ANALOG CIRCUITS DESIGN

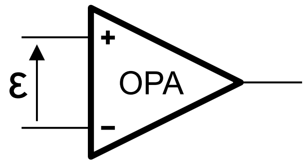
AE2: Operational Amplifiers I,
OPA Basic concepts & circuits

Course overview

1. Basic concepts:
    - What is an operational amplifier? Why negative feedback?
    - OPAs work as expected as long as…
    - What does $\varepsilon = 0$ exactly mean?
    - Output impedance
2. Linear circuits:
    - The voltage amplifier
    - The voltage follower
    - The transresistance amplifier
3. Non-linear circuits: the comparator
4. How to choose an OPA:
    - Split-supply versus single supply
    - Output voltage limitation
    - Output current limitation
    - Offset voltage
    - Bias & offset currents
    - Small-signal bandwidth
    - Slew-rate

1. Basic concepts: What is an operational amplifier? Why negative feedback?

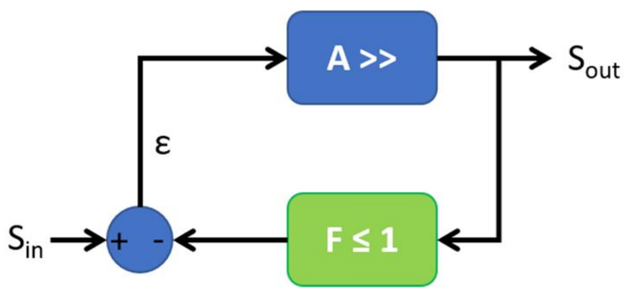
- What is an operational amplifier (OPA)?



Vo = A ε

It's basically a voltage amplifier with a very large voltage gain A

- What is negative feedback?



Negative feedback occurs when a fraction of the output signal S_{out} is substracted from the input signal S_{in} so that error ε tends to zero.

$$\varepsilon = \frac{S_{out}}{A} = \ S_{in} \ - F\ S_{out}$$

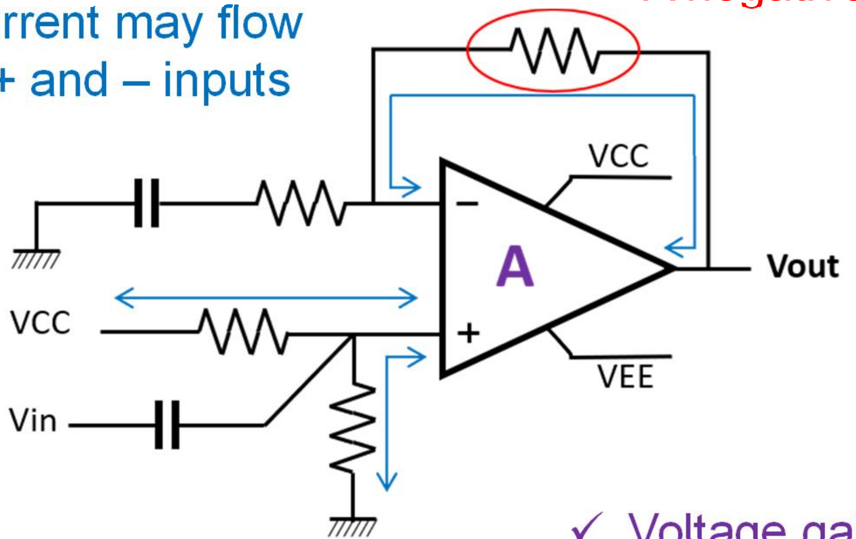
$$\frac{S_{out}}{S_{in}} = \frac{A}{1 + AF} \ \approx \frac{1}{F}\ if\ AF \gg 1$$

- What does the OPA when used with negative feedback?

It only ***attempts*** to adjust its output voltage Vo so that ε→ 0

1. Basic concepts: OPAs work as expected as lond as …

- ✓ A DC current may flow from/to + and – inputs
- ✓ A negative feddback path exists

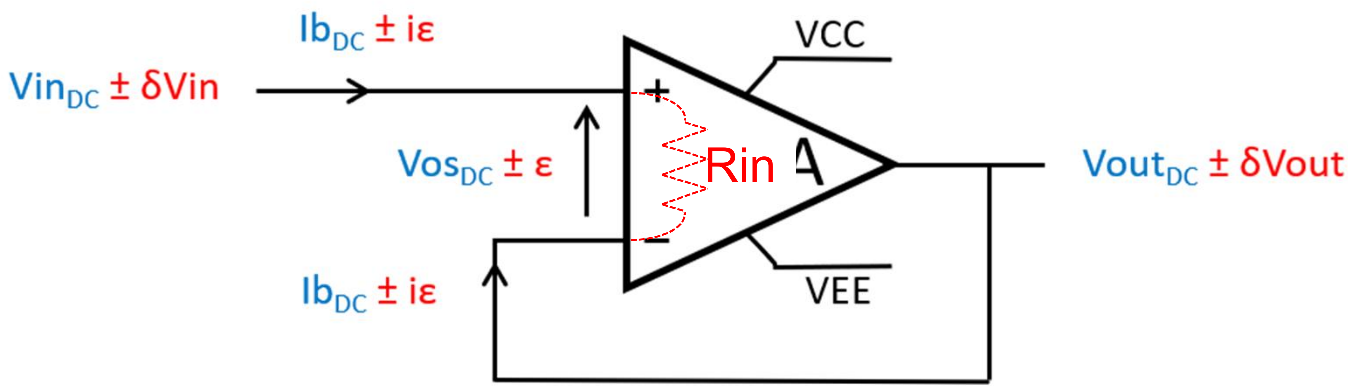


- ✓ VEE ≤ Vout ≤ VCC (linear operation)
- ✓ Voltage gain A remains sufficiently large

These four constraints must be ***simultaneously*** met

1. Basic concepts: What does ε = 0 exactly mean?

- In normal operation, two modes are superimposed:
  - Static (DC) mode (i.e. no signal applied)
  - Dynamic (AC) mode (i.e. signal is applied at input)



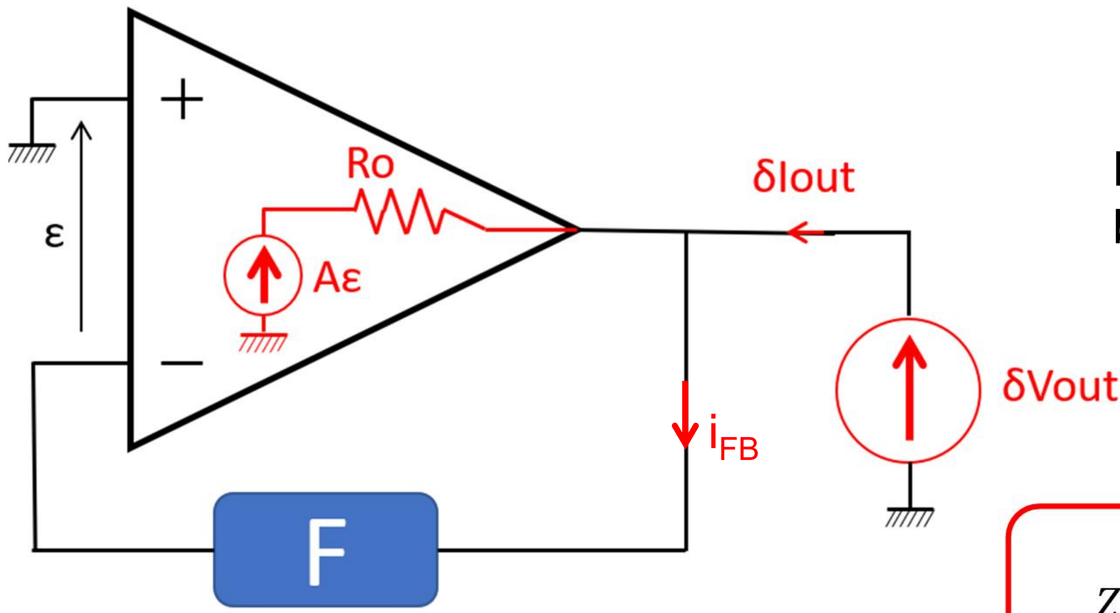
Ib_{DC}: bias current
Vos_{DC}: offset voltage

} Expected to be zero but still existing due to OPA non-idealities

Linear operation ↔ $VEE \leq Vout_{DC} \pm \delta Vout \leq VCC$ OPA gain A is very large

$$\boxed{\varepsilon = \frac{\delta Vout}{A} \rightarrow 0 \qquad i_\varepsilon = \frac{\varepsilon}{Rin} \rightarrow 0}$$

- OPA exhibits a non-zero output impedance Ro (10Ω ~ 50Ω typically)



$$-\varepsilon = \mathrm{F}\ \delta Vout$$

Let's now assume that i_{FB} can be neglected:

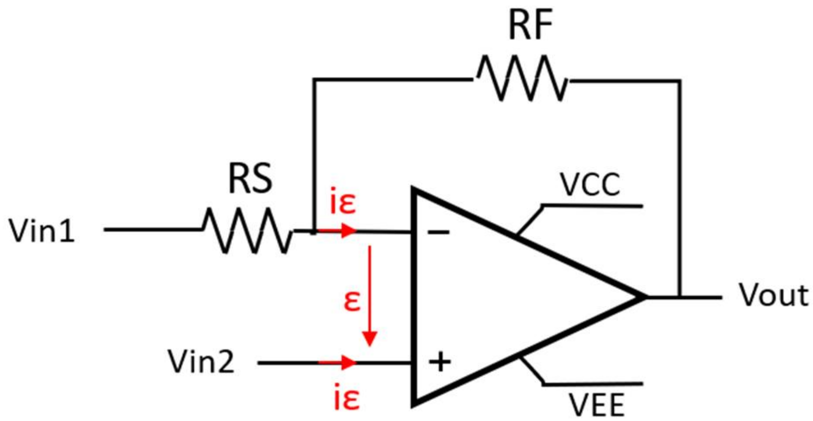
$$\delta Vout \approx A\,\varepsilon + Ro\,\delta Iout$$

$$\boxed{Zout = \frac{\delta Vout}{\delta Iout} \approx \frac{Ro}{1 + AF} \rightarrow 0}$$

- The OPA can be viewed as a nearly ideal voltage source when feedback **senses the output voltage** (most of the circuits)

2. Linear circuits: The voltage amplifier

➢ A circuit that you absolutely must know!



$$\boxed{Vout = \frac{-RF}{RS} Vin1 + (1 + \frac{RF}{RS})Vin2}$$

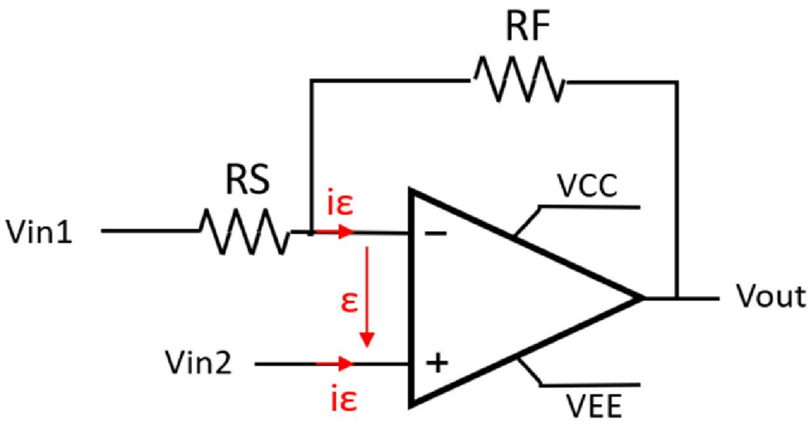
$$Zin1 = \frac{Vin1}{Iin1} = RS$$

$$Zin2 = \frac{Vin2}{I\varepsilon} \to \infty$$

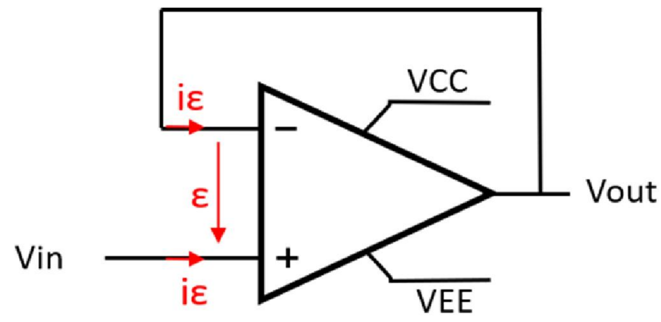
$$Zout \approx 0$$

➢ Possible configurations:
- Inverting amplifier when Vin2=0
- Non-inverting amplifier when Vin1=0
- Differential amplifier
- Voltage follower when RF=0 and RS → ∞

2. Linear circuits: The voltage follower

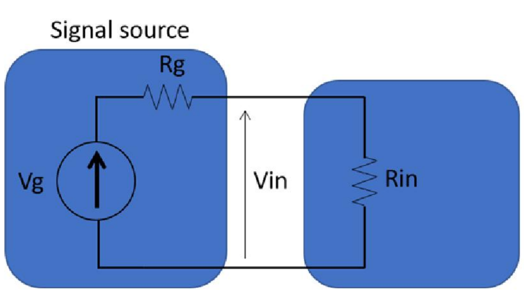


RF=0
RS $\to \infty$

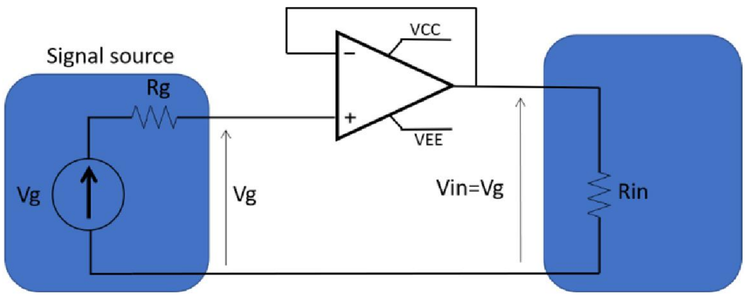


$$Vout = Vin \qquad Zin = \frac{Vin}{I\varepsilon} \to \infty \qquad Zout \approx 0$$

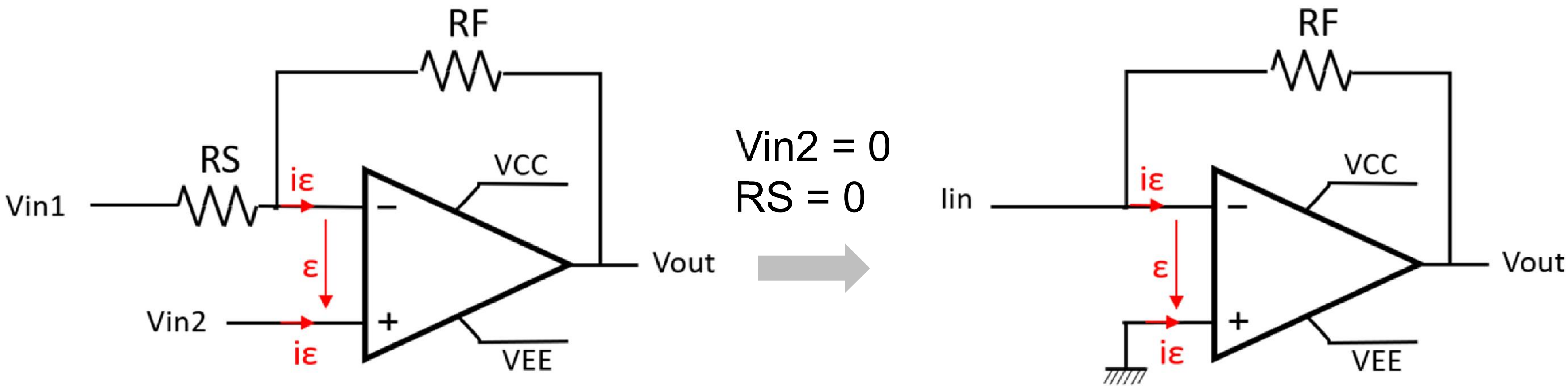
- Typically used as voltage buffer



$$Vin = \frac{Rin}{Rin + Rg} Vg$$



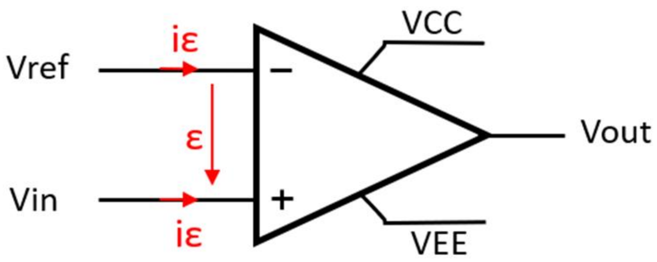
2. Linear circuits: The transresistance amplifier

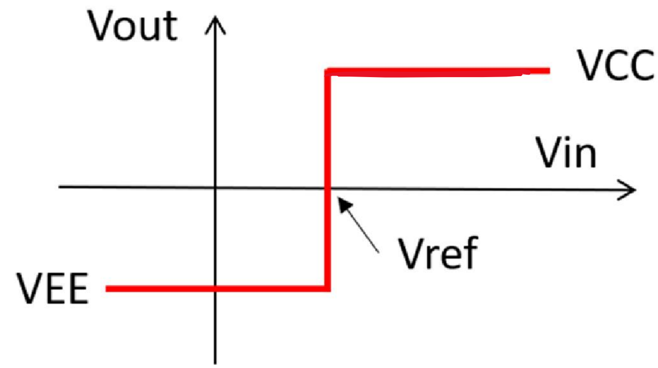


$$Vout = -RF\ Iin \qquad Zin = \frac{\varepsilon}{Iin} \approx 0 \qquad Zout \approx 0$$

➢ Current-to-voltage converter

3. Non-linear circuits: The comparator

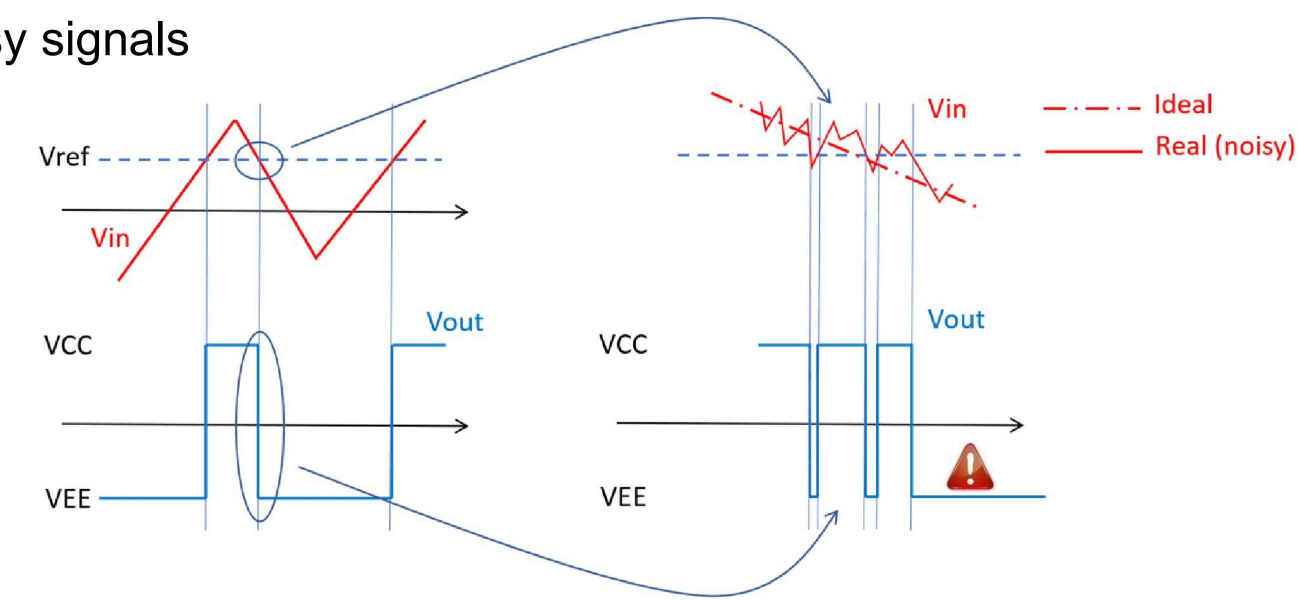




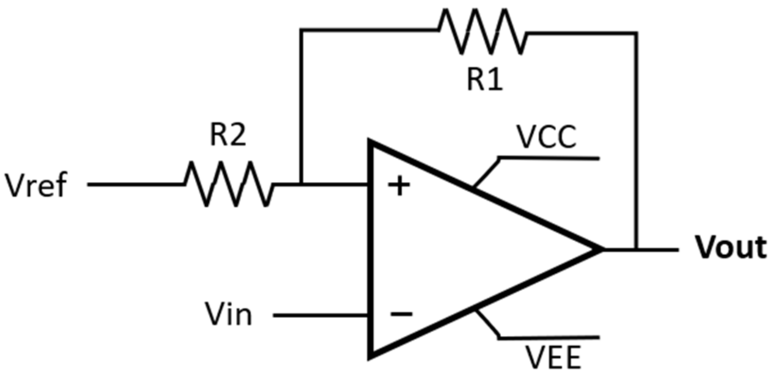
No feedback

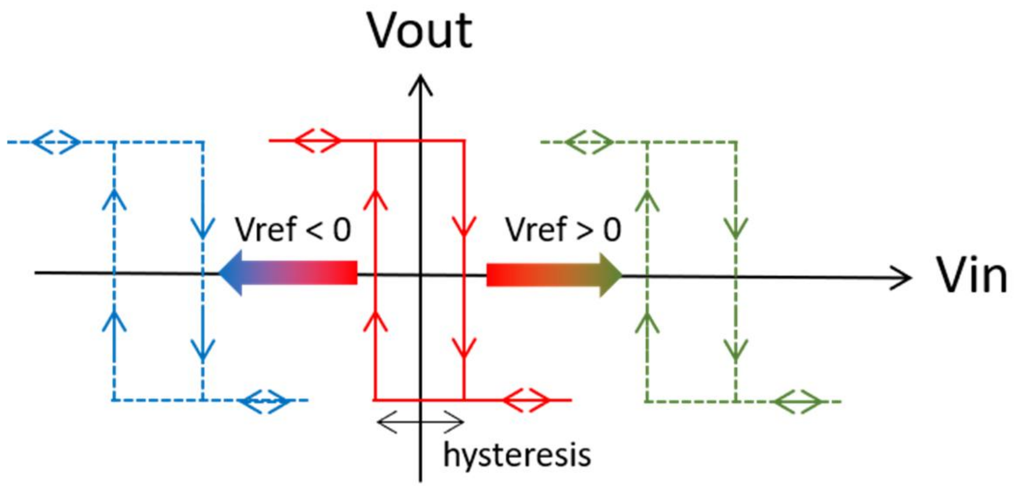
Most of the time:
ε ≠ 0 and iε ≠ 0

- Problem with noisy signals



3. Non-linear circuits: The comparator





Positive feedback

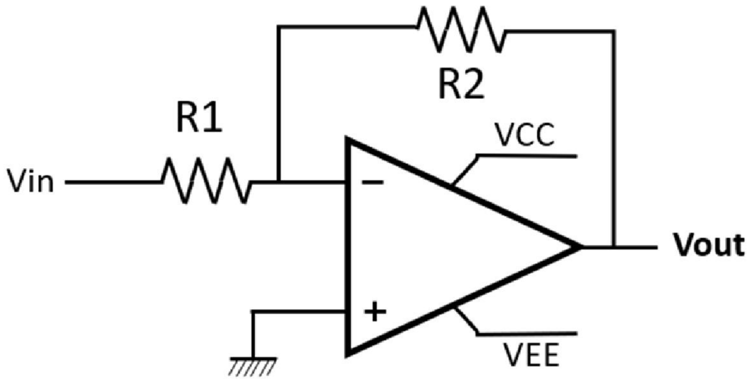
Most of the time:
$\varepsilon \neq 0$ and $i\varepsilon \neq 0$

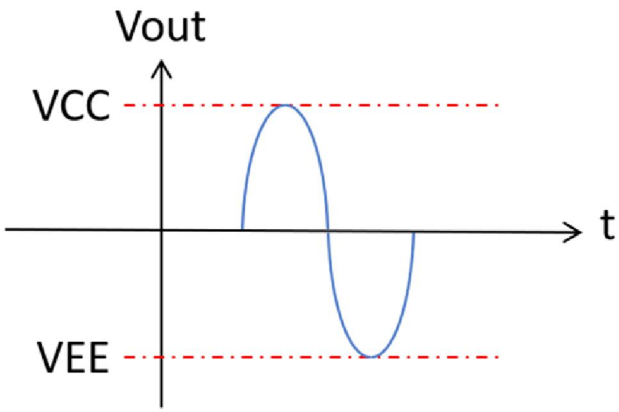
- Hysteresis must be larger than noise

- Some OPA don't work properly as comparator → better use dedicated circuits

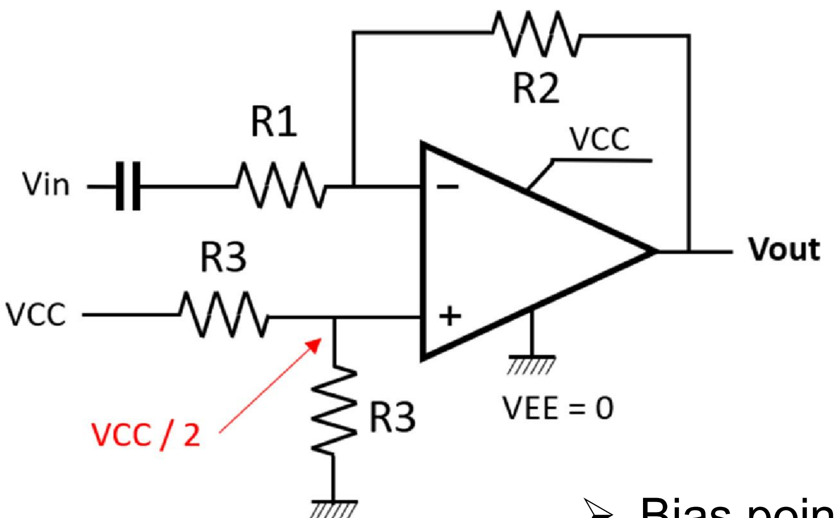
4. How to choose an OPA: Split-supply versus single supply

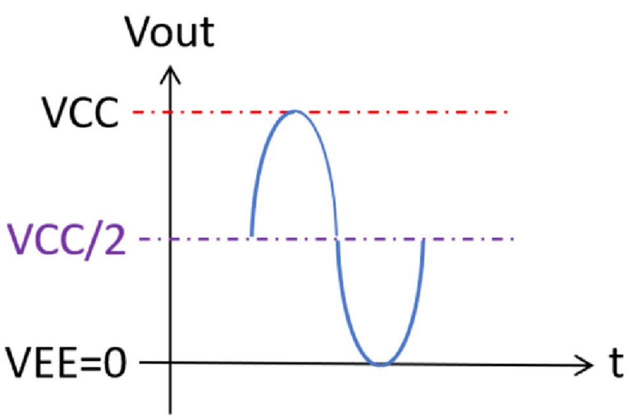
- Split-supply (VEE = -VCC)





- Single supply (VEE = 0) for battery-operated circuits





- Bias point automatically set to VCC/2 (optimal value)

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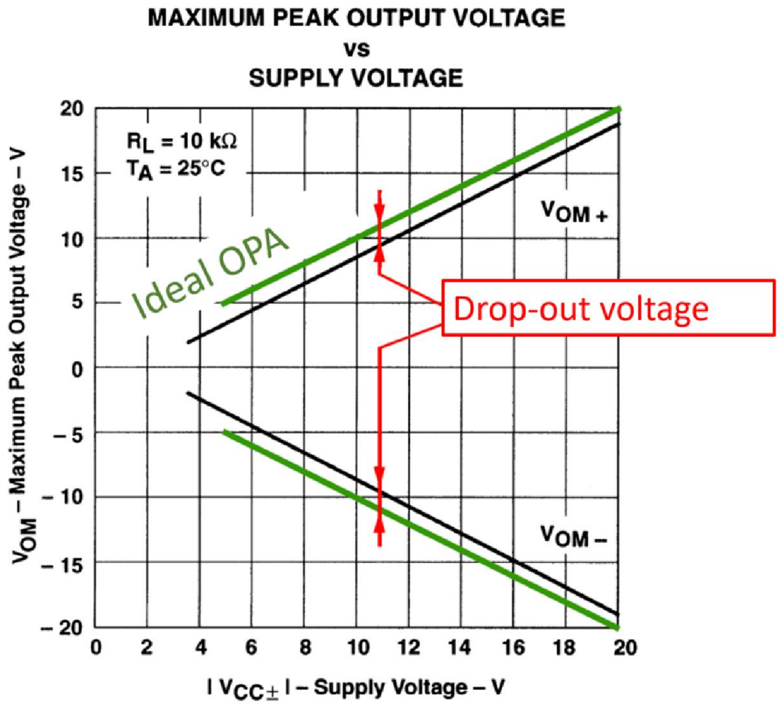
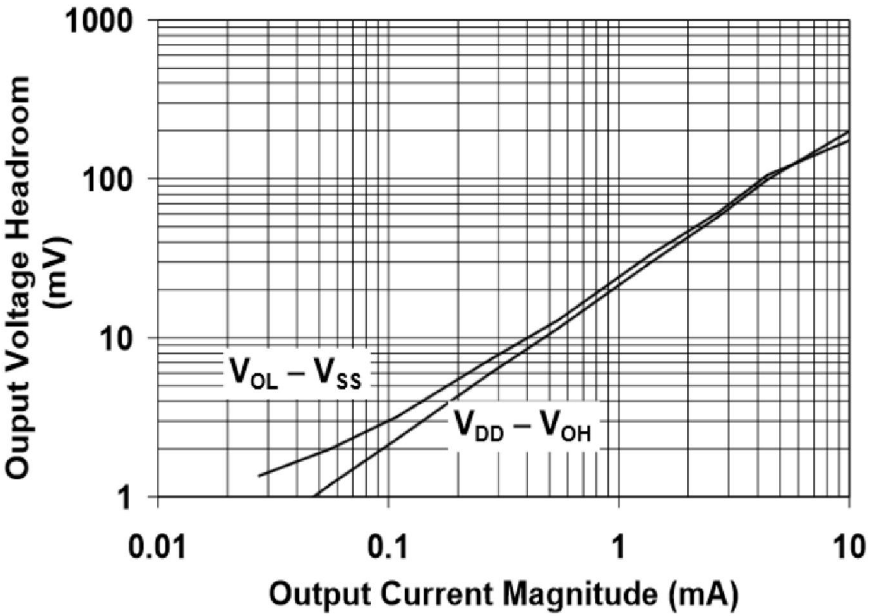
4. How to choose an OPA: Output voltage limitation

- Ideally VEE ≤ Vout ≤ VCC, but drop-out limits output voltage
- Battery-operated circuits require low VCC value → better use rail-to-rail OPA



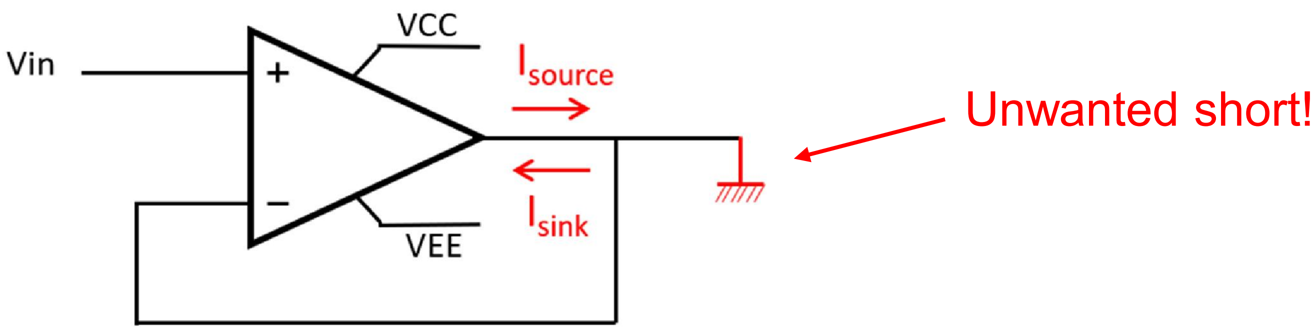


Drop-out is constant → increasing influence as supply voltage decreases

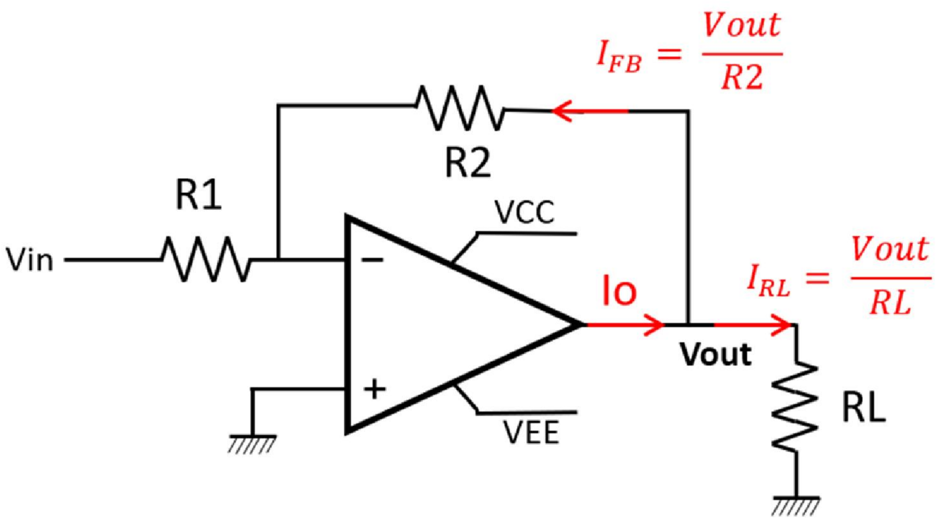
Drop-out greatly reduced but not eliminated

4. How to choose an OPA: Output current limitation

- Output current is limited to protect OPA against circuit defects



- But output current limitation also applies in normal operation!

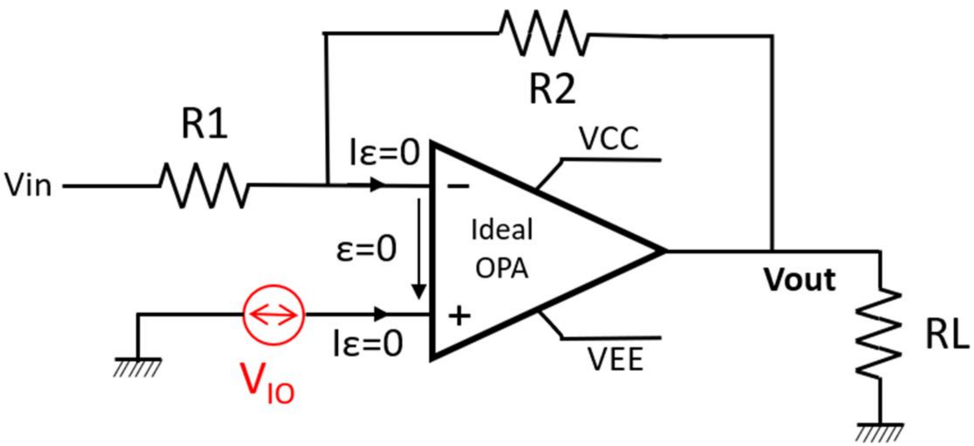


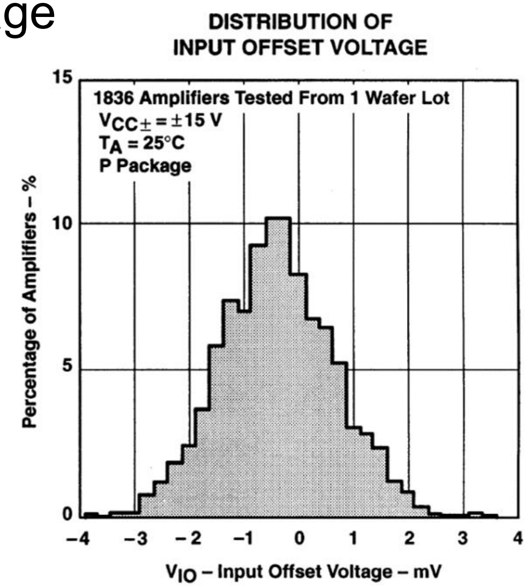
Io is limited → I_{FB} should be minimized to save power for the load → R2 should be large enough, but not too large to minimize noise

Standard OPA: $I_o \approx 20mA$

4. How to choose an OPA: Offset voltage

- Random DC voltage due to asymmetry in OPA input stage
- Model: a DC voltage source added to an ideal OPA



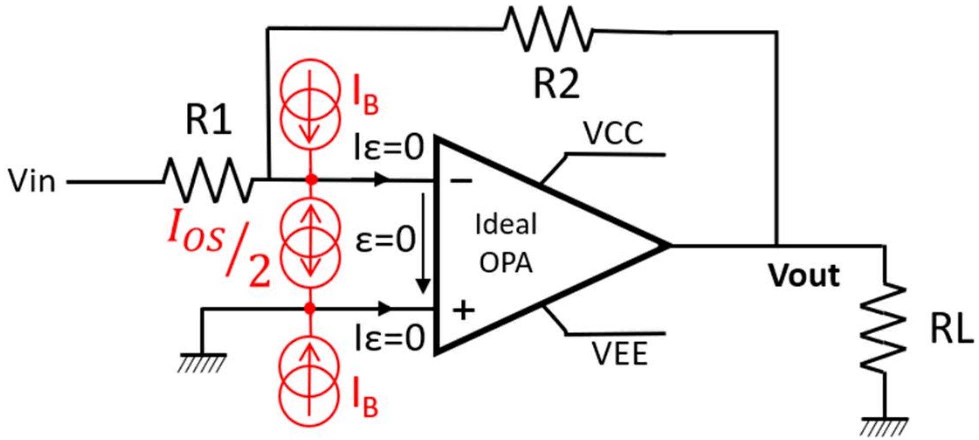


$$Vout = \frac{-R2}{R1} Vin \pm \left(1 + \frac{R2}{R1}\right) V_{IO}$$

- It may be a problem:
  - For high gain and low supply amplifiers
  - For high resolution ADC drivers

4. How to choose an OPA: Bias & offset currents

- DC input currents necessary to operate the OPA input stage
- Model: three DC current sources added to an ideal OPA



Bias current: $I_B = \frac{I_{B+} + I_{B-}}{2}$
(usually known polarity)

Offset current: $I_{OS} = |I_{B+} - I_{B-}|$
(random polarity)

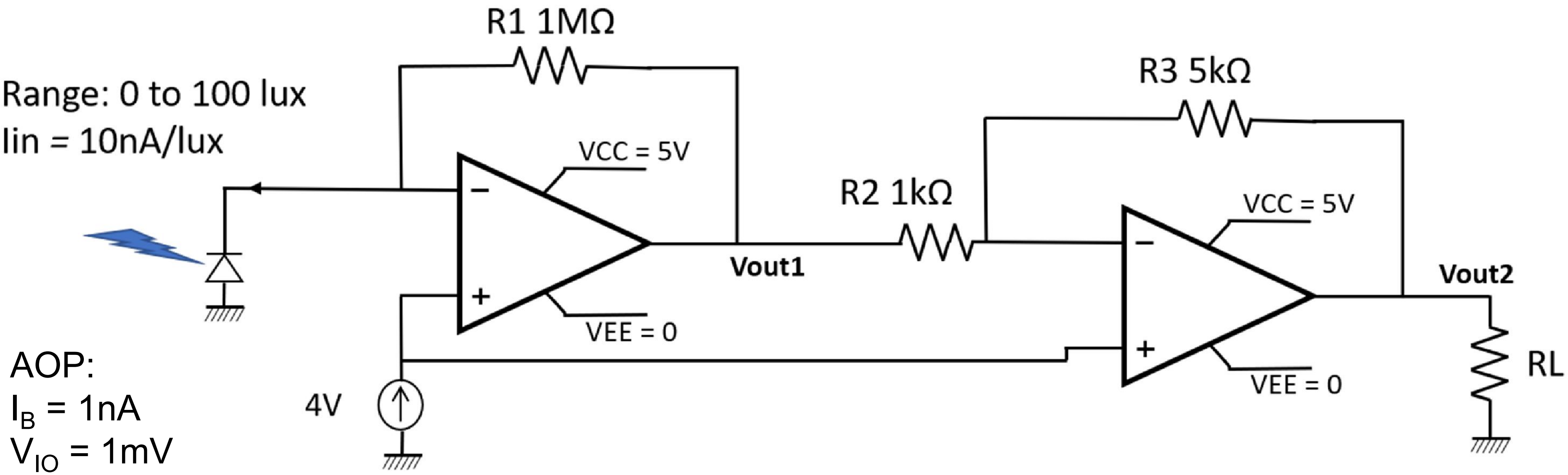
$$Vout = \frac{-R2}{R1} Vin \pm R2\, I_B \pm R2 \frac{I_{OS}}{2}$$

Depends on polarity

Random

- It may be a problem:
  - For low signal currents
  - For high value of resistor R2

4. How to choose an OPA: good or poor design?

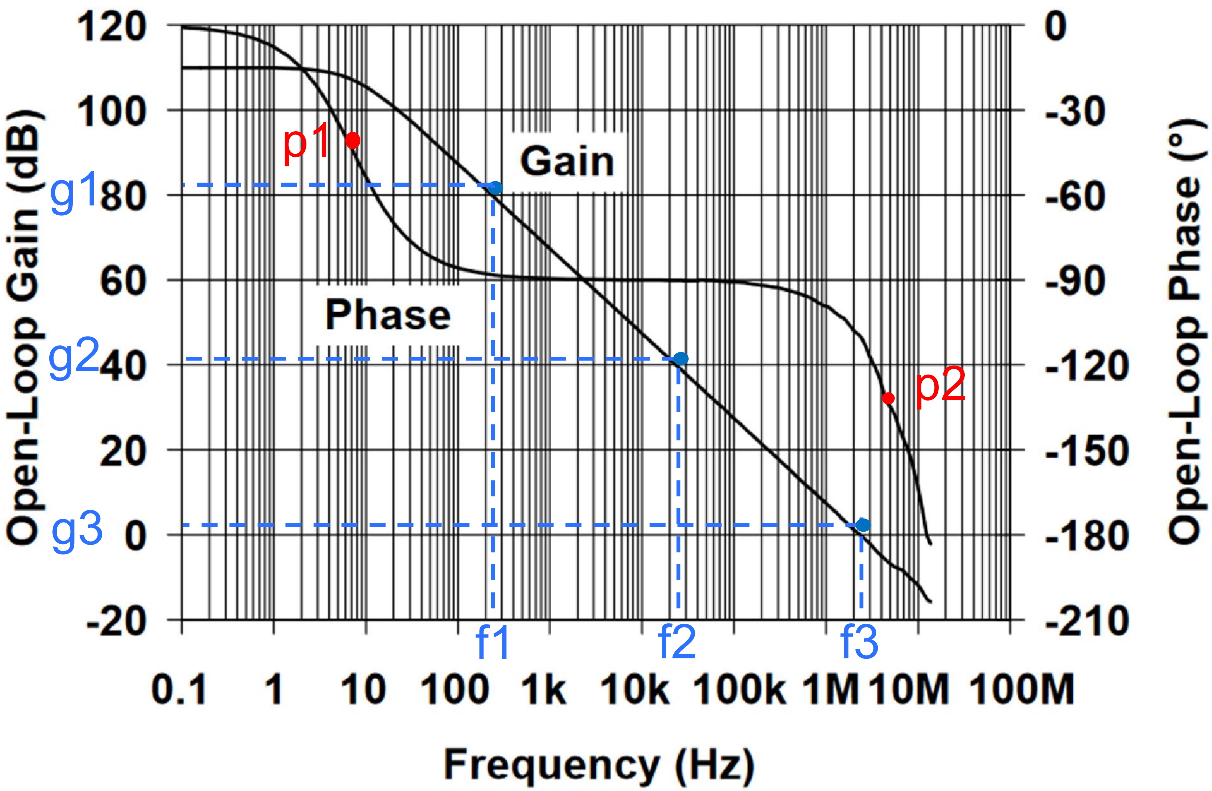


AOP:
I_B = 1nA
V_{IO} = 1mV
Drop-out = 100mV
I_O = 20mA

	OK	**KO**
IB		
VIO		
Drop-out		
IO		

	OK	**KO**
IB		
VIO		
Drop-out		
IO		

- Amplifier's gain is not constant: at last, two poles exist (p1, p2)
- 1st order behaviour dominates in usable frequency range:
  - → GBW = gain x bandwidth = constant
  - → GBW = g1 f1 = g2 f2 = g3 f3 (gi are closed-loop gains)



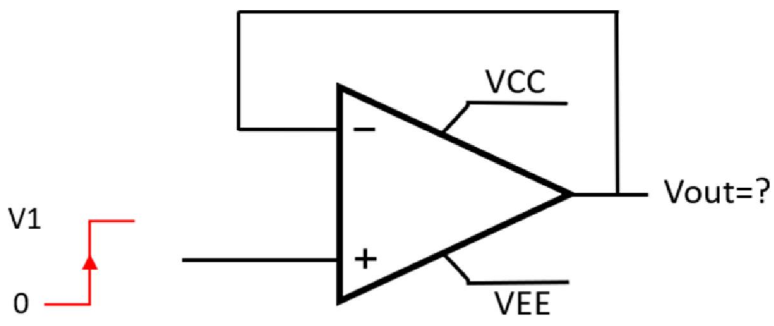
Example: MCP6274
GBW = 2MHz

Gain=1 → BW=2MHz

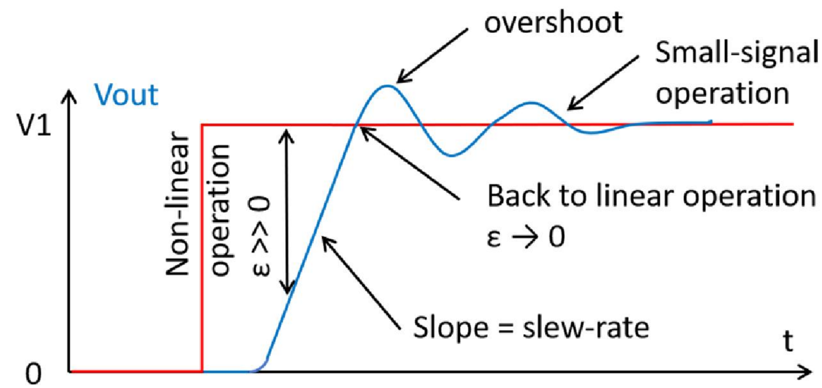
Gain=10 → BW=200kHz

Gain=100 → BW=20kHz

4. How to choose an OPA: Slew-rate

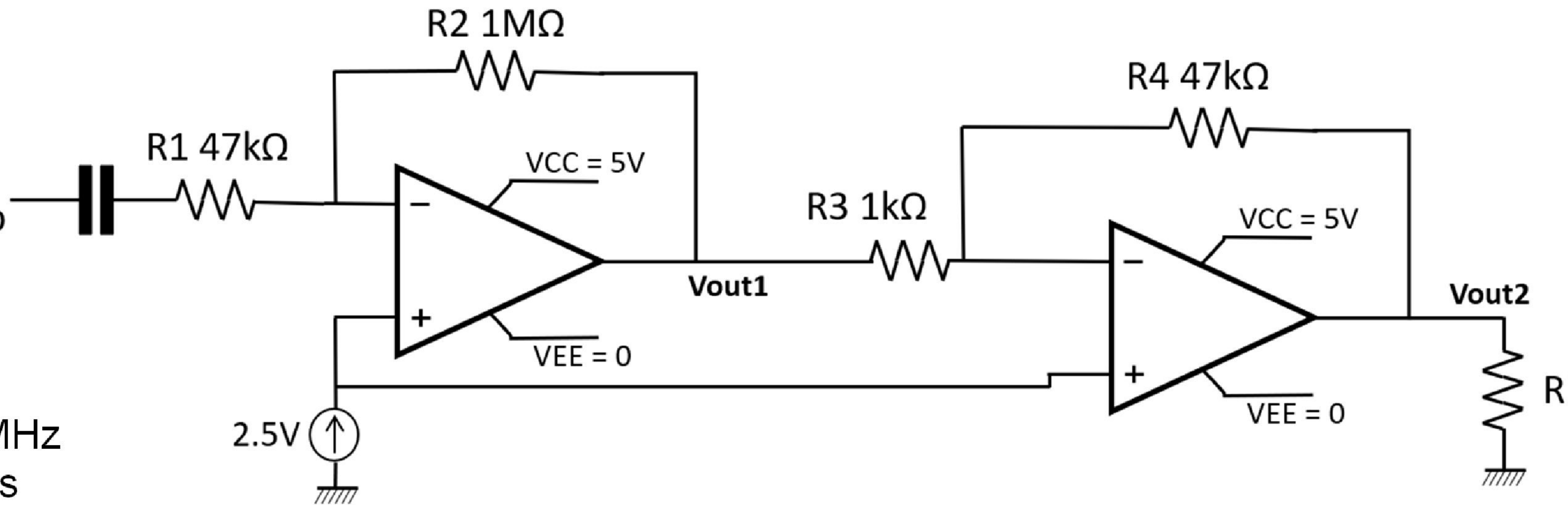


- $\frac{dVout}{dt}$ is limited → slew-rate



- If $\frac{dVout}{dt}$ > slew-rate → signal is distorted
- Sinewave A sin(ω t): $(\frac{dV}{dt})_{max} = 2\,\pi\,f\,A$
- Slew-rate is a concern for large and/or high-frequency signals

4. How to choose an OPA: good or poor design?



AOP:
GBW = 2MHz
SR = 2V/µs

	OK	KO
GBW		
SR		

	OK	KO
GBW		
SR		

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