A Compleat Tutorial on The Quiet Art of Noise in Analogue Audio Circuits

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“The world may be digital…
But people are 4-wire and analogue!”

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Introduction

- Most of our audio processing happens in the digital domain
- However, there are still places in the audio chain that require low noise analogue circuits
- These are primarily at the beginning where transducers:
  - such as microphones
  - magnetic pick-up cartridges
  - tape heads, etc.
- Produce analogue signals that must be amplified prior to analogue to digital conversion
- low noise analogue circuits are also required at the digital to analogue convertors
  - Which often have challenging dynamic ranges

Introduction

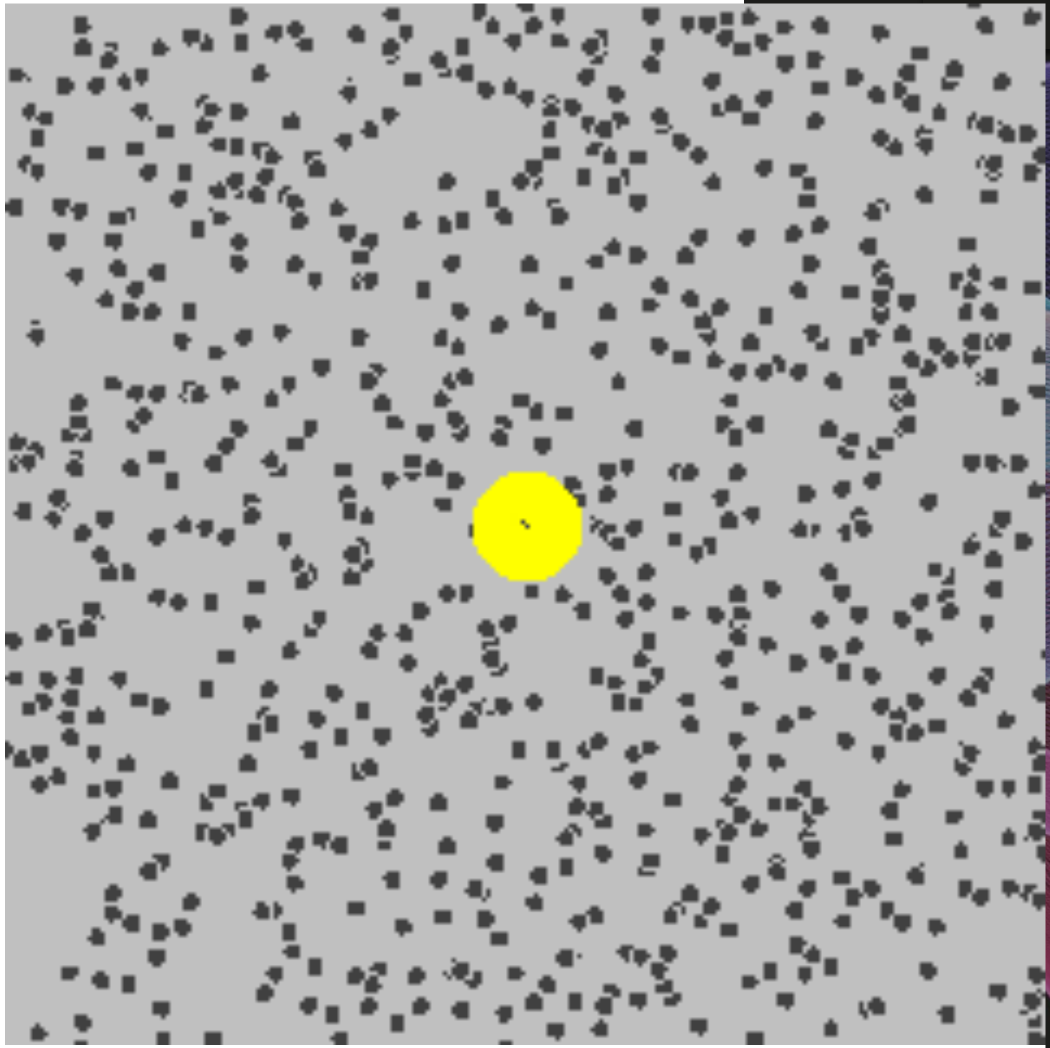
- The purpose of this tutorial is to provide both an introduction to noise in audio circuits
- That takes account of reactive transducers
- And a framework for analysing noise
- And designing for it in:
  - Op-Amp
  - Transistor,
  - FET/MOSFET, and
  - Valve/tube circuits

Structure

- We will cover what sorts of noise occur in analogue circuits and devices.
- It will also develop a framework for identifying which components would work best in different situations and look at basic approaches to achieving low noise operation for a variety of transducers.
- It also will provide some "rules of thumb" for good practice for low noise circuit design.
- Then look at the application of the framework to a variety of electronic devices
- Finally, we will look at some speculative ideas for better low noise circuits.

Thermal Noise

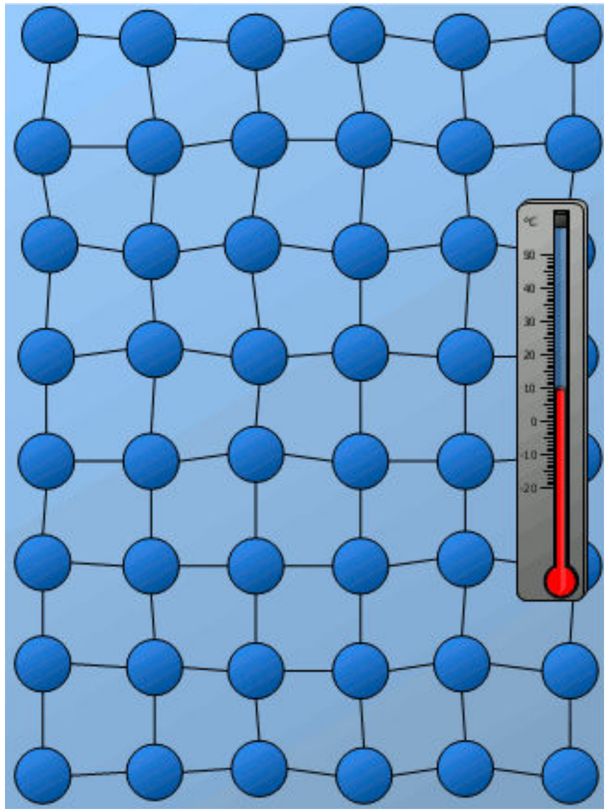
- Atoms and molecules vibrate above absolute zero
  - Due to thermal energy
  - Their vibration is random
- Brownian motion is evidence of this
- This means their electric fields vibrate as well
- And interact with any charge carriers in the material



https://weelookang.blogspot.com/2010/06/ejs-open-source-brownian-motion-gas.html

Thermal Noise

- Charge carriers (electrons and holes)
  - Interact with these vibrating electric fields
  - Generating voltage noise
- This Voltage noise is a function of both:
- Temperature
  - Higher temperatures mean more vibration
- And Resistance
  - There are more interactions (Collisions) with the material at higher resistances



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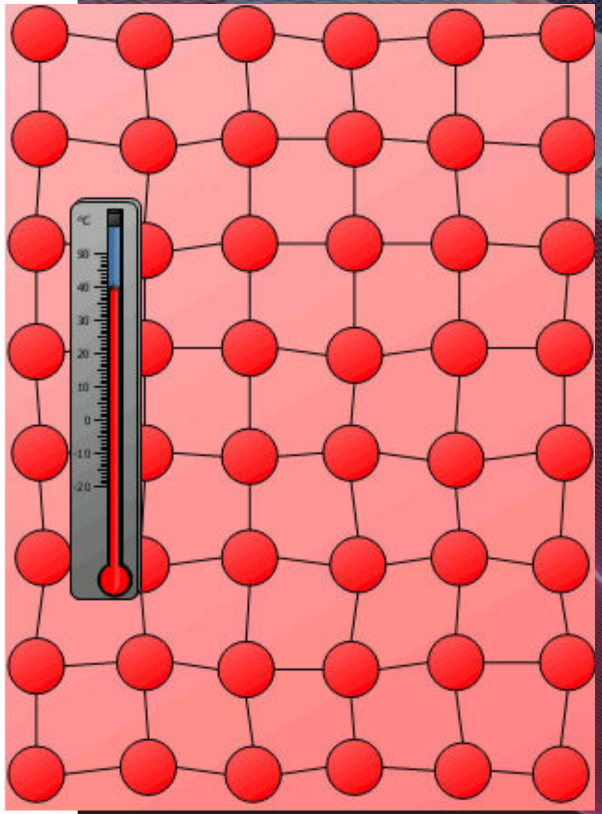
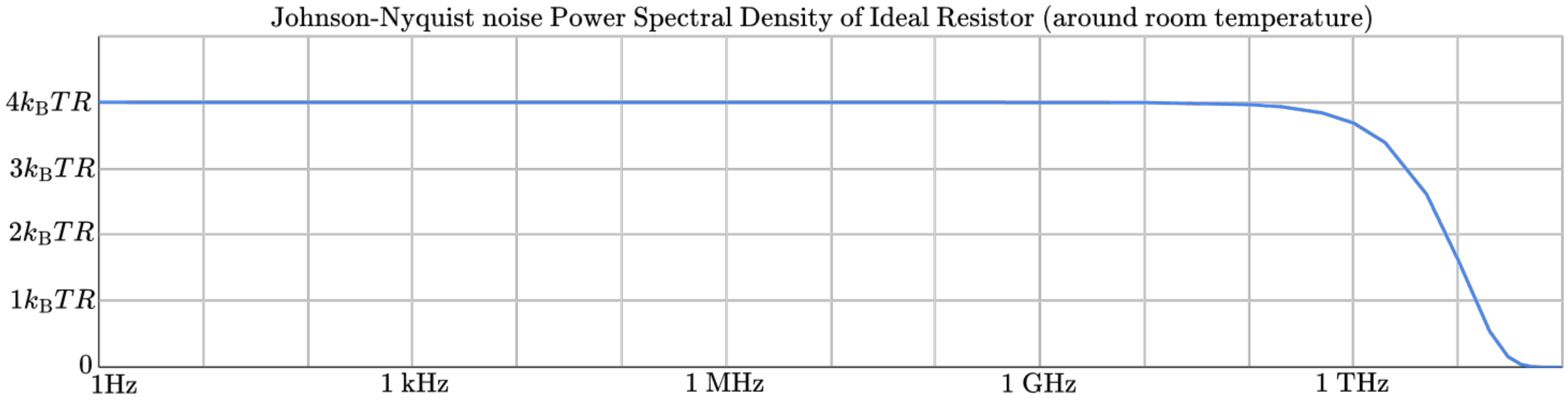
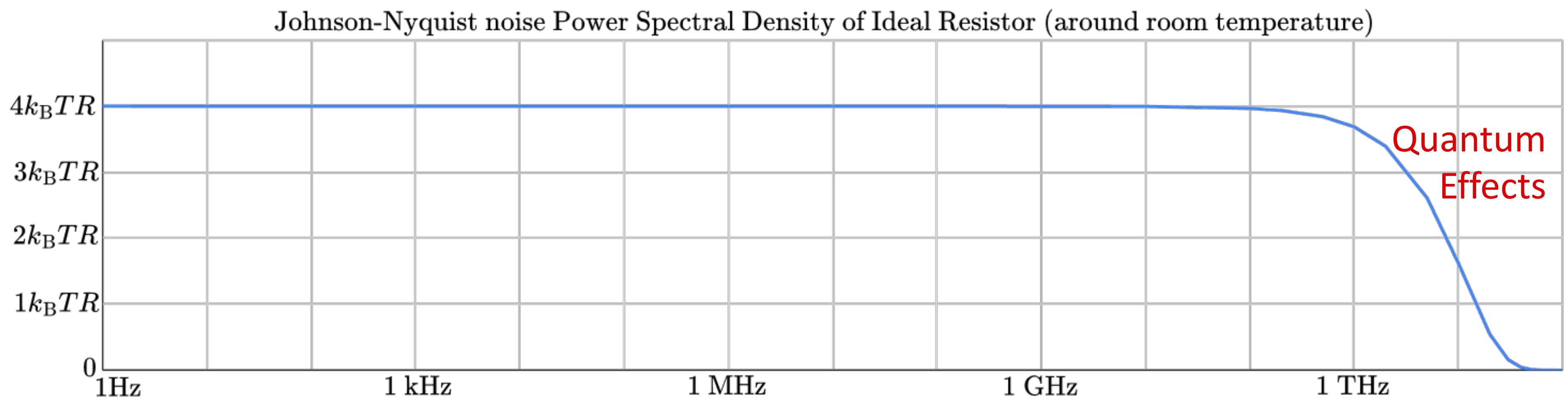


Johnson-Nyquist Noise: Thermal Noise



- It is white noise. That is, flat within the audio band
- Any resistive component generates this type of noise
  - Including loss mechanisms in reactive transducers
- But reactive components like inductors or capacitors do not generate resistive noise
  - Like condenser/capacitive microphones
  - Magnetic pick ups and tape heads

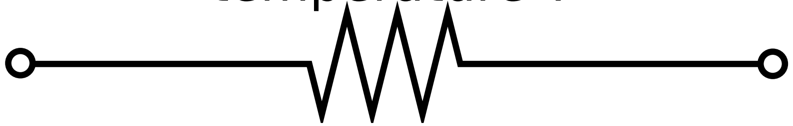
Johnson-Nyquist Noise: Characteristics

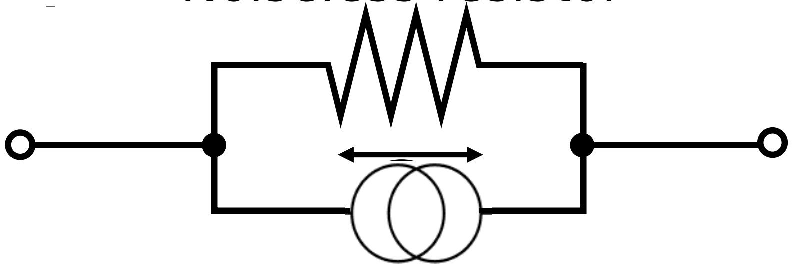


- It is white i.e. flat within the audio band
- Its **Power** is proportional to:
  - Resistance (higher resistance means greater noise)
  - Temperature (higher absolute temperature means greater noise)
  - And Bandwidth (larger bandwidth means greater noise)
- Calculations must be done in the power domain
  - Or a proportional one like voltage squared or current squared

Johnson-Nyquist Noise: Modelling

- Can be modelled as a mean square noise voltage
  - In series with a noiseless resistor (R)
- Or be modelled as a mean square noise current
  - In parallel with a noiseless resistor (R)

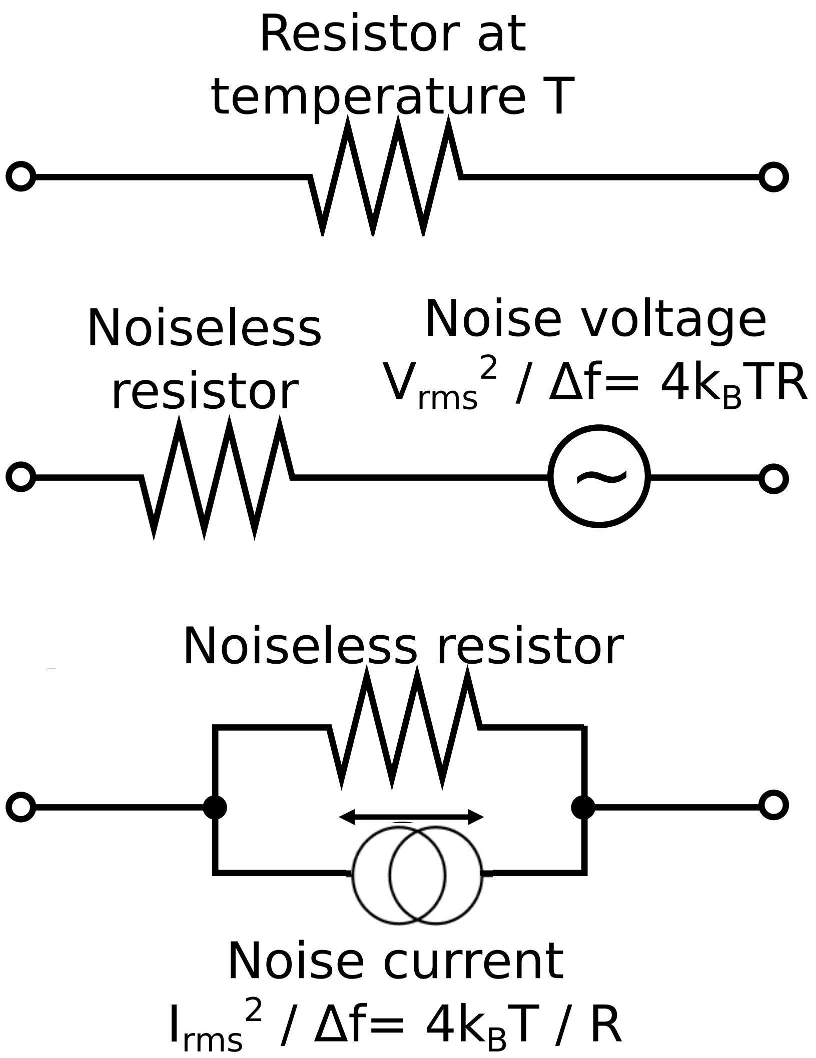




- Δf is the Bandwidth (B)
- R is the Resistance in ohms
- K_B is Boltzmann's constant (1.380649×10−23 joules per kelvin)
- T is the absolute temperature (300K or 27°C for room temp)

Johnson-Nyquist Noise: Numbers

- The noise voltage V_n per $\sqrt{Hz}$ versus resistance is
  - $\sqrt{4K_BT}\sqrt{R} \approx 0.13\sqrt{R}$ nV/$\sqrt{Hz}$
- Giving the following spectral voltage noise density values
  - $100\Omega \approx 1.3$ nV/$\sqrt{Hz}$
  - $400\Omega \approx 2.6$ nV/$\sqrt{Hz}$
  - $1k\Omega \approx 4.11$ nV/$\sqrt{Hz}$
  - $10k\Omega \approx 13$ nV/$\sqrt{Hz}$
- For the total noise multiply by the square root of the bandwidth, Δf, of 20kHz.
  - $\sqrt{20{,}000}$, which equals 141



Shot (Current) Noise

- Charge carrier flow (current flow) is a random process
- Like rain…
- So, the current will have random fluctuations that is Current noise

https://tenor.com/en-GB/view/rain-lights-park-tree-gif-15566169791114717094

Shot Noise: Characteristics

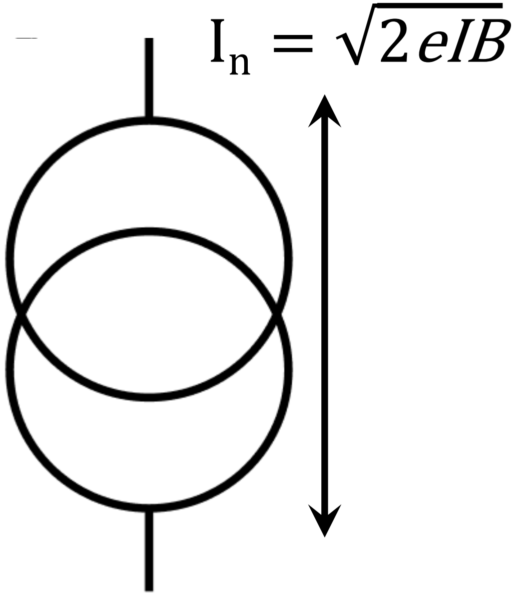
- Need a point to measure shot noise such as:
  - A semiconductor junction
  - The grids in a valve/tube
- This results in Current Noise
  - That can generate noise across any impedance in a circuit
  - Including reactive impedances like inductors and capacitors
  - As well as resistors
- The noise is white
- And proportional to current flow
  - More current means more noise

https://25.media.tumblr.com/tumblr_m8bm7ukgJL1qhx5hjo1_400.gif

Shot Noise: Modelling

- We can model shot noise as a current source
- With an rms noise of:
- $\mathrm{I_n} = \sqrt{2eIB}$

  Where:
  - $\mathrm{I_n}$ is the noise current in Amps
  - e is the charge on the electron (1.602×10^{-19} Coulombs)
  - I is the current in Amps
  - B is the Bandwidth (Δf) in Hz
- For the currents we use this can be quite small!

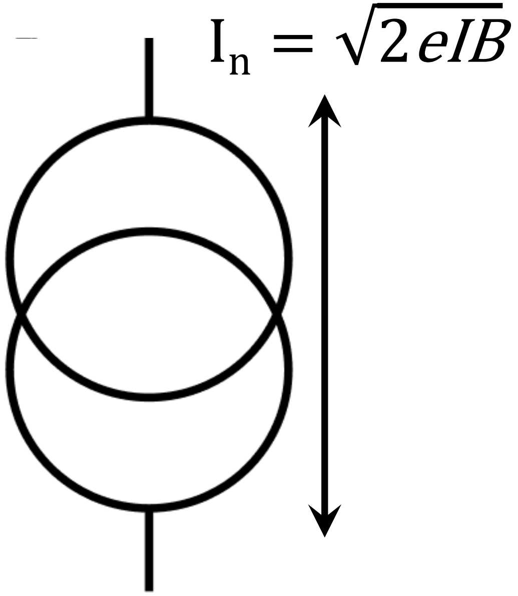


Shot Noise: Numbers

- The noise current I_n per $\sqrt{Hz}$ versus resistance is

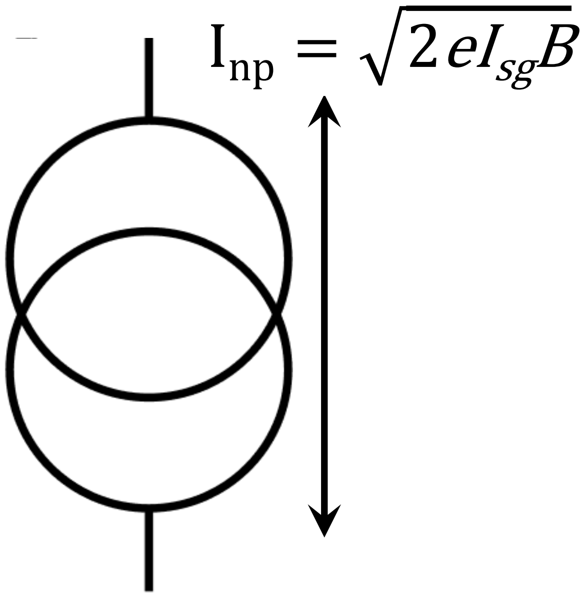
  $I_n = \sqrt{2eI} \approx 0.57\sqrt{I(in\ \mu A)}\ \ pA/\sqrt{Hz}$

- Giving the following spectral current noise density values
  - $1\mu A \approx 0.57\ \ pA/\sqrt{Hz}$
  - $4\mu A \approx 1.14\ \ pA/\sqrt{Hz}$
  - $10\mu A \approx 1.80\ \ pA/\sqrt{Hz}$
  - $100\mu A \approx 5.7\ \ pA/\sqrt{Hz}$
  - $1nA \approx 18.0\ \ fA/\sqrt{Hz}$
  - $4mA \approx 36.0\ \ pA/\sqrt{Hz}$
  - $10pA \approx 1.8\ \ fA/\sqrt{Hz}$



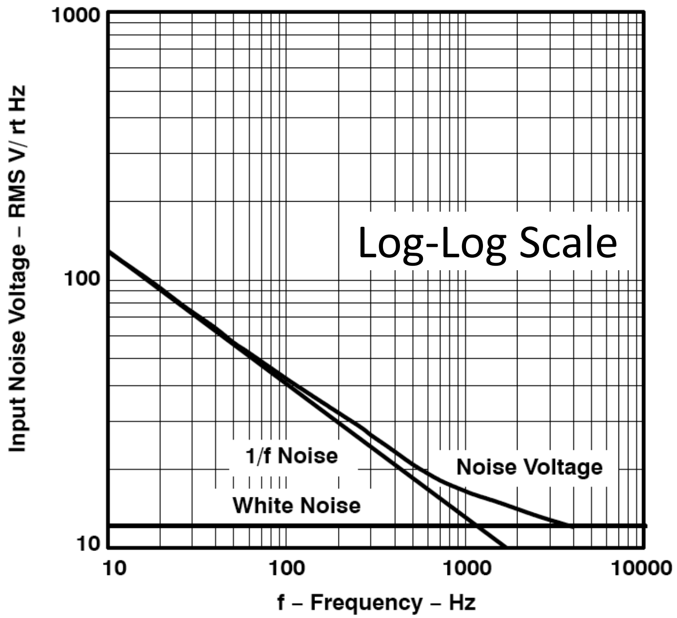
Partition Noise

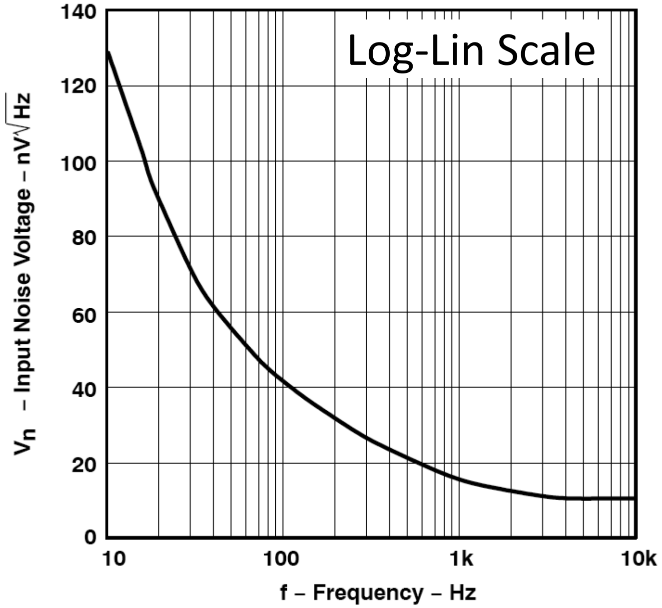
- Partition noise is another name for shot noise
- It happens when current is split into two streams
- Usually used in tubes/valves to account for the excess noise contributed by extra grids in the system
- Can be derived from the same equations as shot noise
- $\mathrm{I}_{\mathrm{np}} = \sqrt{2eI_{sg}B}$



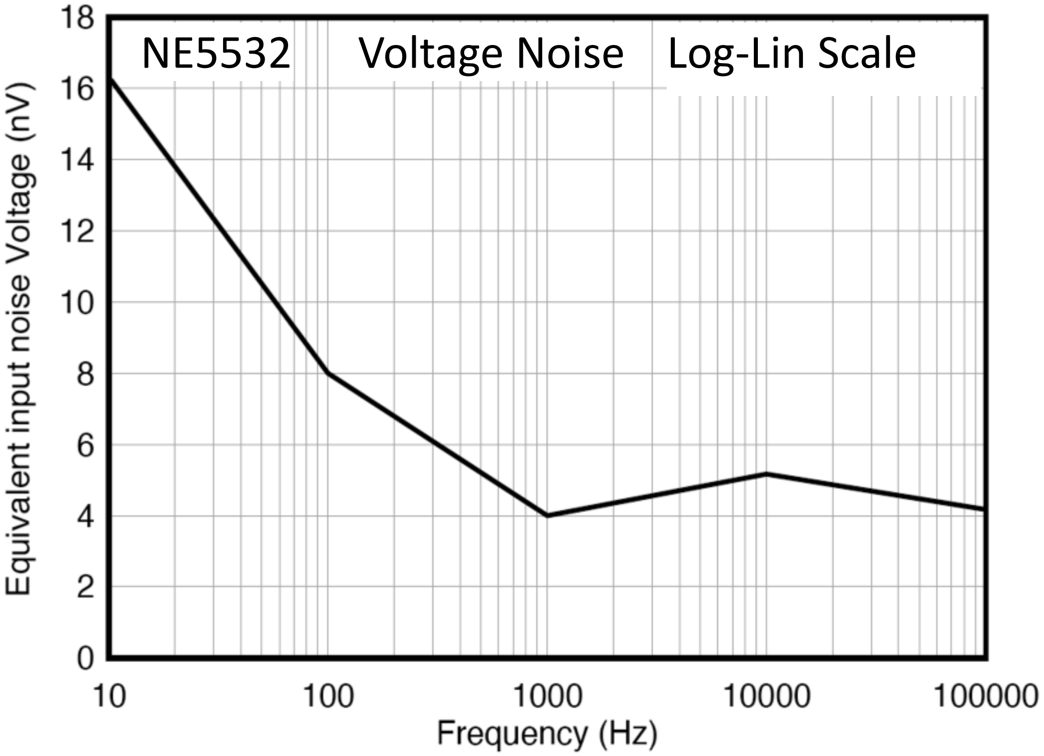
Excess, Flicker, or 1/f Noise

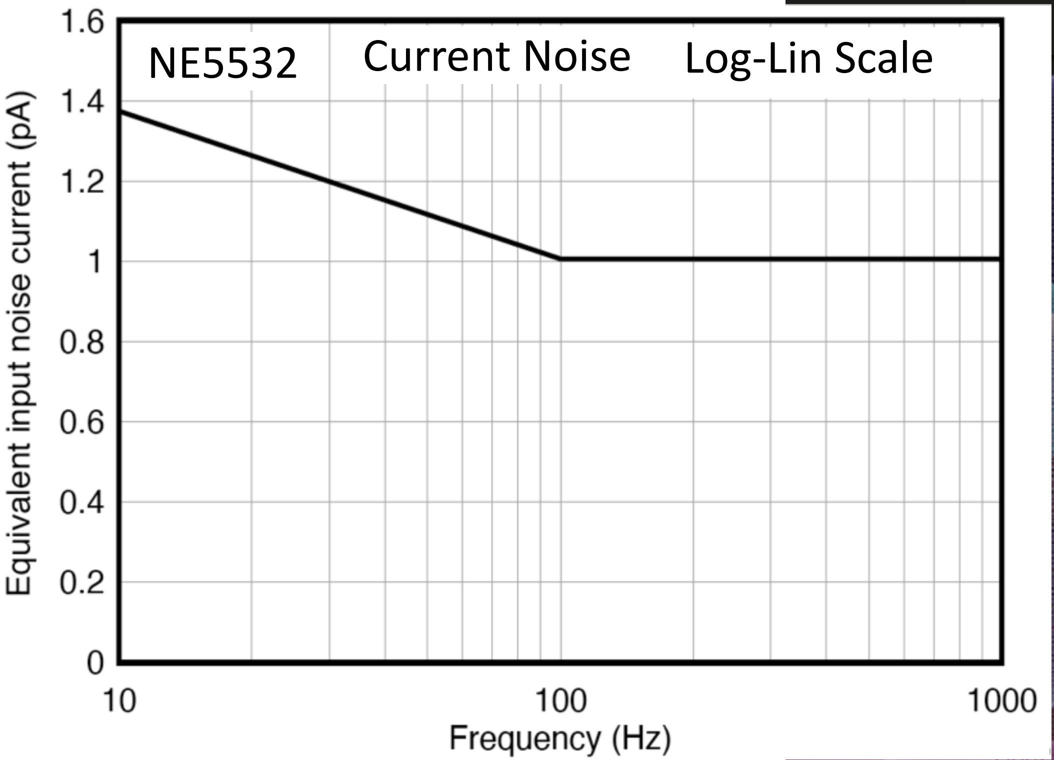
- It is in excess of the usual thermal or shot noise
- It has a 1/f power spectral density.
- It is therefore often referred to as 1/f noise or pink noise
- It occurs in almost all electronic devices
- Due to a a variety of effects,
  - Such as impurities in a conductive channel,
  - Generation and recombination noise in a transistor
  - Surface states in a MOSFET
  - Cathode emission variation





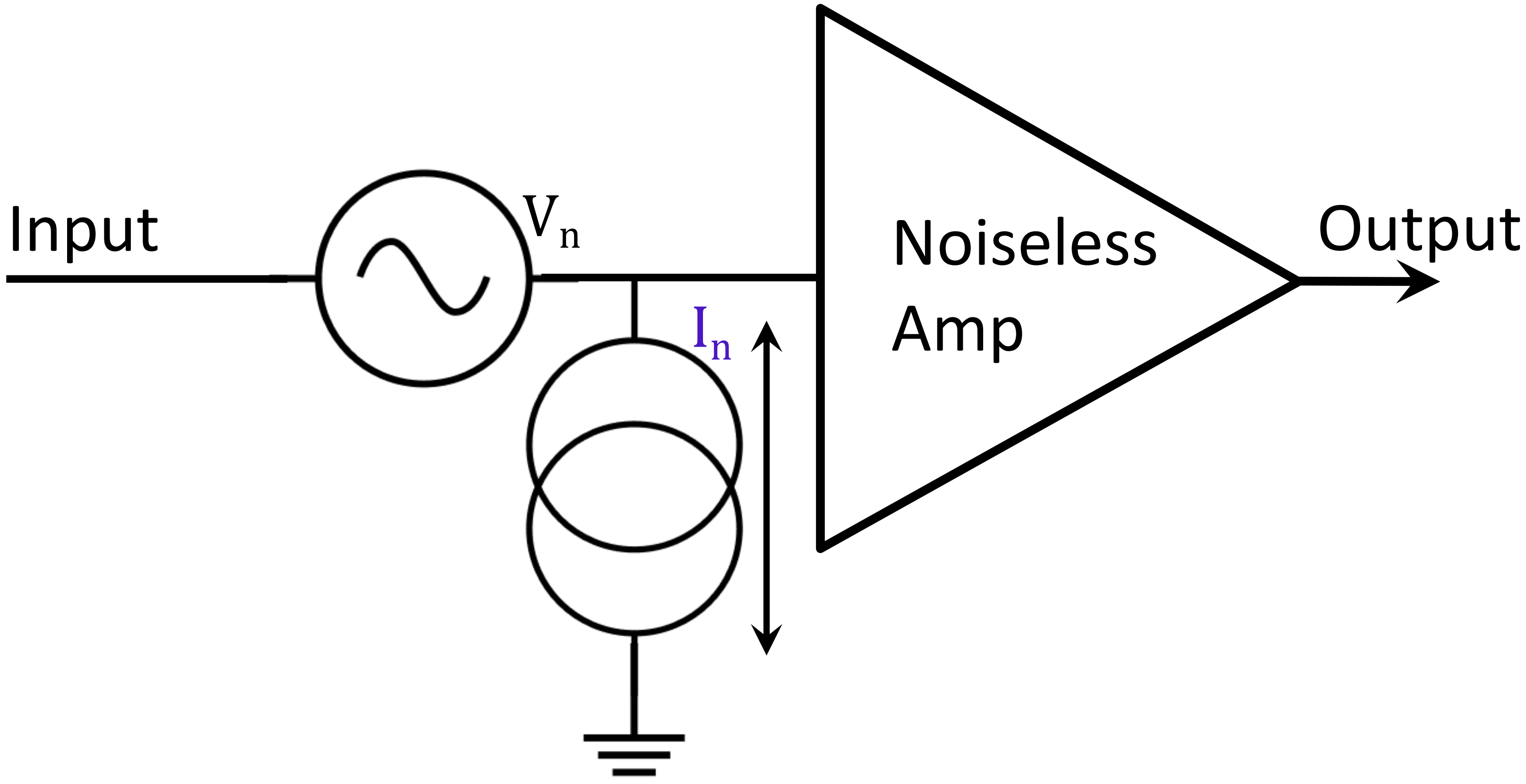
Excess, Flicker, or 1/f Noise





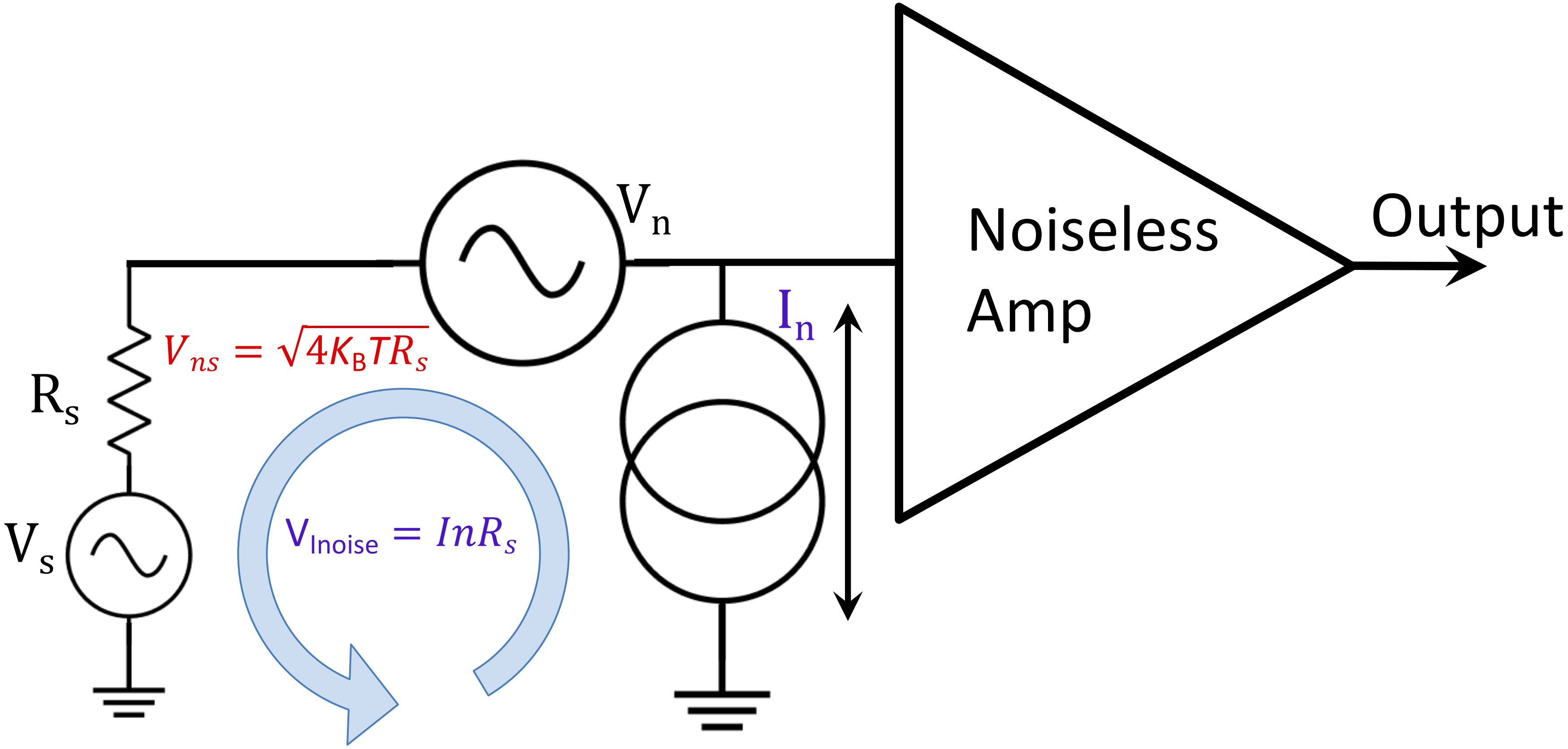
- 1/f noise can happen in both
  - The voltage noise
  - And the current noise
- For example, the NE5532
- Can also have "popcorn" noise which increases at > $1/f^2$

Simple Amplifier Noise Model



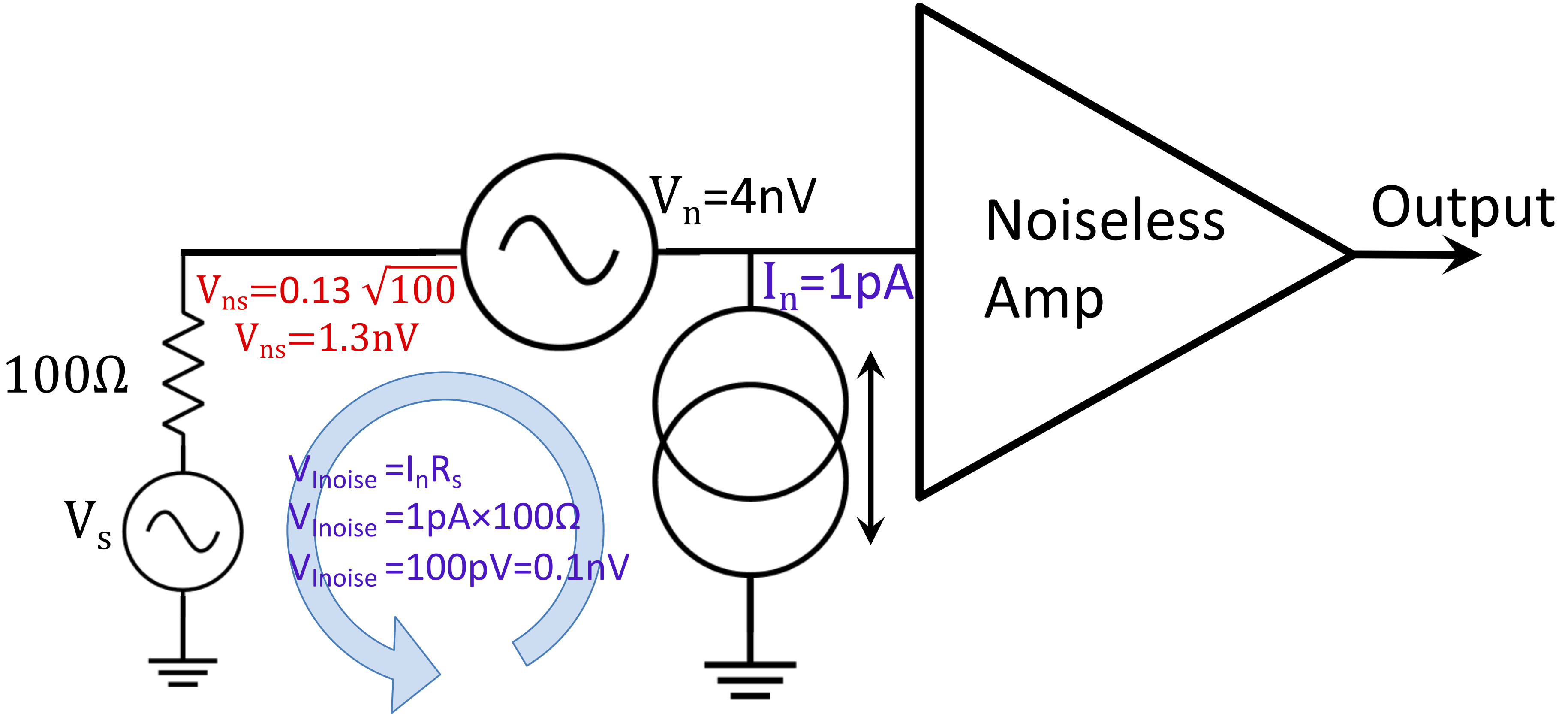
- Has two noise sources:
  - Voltage noise V_n
  - Current noise I_n
- Applicable to all devices

Amplifier Noise Model: Resistive Source



- Resistance of the source will generate a voltage noise (V_{ns})
  - Which will add to the amplifier's noise voltage (V_n)
- It will also generate an additional noise voltage (V_{Inoise})
  - Due to the amplifier's noise current flowing through it.

Amplifier Noise Model: Resistive Source



- Add the squared noises to get the total noise V_{total} (All per $\sqrt{Hz}$)
  - $V_{total} = \sqrt{V_{ns}{}^2 + V_n{}^2 + V_{Inoise}{}^2}$
  - For R_s = 100Ω, and an NE5532 (V_n=4nV/$\sqrt{Hz}$, I_n=1pA /$\sqrt{Hz}$)
  - $V_{total} = \sqrt{(1.3\text{nV})^2+(4\text{nV})^2+(0.1\text{nV})^2}$ =4.21nV/$\sqrt{Hz}$! (10.21dB noise figure)

Side Bar: The Effect of Squared Adding

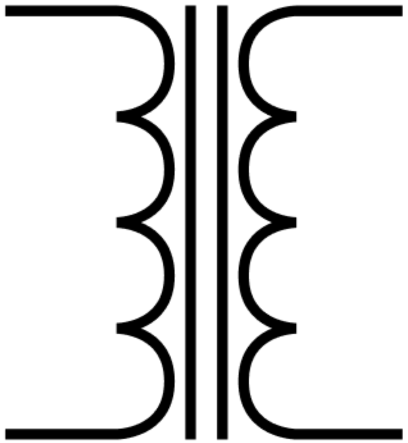
A	B	B	Result	(Result/A) in dB
1	1.000	${}^{1}/_{1}$	1.414	3.010
1	0.500	${}^{1}/_{2}$	1.118	0.969
1	0.316	${}^{1}/_{\sqrt{10}}$	1.049	0.414
1	0.250	${}^{1}/_{4}$	1.031	0.263
1	0.100	${}^{1}/_{10}$	1.005	0.043

- As the numbers become different
  - Then the smaller one of the two rapidly disappears!
- Once they are a factor of 10 different
  - The smaller one becomes irrelevant

Transformers

1:N

Primary



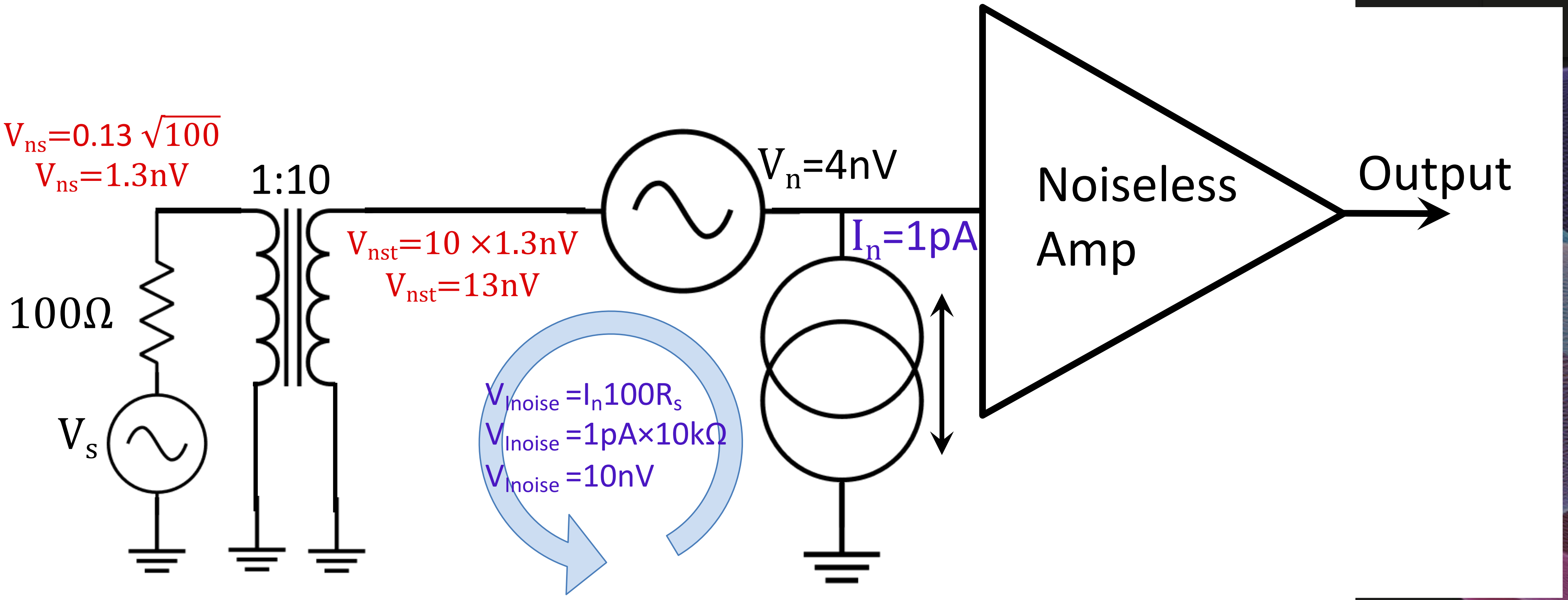
Secondary

$V_S = N V_P$

$I_S = \frac{I_P}{N}$

$Z_S = N^2 Z_P$

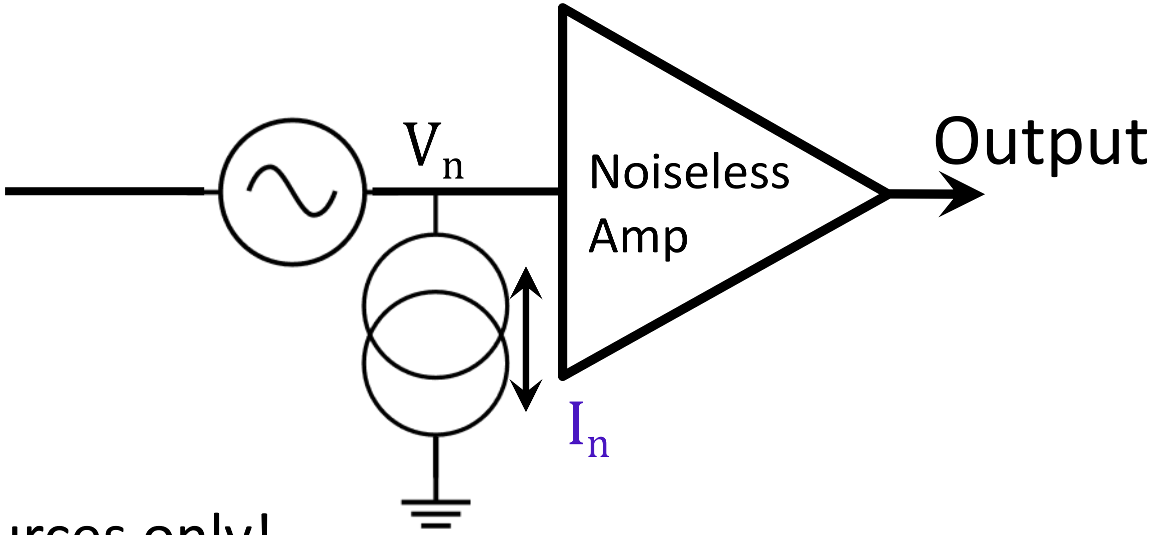
How Can We Do Better? Use a Transformer



- Add the squared noises to get the total noise V_{total} (All per $\sqrt{Hz}$)
  - $V_{total} = \sqrt{V_{nst}^2 + V_n^2 + V_{Inoise}^2}$
  - For R_s = 100Ω, and an NE5532 (V_n=4nV/$\sqrt{Hz}$, I_n=1pA /$\sqrt{Hz}$)
  - $V_{total} = \sqrt{(13nV)^2+(4nV)^2+(10nV)^2}$ =16.9nV/$\sqrt{Hz}$! (2.28dB noise figure)

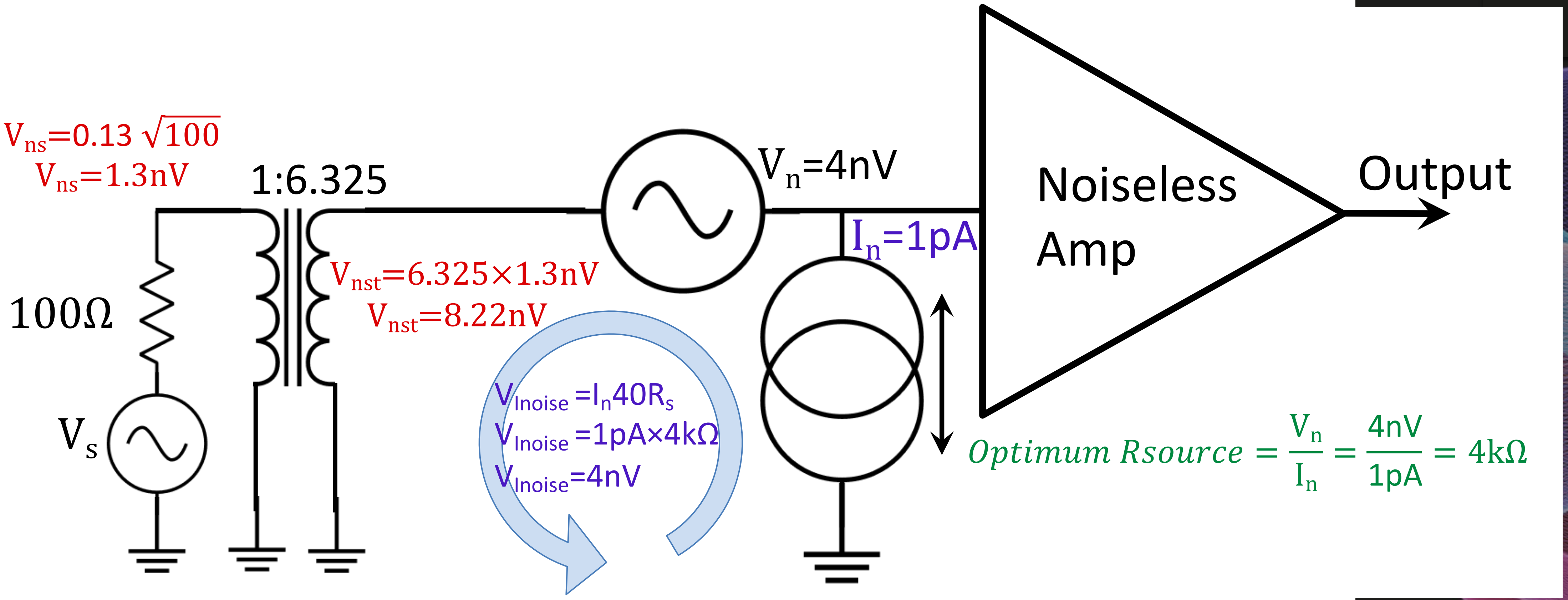
Is There An Optimum Source Resistance

$$R_{source}\,Opt = \frac{V_n}{I_n}$$



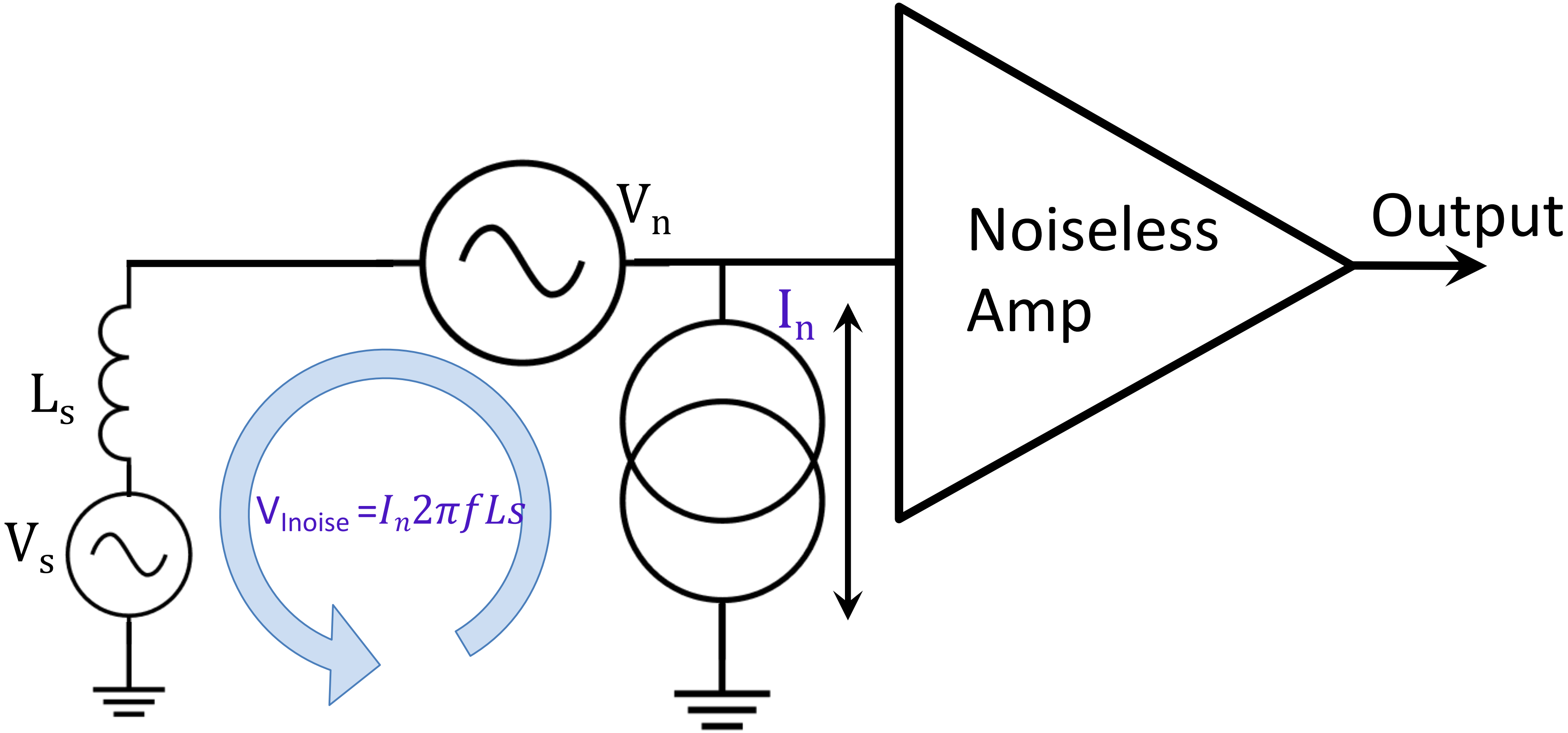
- Yes, For resistive sources only!
- You get the lowest noise figure if the source resistance is equal to:
  - The amplifier's voltage noise V_n
  - Divided by its current noise I_n
- This results in the noise voltage
  - Due to the noise current flowing in the source
  - Being equal to the amplifier's voltage noise
- It can be achieved by choosing an appropriate turns ratio for the transformer.

Is There An Optimum Transformer Ratio



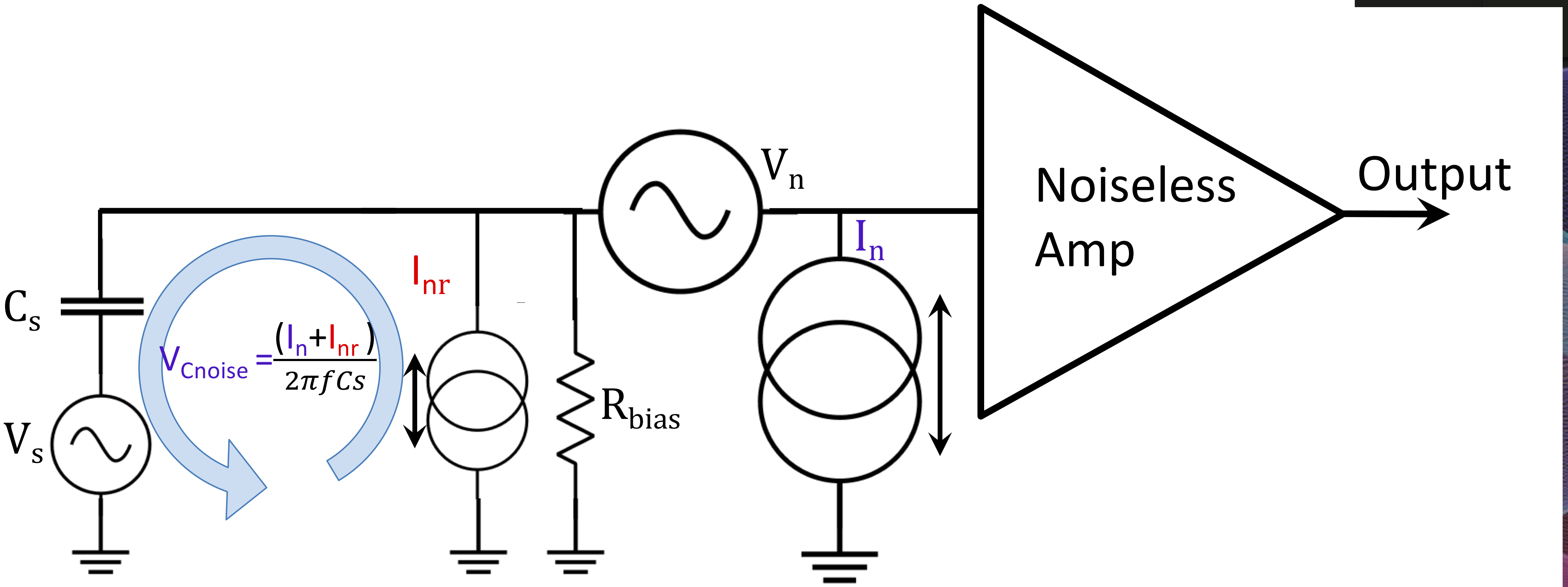
- Add the squared noises to get the total noise V_{total} (All per $\sqrt{Hz}$)
  - $V_{total} = \sqrt{V_{nst}{}^2 + V_n{}^2 + V_{Inoise}{}^2}$
  - For R_s = 100Ω, and an NE5532 (V_n=4nV/$\sqrt{Hz}$, I_n=1pA /$\sqrt{Hz}$)
  - $V_{total} = \sqrt{(8.22nV)^2+(4nV)^2+(4nV)^2}$ =16.9nV/$\sqrt{Hz}$! (1.68dB noise figure)

Amplifier Noise Model: Inductive Source



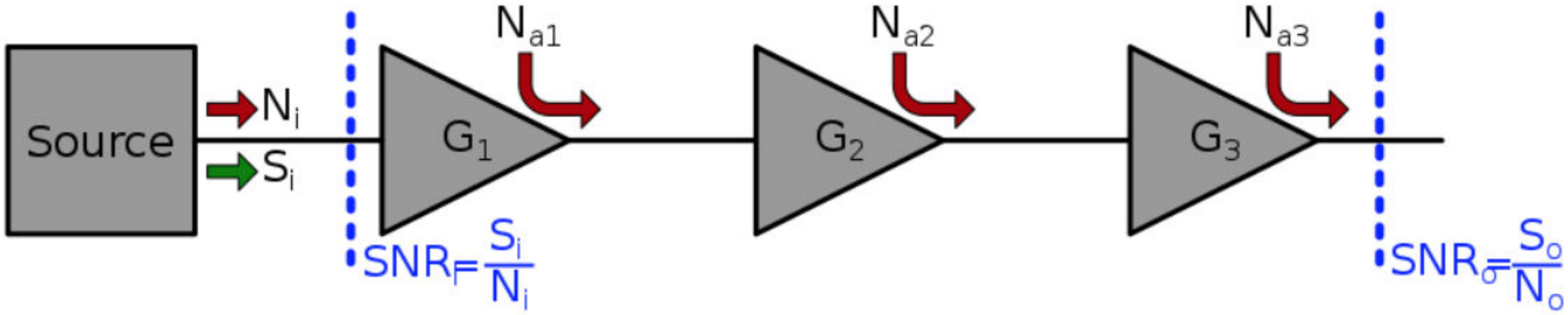
- For an inductive source like a magnetic playback head or phono cartridge
- The noise induced by the current noise rises with frequency
- There is no optimum source impedance
- One needs low current noise and low voltage noise
- As the series resistance may also be quite low

Amplifier Noise Model: Capacitive Source



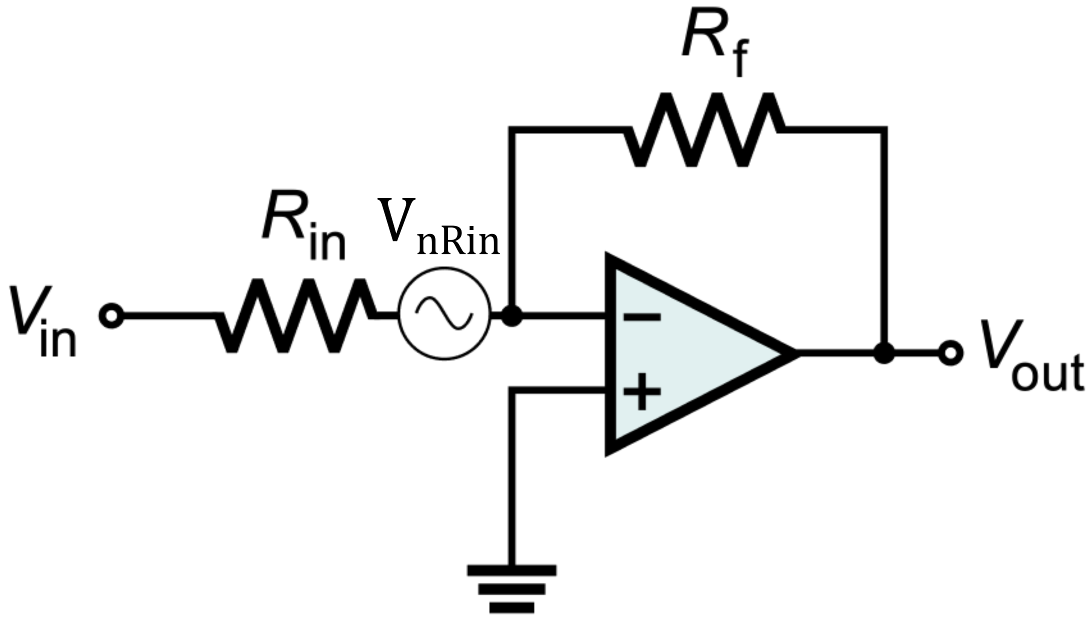
- For capacitive sensor's, the impedance is highest at low frequencies (30pF = 265MΩ at 20Hz)
- And the noise falls with frequency
- So, I_n needs to be low
- But the dominant source of noise is R_{bias} which needs to be as high as possible

Does Every Stage Have to Have Low Noise?



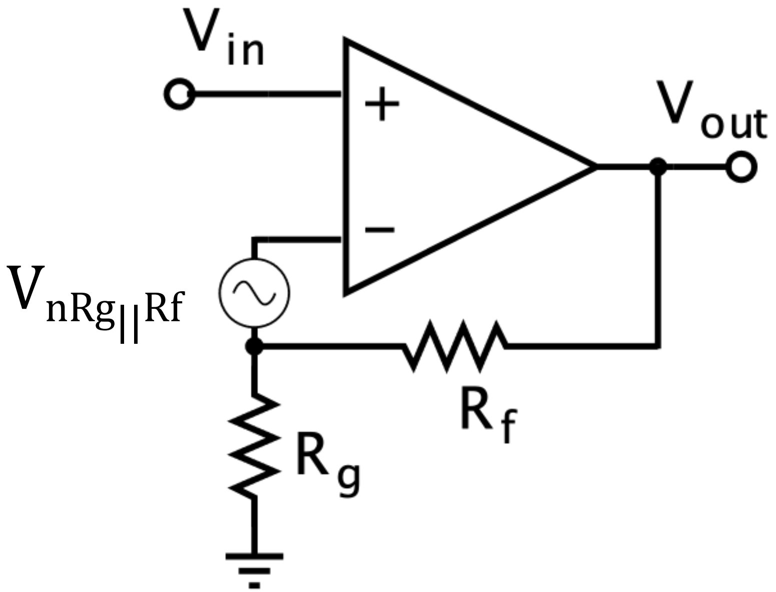
- The first stage in the system dominates the noise
  - Providing the first stage gain is high enough
  - A gain of 10 is usually enough
- The first stage increases the size of the signal thus reducing the effect of the noise in the second stage
  - Unless the second stage noise is outrageous!

Inverting Amplifier Noise



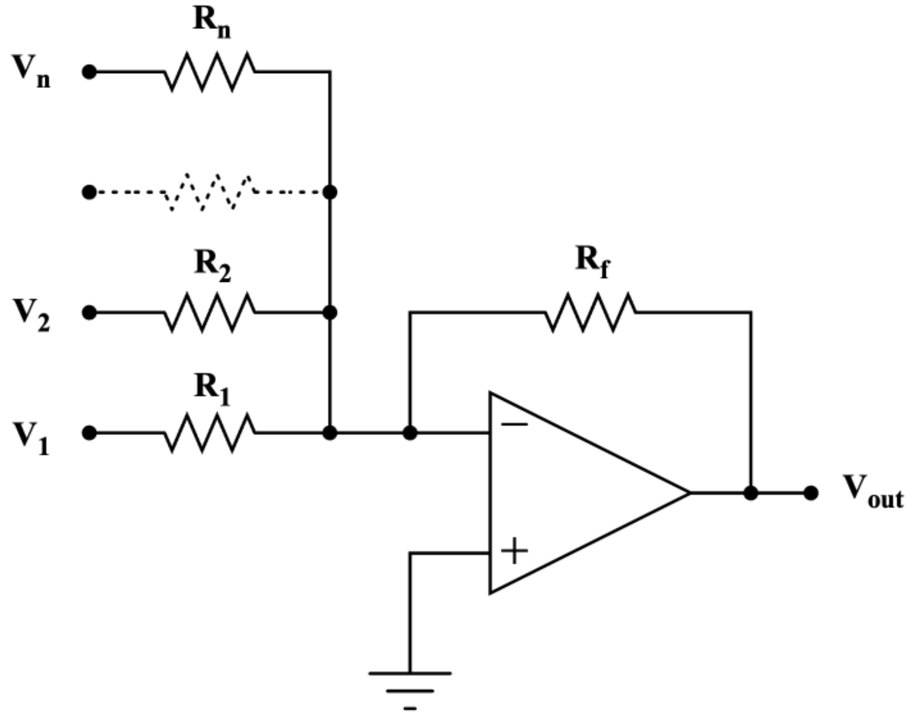
- An inverting amplifier puts a resistor in series with the input
- This is a very bad idea as it means you have put an additional voltage noise source between your source and the amplifier
- Do not do this:
  – Unless the transducer is effectively R_{in}
  – Or R_{in} is very small!

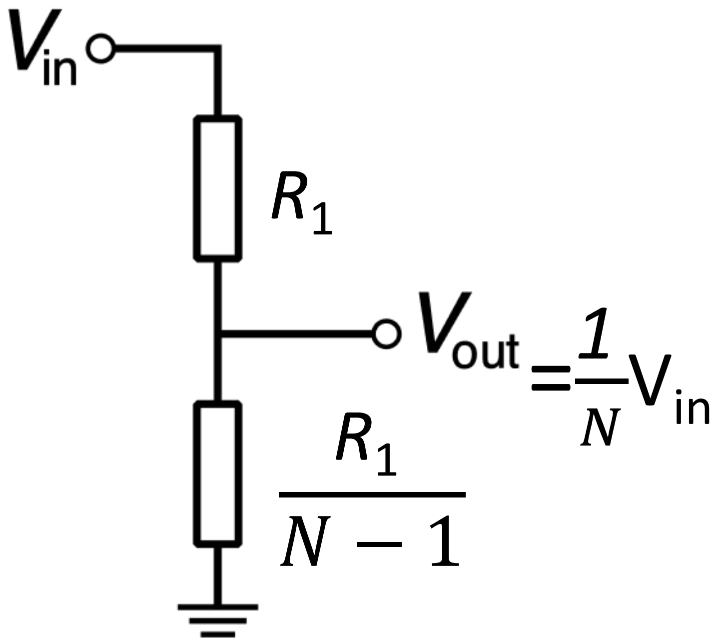
Non-Inverting Amplifier Noise



- A non-inverting amplifier avoids putting a resistor in series with the input
- However, you must ensure that the parallel combination of R_g and R_f
  - Are small enough so that they generate less noise voltage than V_n
- Also, the necessary bias resistor on the +input should be significantly larger than the source impedance to avoid noise

Summing Amplifier Noise: Hidden Gain

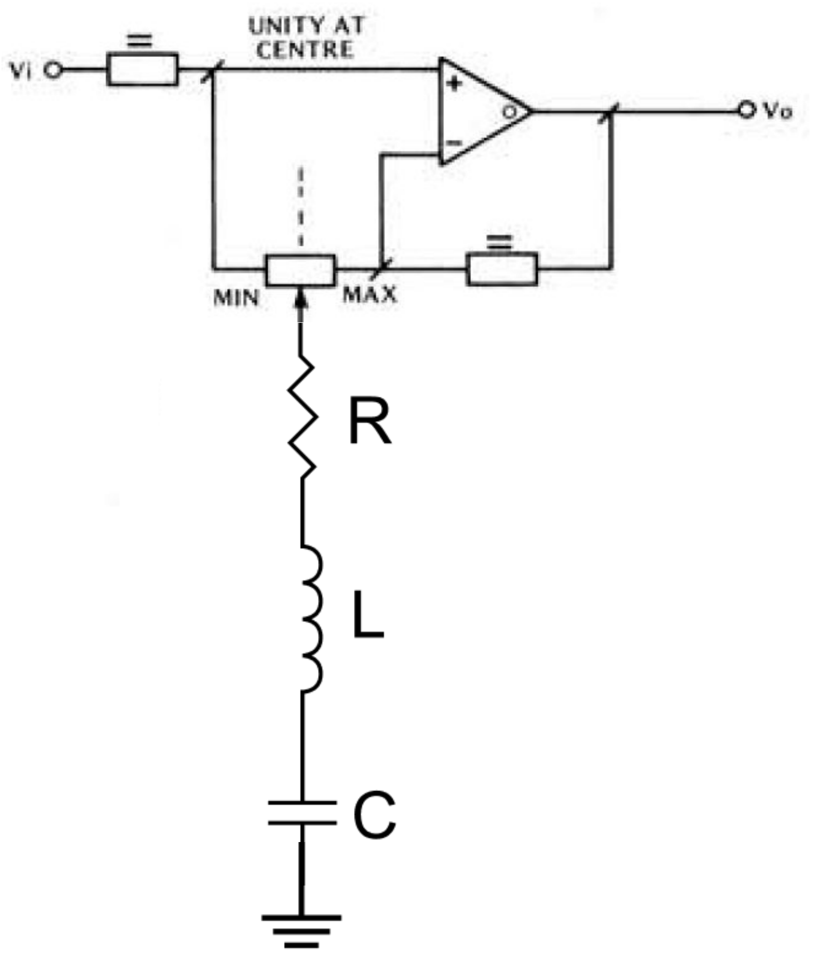




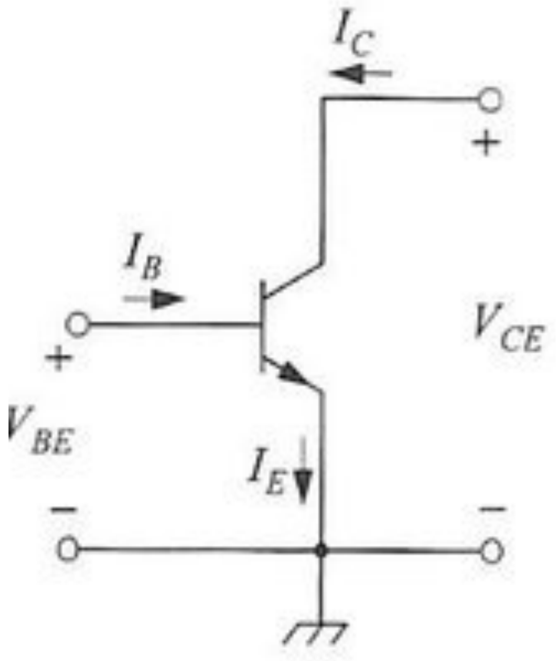
- A summing amplifier effectively attenuates the signal and then reamplifies it
- The other inputs act in parallel to form an attenuator
  - But a there is a compensating attenuation in the feedback path
  - So, the end-to-end gain is one, but the internal gain can be high!
- Also, happens in equalisers and high Q filters

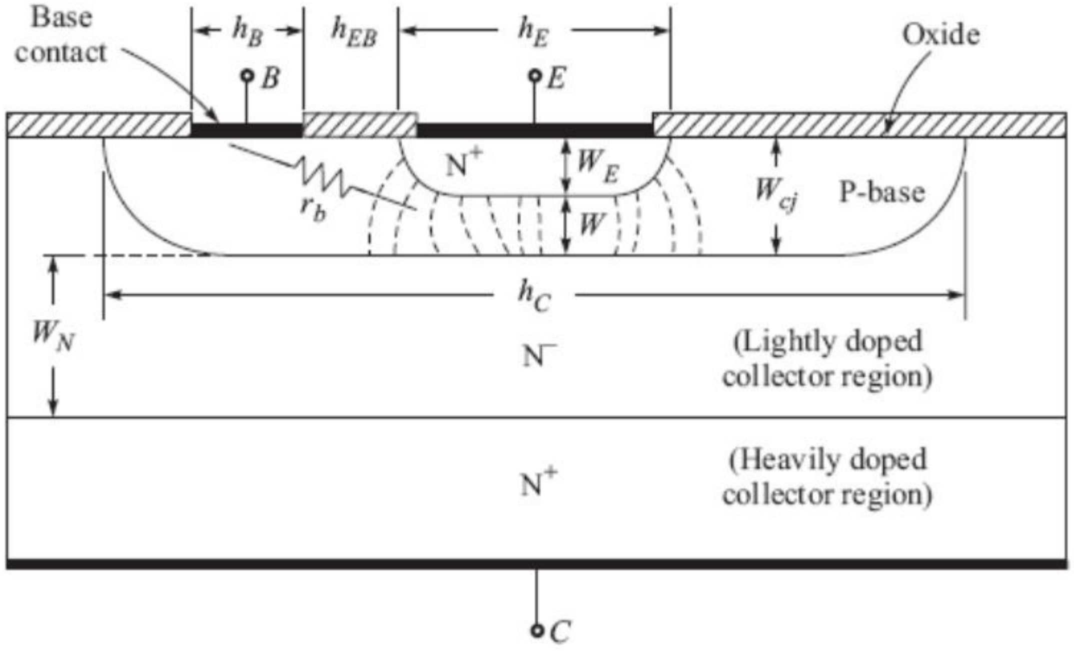
Equaliser Amplifier Noise: Hidden Gain

- A summing amplifier effectively attenuates the signal and then reamplifies it
- The other inputs act in parallel to form an attenuator
  - But a there is a compensating attenuation in the feedback path
  - So, the end-to-end gain is one, but the internal gain can be high!
- Also, happens in equalisers and high Q filters



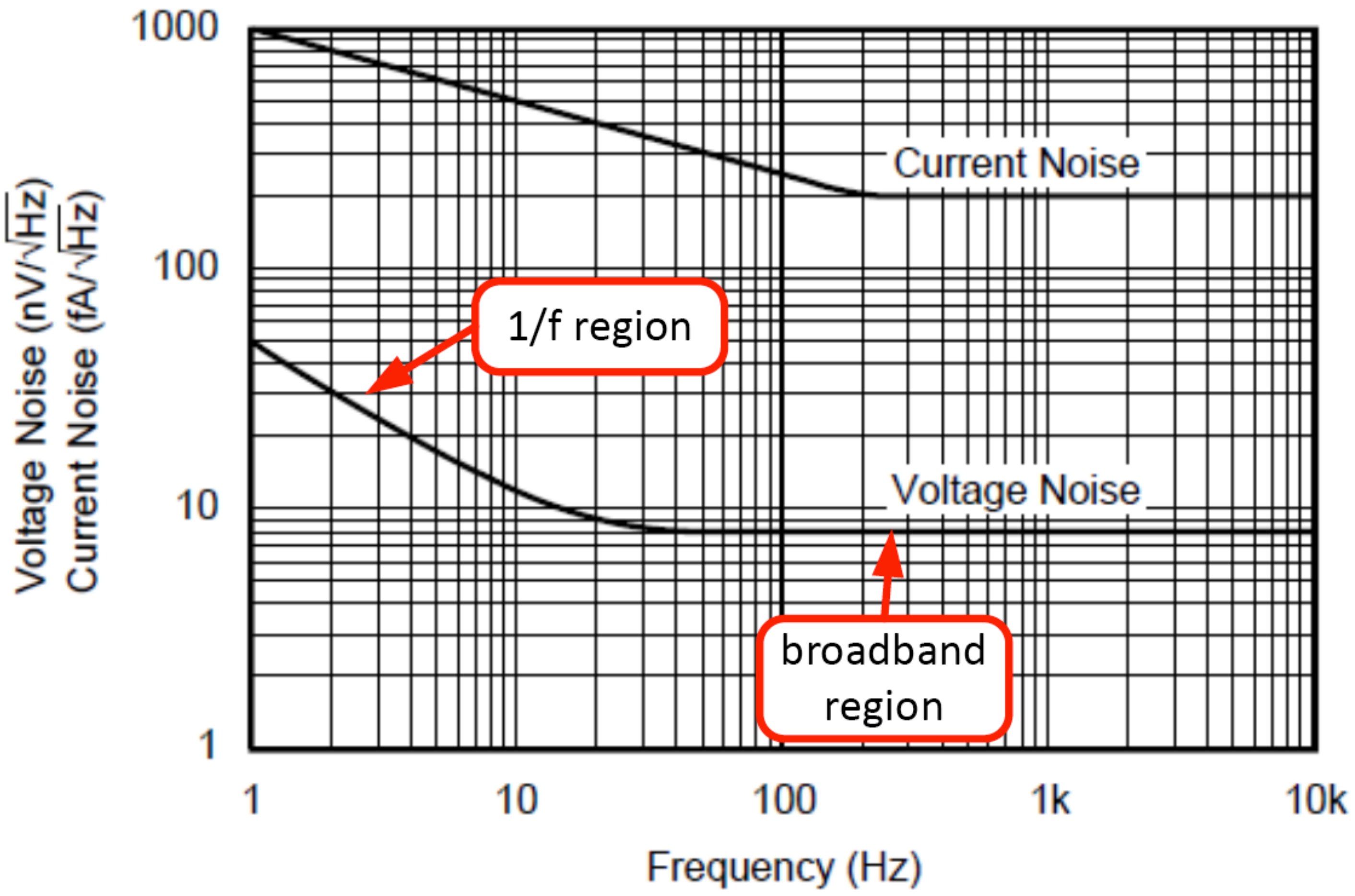
Noise in Bipolar Transistors





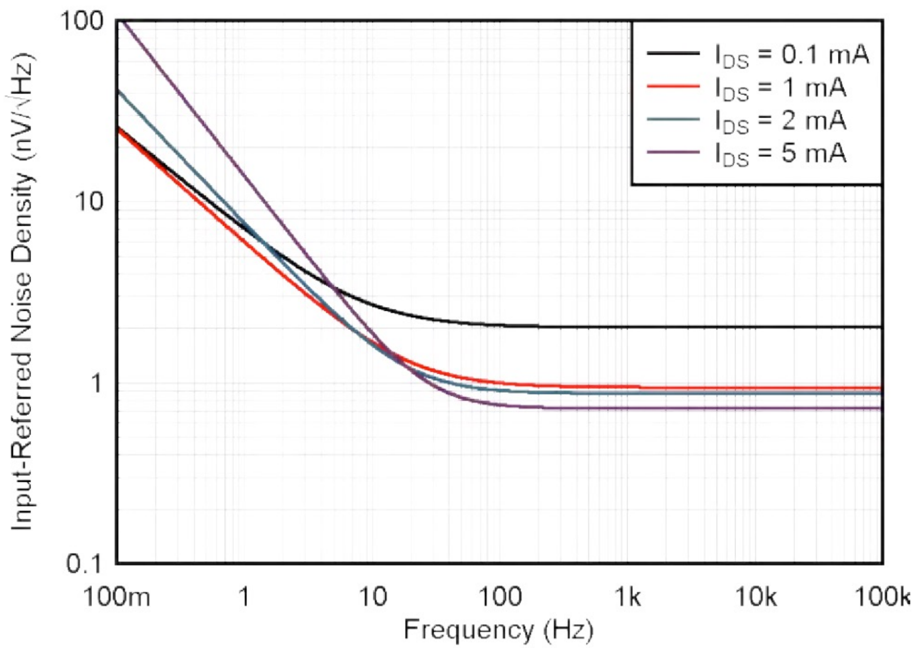
- The voltage noise (V_n) depends the collector current which defines the transconductance $gm = 40IC$
  - The noise resistance is $R_{noise} = \frac{1}{gm} + r_{bb'} = \frac{25}{I_C} + r_{bb'}$ (I_c in mA)
  - As current increases noise goes down but limited by $r_{bb'}$
- The current noise (I_n) depends on the base current
  - Which is related to the collector current by the current gain

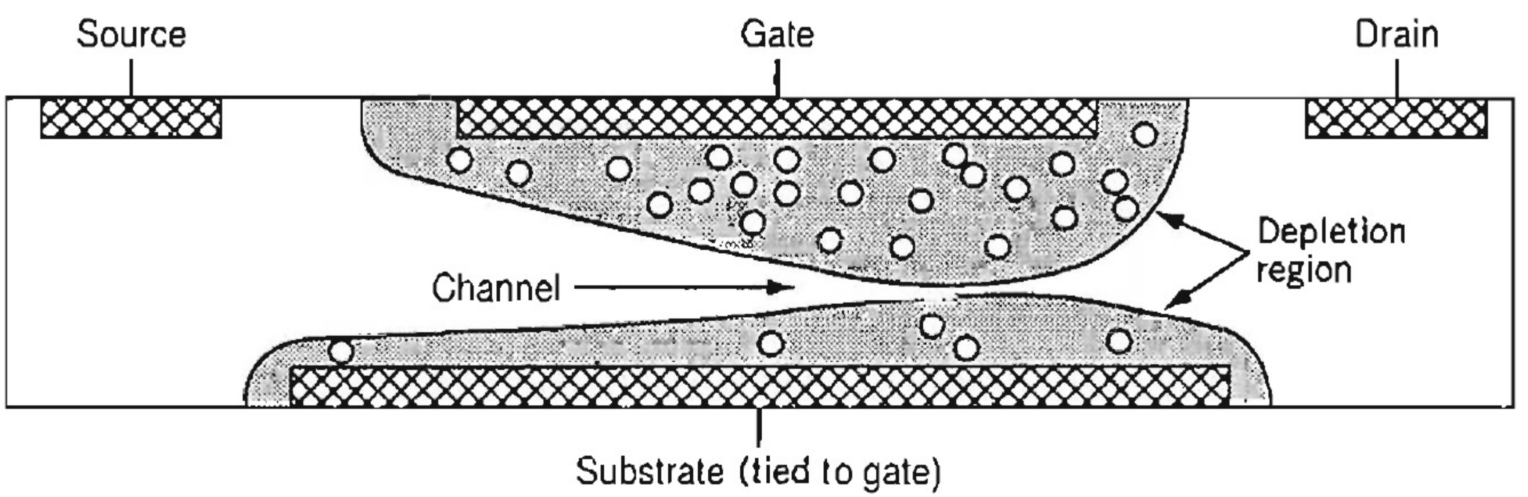
1/f Noise in Bipolar Transistors



- There is 1/f noise in both current and voltage noise in bipolar transistors
  - Related to the quality/purity of the materials and the processing

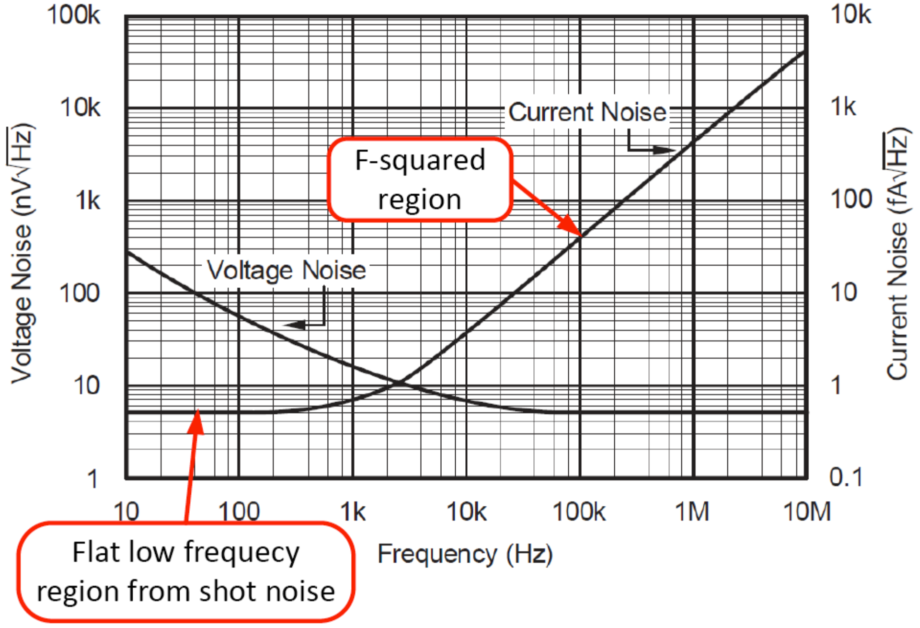
Noise in JFET Transistors

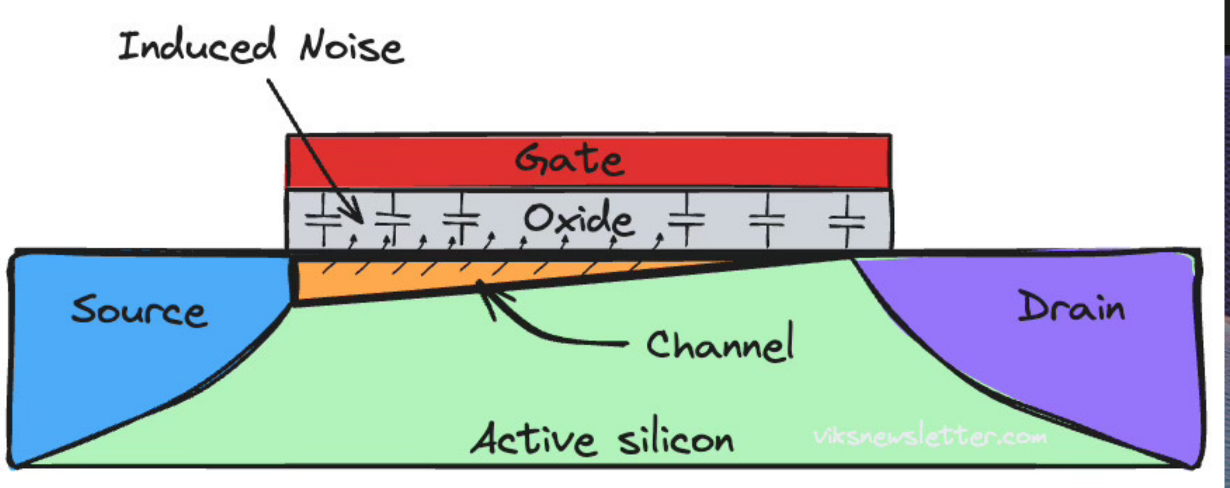




- The voltage noise (V_n) is proportional to the transconductance of the JFET
  - The noise resistance is $R_{noise} \approx \frac{0.67}{gm}$ Higher *gm* implies lower V_n
  - There is a significant 1/f noise corner
- The current noise (I_n) depends on the gate current
  - Which is a reverse biased diode and can be very small (fA/$\sqrt{Hz}$)
  - Tend to be white with no 1/f noise

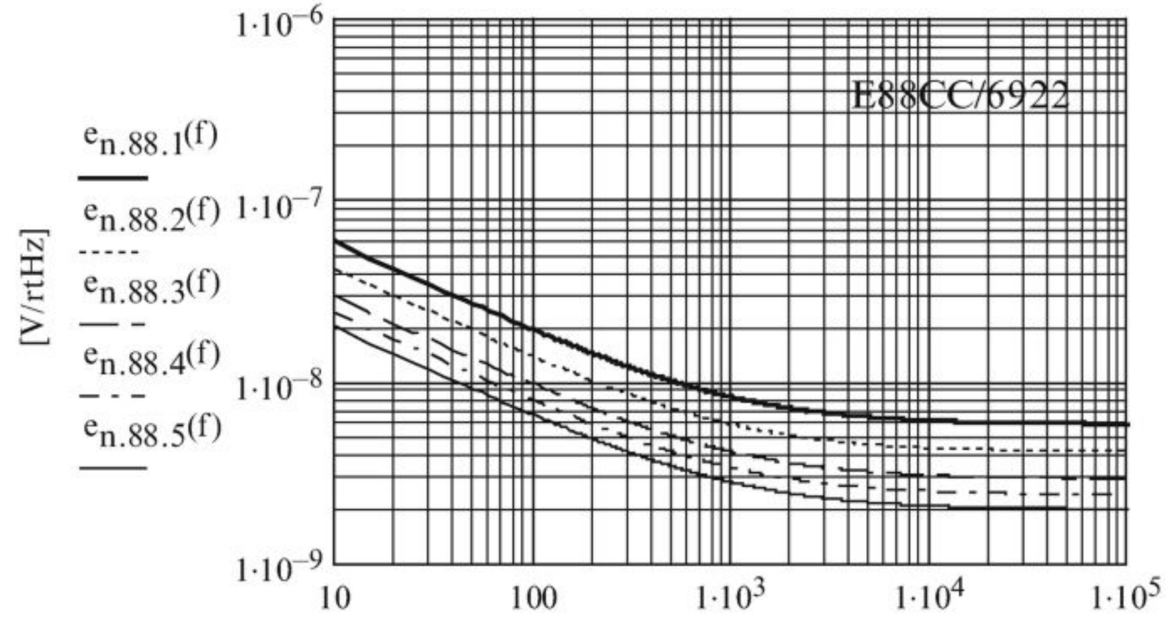
Noise in MOSFET Transistors





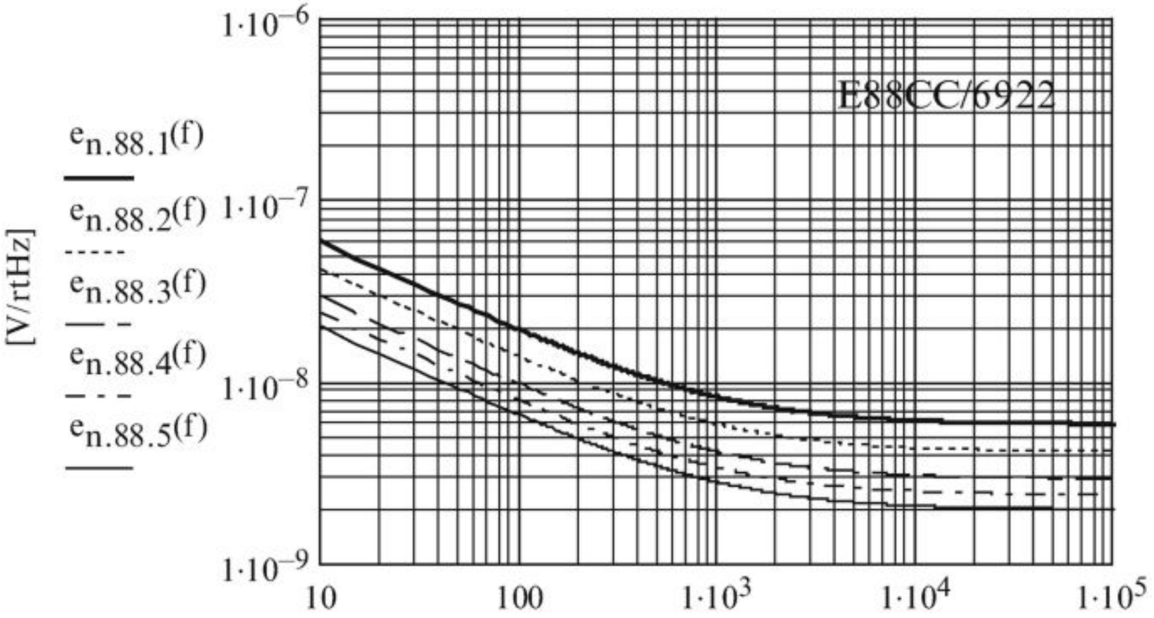
- The voltage noise (V_n) is proportional to the transconductance of the MOSFET
  - The noise resistance is $R_{noise} \approx \frac{0.67}{gm}$ Higher *gm* implies lower V_n
- There is a significant 1/f noise corner
  - Due to surface states with the oxide as well as the bulk effects
- There is current noise due to leakage through the gate!
  - And $1/f^2$ noise at high frequencies due induced gate current noise

Noise in Tubes or Valves: Triodes



- The voltage noise (V_n) is proportional to the transconductance of the tube/valve
  - The noise resistance is $R_{noise} \approx \frac{3.06}{gm}$ Higher *gm* implies lower V_n
- There is a significant 1/f noise corner
  - Due to surface states within the cathode oxide
- There is current noise due to grid current
  - grid current of the order of 1 – 100 nA
  - corresponding to an input noise current I_n of 18 – 180 fA/$\sqrt{Hz}$

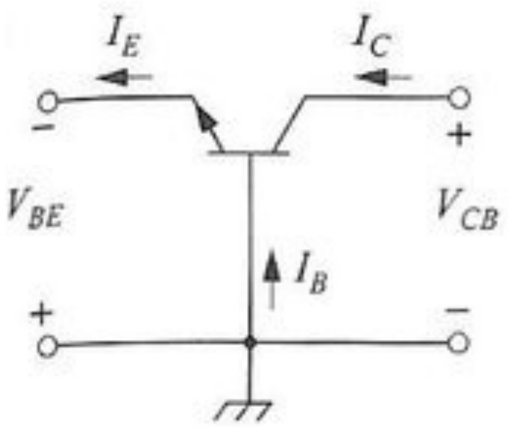
Noise in Tubes or Valves: Pentodes



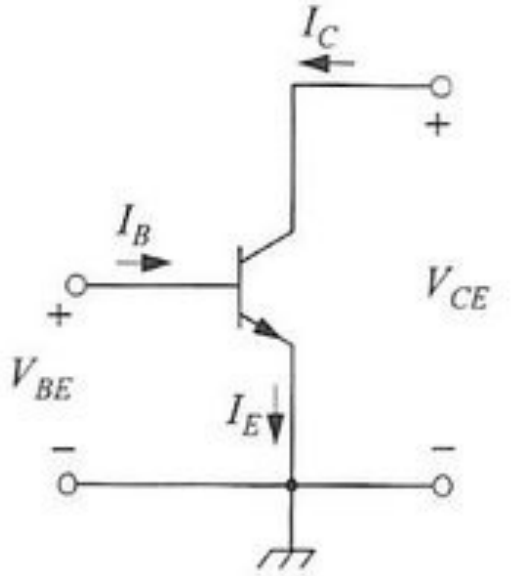
- There is current noise due to the screen grid current I_{sg}
  - Screen grid current I_{sg} is of the order of 3 – 6 mA
  - corresponding to screen noise current I_{nsg} of 31 – 44 pA/$\sqrt{Hz}$
  - Which can develop a significant voltage across the $\frac{1}{gm}$ resistance of the cathode
  - Thus, giving extra "Partition noise"

Independence Of Device Configuration

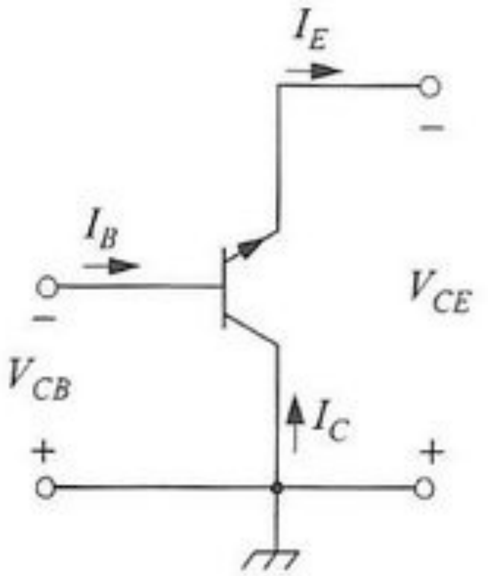
Common Base/Gate/Grid



Common Emitter/Source/Cathode

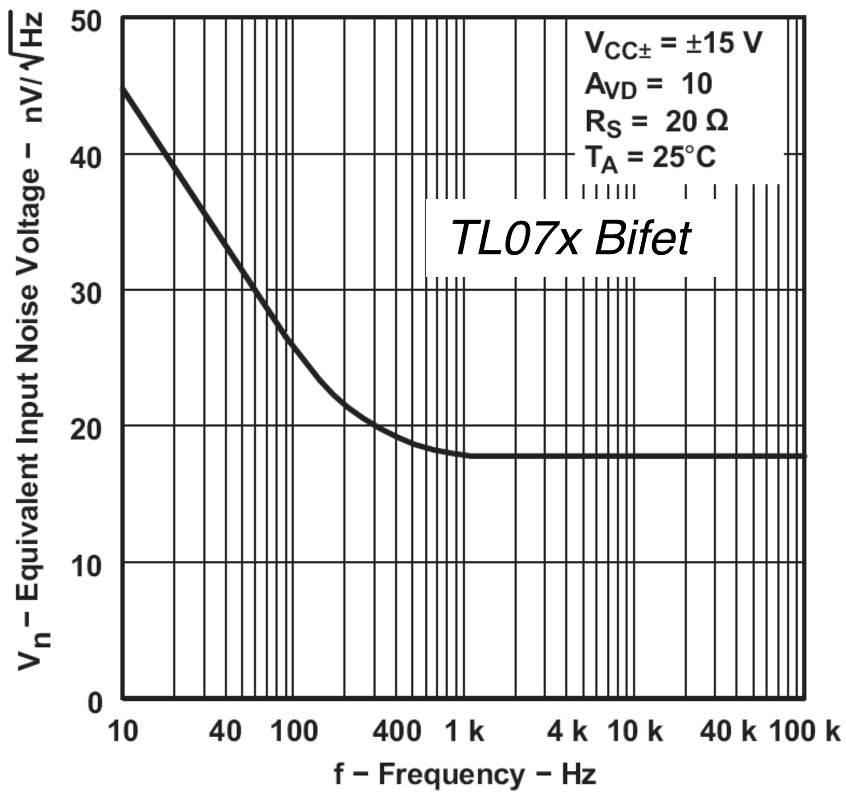


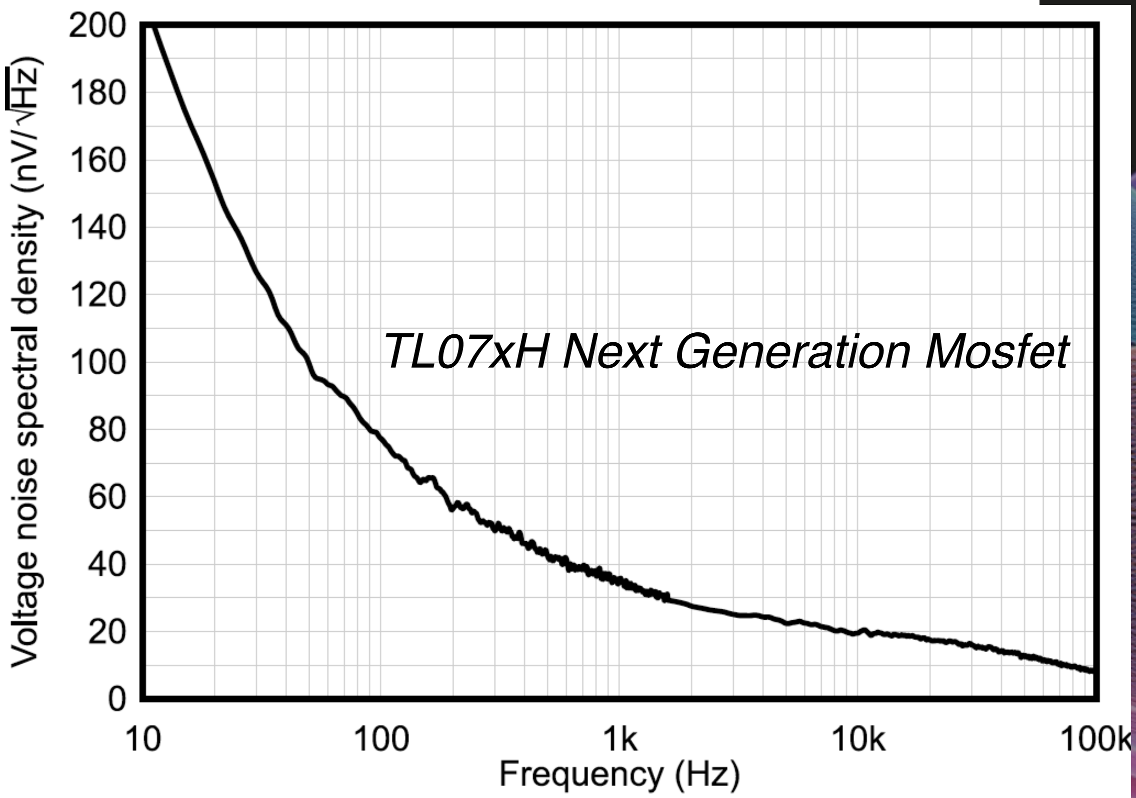
Common Collector/Drain/Anode



- Irrespective of the devices circuit configuration
  - The voltage noise is still present at the input
  - And the current noise still flows in the input circuit
- The effects of cascading may change
  - For example, the common collector will not be so good for voltage noise when cascaded
  - For current noise however…

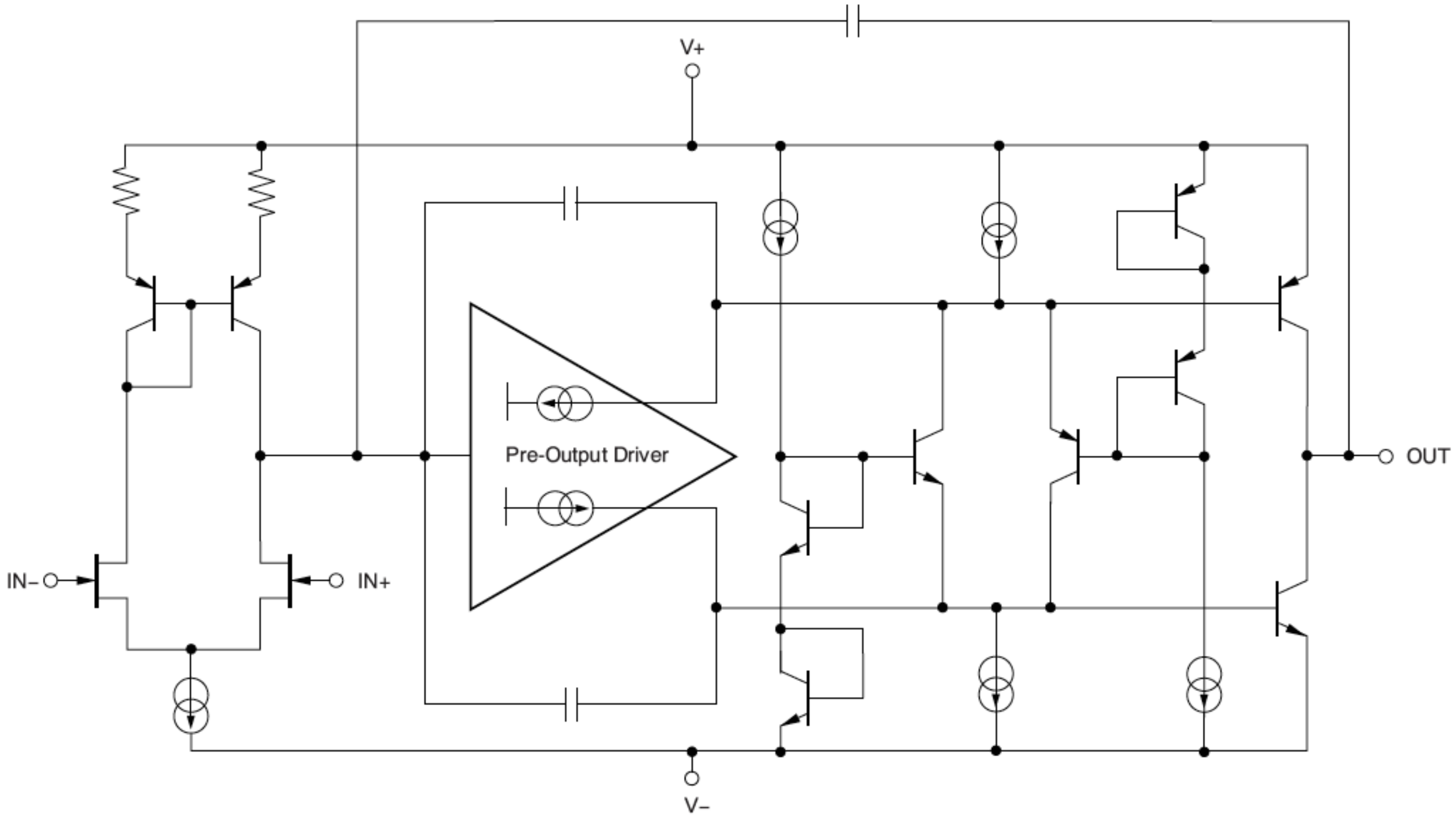
Differences in Noise BiFet Versus Mosfet





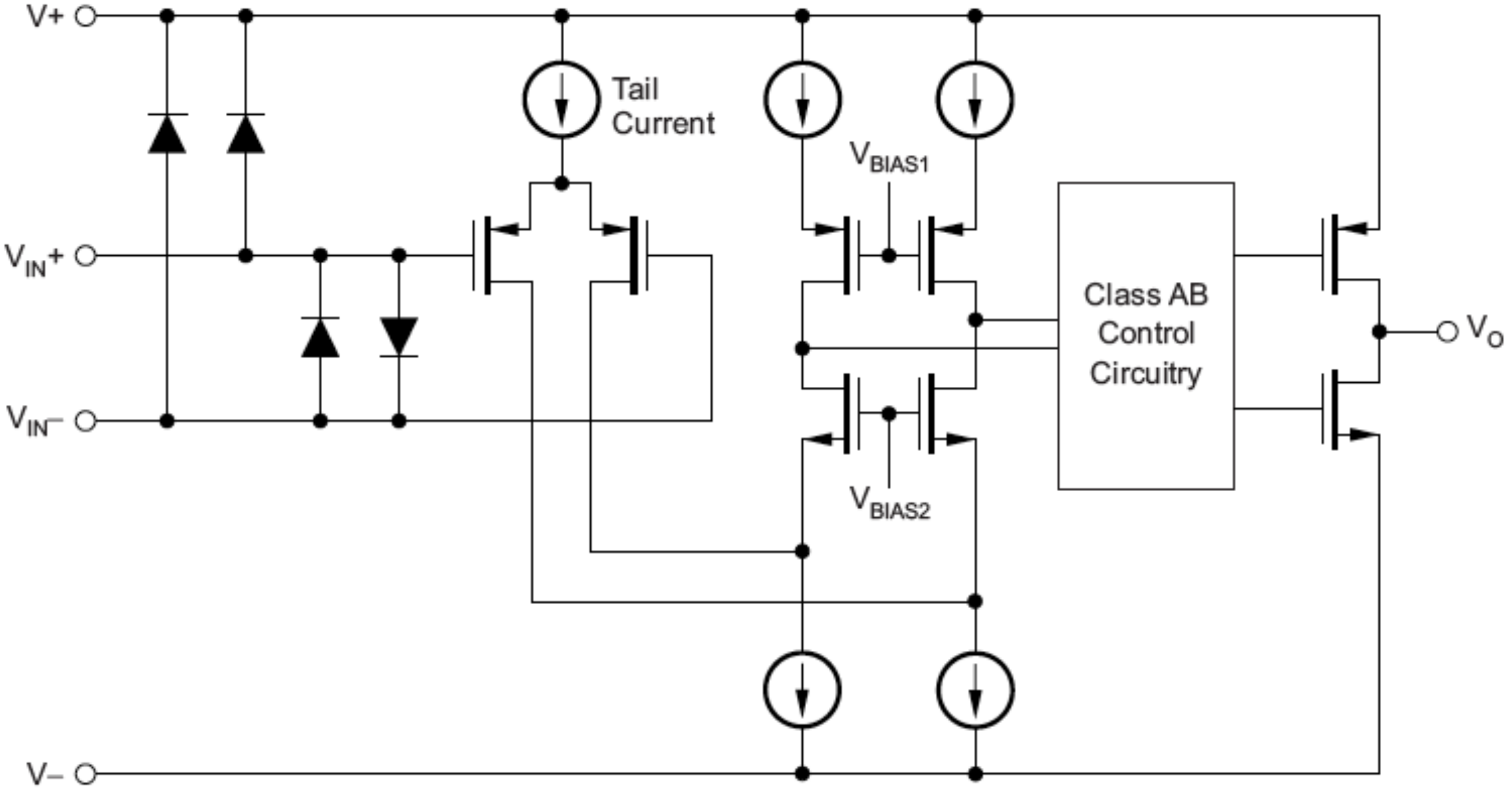
- The BiFet TL07x
  - Junction fet input and bipolar circuitry
  - Has a lower 1/f noise corner
- Compared to the all Mosfet TL07xH
  - 1/f noise corner is much higher

Two Op Amps… Both Alike in Circuitry



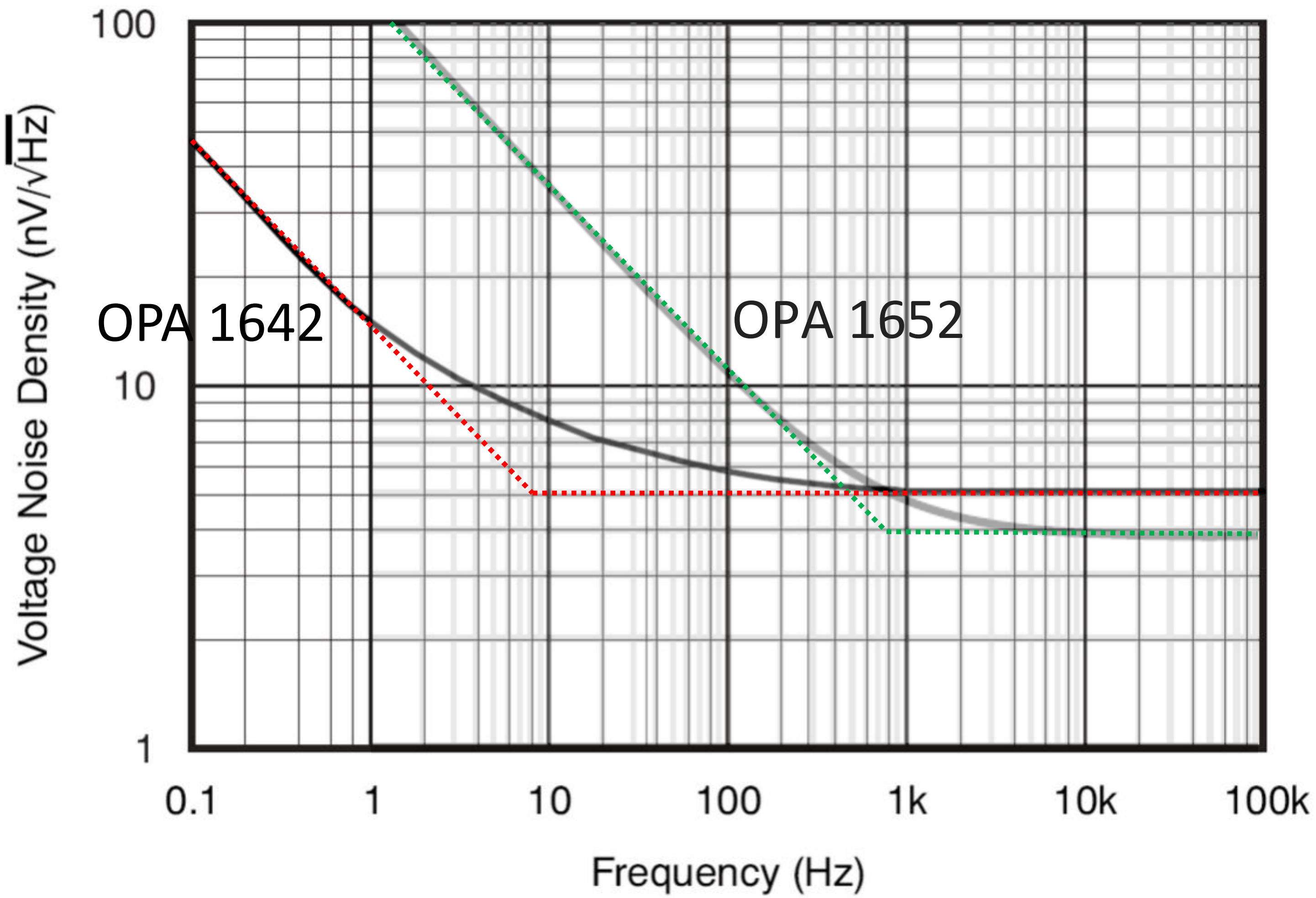
- OPA 1642
  - JFET Input
  - Bipolar, Transimpedance Class AB Output

Two Op Amps… Both Alike in Circuitry



- OPA 1652
  - MOSFET Input
  - MOSFET, Transimpedance Class AB Output

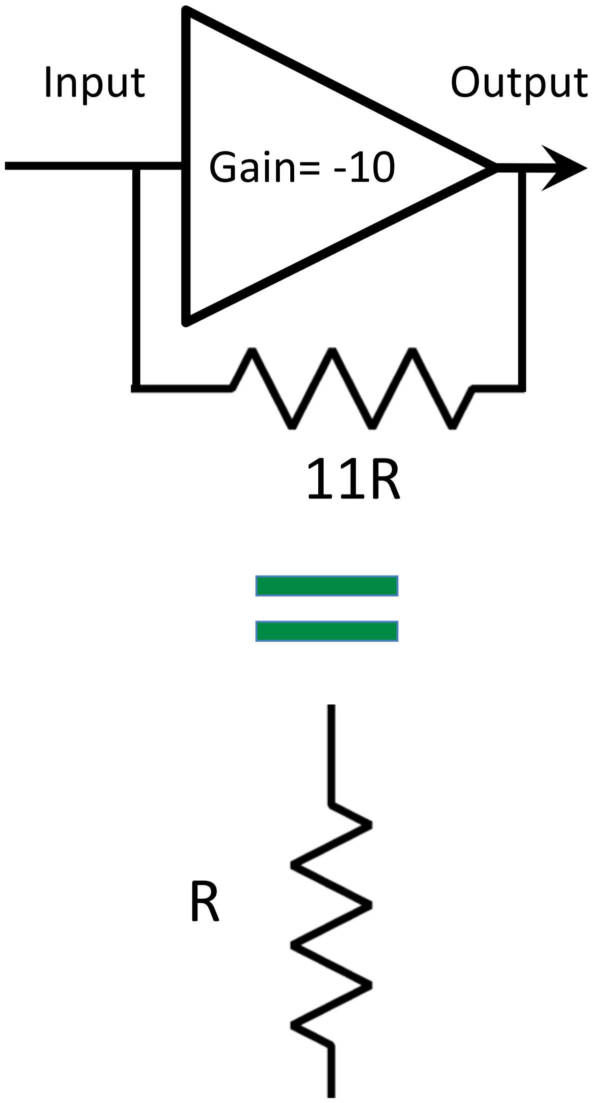
Differences in Noise, Mos Versus Bifet



- OPA 1652 has a lower noise floor but a higher corner frequency:
  - Almost a 20 dB difference at low frequencies
  - Matters for Bass controls, RIAA equalization, and Magnetic tape heads

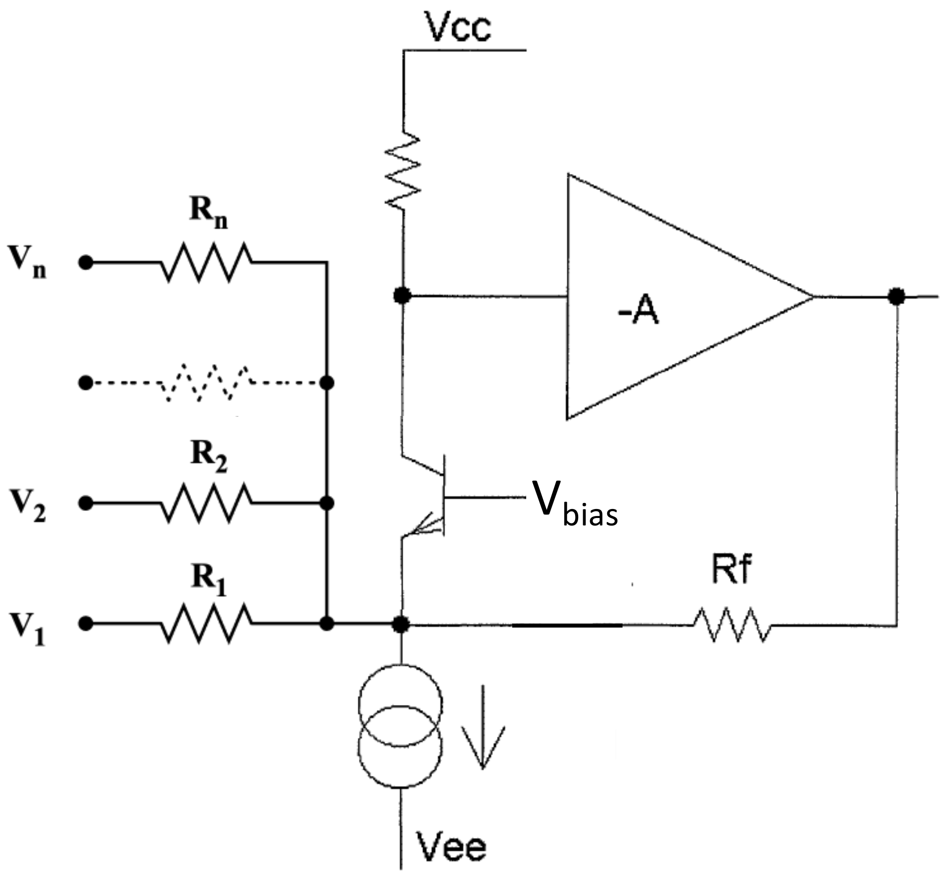
Mimicking Impedance

- Some transducers need to see a particular load
  - Using a resistor is a not the best idea
  - Because it generates extra noise
- It might be better to try and mimic that impedance using feedback
  - For example, using an amplifier with a gain of -10
  - And a resistor that is 11 times larger
  - The effect of the feedback to make it look 11 times smaller
- This will produce less current noise in the transducer



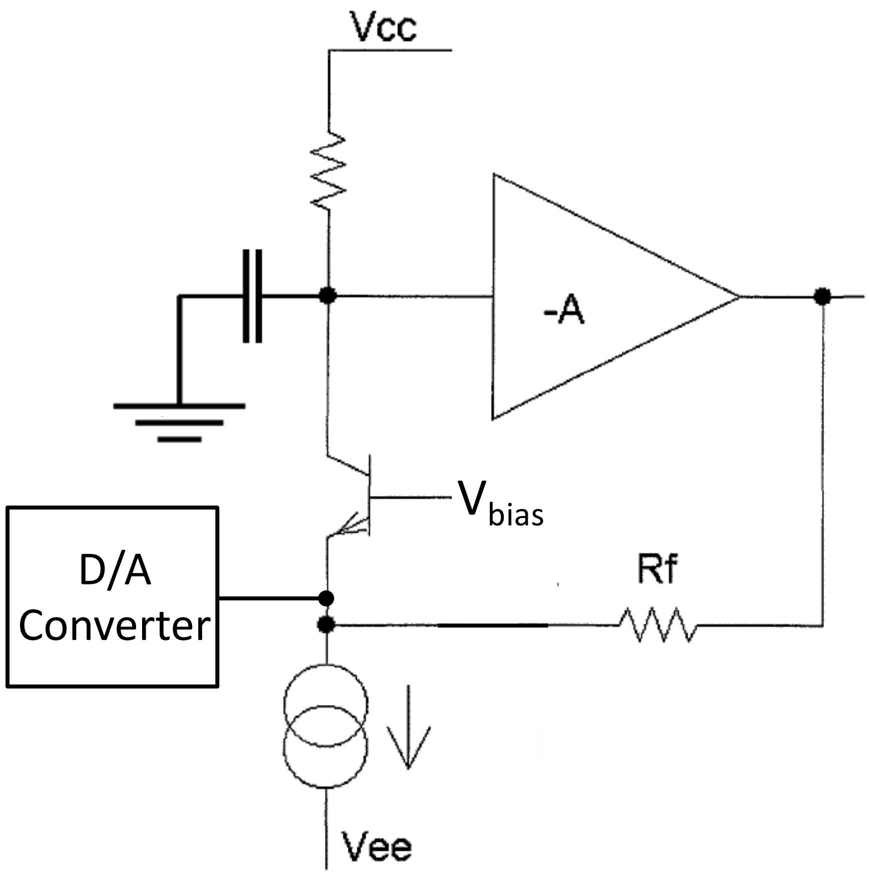
Summing Bus Idea

- To reduce the signal loss in a summing amplifier
- Feed it into a low impedance point
- Current will then not be attenuated
- By dividing into the other resistors
- Could even use current summing



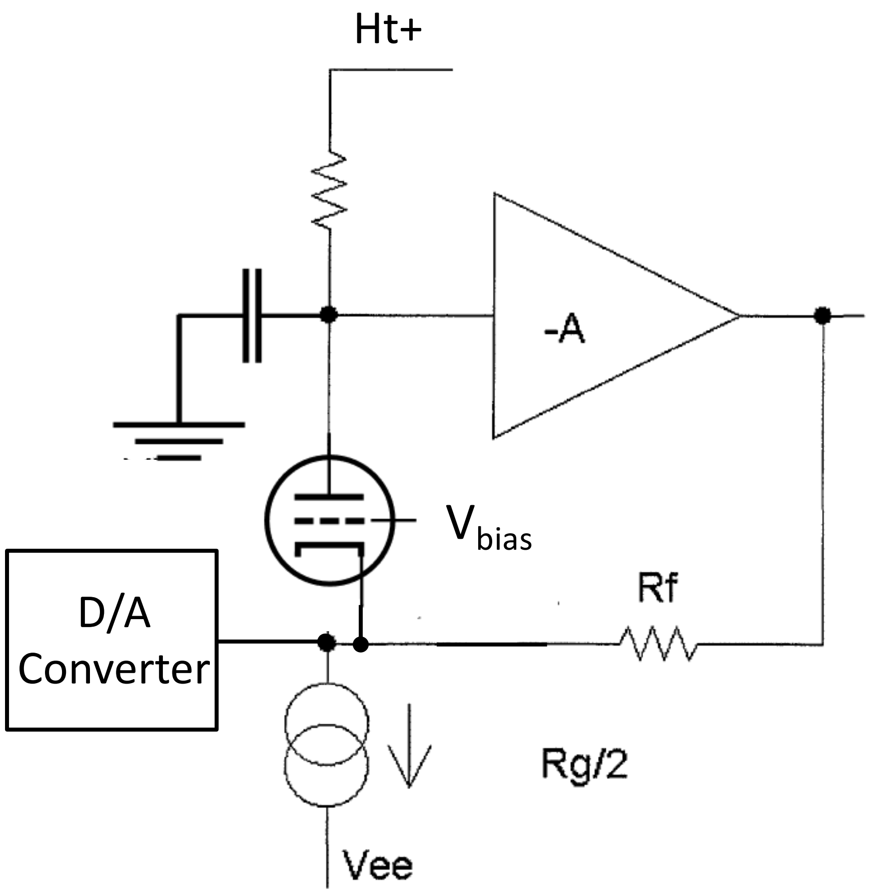
Digital to Analogue Amp Input cathode

- Many Digital to Analogue converters like to see a low impedance
- But they have fast edges etc.
- Using a virtual earth risks dynamic non linearities in the amplifier
- So, using a low impedance point that doesn’t require feedback to create it
- Might be a good idea
- One could even slow fast edges down isolated from the D/A circuitry.



Digital to Analogue Amp Cathode Input

- Many Digital to Analogue converters like to see a low impedance
- But they have fast edges etc.
- Using a virtual earth risks dynamic non linearities in the amplifier
- So, using a low impedance point that doesn't require feedback to create it might be better
- One could even slow fast edges down isolated from the D/A circuitry
- Or use a tube/valve



Summary

- Examined and quantified different sources of noise
  - Developed a universal noise analysis approach using current and voltage noise concepts
- Used it in an example with a resistive transducer
  - And shown the “optimum noise resistance” only applies to resistive sources
  - And shown how reactive transducers need low current and voltage noise and do not have an optimum
- Shown that:
  - V_n is a function of 1/gm irrespective of the device
  - I_n is a function of the devices input current including partition noise
- For low noise:
  - Avoid series resistors
  - And maximise parallel ones
  - Make sure feedback resistors are small enough not to contribute
- Consider circuit remedies to mimic desired load impedances

"The world may be digital…
But people are 4-wire and analogue!"

Jamie Angus-Whiteoak

Questions?