Ref = 0V

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

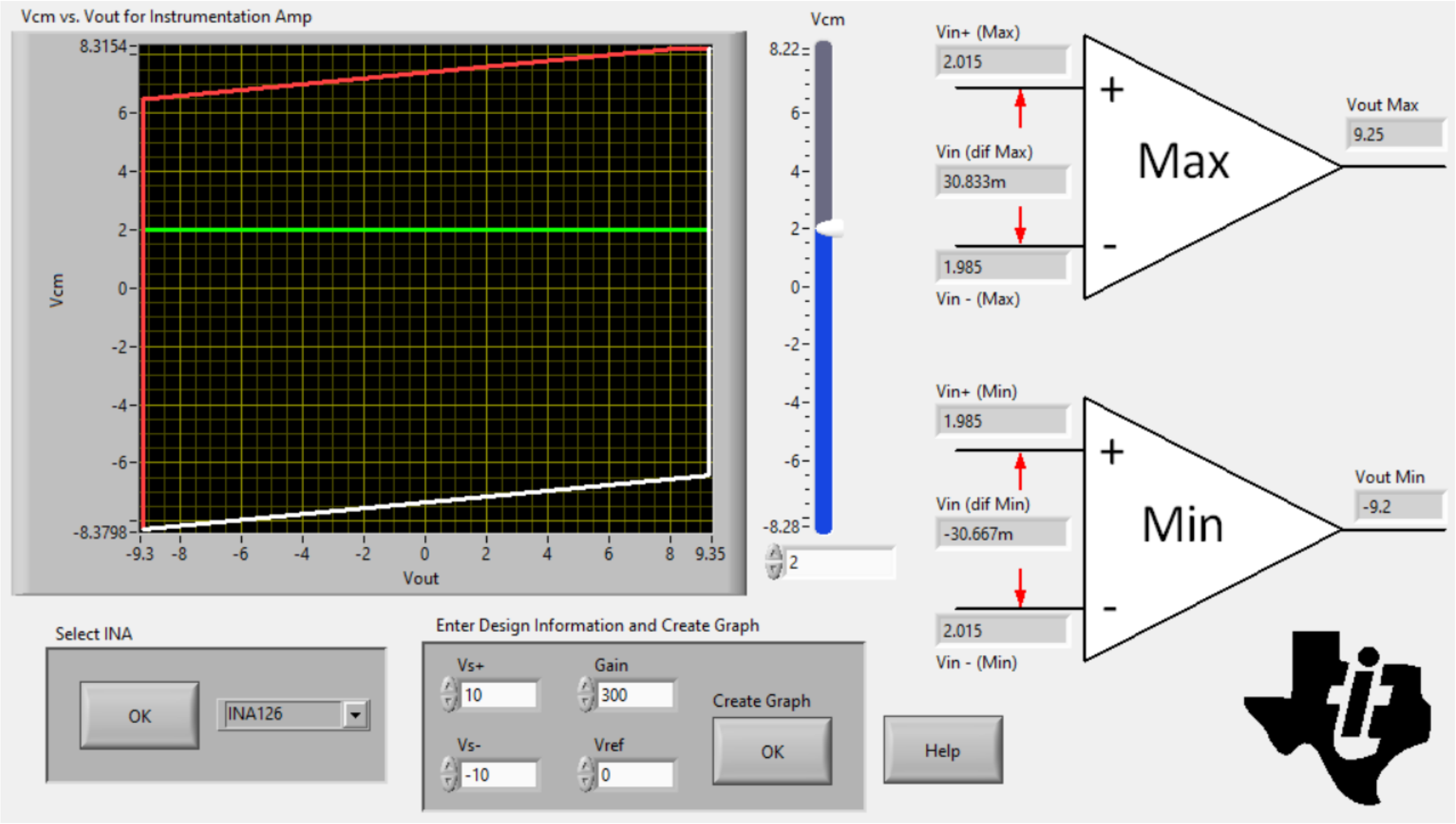
$$Gain = \frac{\Delta Vout}{\Delta Vin} = \frac{3V}{10mV} = 300V/V$$

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



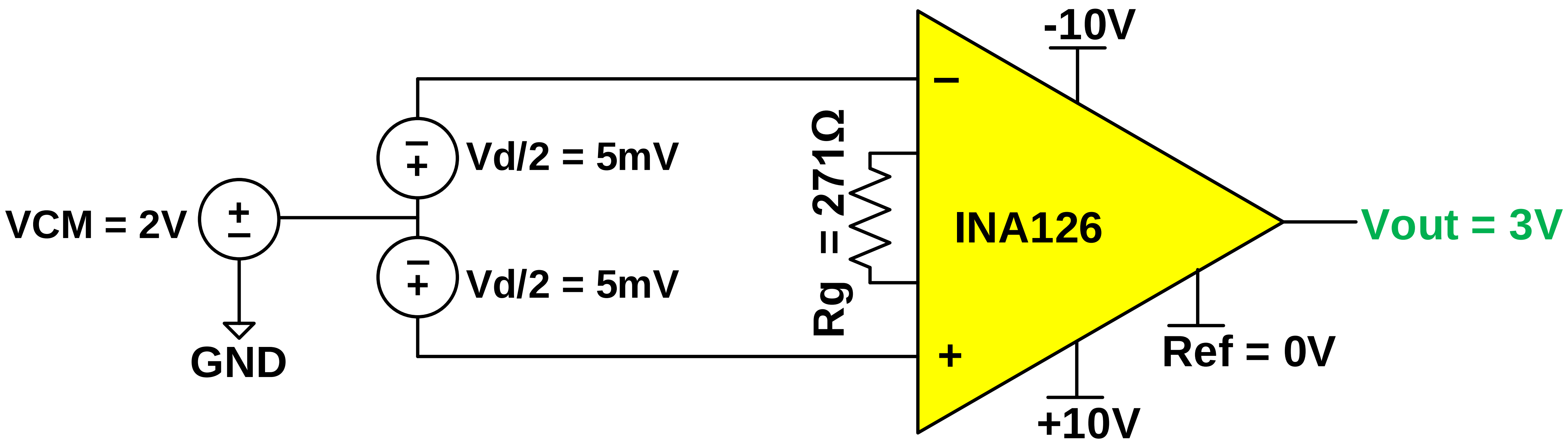
Analog engineer's calculator → INA VCM vs Vout

2 amp IA – Example cont'd

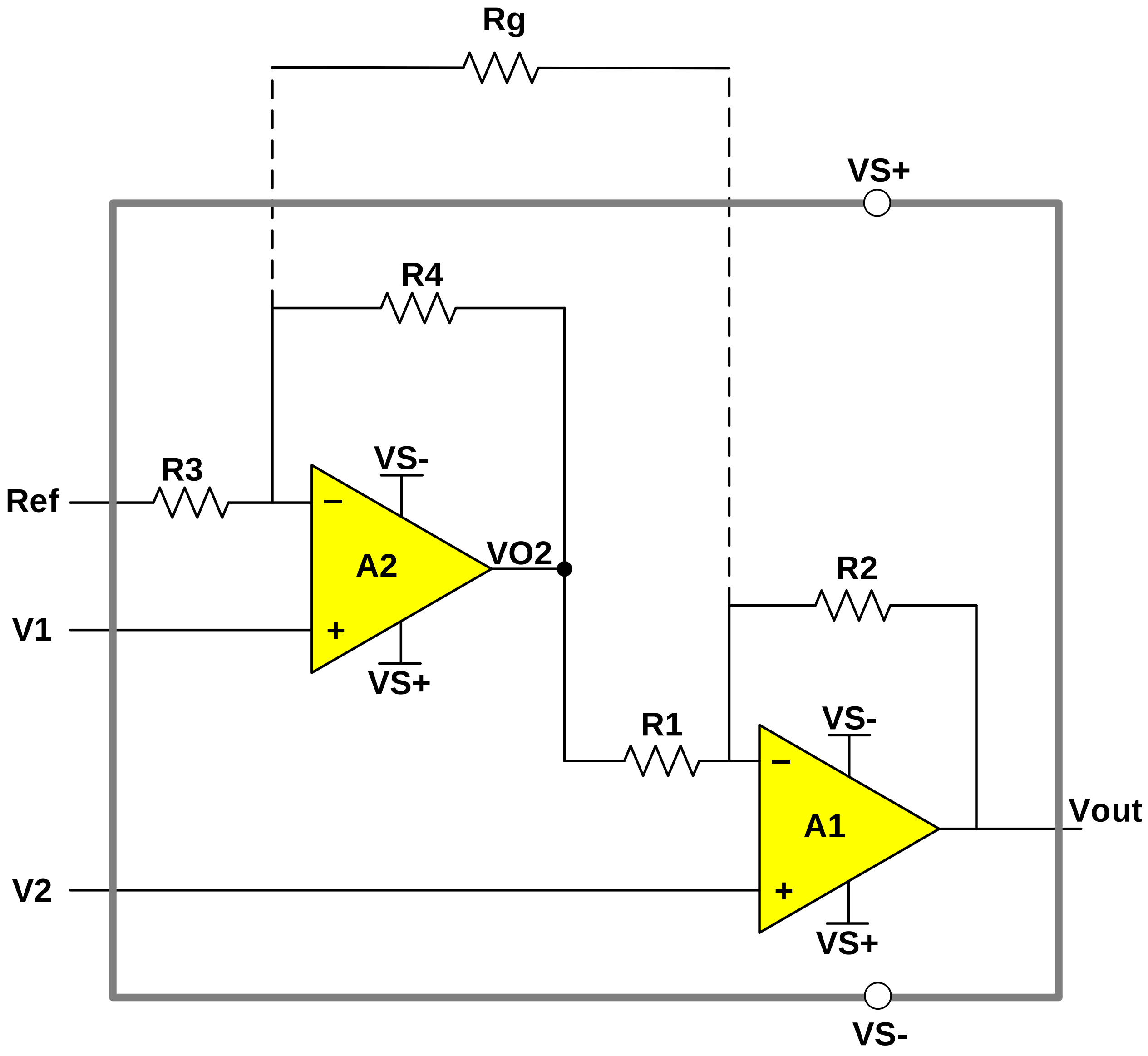
3. Determine Rg required

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.

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