What does precision mean for an op amp?

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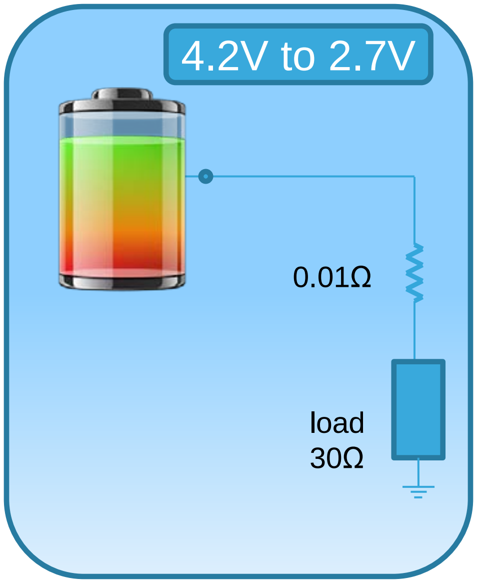
Why op amps and why precision

Battery fuel gauging



0.9 mV ≤ **V1max** ≤ 1.4 mV

Very small signal

Need to Amplify

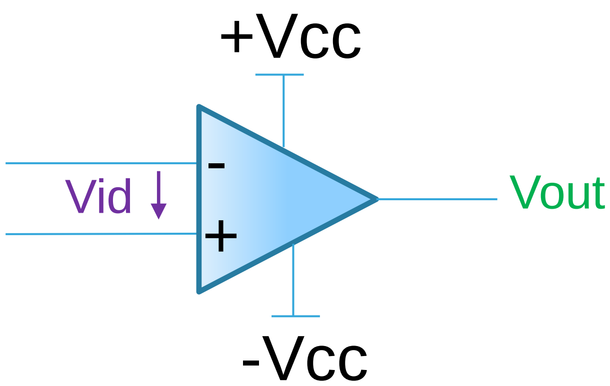
STM32 power supply:
1.65V to 3.6V

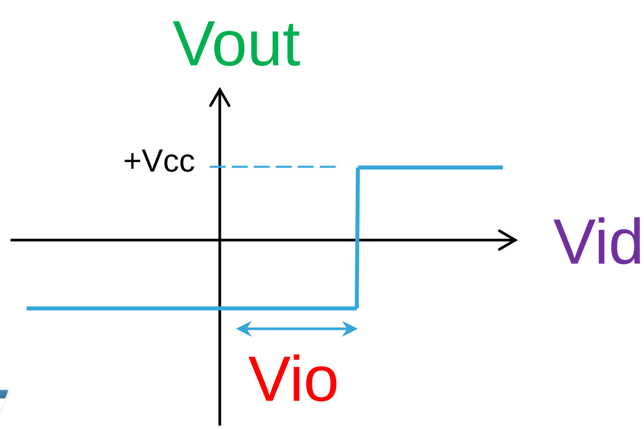
ADC
12bits

LSB of the ADC
$= 3.6V / 2^{12}$
$= 0.88$ mV !

Input offset voltage
What is this?

- Vio offset





LM324

Symbol	Parameter	Min.	Typ.	Max.	Unit
V_{io}	Input offset voltage [1] $T_{amb} = +25° C$ LM124-LM224 LM324		2	5 7	mV
	$T_{min} \leq T_{amb} \leq T_{max}$ LM124-LM224 LM324			7 9	

TS507

V_{io}	Input offset voltage[2]	V_{icm} = 0 to 3.8 V, T=25 °C TS507C full temperature range TS507I full temperature range		25	100 250 400	µV
		V_{icm} = 0 V to 5 V, T=25 °C TS507C full temperature range TS507I full temperature range			450 550 750	

TSZ121 (Very high accuracy)

Symbol	Parameter	Conditions	Min.	Typ.	Max.	Unit
DC performance						
V_{io}	Input offset voltage	T = 25 °C		1	5	µV
		-40 °C < T< 125 °C			8	
$\Delta V_{io}/\Delta T$	Input offset voltage drift[1]	-40 °C < T< 125 °C		10	30	nV/°C

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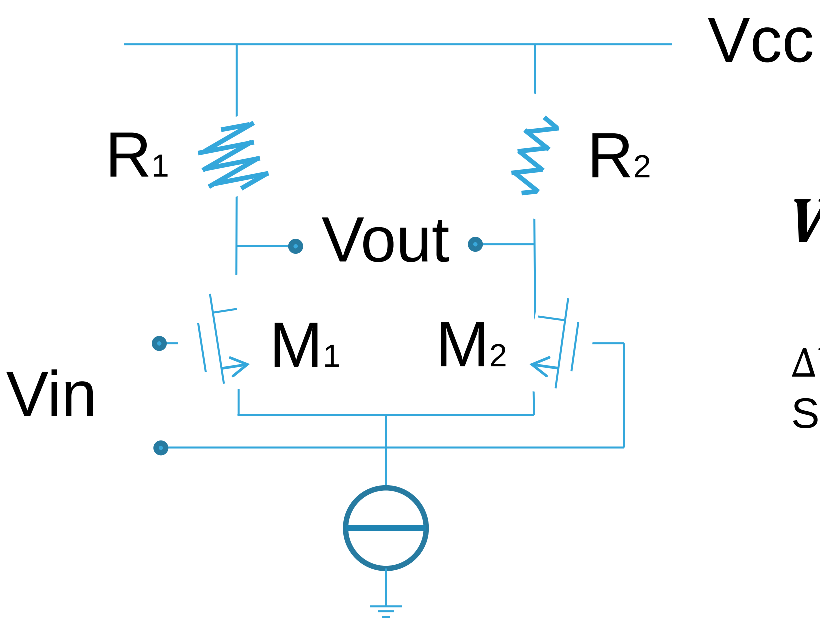
Input offset voltage
Where does it comes from?

- Differential input



For CMOS technology

$$Vos = \Delta Vth + \frac{VGS - VT}{2}\left(\frac{\Delta R}{R} + \frac{\Delta k'}{k'} + \frac{\Delta W/L}{W/L}\right)$$

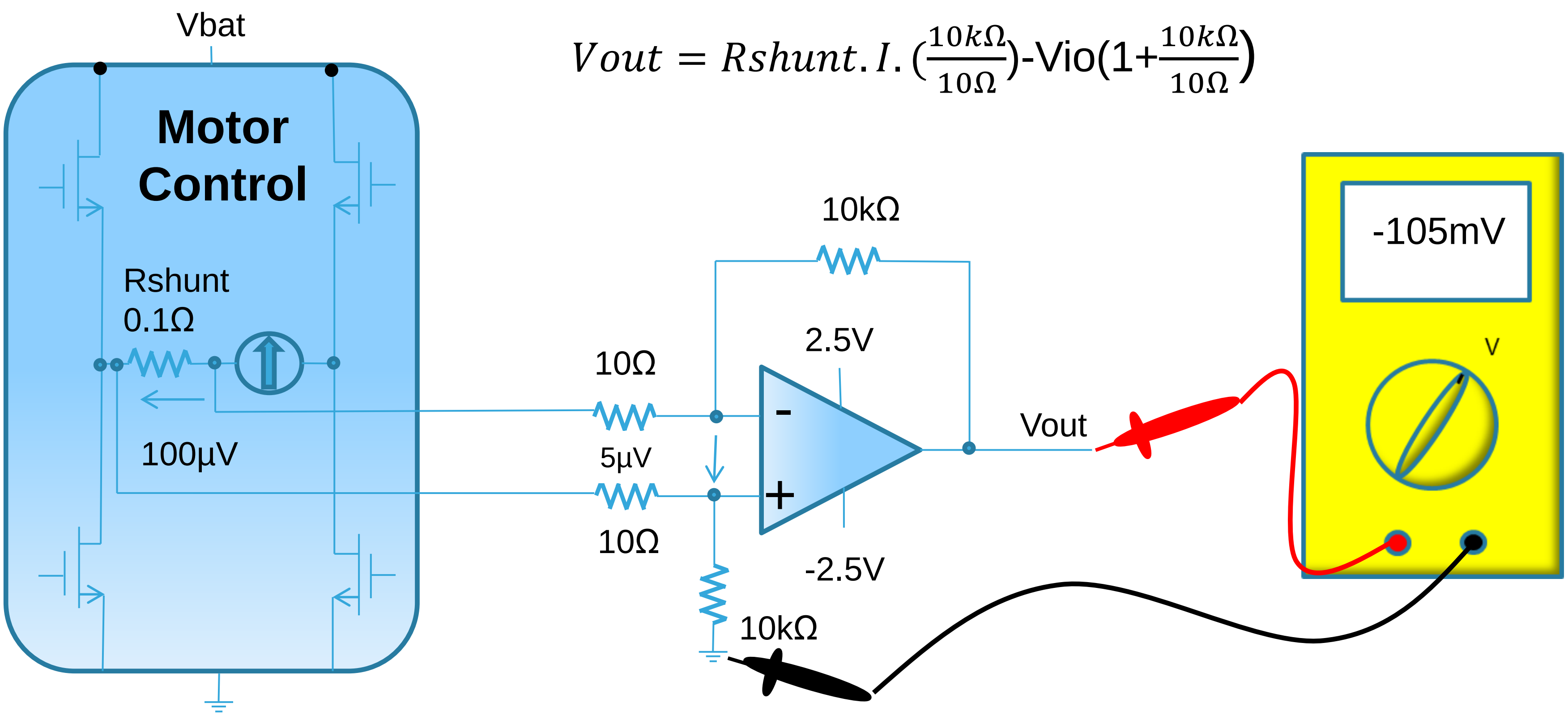
ΔVth linked to the substrate doping
Second term linked to the size of MOS

Component mismatch
R1≠R2, M1≠M2 ⇒ **offset**

Mismatch is mainly due to:
- Doping variations
- Lithographic errors
- Packaging & local stress

Impact of V_{IO} on a real application
current sensing for Motor control

$$Vout = Rshunt.I.(\frac{10k\Omega}{10\Omega})\text{-Vio}(1+\frac{10k\Omega}{10\Omega})$$



I=1mA

TSZ121

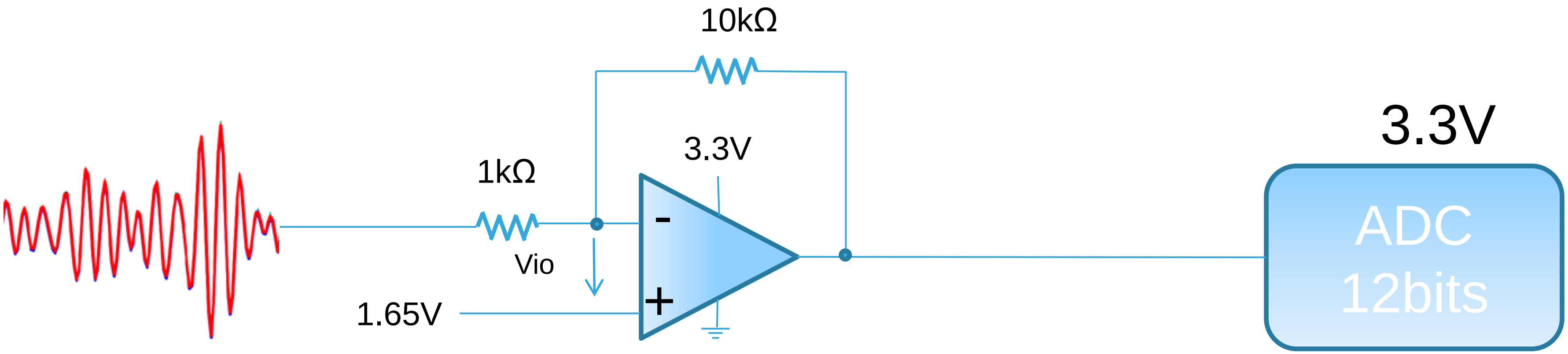
Vio=5µV

5% error on speed information
rotation information is correct

Summary of V_{IO} impact on motor control applications

Opamp	Offset @ 25°C	V_{OUT} for a current I = 1 mA	Comment
Ideal	0 µV	100 mV	Theoretical measurement in a perfect world!
TS507	+100 µV	-100 µV	Speed of the motor is incorrect. Information about the motor rotation is incorrect
	-100 µV	200 mV	100% error on motor speed Information about the motor rotation is correct
TSZ121	+5 µV	95 mV	5% error on the motor speed Information about the motor rotation is correct
	-5 µV	-105 mV	5% error on the motor speed Information about motor rotation is correct

The real cost of V_{IO}!



The LSB of the ADC is $3.3\ V/2^{12} = 805\ \mu V$

The input signal is amplified by -10, and the V_{IO} by 11

	Maximum V_{IO}	Maximum offset at ADC	Equivalent effective ADC
TSZ121	5 µV	55 µV	~12 bits
TS507	100 µV	1.1 mV	~11 bits
TS512A	500 µV	5.5 mV	~9 bits
TS512	2.5 mV	27.5 mV	~7 bits

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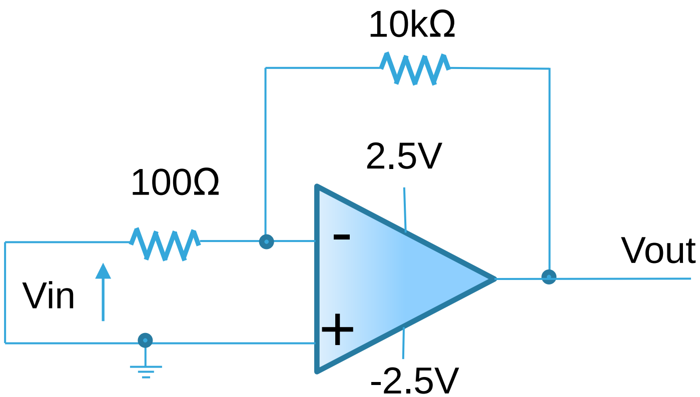
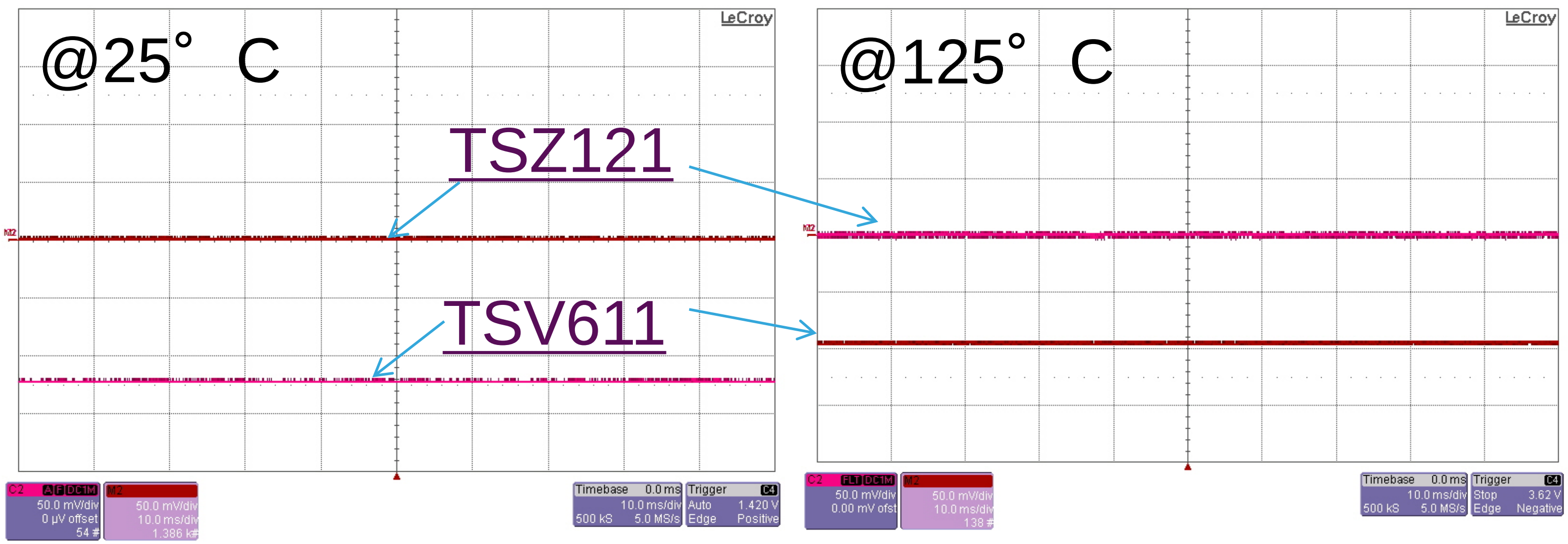
ΔVio/ΔT and Calibration



$$Vout = Vin\left(\frac{-10k\Omega}{100\Omega}\right) \pm Vio\left(1+\frac{10k\Omega}{100\Omega}\right) \quad (1)$$

$$Vout = Vin\left(\frac{-10k\Omega}{100\Omega}\right) \pm \left(Vio \pm dT\left(\frac{\Delta Vio}{\Delta T}\right)\right)\left(1+\frac{10k\Omega}{100\Omega}\right) \quad (2)$$



	Vio @25°C max	Δvio/Δt max
TSZ121	5µV	30nV/°C
TSV611	4mV	10µV/°C

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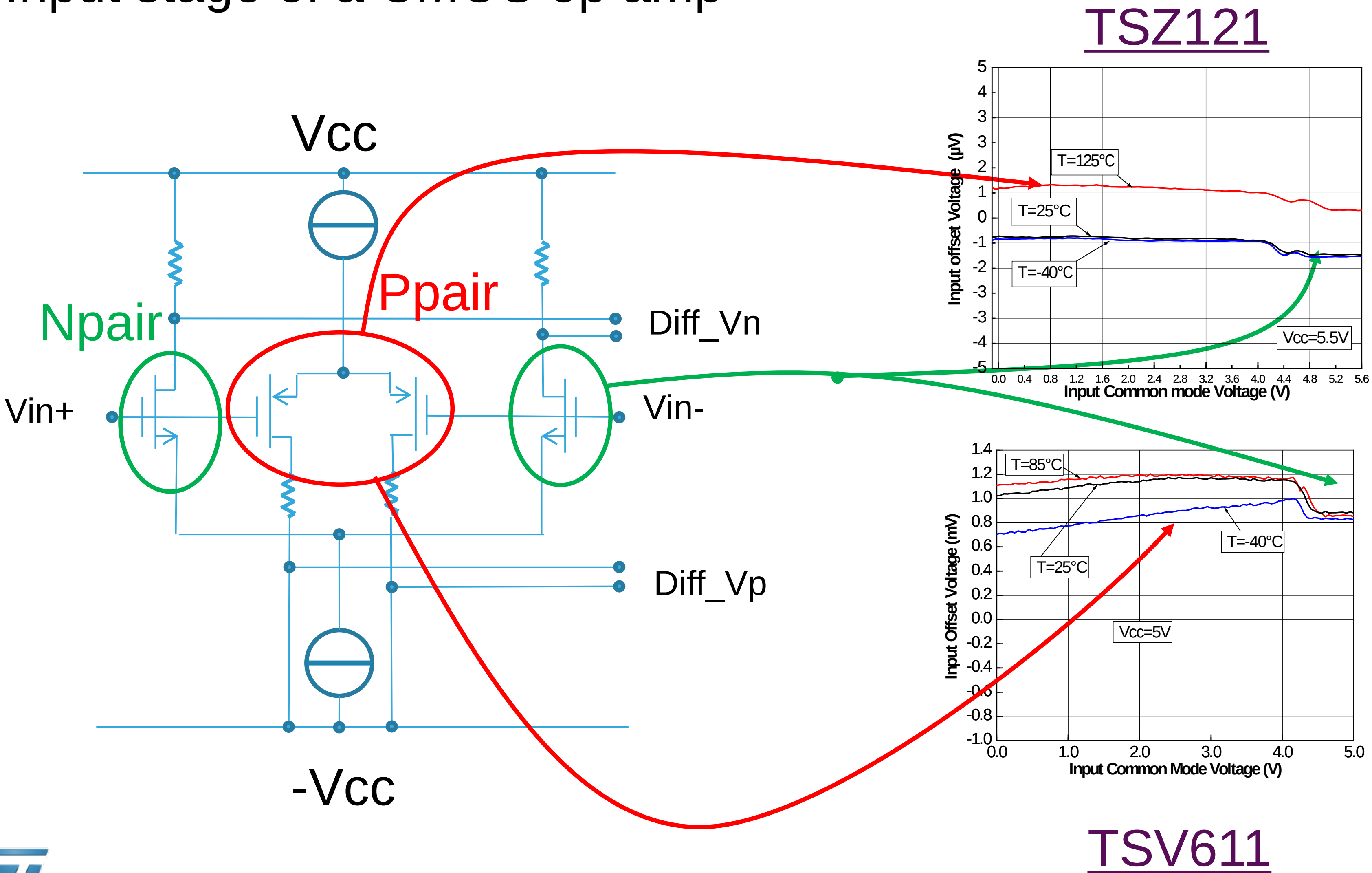
Common mode rejection ratio

Input stage of a CMOS op amp

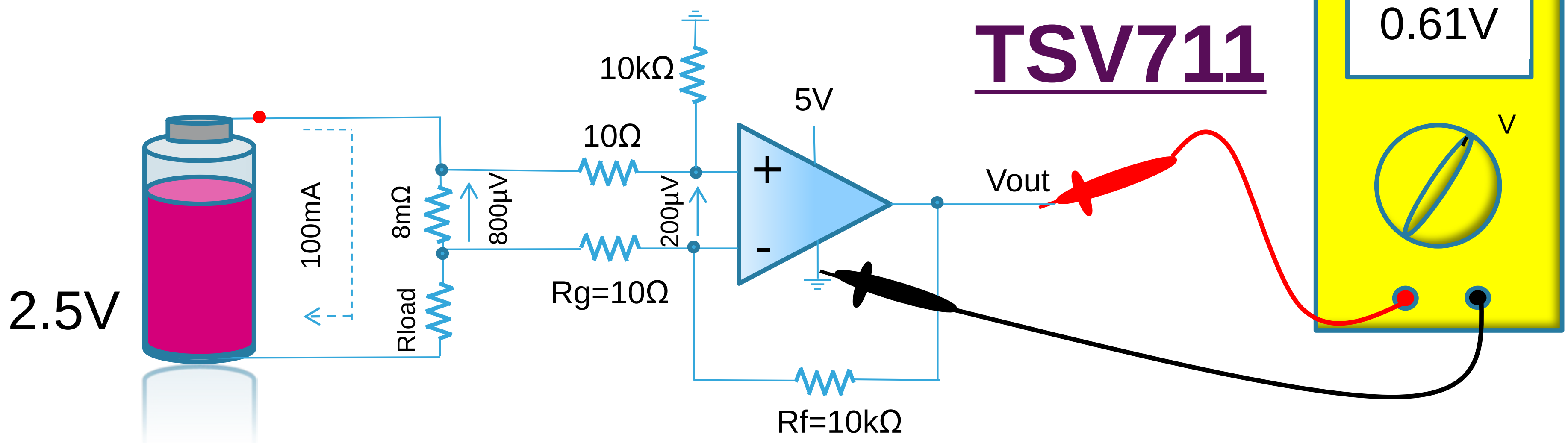


Impact of CMRR on a battery monitoring
High-side current sensing

$$CMRR_{res} = \frac{1+\frac{Rf}{Rg}}{4\varepsilon}$$

$$Vout = 0.8 - \left(1+\frac{Rf}{Rg}\right).Vio \pm \frac{vbat}{CMRRres}\left(\frac{Rf}{Rg}\right) \pm \frac{vicm - vcc/2}{CMRRop}\left(1+\frac{Rf}{Rg}\right)$$

With ε=0.1% precision resistance
and a gain of 1000
The CMRR of the whole schematics is 250250 (108 dB)



TSV711	Impact on Vout	Error %
Vio	0.2V	25%
CMRRres @4.2V (108dB)	16.8mV	2.1%
CMRRop @4.2V (74dB)	340mV	42.5%
CMRRres @2.5V (108dB)	10mV	1.2%
CMRRop @2.5V (74dB)	0mV	0%

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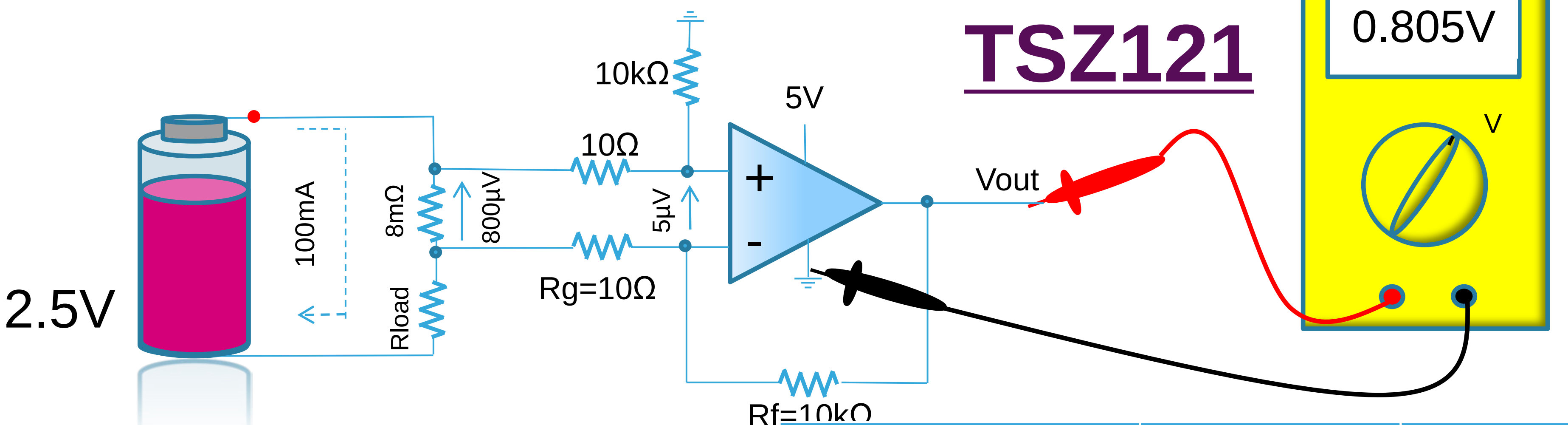

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CMRRres @2.5V (108dB)	10mV	1.2%
CMRRop @2.5V (74dB)	0mV	0%

TSZ121	Impact on Vout	Error %
Vio	0.005V	0.5%
CMRRres @4.2V (108dB)	16.8mV	2.1%
CMRRop @4.2V (115dB)	3mV	0.4%
CMRRres @2.5V (108dB)	10mV	1.2%
CMRRop @2.5V (115dB)	0mV	0%

V_{IO}, CMRR, PSRR and A_{VD}

Input Offset

PSRR

$$Vid = Vio + \frac{\partial Vid}{\partial Vout}\Delta Vout + \frac{\partial Vid}{\partial Vicm}\Delta Vicm + \frac{\partial Vid}{\partial Vcc}\Delta Vcc + \frac{\partial Vid}{\partial T}\Delta T \quad (1)$$

AVD

CMRR

Input Offset drift

$$We\ define: Avd = -20\log\left(\left|\frac{\partial Vid}{\partial Vout}\right|\right),\ CMRR = -20\log\left(\left|\frac{\partial Vid}{\partial Vicm}\right|\right),\ SVR = -20\log\left(\left|\frac{\partial Vid}{\partial Vcc}\right|\right)\ and\ DV_{io} = \left|\frac{\partial Vid}{\partial T}\right|$$

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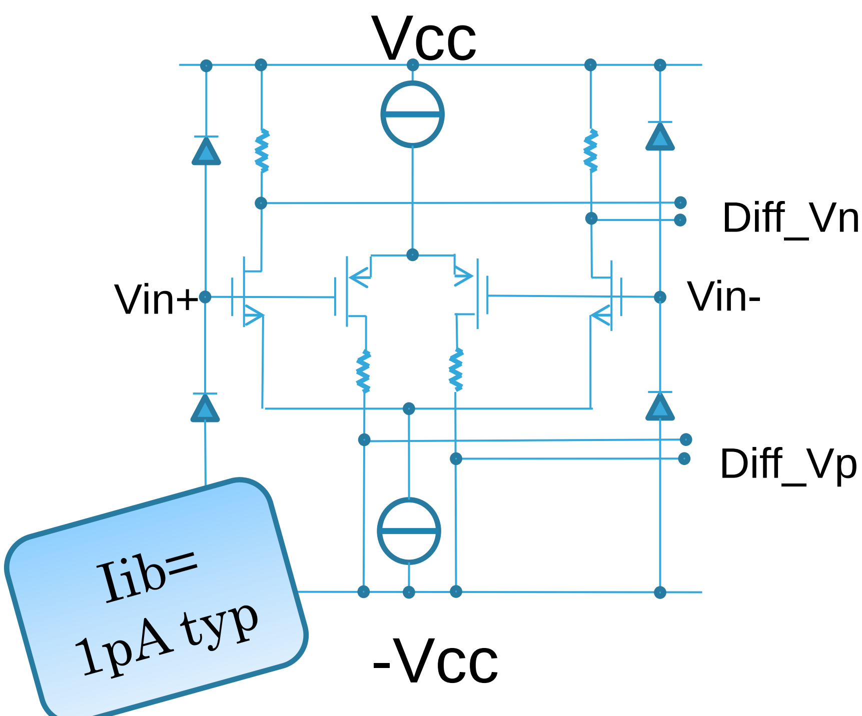
Input bias current

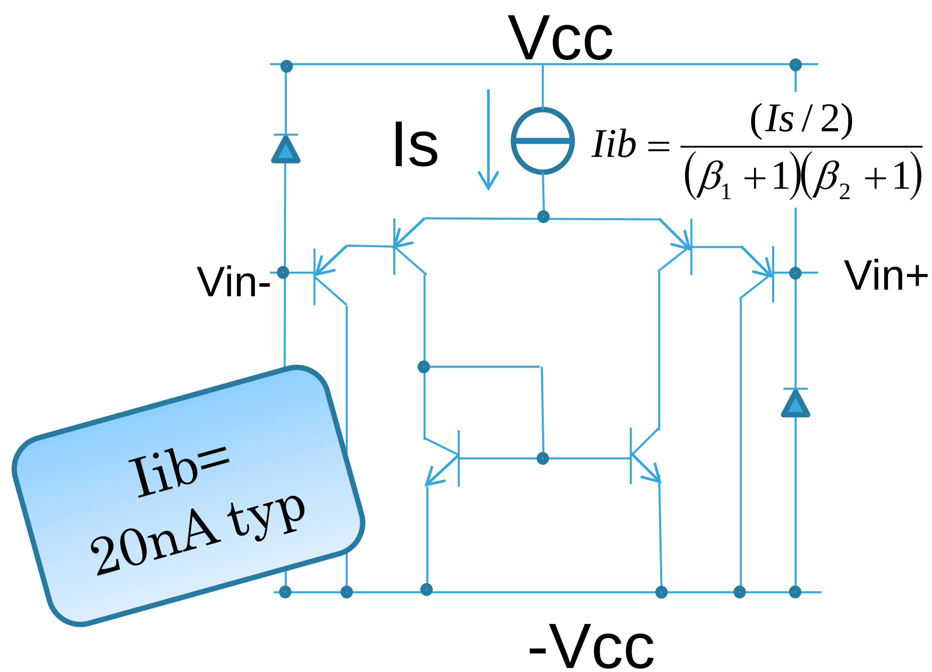
CMOS

- No gate current only diode leakage



BIPOLAR

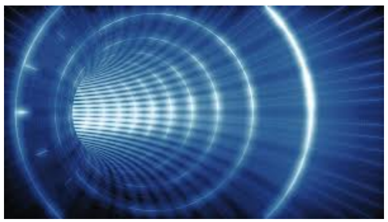
- Current in/out (NPN/PNP) in the base

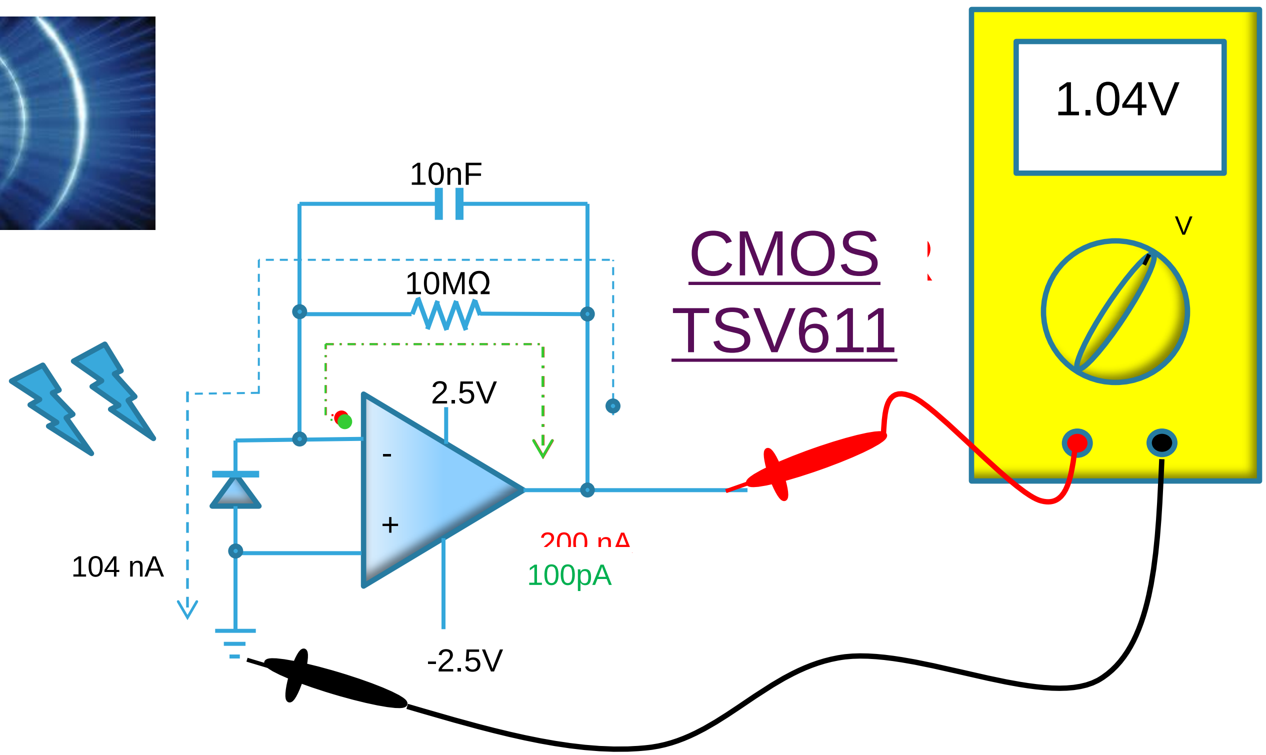


$$I_{ib} = \left| \frac{I_{ibn} + I_{ibp}}{2} \right|$$

UV sensor application

UV source Index 4





UV table translation for the UV sensor and Gain of 10M						
UV1	UV2	UV3	UV4	UV5	UV6	UV7
0.26 V	0.52 V	0.78 V	1.04 V	1.3 V	1.56 V	1.82 V

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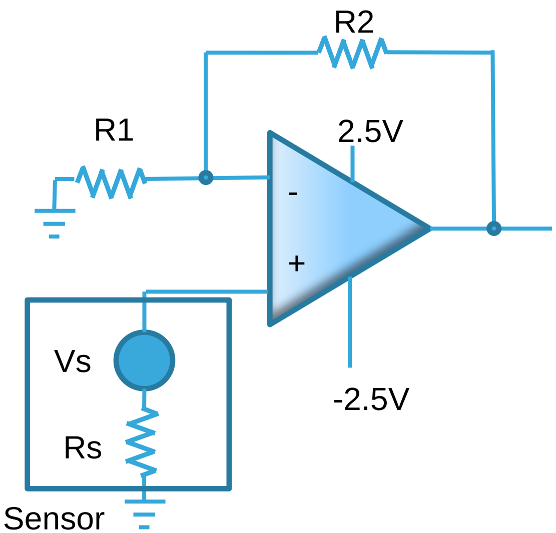
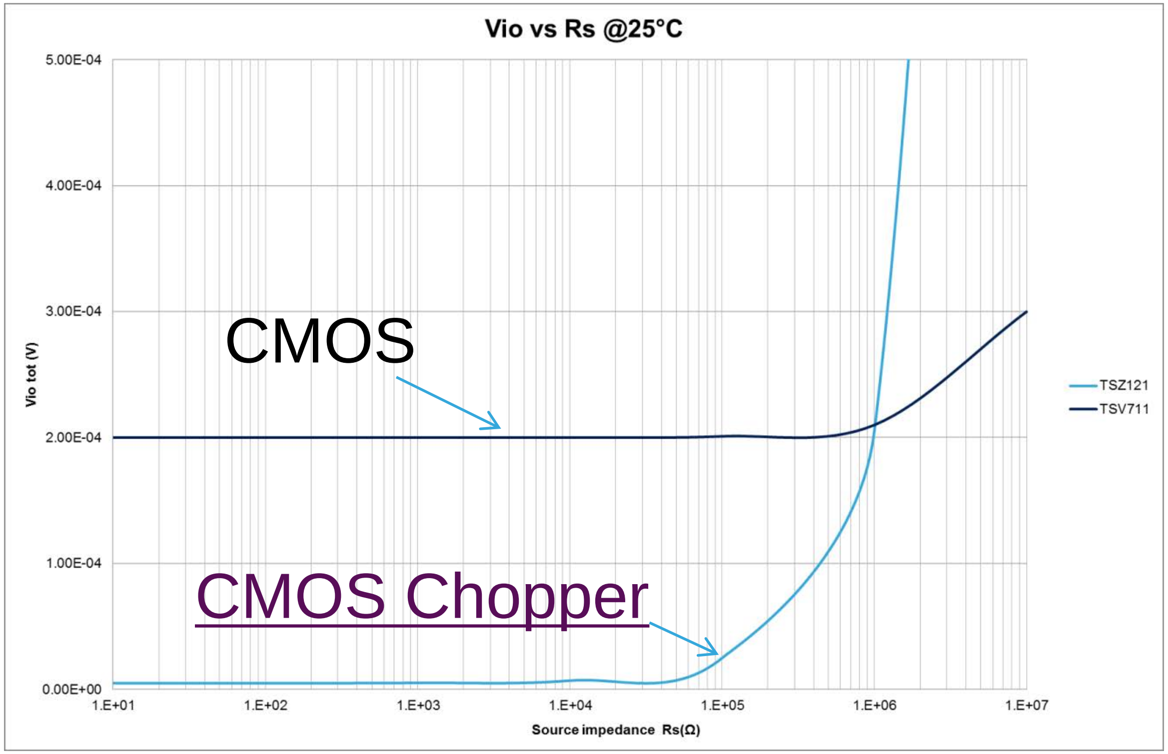
Is the TSZ121 chopper always a good choice?

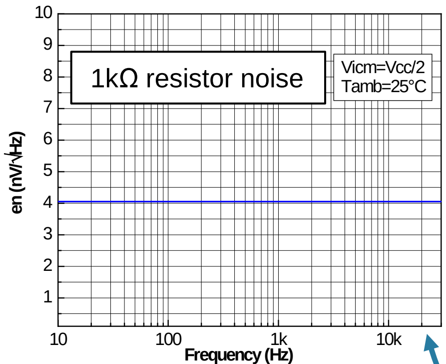




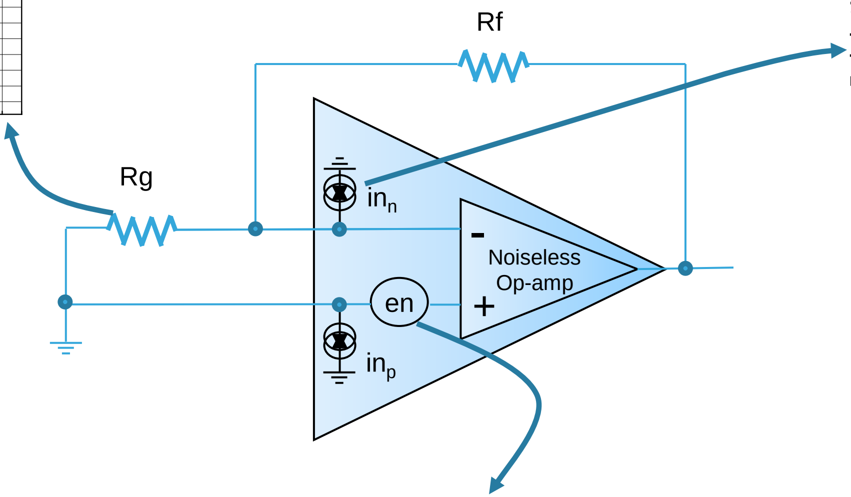
Vio tot= $Vio + Rs.In$ (1)

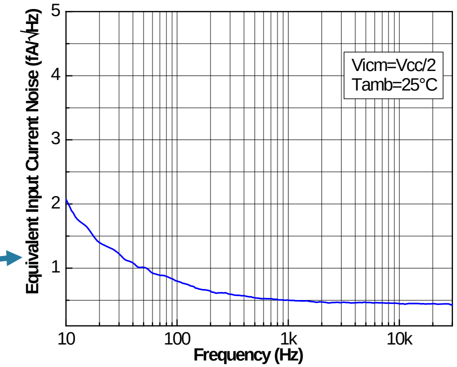
Rs $> \frac{Vio}{In+}$ (2)

Noise sources of an op amp



There are 5 sources of noise





Resistors generate a white noise with a spectral density of:

$$e_n = \sqrt{4kTR} \quad VHz^{-\frac{1}{2}}$$

Where

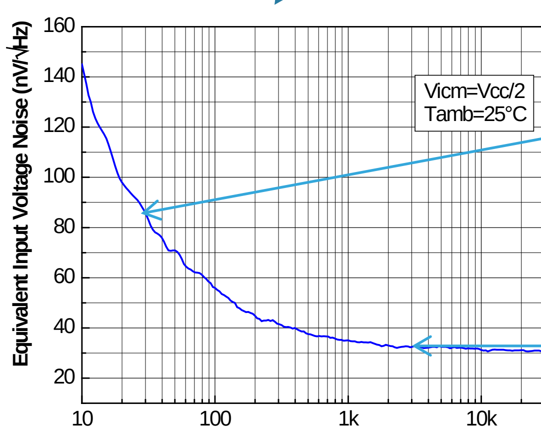
$$k = 1.38\,10^{-23} \;\; JK^{-1}$$

(Boltzmann's constant)

$$T = T(^\circ C) + 273.15$$

(Temperature in Kelvin)

For CMOS input op amps Input noise current is extremely low (0.5fA/√Hz) and generally does not affect design



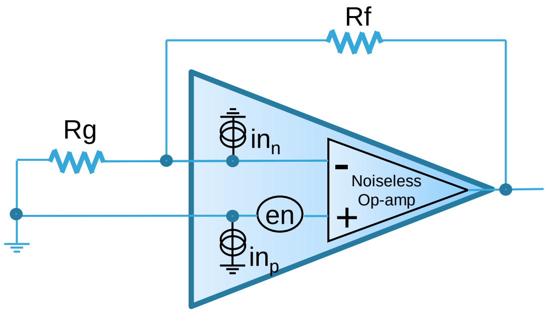
$\frac{1}{f}$ noise (flicker noise)

$$enf\,(f) = \sqrt{\frac{enf\,(1Hz)}{f}} \;\; V/\sqrt{hz}$$

White noise

en V/√hz

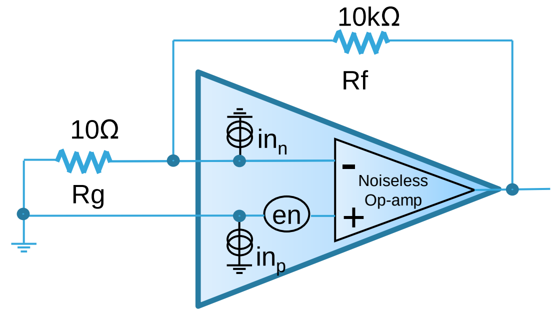
Contribution of each source of noise



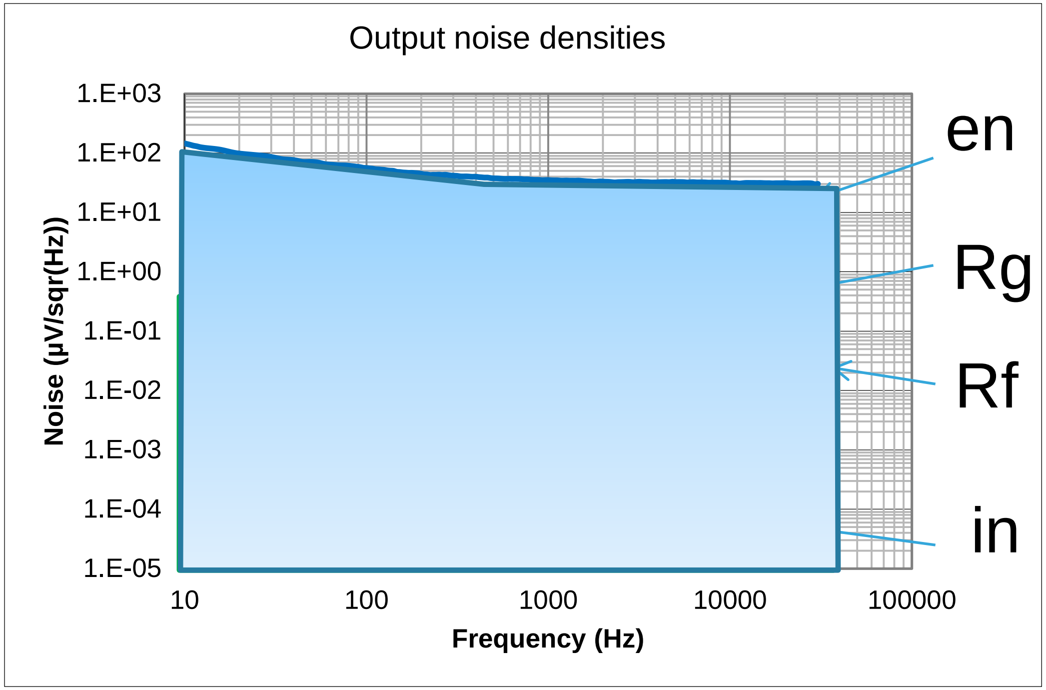
$$Vout_{rms} = \sqrt{\int_{fL}^{fH} \left[e_n^2 \left(1 + \frac{R_f}{R_g}\right)^2 + R_f^2 I_{nn}^2 + 4kTR_g \left(\frac{R_f}{R_g}\right)^2 + 4kTR_f \right] df}$$

Noise source	Spectral density noise referred to the output	RMS noise value over a given bandwidth referred to the output
e_n	$en.(1+\frac{Rf}{Rg})$	$(1+\frac{Rf}{Rg}).\sqrt{en^2(FH-FL)}$ if white noise $(1+\frac{Rf}{Rg}).\sqrt{en^2(1Hz).ln(\frac{FH}{FL})}$ if 1/f noise
I_{nn}	$Inn.Rf$	$Rf.\sqrt{Inn^2(FH-FL)}$ if white noise
R_g	$\frac{Rf}{Rg}.\sqrt{4.k.T.Rg}$	$\frac{Rf}{Rg}.\sqrt{4.k.T.Rg.(FH-FL)}$
R_f	$\sqrt{4.k.T.Rf}$	$\sqrt{4.k.T.Rf.(FH-FL)}$

Contribution of each source of noise



TSV731



Noise voltage contribution to the output BW=30kHz		
Noise Source		en Vrms
OPAMP	en	$5.37 \ 10^{-3}$
	In	$8.66 \ 10^{-9}$
THERMAL	Rf	$2.2 \ 10^{-6}$
	Rg	$70.5 \ 10^{-6}$

$$VoutRms=\sqrt{en^2+In^2+Rf^2+Rg^2}$$

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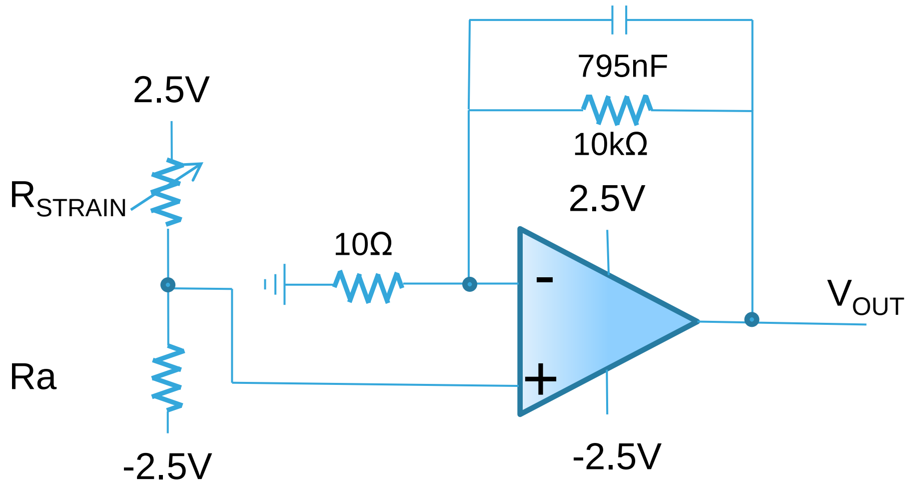
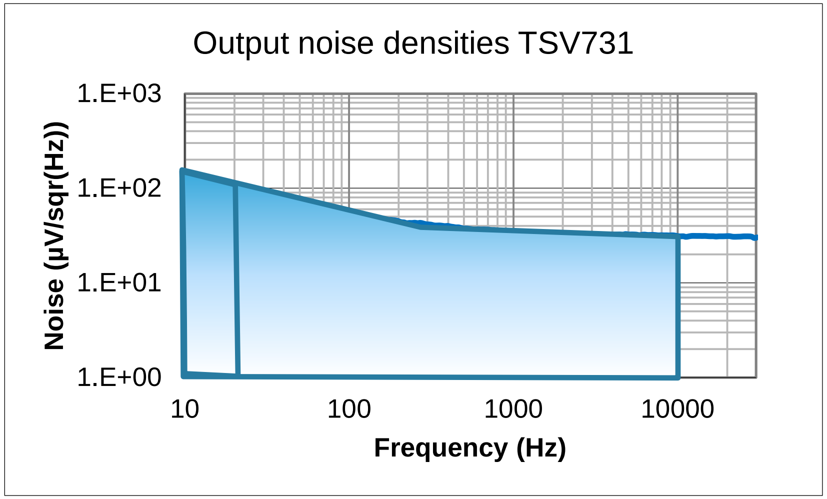
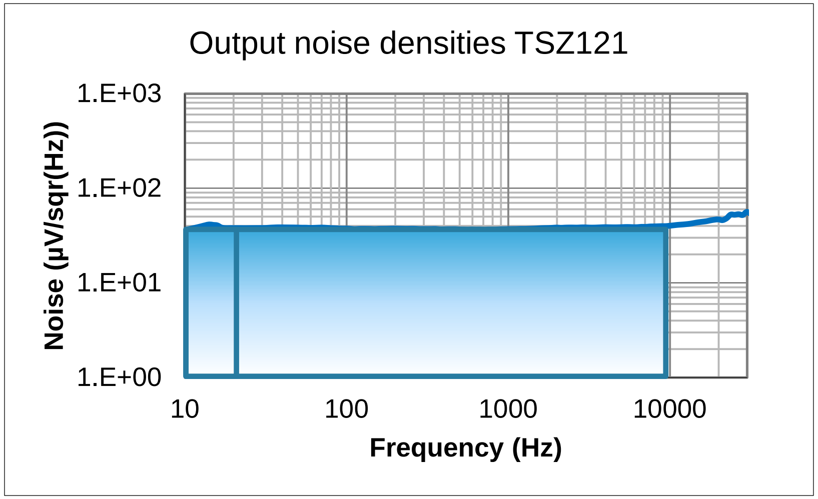
Impact of noise in a application







Bandwidth 20Hz

$en\_Vout_{Rms}=0.69mV_{Rms}$ $en\_Vout_{Rms}=0.16mV_{Rms}$

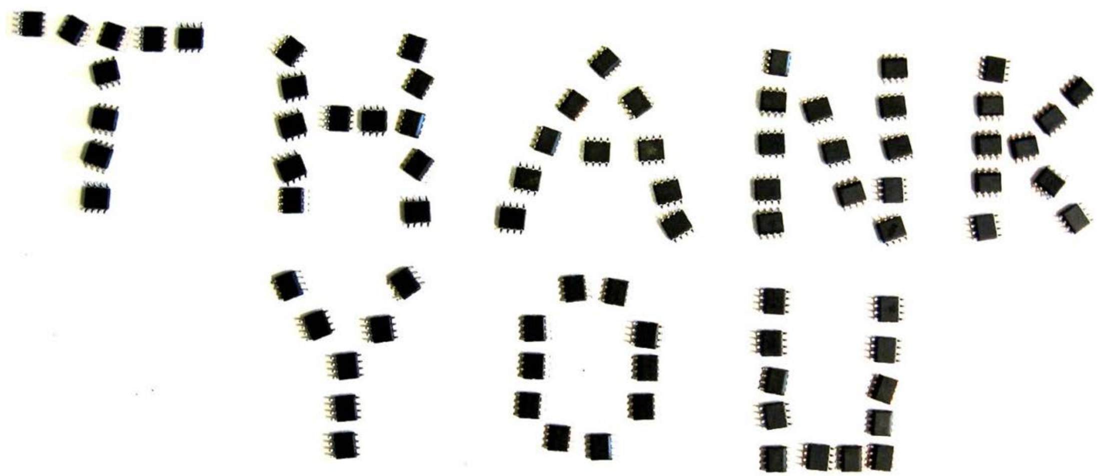
Summary of the errors impacting precision

Input Referred Error:

The various non-ideal components of an operational amplifier all contribute to its total input referred error.

	Parameter value	Condition	Real Value
Offset	100µV	-	100µV
Offset drift	10µV/°C	70°C	700µV
CMRR	80dB	0-3V	300µV
PSRR	80dB	5V +/- 10%	50µV
Noise	10µVpp	0.1-10Hz	10µVpp

All the errors are summed and must be compared to the input signal.



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