"Rules" of low noise amplifier systems

- Combine uncorrelated noise sources in quadrature

  $e^2_{tot} = e_1^2 + e_2^2 + e_3^2 + \ldots + i_n^2 R^2 + \ldots$

  follows from Campbell's theorem

  consider as combinations of gaussian distributions

- First stage of amplifier dominates

  noise originates at input

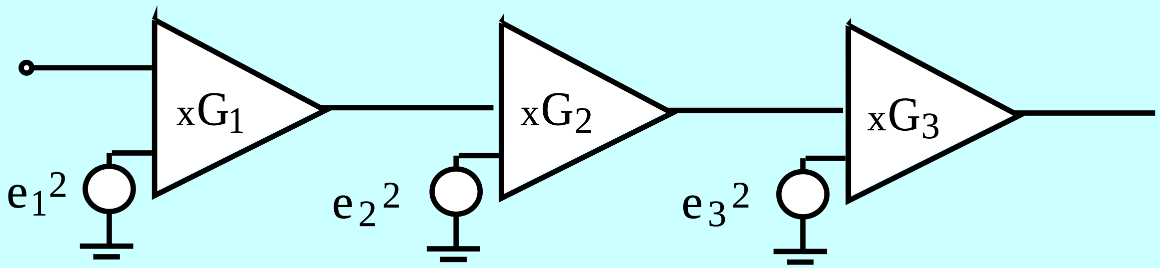
- Noise is independent of amplifier gain or input impedance

  so noise can be referred to input

- In real systems both are approximations - but normally good ones

  so often sufficient to focus on input device

Amplifiers - dominance of input stage



- Amplifier systems (and amplifiers!) usually consist of several stages

  impractical to put all gain at one location - power, heating, material, size,...

- Calculate signal and noise at output

  $S_{out} = G_1.G_2.G_3 S_{in}$ for 3 stage system, but can easily extend to N

  $(e_{out})^2 = G_1^2.G_2^2.G_3^2 e_1^2 + G_2^2.G_3^2 e_2^2 + G_3^2 e_3^2$

  $(e_{out} / S_{out})^2 = (e_1^2 + e_2^2/G_1^2 + e_3^2 /G_1^2.G_2^2)/S_{in}^2$

- Desirable to <u>maximise gain at input stage</u>

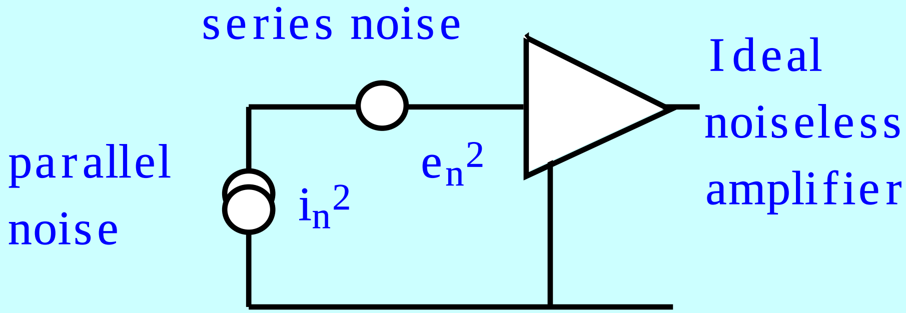
  eg stage 1 boosts signal enough for transmission down cable and should be large enough that environmental noise is not significant

Amplifiers - location of noise sources

- Normal to partition noise sources

  not fundamental to calculations

  but can simplify!

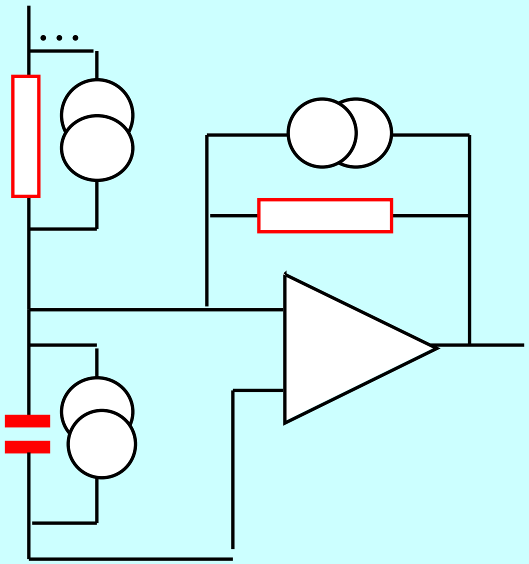


- Parallel noise sources appear as currents at input

  detector leakage current

  bias resistors

  feedback resistor



Series noise sources appear as voltage at input

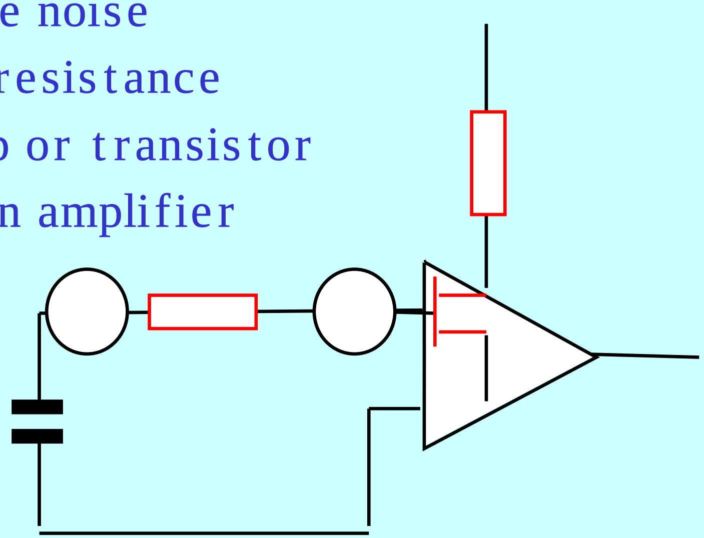
transistor gate noise

device series resistance

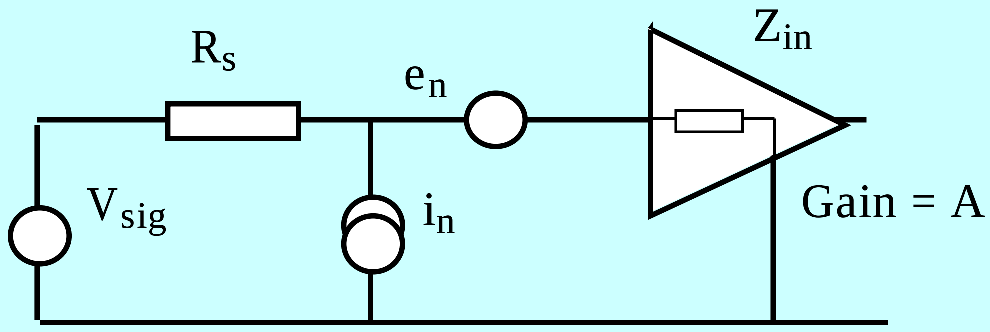
microstrip or transistor

load resistor in amplifier

...



Amplifiers - reference to input



assume:

signal source and associated impedance

noise sources

amplifier with gain & input impedance

• noise at output $\quad E_{no}^2 = A^2 \{e^2_n Z^2_{in}/(Z_{in} + R_s)^2 + i^2_n R^2_s Z^2_{in}/(Z_{in} + R_s)^2\}$

• transfer function $\quad K = V_{out}/V_{in} = A.V_{sig}.Z_{in}/(Z_{in} + R_s)V_{sig} = AZ_{in}/(Z_{in} + R_s)$

• noise at input $\quad E_{ni}^2 = E_{no}^2/K^2 \Rightarrow \mathbf{E^2_{ni} = e^2_n + i^2_n R^2_s}$ $\quad$ <u>no Z_{in} or A dependence</u>

easy to show analogous result $\quad \mathbf{I^2_{ni} = i^2_n + e^2_n/R^2_s}$ $\quad$ choice is for convenience

in most detector systems, there is a current signal source and a parallel capacitance

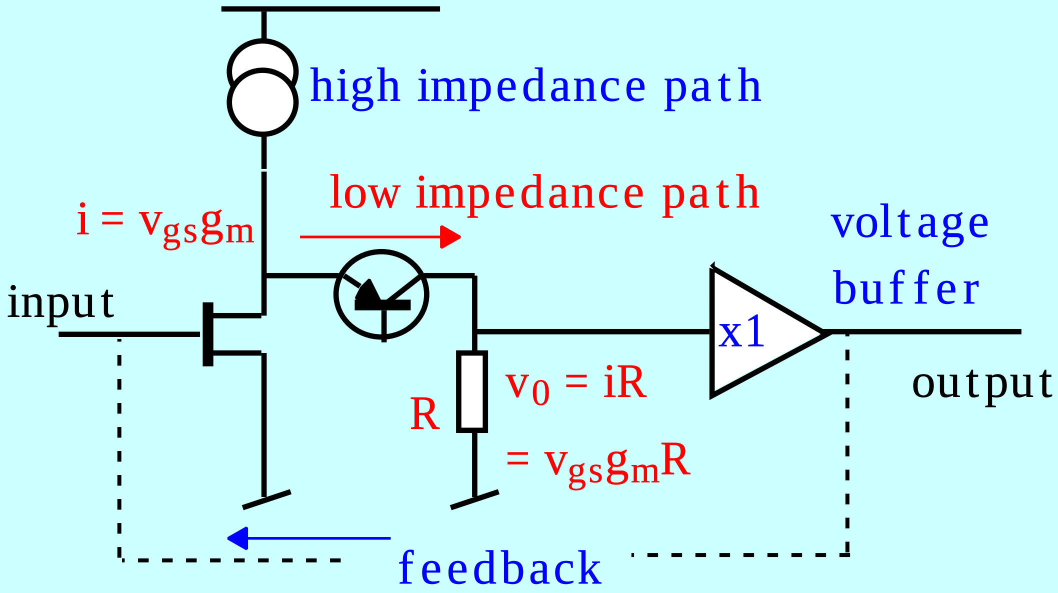
• then the spectral distribution of noise at the input is affected

$$\mathbf{I^2_{ni} = i^2_n + e^2_n \omega^2 C^2}$$ <u>no longer white</u>

Real amplifiers

- The first amplifier stage dominates - reason for distinction of pre-amplifier

  most low-noise amplifiers are based on very simple concepts



voltage amplifier

$G = g_mR$

add feedback to define type

eg. charge or current sensitive

within the preamplifier we expect the input device to be the most important

- To understand noise performance we need to study input device

  bipolar or FET

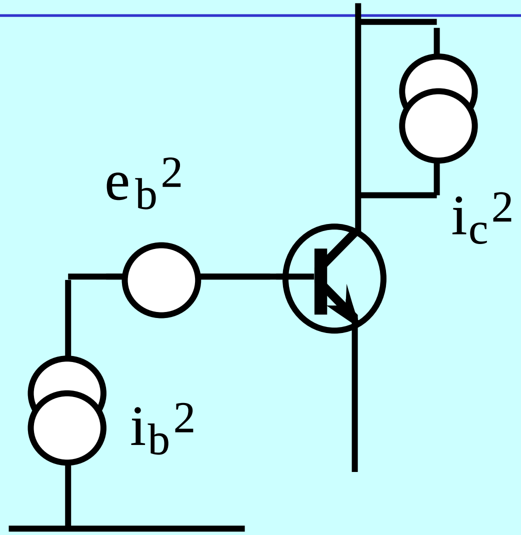
Bipolar transistor noise

- <u>Two shot noise</u> sources

  Fluctuations in I_C $\quad i_c^2 = 2eI_C\Delta f$

  Fluctuations in I_B $\quad i_b^2 = 2eI_B\Delta f$

  but these are correlated since $I_B \approx I_C/\beta$



- <u>Thermal noise</u> in base & contacts $\quad e_b^2 = 4kTr_b\Delta f$

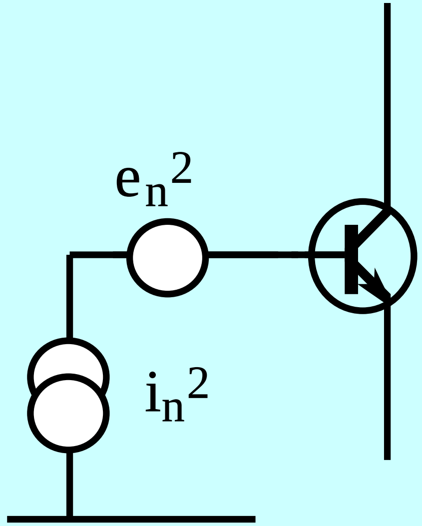
  r_b = base spreading resistance

- Transfer noise sources to input

  use $\quad v_{be} = i_c r_e = (kT/qI_c)i_c$

  $e_n^2 = (4kTr_b + 2qI_c r_e^2)\Delta f \quad = [4kTr_b + 2(kT)^2/qI_c]\Delta f$

  $i_n^2 \; = \; 2eI_B\Delta f$



- The constraint that i^2_n, e^2_n are correlated gives a limited range of noise

  with best performance for high speed applications

Some useful numerical values

$kT/e \approx 0.025\ V = 25mV$ at 293K (Room temperature)

$e = 1.6\ 10^{-19}$ coulomb

•Parallel noise - what resistor is equivalent to given current?

$4kT/R_p = 2eI$

$I = 2(kT/e)(1/R_p) = 50mV/R$

eg, $1M\Omega \approx 50nA$

•Parallel noise spectral density - units and magnitudes

$i_n = [2eI_B]^{1/2} = [32e^{-18}I_B]^{1/2} = 0.6 I_B^{1/2}$ **nA/√Hz**

eg, $3A \approx 1$**n**A/√Hz $\quad$ 3**μ**A ≈ 1**p**A/√Hz

•Series noise spectral density - units and magnitudes

$e_n = [4kTR_s]^{1/2} = [4(kT/e)eR]^{1/2} = [1.6\ 10^{-20}R]^{1/2} = 0.13R^{1/2}$ **nV/√Hz**

eg, $60\Omega \approx 1nV/\sqrt{Hz}$

Bipolar noise example

- r_b is often small so neglect

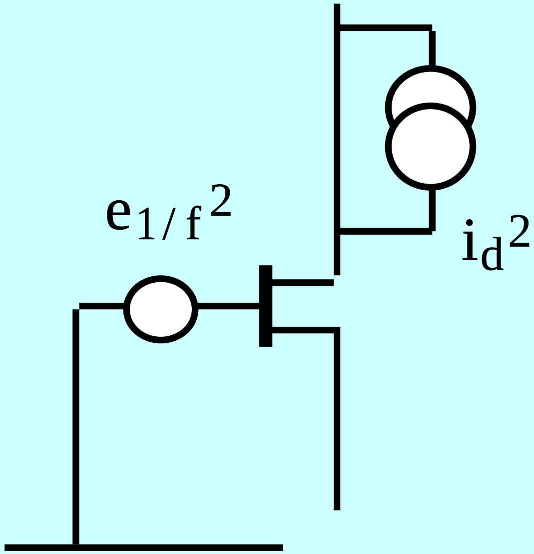
$\beta = 100$	$I_C = 1mA$ $I_B = 10\mu A$	$I_C = 100\mu A$ $I_B = 1\mu A$
$e_n = [2(kT)^2/qI_C]^{1/2}$ $= [2(kT/q)^2(q/I_C)]^{1/2}$	0.45 nV/√Hz	1.4 nV/√Hz
$i_n = [2qI_B]^{1/2}$	1.8 pA/√Hz	0.6 pA/Hz
i_nR_S for $R_S = 1k\Omega$	1.8 nV/√Hz	0.6 nV/Hz
$[4kTR_S]^{1/2}$ for $R_S = 1k\Omega$	4.0 nV/√Hz	4.0 nV/√Hz
NF for $R_S = 1k\Omega$	0.84 dB	0.59 dB

- Noise figure - often used to characterise voltage amplifier performance

NF [dB] $= 10\log_{10}$(Total noise power at input/Source noise power)

$$= 10\log_{10}\left(\frac{e_n^2 + i_n^2R_s^2 + 4kTR_s}{4kTR_s}\right) \qquad = 10\log_{10}\left(1 + \frac{e_n^2 + i_n^2R_s^2}{4kTR_s}\right)$$

MOSFET Noise



- Gate current <u>shot noise</u>

  $i_g^2 = 2eI_G\Delta f$ <u>negligibly small</u> for most applications

  high impedance of gate oxide (insulator) to substrate

- <u>Thermal noise</u> inside the transistor

  thermal <u>current</u> fluctuations in channel (- but **not** shot)

  $$i_d^2 = (4kT/R_n)\,\Delta f = 4kT(2/3)g_m\Delta f$$

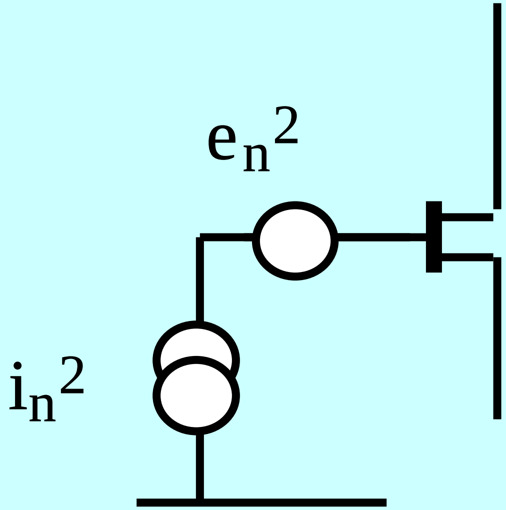
  1/f noise $e_n^2 \approx A/f$

- Transfer noise sources to input

  $i_d = g_m v_{gs}$ => $e_n^2 = i_d^2/g_m^2$

  $e_n^2 = [4kT(2/3g_m) + A/f]\Delta f$

  $i_n^2 \approx 0$



MOSFET thermal noise

- Parameters are (almost) controlled by geometry and current alone

$g_m = [2\mu C_{ox}(W/L)I_{DS}]^{1/2}$ $C_{ox} = \varepsilon_{ox}/t_{ox}$

$e_n{}^2 = 4kT(2/3g_m)\Delta f \sim 1/g_m$

- How to get large g_m?

Increase I_{DS} - but $e_n \sim I^{-1/4}$ power is a concern

Increase C_{ox} - it scales with technology feature size so modern processes help

1980 ~10μm 2000 ~ 0.25μm for $L_{min} \approx 0.25\mu m$ $t_{ox} \sim 5nm$

Make W/L large

W can be made very large, eg 2-3mm

L can be ≈ minimum feature size

Cooling - can gain small amount - but device heats

- Caveat carrier mobility **μ** - unfortunately not a constant

carriers typically approach saturation velocity at high electric fields

$1V/0.25\mu m = 4x10^4$ V/cm so $\mu = v/E$ falls as transistors shrink

MOSFET 1/f noise

- $e_{1/f}^2 \approx A_f/f$

  $A_f \approx K_f/[WL(C_{ox})^2]$

  K_f is technology dependent $K_f \sim 10^{-30} - 10^{-32}$ C.cm^{-2}

  PMOS transistors are significantly better than NMOS

- Corner frequency

  f_{corner} where $e_{thermal} = e_f$ typically ~ 10-1000kHz

  dependent on technology details, device dimensions

JFET Noise

- Almost identical to MOSFET
- \- differences are

Negligible 1/f noise - channel is buried below surface

Small gate current - gate is p-n diode

both can be reduced by cooling

- JFET is interesting for high resolution spectroscopy

allows to employ long shaping time constants (low f)

because of the very low 1/f noise

- Noise sources referred to input

$e_n^2 = 4kT(2/3g_m)\,\Delta f$

$i_n^2 = 2eI_g\,\Delta f$