# "Rules" of low noise amplifier systems

- Combine uncorrelated noise sources in quadrature

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

  follows from Campbell's theorem

  consider as combinations of gaussian distributions

- First stage of amplifier dominates

  noise originates at input

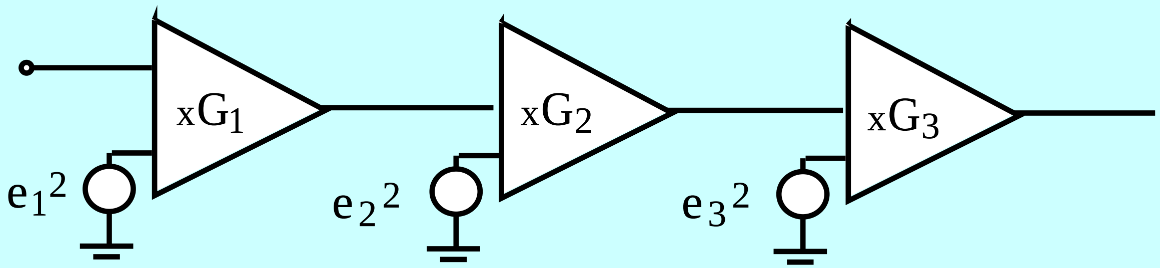
- Noise is independent of amplifier gain or input impedance

  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>

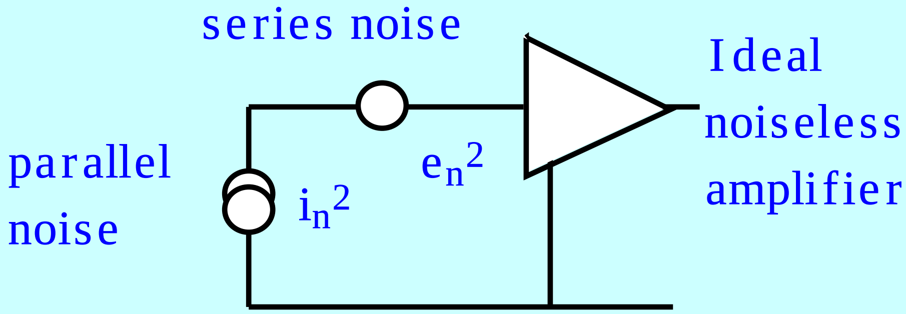
  eg stage 1 boosts signal enough for transmission down cable and should be large enough that environmental noise is not significant

# Amplifiers - location of noise sources

• Normal to partition noise sources

not fundamental to calculations

*but can simplify!*

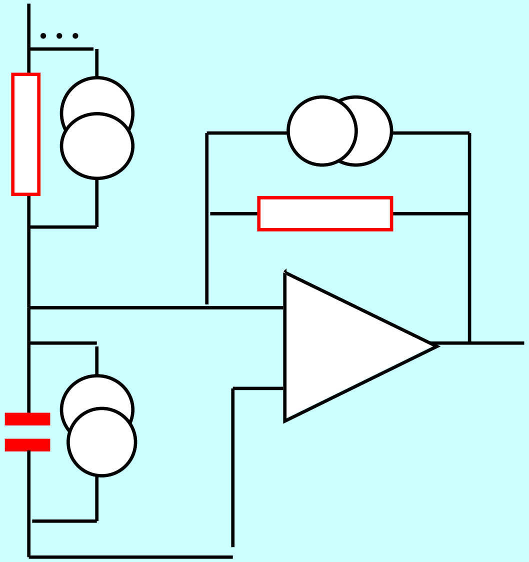



• Parallel noise sources appear as currents at input

detector leakage current

bias resistors

feedback resistor




Series noise sources appear as voltage at input

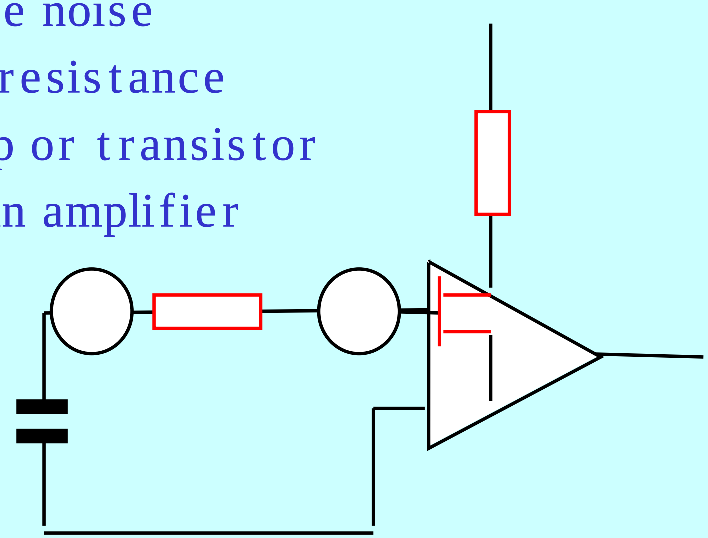
transistor gate noise

device series resistance

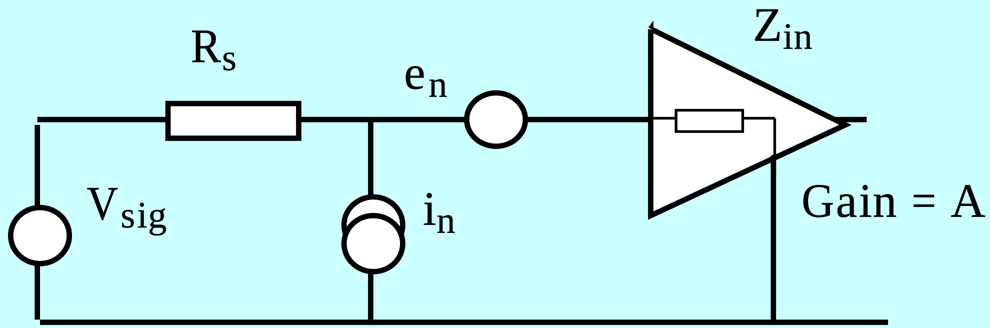
microstrip or transistor

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

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

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

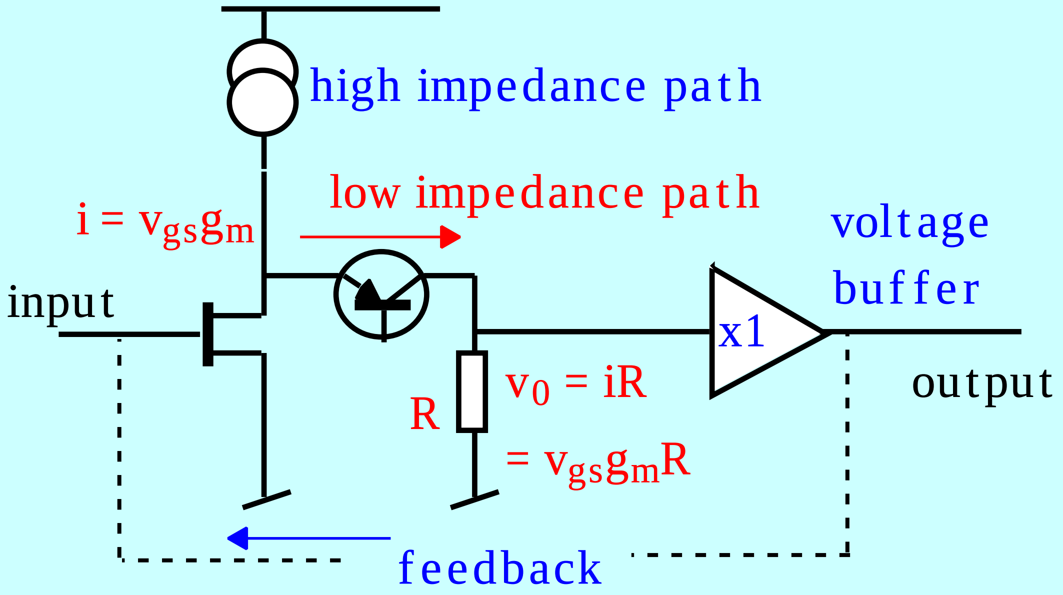
- then the spectral distribution of noise at the input is affected

$$\mathbf{I^2_{ni} = i^2_n + e^2_n \omega^2 C^2}$$ <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

- Two shot noise sources

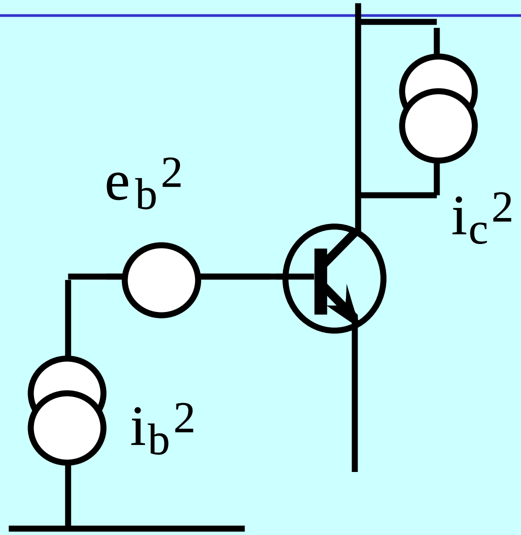
  Fluctuations in $I_C$  $i_c^2 = 2eI_C\Delta f$

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

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

- Thermal noise in base & contacts  $e_b^2 = 4kTr_b\Delta f$

  $r_b$ = base spreading resistance

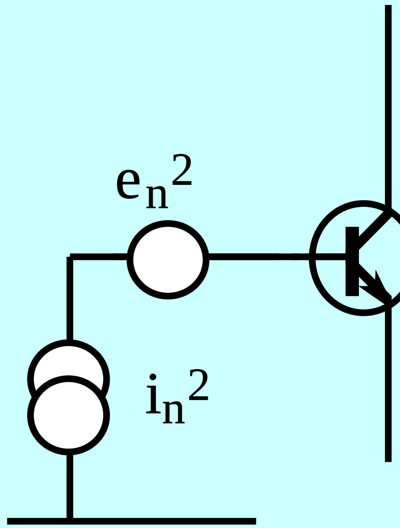



- Transfer noise sources to input

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

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

  $i_n^2 = 2eI_B\Delta f$




- 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 ≈ 1**n**A/√Hz     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/√Hz

# Bipolar noise example

• $r_b$ is often small so neglect

| $\beta = 100$ | $I_C$ = 1mA<br>$I_B$ = 10µA | $I_C$ = 100µA<br>$I_B$ = 1µA |
|---|---|---|
| $e_n = [2(kT)^2/qI_C]^{1/2}$<br>$= [2(kT/q)^2(q/I_C)]^{1/2}$ | 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 $R_S$ = 1kΩ | 1.8 nV/√Hz | 0.6 nV/Hz |
| $[4kTR_S]^{1/2}$ for $R_S$= 1kΩ | 4.0 nV/√Hz | 4.0 nV/√Hz |
| NF for $R_S$ = 1kΩ | 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 shot noise

$i_g^2 = 2eI_G\Delta f$ negligibly small for most applications

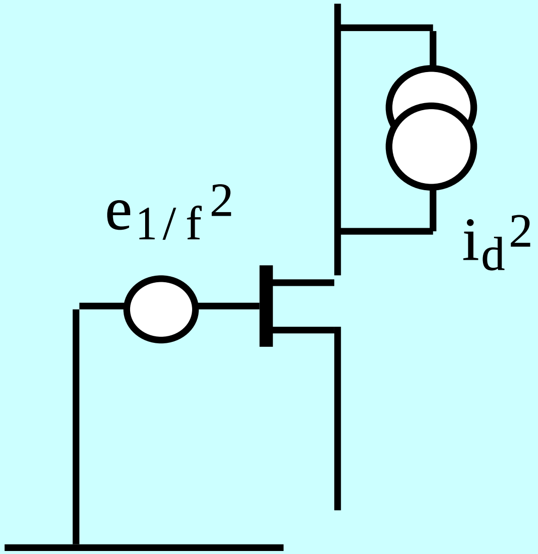
high impedance of gate oxide (insulator) to substrate

- Thermal noise inside the transistor

thermal current fluctuations in channel (- but **not** shot)

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

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

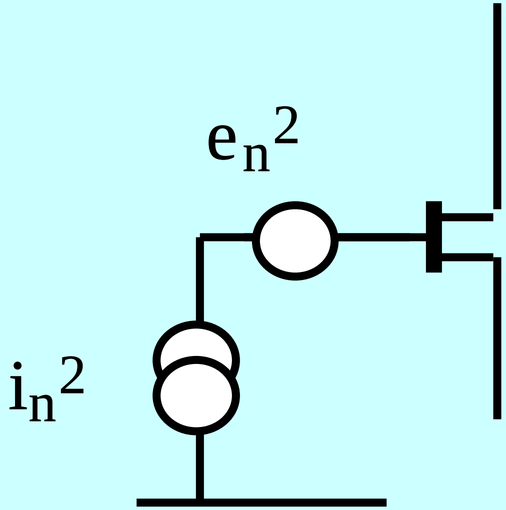



- Transfer noise sources to input

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

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

$i_n^2 \approx 0$



# 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 $L_{min} \approx 0.25$µm $t_{ox} \sim 5$nm

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/0.25µm = $4\times10^4$ 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

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

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