Noise in Electronics

- All modern measurement systems have electronic components
- Electronic components have inherent noise

Why do electronic components have inherent noise?

- Electronic components are physical devices
- They are in contact with the environment at a finite temperature, and Equipartition Theorem of statistical physics applies to them
- Electronic conduction is particulate, transmission of electrons are subject to random reflection and transmission events.

Components

- Resitors: Produce noise due to the finite temperature, as a result of Equipartition Theorem (thermal fluctuations)

- Ideal Capacitors and Inductors :

  No dissipation, and as a result of dissipation-fluctuation theorem *No Noise*

- Diodes: Noise due to the particulate nature of electrons and random transmission events.

Equipartition Theorem

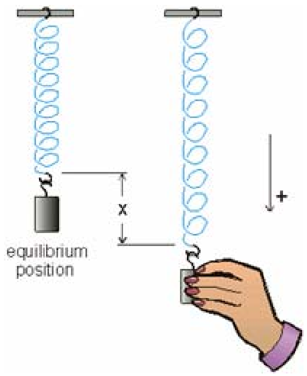
- A system has an average energy of $k_B T$ for each quadratic term appearing in its Hamiltonian
- i.e.

EACH DEGREE OF FREEDOM HAS A FLUCTUATION WITH AN AVERAGE TOTAL ENERGY OF $k_B T$

Boltzmann Constant

Equipartition Theorem

EACH DEGREE OF FREEDOM HAS A FLUCTUATION WITH AN AVERAGE TOTAL ENERGY OF $k_B T$



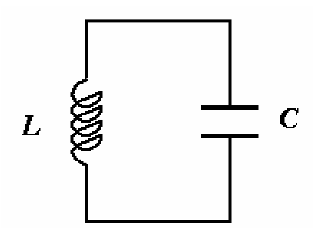
$$\tfrac{1}{2}k\,\langle x^2 \rangle = \tfrac{1}{2}k_B T \qquad [J]$$

$$\frac{1}{2}m\langle v^2\rangle + \frac{1}{2}k\langle x^2\rangle = k_B T$$

$$v = \frac{dx}{dt}$$

Equipartition Theorem

EACH DEGREE OF FREEDOM HAS A FLUCTUATION WITH AN AVERAGE TOTAL ENERGY OF $k_B T$

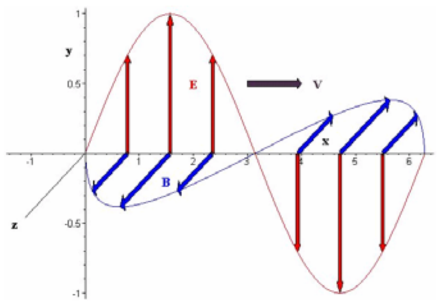


$$\frac{1}{2}L\langle i^2\rangle + \frac{1}{2}C\langle v^2\rangle = k_B T$$

$$i = \frac{dv}{dt}$$

Equipartition Theorem

EACH DEGREE OF FREEDOM HAS A FLUCTUATION WITH AN AVERAGE TOTAL ENERGY OF $k_B T$



$$\frac{1}{2}\varepsilon_0\langle E^2\rangle + \frac{1}{2\mu_0}\langle B^2\rangle = k_B T$$

Per electromagnetic mode

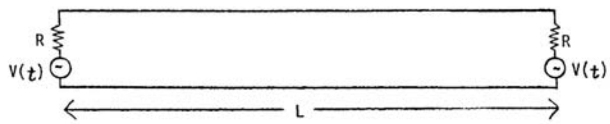
Johnson Noise in a Resistor

Noise emf

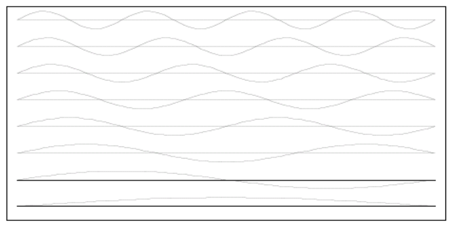
$$\langle {e_n}^2\rangle = 4k_B TR\cdot(\Delta Bandwidth)$$

Can be understood in terms of Electromagnetic mode density in a certain bandwidth

Johnson Noise in a Resistor



Electromagnetic modes in a black body box



$$\sigma(f)\,\Delta f = (2L/c)\,\Delta f$$

Number of modes in a frequency interval

Thermal power in a certain bandwidth $P(f)\Delta f = k_B T \Delta f.$

Johnson Noise in a Resistor

$$e_n \approx \sqrt{\langle e_n{}^2 \rangle} = \sqrt{4k_B TR \cdot \Delta f}$$

For example:

1 KOhm resistor at room temperature has 4 nV/sqrt(Hz)
Noise voltage density.

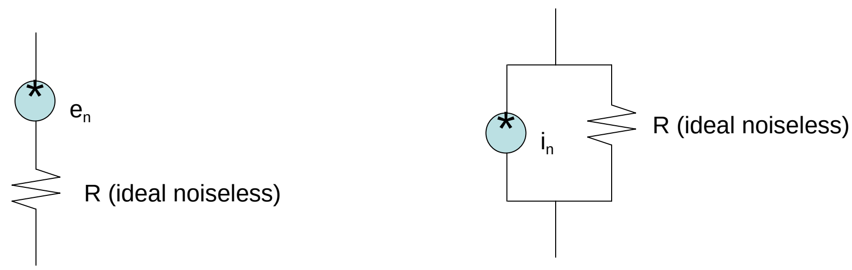
Power delivered to a matched resistor is

$P = k_B T$*Bandwidth

Johnson Noise in a Resistor

$$e_n \approx \sqrt{\langle e_n{}^2 \rangle} = \sqrt{4k_B TR \cdot \Delta f}$$

$$i_n = \sqrt{\frac{4k_B T \Delta f}{R}}$$



Johnson Noise in a Resistor

$$e_n \approx \sqrt{\langle e_n{}^2 \rangle} = \sqrt{4k_B TR \cdot \Delta f}$$

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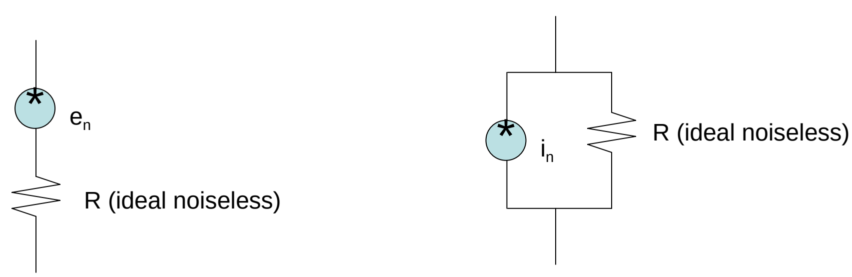

Johnson Noise in a Resistor

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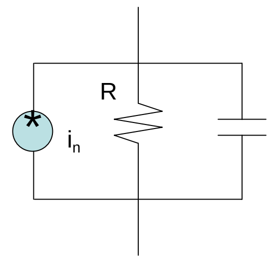
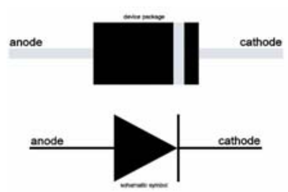


Maximum bandwidth = 1.5 / RC

Shot Noise

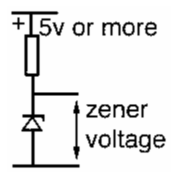
Due to particulate nature of electrons

$$\langle i_n^2 \rangle = 2q\langle I \rangle \cdot Bandwidth$$



diode

photodiode



Zener diode

Shot Noise

Due to particulate nature of electrons

$$\langle i_n^2 \rangle = 2q\langle I \rangle \cdot Bandwidth$$

$$\langle x^2 \rangle = \sigma^2 = \mathrm{var}(X) \propto E(X)$$

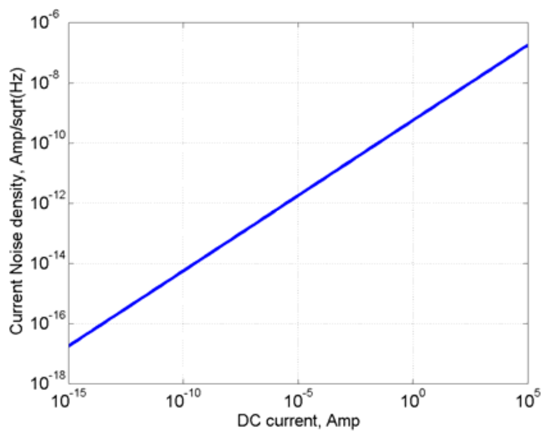
Poisson distribution ???

$$i_n \cong \sqrt{\langle i_n^2 \rangle} = \sqrt{2q\langle I \rangle \cdot Bandwidth}$$

Shot Noise

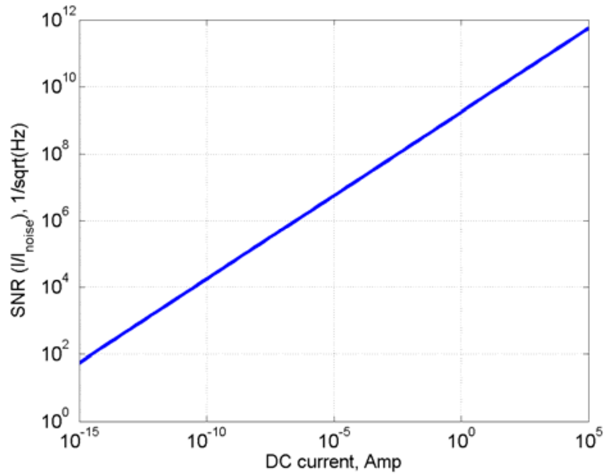
$$\langle i_n^2 \rangle = 2q\langle I \rangle \cdot Bandwidth$$

$$i_n \cong \sqrt{\langle i_n^2 \rangle} = \sqrt{2q\langle I \rangle \cdot Bandwidth}$$



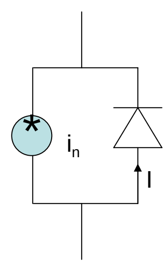
Shot Noise

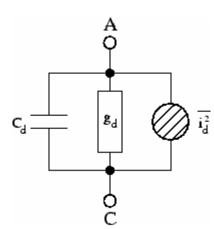
$$i_n \cong \sqrt{\langle i_n^2 \rangle} = \sqrt{2q\langle I \rangle \cdot Bandwidth}$$



Shot Noise

$$i_n \cong \sqrt{\langle i_n^2 \rangle} = \sqrt{2q\langle I \rangle \cdot Bandwidth}$$





1/f noise

$$\frac{\overline{i_d^2}}{\Delta f} = 2eI_d + K_F \frac{I_d^{A_F}}{f^{F_{FE}}}$$

Full shot noise

Shot Noise

$$i_n \cong \sqrt{\langle i_n^2 \rangle} = \sqrt{2q\langle I \rangle \cdot Bandwidth}$$

Can be partially suppressed if transmission events are correlated (i.e. not completely random)

UME 75, NUMBER 18 PHYSICAL REVIEW LETTERS 30 OCTOBER 1995

Temporal Correlation of Electrons: Suppression of Shot Noise in a Ballistic Quantum Point Contact

M. Reznikov, M. Heiblum, Hadas Shtrikman, and D. Mahalu
Braun Center for Submicron Research, Department of Condensed Matter Physics, Weizmann Institute of Science, Rehovot 76100, Israel
(Received 13 February 1995)

Wideband shot noise, associated with dc current flow through a quantum point contact (QPC), is measured in the microwave frequency range of 8–18 GHz. As the number of conducting channels in the QPC changes the noise power oscillates. Consistent with existing theories, the noise peaks depend linearly on the dc current. Surprisingly, however, in the pinch off region, where QPC is expected to behave as a classical injector, we find strong noise suppression, possibly mediated by the Coulomb interaction.

Shot Noise

E 75, NUMBER 8 PHYSICAL REVIEW LETTERS 21 AUGUST 1995

Shot-Noise Suppression in the Single-Electron Tunneling Regime

H. Birk, M. J. M. de Jong, and C. Schönenberger*
Philips Research Laboratories, Professor Holstlaan 4, 5656 AA Eindhoven, The Netherlands
(Received 10 April 1995)

Electrical current fluctuations through tunnel junctions are studied with a scanning-tunneling microscope. For single-tunnel junctions classical Poisson shot noise is observed, indicative for uncorrelated tunneling of electrons. For double-barrier tunnel junctions, formed by a nanoparticle between tip and surface, the shot noise is observed to be suppressed below the Poisson value. For strongly asymmetric junctions, where a Coulomb staircase is observed in the current-voltage characteristic, the shot-noise suppression is periodic in the applied voltage. This originates from correlations in the transfer of electrons imposed by single-electron charging effects.

Shot Noise

Can be partially suppressed if transmission events are correlated (i.e. not random)

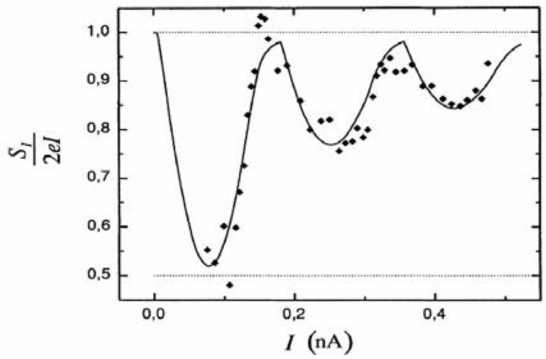


FIG. 4. Ratio of the measured current noise S_I to S_{Poisson} as a function of current I (diamonds). The solid theoretical curve is calculated for $T = 4.2$ K, $Q_0 = 0.33\,e$, $R_1/R = 0.01$, and $C_1/C = 0.2$ [5].

Shot Noise

Can be ENHANCED as well

80, NUMBER 5 PHYSICAL REVIEW LETTERS 2 FEBRUARY 1998

Enhanced Shot Noise in Resonant Tunneling: Theory and Experiment

G. Iannaccone,* G. Lombardi, M. Macucci, and B. Pellegrini
Dipartimento di Ingegneria dell'Informazione: Elettronica, Informatica e Telecomunicazioni
Università degli studi di Pisa, Via Diotisalvi 2, I-56126 Pisa, Italy
(Received 26 September 1997)

We show that shot noise in a resonant-tunneling diode biased in the negative differential resistance regions of the I-V characteristic is enhanced with respect to "full" shot noise. We provide experimental results showing a Fano factor of up to 6.6, and show that it is a dramatic effect caused by electron-electron interaction through the Coulomb force, enhanced by the particular shape of the density of states in the well. We also present numerical results from the proposed theory, which are in agreement with the experiment, demonstrating that the model accounts for physics relevant to the phenomenon. [S0031-9007(97)05143-0]

Fano Factor

To characterize enhancement or suppression of noise, we can compare
It to a poisson variable. This is the so called Fano Factor

$$F = \frac{\sigma_W^2}{\mu_W}$$

Large Fano factor : Enhanced Noise

F=1 means *Poisson-like* noise behaviour

Addition of noise voltages

If the noise voltages are known to be UNCORRELATED

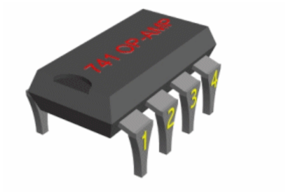
$$\langle v_t^2 \rangle = \langle (v_1 + v_2)^2 \rangle = \langle v_1^2 \rangle + \langle v_2^2 \rangle + 2\langle v_1 v_2 \rangle$$

0

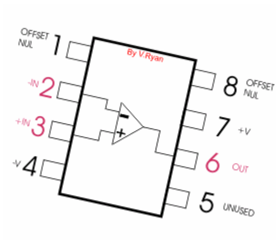
Because they are not correlated

$$e_n = \sqrt{e_1^2 + e_2^2}$$

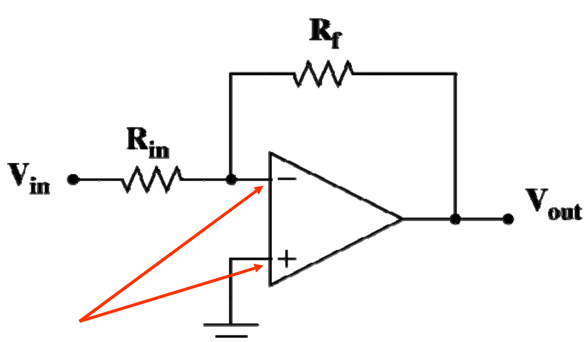
Operational Amplifiers



Can be used to do Analog Computation

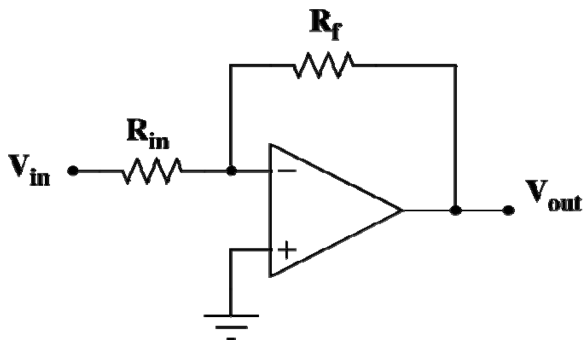


Opamp circuits



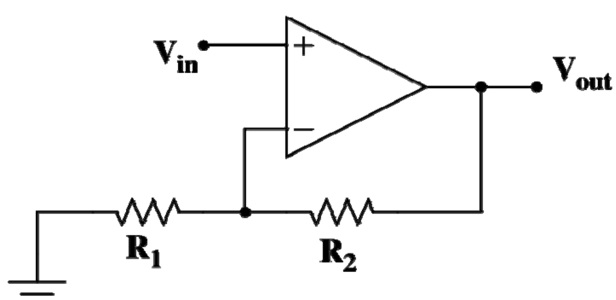
Assume these voltages are the same and then solve
The circuit.

Inverting Amplifier



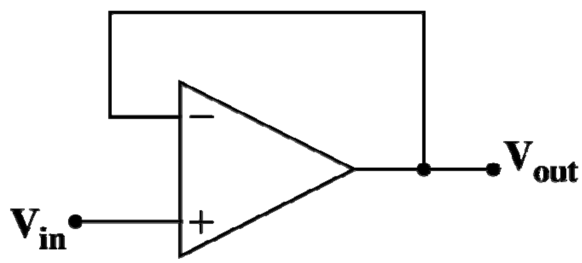
GAIN = Vo/Vi= $-R_f / R_{in}$

Noninverting Amplifier



$$V_{\text{out}} = V_{\text{in}} \left(1 + \frac{R_2}{R_1}\right)$$

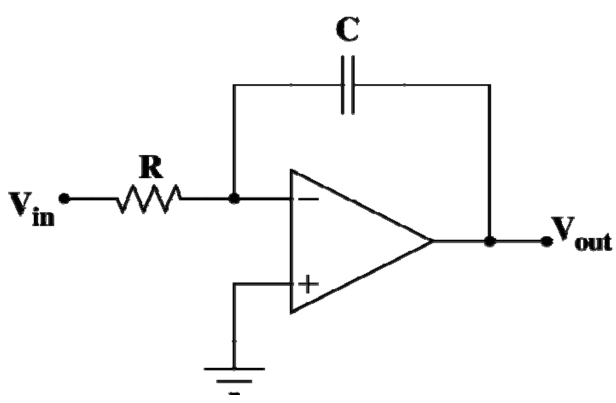
Buffer



$$V_{\text{out}} = V_{\text{in}}$$

Input can be high impedance (resistance) and output is low impedance

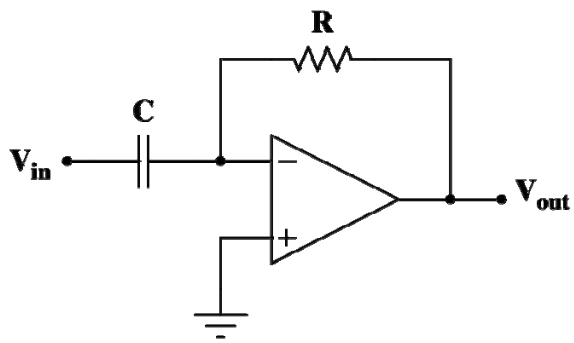
Integrating Amplifier



$$V_{\text{out}} = \int_0^t -\frac{V_{\text{in}}}{RC}\,dt + V_{\text{initial}}$$

A similar circuit can be used as a low pass filter

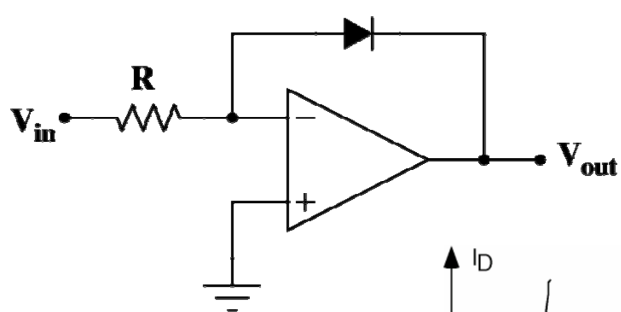
Differentiating Amplifier

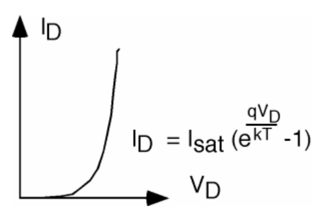


$$V_{\mathrm{out}} = -RC\left(\frac{dV_{\mathrm{in}}}{dt}\right)$$

A similar circuit can be used as a High pass filter

Logarithmic Amplifier



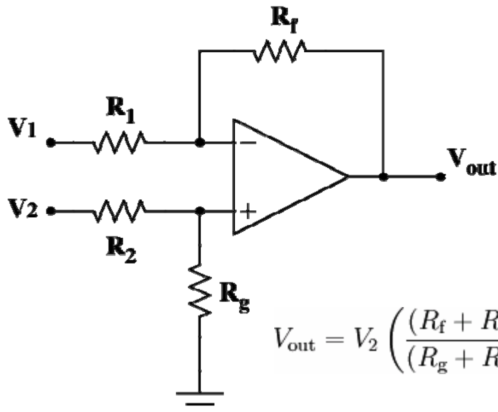


Diode IV relation

$$v_{\mathrm{out}} = -V_\gamma \ln\left(\frac{v_{\mathrm{in}}}{I_{\mathrm{S}} \cdot R}\right)$$

$$I_{\mathrm{D}} = I_{\mathrm{S}}\left(e^{\frac{V_{\mathrm{D}}}{V_\gamma}} - 1\right)$$

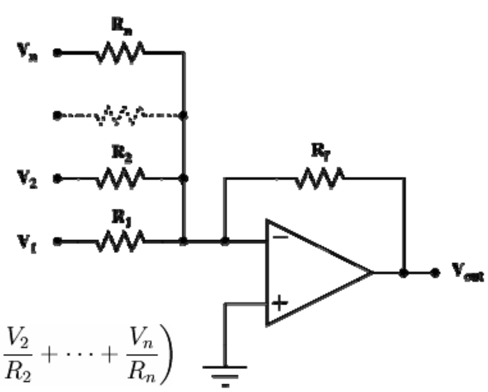
Subtractor



$$V_{\mathrm{out}} = V_2 \left(\frac{(R_{\mathrm{f}} + R_1)\, R_{\mathrm{g}}}{(R_{\mathrm{g}} + R_2)\, R_1} \right) - V_1 \left(\frac{R_{\mathrm{f}}}{R_1} \right)$$

$R_1 = R_2$ and $R_f = R_g$ → $V_{\mathrm{out}} = \frac{R_{\mathrm{f}}}{R_1} (V_2 - V_1)$

Adder



$$V_{\mathrm{out}} = -R_{\mathrm{f}} \left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n} \right)$$

$R_1 = R_2 = \cdots = R_n = R_{\mathrm{f}}$ → $V_{\mathrm{out}} = -(V_1 + V_2 + \cdots + V_n)$

Transfer Function

$$H(w) = V_{out}(w)/V_{in}(w)$$

Operational Amplifiers

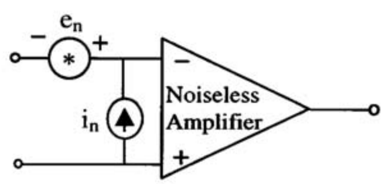
Frequency response (G(w)) depends on the choice of the amplifier

Part#	# OpAmps per Pkg	Vos	-3dB Bandwidth	Slew Rate	Ib	Rail-Rail In	Rail-Rail Out	Vcc-Vee Supply (V)	Iq per Amplifier (max)
Sort Parameter:									
ADD8702	12	n/a	n/a	n/a	n/a	No	No	7 to 16	1.25mA
AD8628	1	1µV	2.5MHz	1V/µs	30pA	Yes	Yes	2.7 to 6	1.1mA
AD8571	1	1µV	1.5MHz	400mV/µs	10pA	Yes	Yes	2.7 to 6	975µA
AD8551	1	1µV	1.5MHz	0.4V/µs	10pA	Yes	Yes	2.7 to 6	975µA
AD8630	4	1µV	2.5MHz	1V/µs	30pA	Yes	Yes	2.7 to 6	1.1mA
AD8538	1	5µV	600kHz	0.4V/µs	15pA	No	Yes	2.7 to 5.5	180µA
AD8675	1	10µV	10MHz	2.5V/µs	0.5nA	No	Yes	10 to 36	2.9mA
OP177	1	10µV	0.6MHz	0.3V/µs	1.2nA	No	No	6 to 36	2mA
AD8603	1	12µV	400kHz	0.1V/µs	0.2pA	Yes	Yes	1.8 to 6	50µA
AD8676	2	12µV	10MHz	2.5V/µs	0.5nA	No	Yes	10 to 36	2.9mA
OP1177	1	15µV	1.3MHz	700mV/µs	500pA	No	No	5 to 36	500µA

Shows how fast the op-amp can operate

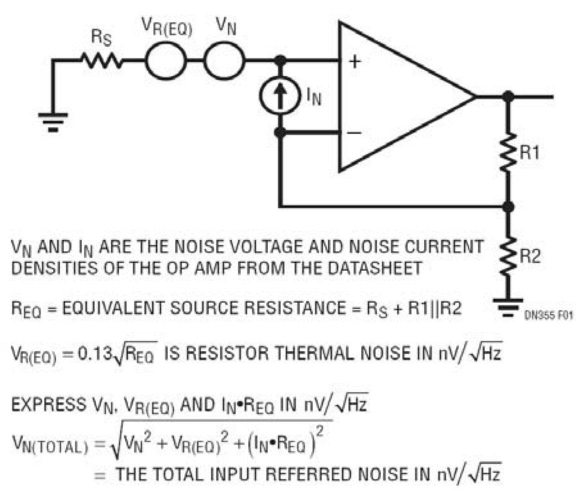
Operational Amplifier Noise

Noise properties depend on the choice of the amplifier



Operational Amplifier Noise

Noise properties depend on the choice of the amplifier



Operational Amplifier Noise

Noise properties depend on the choice of the amplifier

SPECIFICATIONS

OP07E ELECTRICAL CHARACTERISTICS

V_S = ±15 V, unless otherwise noted.

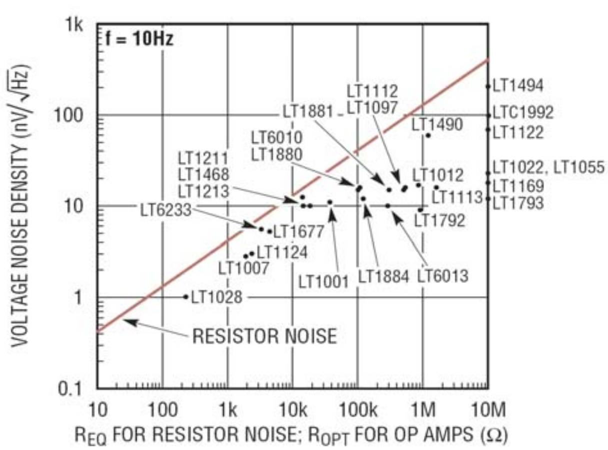
Table 1.

Parameter	Symbol	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS						
T_A = 25°C						
Input Offset Voltage[1]	V_{OS}			30	75	µV
Long-Term V_{OS} Stability[2]	V_{OS}/Time			0.3	1.5	µV/Month
Input Offset Current	I_{OS}			0.5	3.8	nA
Input Bias Current	I_B			±1.2	±4.0	nA
Input Noise Voltage	e_n p-p	0.1 Hz to 10 Hz[3]		0.35	0.6	µV p-p
Input Noise Voltage Density	e_n	f_O = 10 Hz		10.3	18.0	nV/√Hz
		f_O = 100 Hz[3]		10.0	13.0	nV/√Hz
		f_O = 1 kHz		9.6	11.0	nV/√Hz
Input Noise Current	I_n p-p			14	30	pA p-p
Input Noise Current Density	I_n	f_O = 10 Hz		0.32	0.80	pA/√Hz
		f_O = 100 Hz[3]		0.14	0.23	pA/√Hz
		f_O = 1 kHz		0.12	0.17	pA/√Hz
Input Resistance, Differential Mode[4]	R_{IN}		15	50		MΩ
Input Resistance, Common Mode	R_{INCM}			160		GΩ
Input Voltage Range	IVR		±13	±14		V

Noise performance data can be found on the datasheet

Operational Amplifier Noise

Noise properties depend on the choice of the amplifier

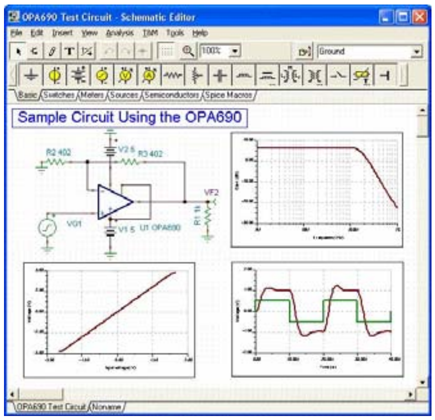


Noise performance data can be found on the datasheet

Operational Amplifier Noise

Noise properties depend on the circuit topology and element values

Use a circuit simulator to calculate frequency response and Noise density.



TINA SPICE

http://focus.ti.com/docs/toolsw/folders/print/tina-ti.html

dB Scale

X Volts in dB = 20 Log_{10} X

If the variable to be converted to dB is a measure of Power Then

X Watts in dB = 10 Log_{10} X

Since

Power = Voltage^2

Above definitions clear misunderstandings

Then SNR in dB is the same if noise power or voltage is used

0 dB = 1, 20 dB = 10, 40 dB=100, 120 dB= 1,000,000

Noise Figure of an Amplifier

Noise Figure, NF = $SNR_{input} – SNR_{output}$

All SNRs are in dB scale

If

$F = SNR_{in} / SNR_{out}$

and SNRs are absolute linear

$NF = 10log(F)$

Noise Figure of an Amplifier

Noise Figure, NF = $SNR_{input} – SNR_{output}$

Best you can do is not to add any noise, i.e. NF = 0 dB

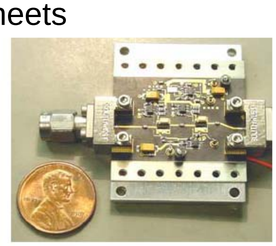
Electrical and Microwave Specifications

Pass-band specifications

Parameter	Value– typical			
Frequency range	0.045 - 6 GHz	6 - 8 GHz	8 - 12 GHz	12 - 20 GHz
Gain	28 dB	28 dB	26 dB	24 dB
Gain flatness	± 1 dB	± 0.3 dB	± 0.3 dB	± 0.5 dB
Noise figure	4 dB	2.5 dB	2.5 dB	4 dB

Noise figure is sometimes specified in datasheets
For 50 Ohm input output resistance
Example

PSI-1628 20 GHz Low Noise Microwave Amplifier



Dynamic Range

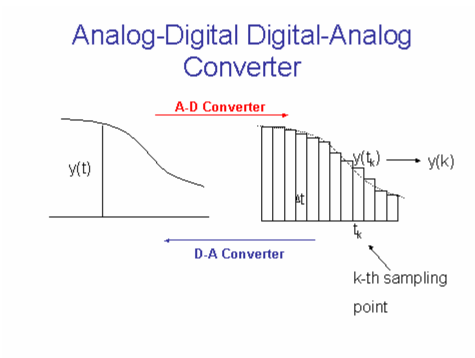
The ratio of maximum measurable signal
To minimum measurable signal

Generally in dB

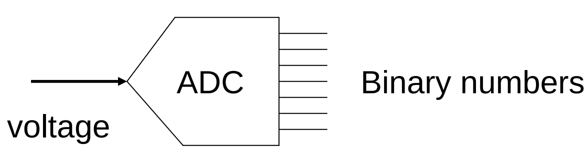
120 dB dynamic range means
Max. signal / Min. signal = 10^6

96 dB dynamic range means
Max. signal / Min. signal = 6×10^4

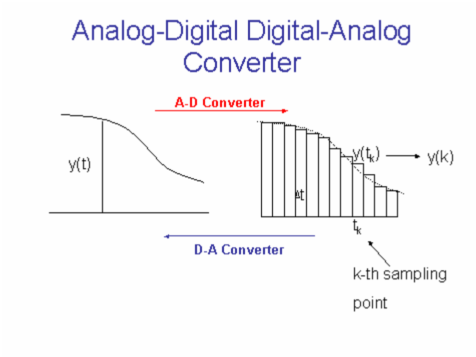
Analog to Digital Conversion



N Bits	2^N
1	2
2	4
3	8
4	16
8	256
12	4096
16	65536



Analog to Digital Conversion



N Bits	2^N
1	2
2	4
3	8
4	16
8	256
12	4096
16	65536

Divides full scale by 2^N

Ex: Full scale -+ 5 V, 12 Bit ADC gives about 10 mV resolution
16 Bit gives 0.15 mV resolution.

Analog to Digital Conversion

N Bits	2^N	
1	2	
2	4	
3	8	
4	16	Dynamic Range ~ 24 dB
8	256	
12	4096	
16	65536	Dynamic Range ~ 96 dB

Low bit ADCs are generally faster (can sample signals at higher frequencies)

Analog to Digital Conversion

After the ADC, digital processing can be used to filter or manipulate the signal

(or just record it into your data file for future analysis)