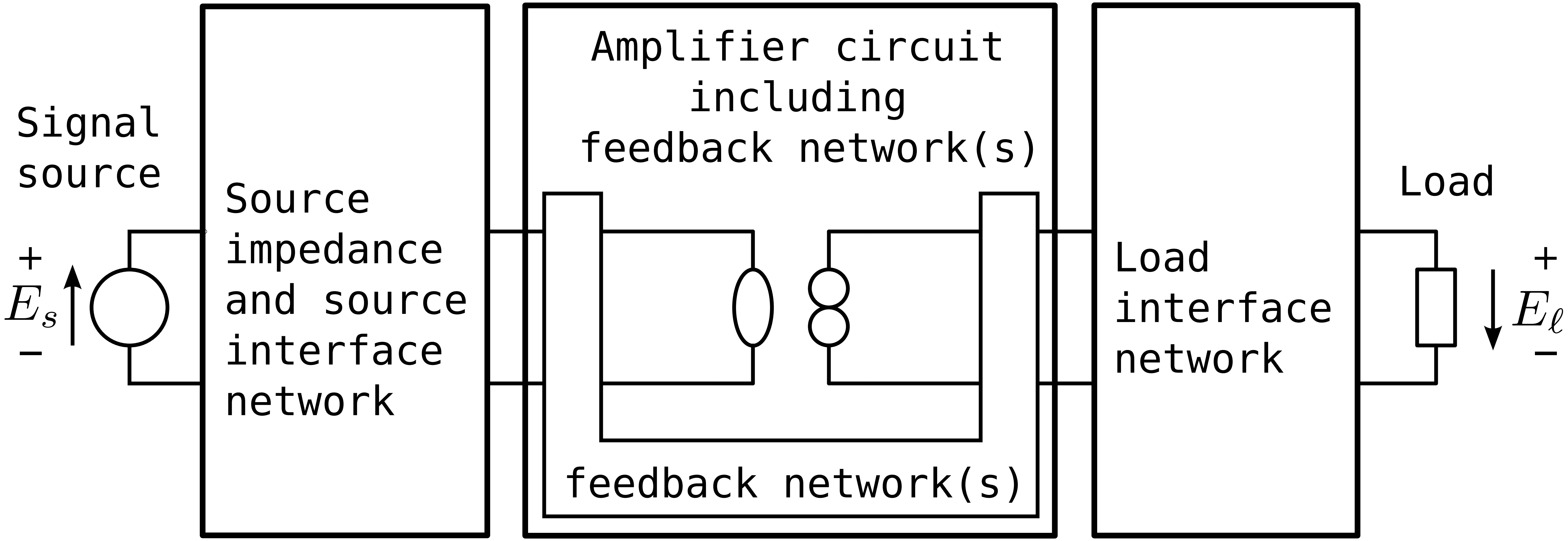
Structured Electronic Design

Noise Design of Input Stage MOS in Feedback Amplifiers

Anton J.M. Montagne

Structure Feedback Amplifier

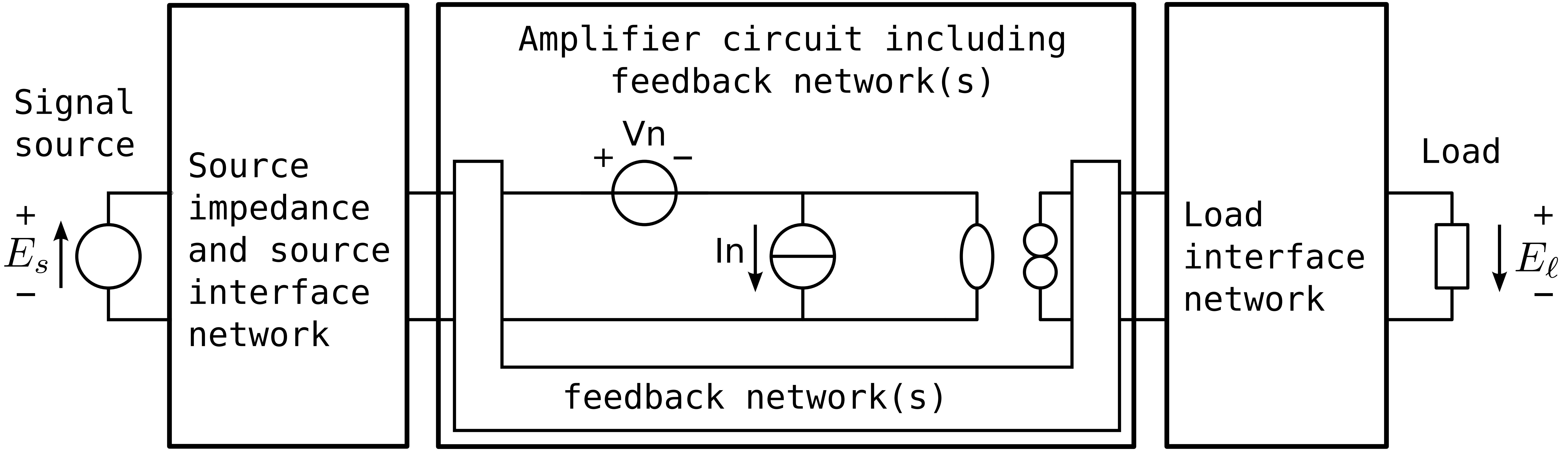


Known at the start of the controller's noise design

Source impedance
Load impedance
Feedback network(s)

Source interface network
Load interface network
Output noise weighting function

Noise Transfer Functions



$H_v(f)$: Transfer function from V_n to the output noise e_{ℓ_n}

$H_i(f)$: Transfer function from I_n to the output noise e_{ℓ_n}

$\frac{H_i(f)}{H_v(f)} = Z_n(f)$: Driving-point impedance at nullor input.

$W(f)$: Noise weighting function

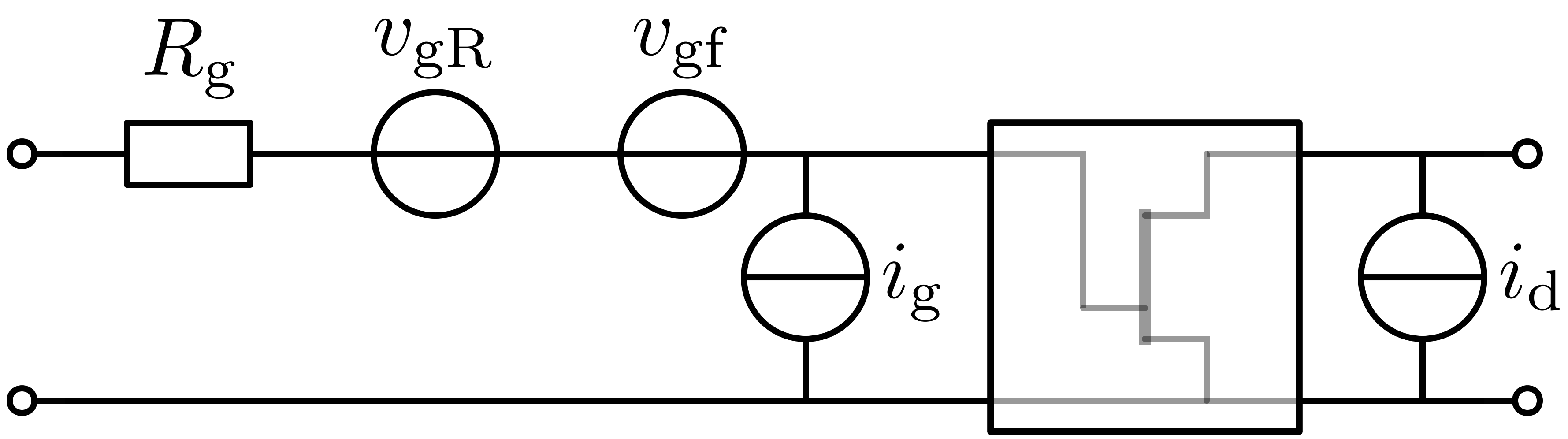
$$e_{\ell_n}^2 = \int_{f_{\min}}^{f_{\max}} S_{v_n} \left|H_v(f)W(f)\right|^2 df + \int_{f_{\min}}^{f_{\max}} S_{i_n} \left|H_i(f)W(f)\right|^2 df + \int_{f_{\min}}^{f_{\max}} S_0 \left|W(f)\right|^2 df$$

Contribution of Vn to the weighted output noise

Contribution of In to the weighted output noise

Contribution of the source, the feedback and the interface network(s) to the weighted output noise

MOS Noise Model



R_g: gate (series) resistance

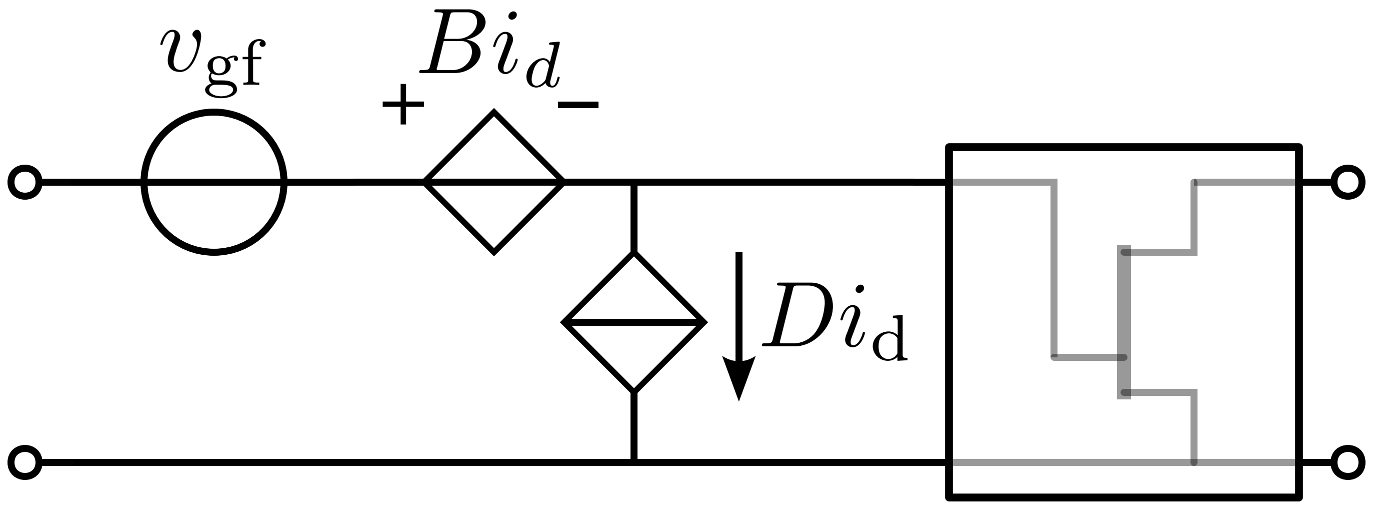
v_{gR}: noise voltage gate (series) resistance: $S_{v_{gR}} = 4kTR_g \, \mathrm{V}^2/\mathrm{Hz}$

v_{gf}: input-referred flicker noise voltage: $S_{v_{gf}} = \frac{K_F}{C_{\mathrm{OX}}^2 W L f^{\mathrm{AF}}} \, \mathrm{V}^2/\mathrm{Hz}$

i_g: gate leakage current noise: $S_{i_g} = 2qI_G \, \mathrm{A}^2/\mathrm{Hz}$

i_d: channel current noise: $S_{i_d} = 4kTn\Gamma g_m \, \mathrm{A}^2/\mathrm{Hz}$

MOS Noise Transformations-1

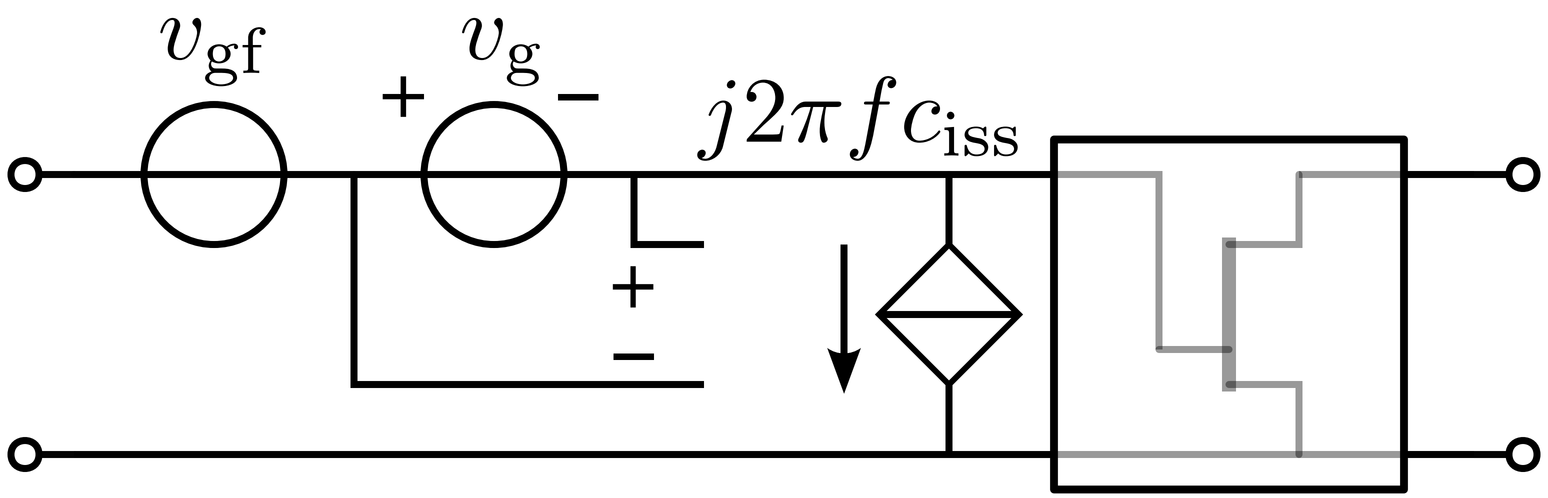


$$B = \frac{1}{j2\pi f c_{\mathrm{dg}} - g_m} \approx \frac{1}{g_m}$$

$$D = \frac{j2\pi f c_{\mathrm{iss}}}{j2\pi f c_{\mathrm{dg}} - g_m} \approx \frac{j2\pi f c_{\mathrm{iss}}}{g_m}$$

Negative signs accounted for in the source directions

MOS Noise Transformations-2



$$S_{v_g} = \frac{4kTn\Gamma}{g_m}$$

Ignore the overlap capacitances:
the input capacitance is proportional with the oxide capcitance:

$$c_{\mathrm{iss}} = \chi W L C_{\mathrm{OX}} \qquad S_{v_{gf}} = \frac{K_F}{C_{\mathrm{OX}}^2 W L f^{\mathrm{AF}}} \approx \frac{\chi K_F}{C_{\mathrm{OX}} c_{\mathrm{iss}} f^{\mathrm{AF}}} \ \mathrm{V}^2/\mathrm{Hz}$$

χ, Γ and K_F depend on the inversion level

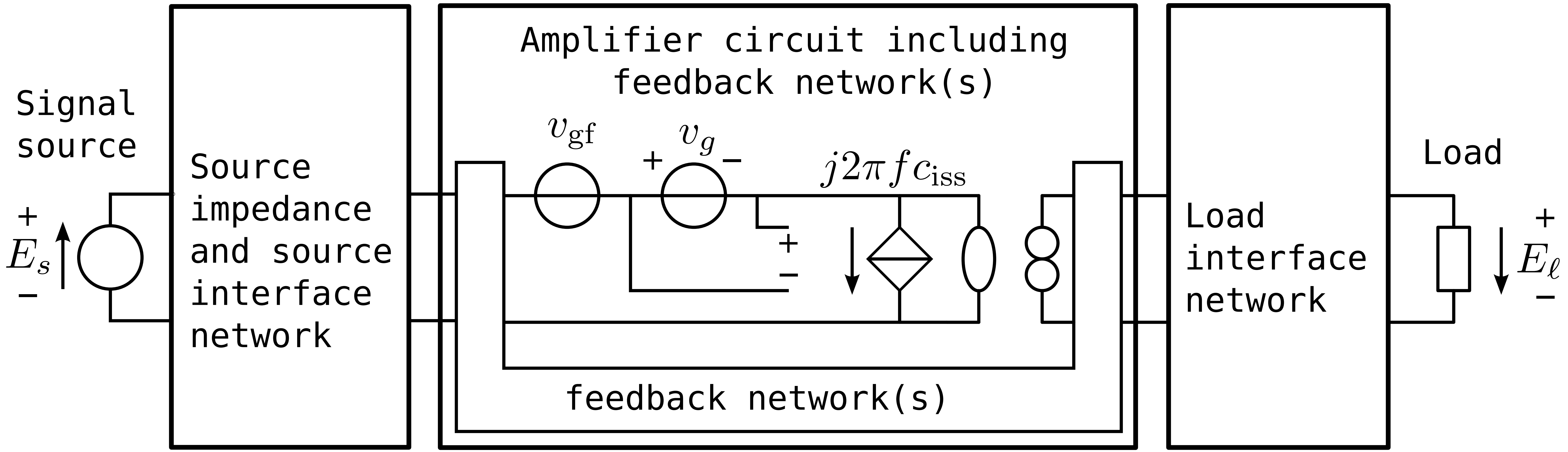
$\chi = 0.26 \cdots 0.6$ with $IC = 0 \cdots \infty$ and $n = 1.35$

$\Gamma = \frac{1}{2} \cdots \frac{2}{3}$ with $IC = 0 \cdots \infty$

S_{v_g} and $S_{v_{gf}}$ are now expressed in the MOS design parameters g_m and c_{iss}

$$K_F = K_{F0}\left(1 + \frac{V_{\mathrm{EFF}}}{V_{\mathrm{KF}}}\right)^2 \qquad V_{\mathrm{KF}} = 0.2 \cdots 2$$

Feedback amplifier MOS Noise



$$S_{v_g} = \frac{4kTn\Gamma}{g_m} \quad \mathrm{V}^2/\mathrm{Hz}$$

$$S_{v_{gf}} = \frac{\chi K_F}{C_{\mathrm{OX}} c_{\mathrm{iss}} f^{\mathrm{AF}}} \quad \mathrm{V}^2/\mathrm{Hz}$$

Next step: determine MOS parameters g_m and c_{iss} at a given inversion level

Feedback amplifier MOS noise design equation

Unweighted output noise spectrum

$$S_{e\ell} = \frac{\chi K_F}{C_{\mathrm{OX}}} \frac{1}{c_{\mathrm{iss}} f^{\mathrm{AF}}} |H_{\mathrm{v}}|^2 + \frac{4kTn\Gamma}{g_m} |H_{\mathrm{v}} + H_{\mathrm{i}} 2\pi j f c_{iss})|^2 + S_0$$

$$\begin{aligned} S_{e\ell} = & \frac{1}{c_{iss}} \frac{\chi K_F |H_{\mathrm{v}}|^2}{C_{OX} f^{\mathrm{AF}}} \\ & + \frac{1}{g_m} 4kTn\Gamma |H_{\mathrm{v}}|^2 \\ & + \frac{c_{iss}}{g_m} 16kTn\Gamma\pi f (\Im(H_{\mathrm{v}})\Re(H_{\mathrm{i}}) - \Re(H_{\mathrm{v}})\Im(H_{\mathrm{i}})) \\ & + \frac{c_{iss}^2}{g_m} 16kTn\Gamma\pi^2 f^2 |H_{\mathrm{i}}|^2 \\ & + S_0 \end{aligned}$$

$$e_\ell^2 = \int_0^\infty |W_f|^2 S_{\mathrm{no}} df$$

$$e_\ell^2 = \alpha \frac{1}{c_{iss}} + \beta \frac{1}{g_m} + \gamma \frac{c_{iss}}{g_m} + \delta \frac{c_{iss}^2}{g_m} + \epsilon$$

Feedback amplifier MOS noise design equation

$$e_\ell^2 = \alpha \frac{1}{c_{iss}} + \beta \frac{1}{g_m} + \gamma \frac{c_{iss}}{g_m} + \delta \frac{c_{iss}^2}{g_m} + \epsilon$$

$$\alpha = \frac{\chi K_F}{C_{OX}} \int_0^\infty \frac{|W_f H_{\mathrm{v}}|^2}{f^{\mathrm{AF}}} df$$

$$\beta = 4kTn\Gamma \int_0^\infty |W_f H_{\mathrm{v}}|^2 df$$

$$\gamma = 16kTn\Gamma\pi \int_0^\infty f|W_f|^2[\Im(H_{\mathrm{v}})\Re(H_{\mathrm{i}}) - \Re(H_{\mathrm{v}})\Im(H_{\mathrm{i}})]df = -16kTn\Gamma\pi \int_0^\infty f|W_f|^2 \Im(Z_n)|H_{\mathrm{v}}|^2 df$$

$$\delta = 16kTn\Gamma\pi^2 \int_0^\infty f^2|W_f H_{\mathrm{i}}|^2 df$$

$$\Im(Z_n) = \frac{\Im(H_{\mathrm{i}})\Re(H_{\mathrm{v}}) - \Re(H_{\mathrm{i}})\Im(H_{\mathrm{v}})}{|H_{\mathrm{v}}|^2}$$

$$\epsilon = \int_0^\infty |W_f|^2 S_0 df$$

Coefficients $\alpha \cdots \epsilon$ have numeric values at the start of the MOS noise design.

Feedback amplifier MOS noise design equation

Total squared weighted output noise:

$$e_\ell^2 = \alpha\frac{1}{c_{iss}} + \beta\frac{1}{g_m} + \gamma\frac{c_{iss}}{g_m} + \delta\frac{c_{iss}^2}{g_m} + \epsilon$$

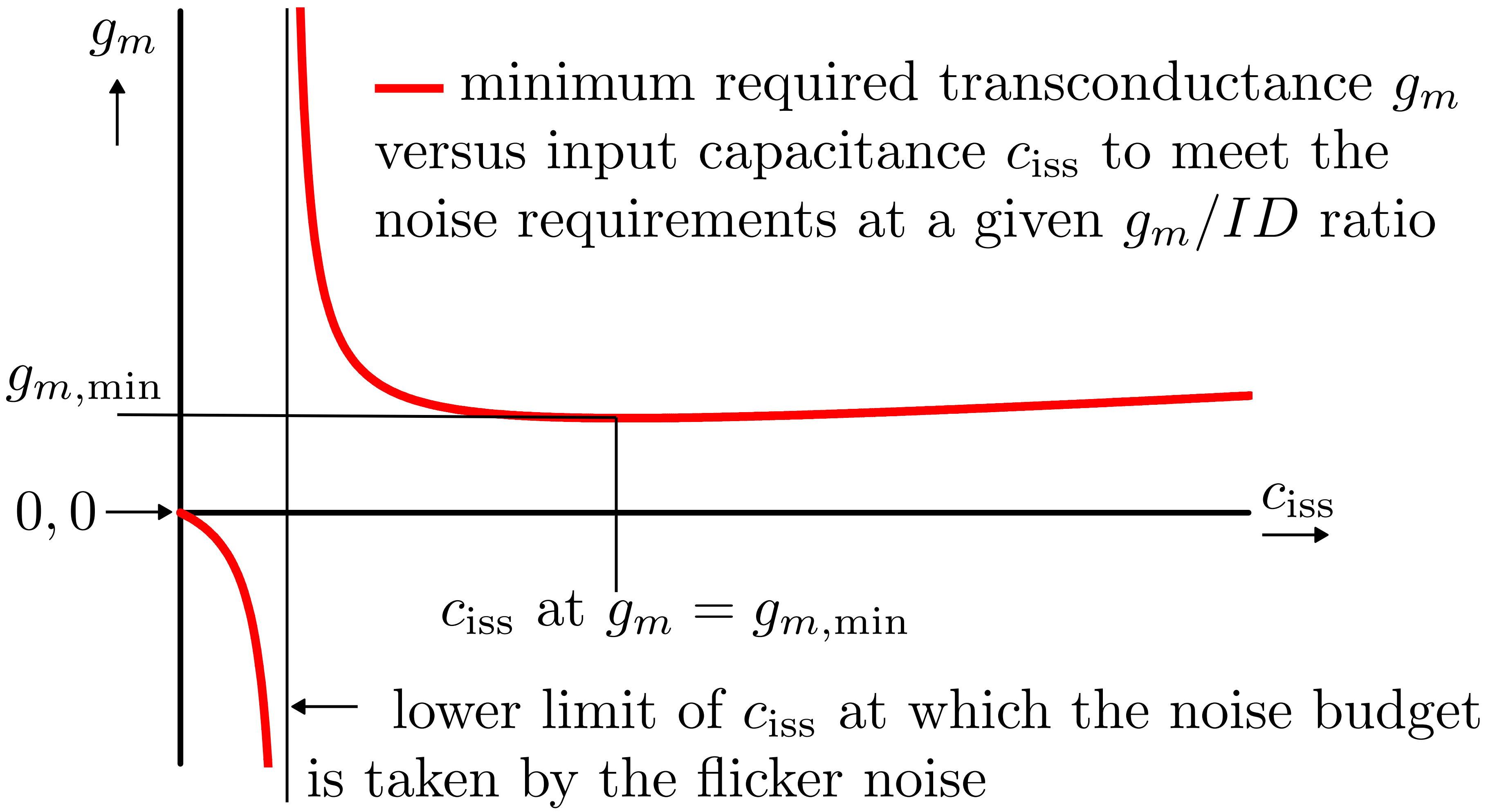
MOS contribution to squared weighted output noise:

$$e_{\ell M}^2 = \alpha\frac{1}{c_{iss}} + \beta\frac{1}{g_m} + \gamma\frac{c_{iss}}{g_m} + \delta\frac{c_{iss}^2}{g_m}$$

Remember coefficients depend on inversion level!

Relation between transconductance and input capacitance to meet requirement:

$$g_m \geq \frac{c_{\mathrm{iss}}}{e_{\ell M}^2 c_{\mathrm{iss}} - \alpha}\left(\beta + \gamma c_{\mathrm{iss}} + \delta c_{\mathrm{iss}}^2\right)$$



This noise design equation has one minimum transconductance for: $c_{\mathrm{iss}} > \frac{\alpha}{e_{\ell M}^2}$

Minimum can be below technological minimum set by the minimum channel width and length.

Feasibility of the noise design

Total squared weighted output noise:

$$e_\ell^2 = \alpha \frac{1}{c_{iss}} + \beta \frac{1}{g_m} + \gamma \frac{c_{iss}}{g_m} + \delta \frac{c_{iss}^2}{g_m} + \epsilon$$

MOS contribution to squared weighted output noise:

$$e_{\ell M}^2 = \alpha \frac{1}{c_{iss}} + \beta \frac{1}{g_m} + \gamma \frac{c_{iss}}{g_m} + \delta \frac{c_{iss}^2}{g_m}$$

NOT FEASIBLE:

If ϵ exeeds the requirement for the total squared weighted output noise.

If $f_T = \frac{g_m}{2\pi c_{\mathrm{iss}}}$ is too low.

$$e_\ell^2 = \frac{\alpha}{c_{\mathrm{iss}}} + \frac{\beta}{2\pi f_T c_{\mathrm{iss}}} + \frac{\gamma}{2\pi f_T} + \frac{\delta c_{\mathrm{iss}}}{2\pi f_T} + \epsilon \qquad c_{\mathrm{iss}_{\mathrm{Opt}}} = \sqrt{\frac{2\pi f_T \alpha + \beta}{\delta}}.$$

Lowest noise:

$$e_\ell^2 = \frac{\alpha}{c_{\mathrm{iss}_{\mathrm{Opt}}}} + \frac{\beta}{2\pi f_{T_{\max}} c_{\mathrm{iss}_{\mathrm{Opt}}}} + \frac{\gamma}{2\pi f_{T_{\max}}} + \frac{\delta c_{\mathrm{iss}_{\mathrm{Opt}}}}{2\pi f_{T_{\max}}} + \epsilon$$

Area and current limitations may put extra contraints to the feasibility.

From transconductance and capacitance to current and geometry

$$c_{\mathrm{iss}} = \chi C_{\mathrm{OX}} W L + W\left(C_{\mathrm{GSO}} + C_{\mathrm{GDO}}\right) + 2 L C_{\mathrm{GBO}}$$

$$\chi = \frac{2-x}{3} + \frac{(1+x)(n-1)}{3n}$$

$$x = \frac{\sqrt{IC+0.25}+1.5}{\left(\sqrt{IC+0.25}+0.5\right)^2}$$

$$I_{\mathrm{DS}} = IC\frac{W}{L}I_0 \qquad I_0 \triangleq 2n\mu_0 C_{\mathrm{OX}} V_T^2$$

$$\frac{g_m}{I_{\mathrm{DS}}} = \frac{1}{nV_T\sqrt{IC\left(1+\frac{IC}{IC_{\mathrm{crit}}}\right)+0.5\sqrt{IC\left(1+\frac{IC}{IC_{\mathrm{crit}}}\right)}+1}}$$

Ignore lateral field velocity saturation:

$$IC_{\mathrm{crit}} = \left(4nV_T\theta\right)^{-2}$$

$$c_{\mathrm{iss}} = aWL + bW + cL$$

$$g_m = d\frac{W}{L}$$

$$a = \chi C_{\mathrm{OX}}$$

$$b = C_{\mathrm{GSO}} + C_{\mathrm{GDO}}$$

$$c = 2C_{\mathrm{GBO}}$$

$$d = \frac{2\mu_0 C_{\mathrm{OX}} IC}{\sqrt{IC\left(1+\frac{IC}{IC_{\mathrm{crit}}}\right)+0.5\sqrt{IC\left(1+\frac{IC}{IC_{\mathrm{crit}}}\right)}+1}}$$

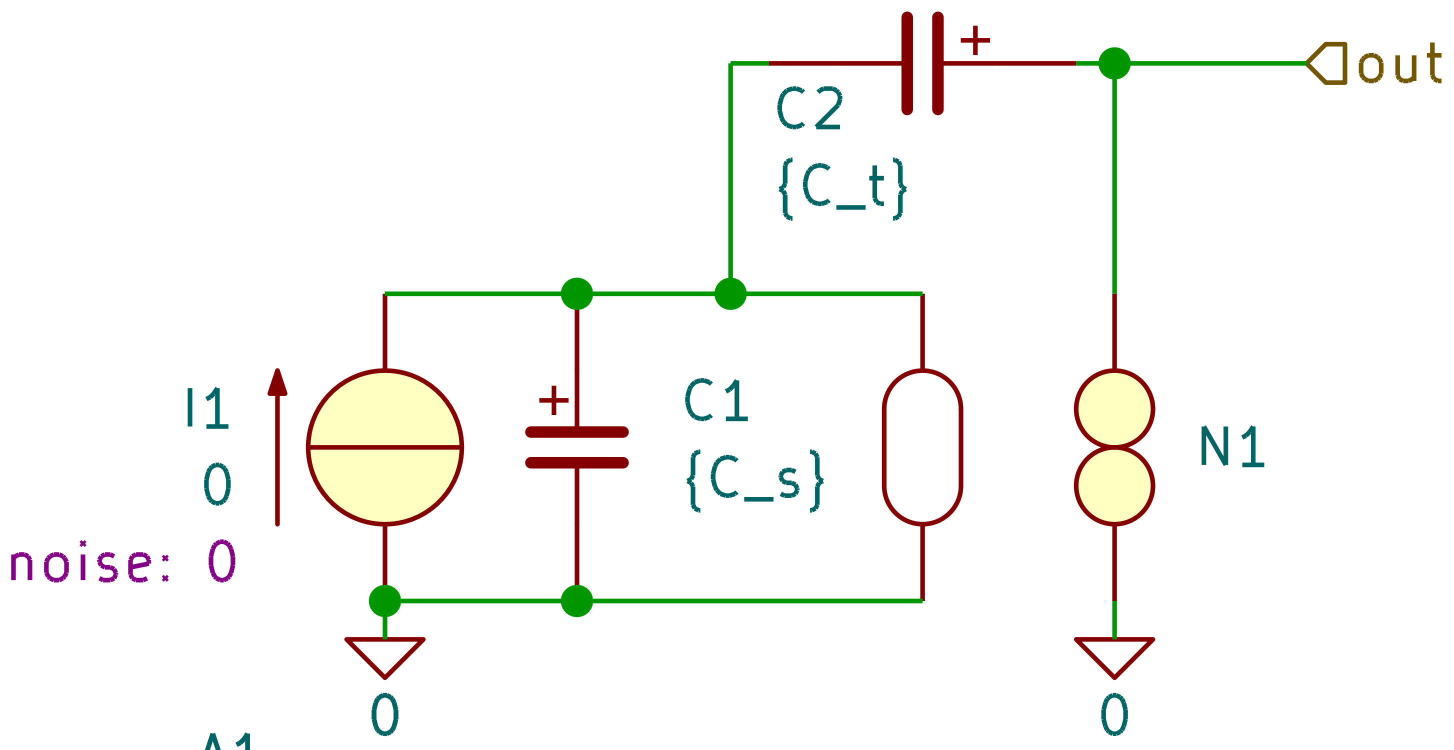
$$W = \frac{c\,d + b\,g_m}{2a\,d}\left(\sqrt{1+\frac{4a\,d\,g_m c_{\mathrm{iss}}}{\left(c\,d+b\,g_m\right)^2}}-1\right) \approx \sqrt{\frac{g_m c_{\mathrm{iss}}}{a\,d}}$$

$$L = \frac{c\,d + b\,g_m}{2a\,g_m}\left(\sqrt{1+\frac{4a\,d\,g_m c_{\mathrm{iss}}}{\left(c\,d+b\,g_m\right)^2}}-1\right) \approx \sqrt{\frac{d\,c_{\mathrm{iss}}}{a\,g_m}}$$

$$I_{\mathrm{DS}} = \frac{1}{g_m/I_{\mathrm{DS}}}g_m$$

Example

Transimpedance integrator with capacitive source



A1

.detector V_out

A2

.param C_s=1p C_t=0.2p IG=0

Coefficients of the symbolic noise equition (determined with SLiCAP):

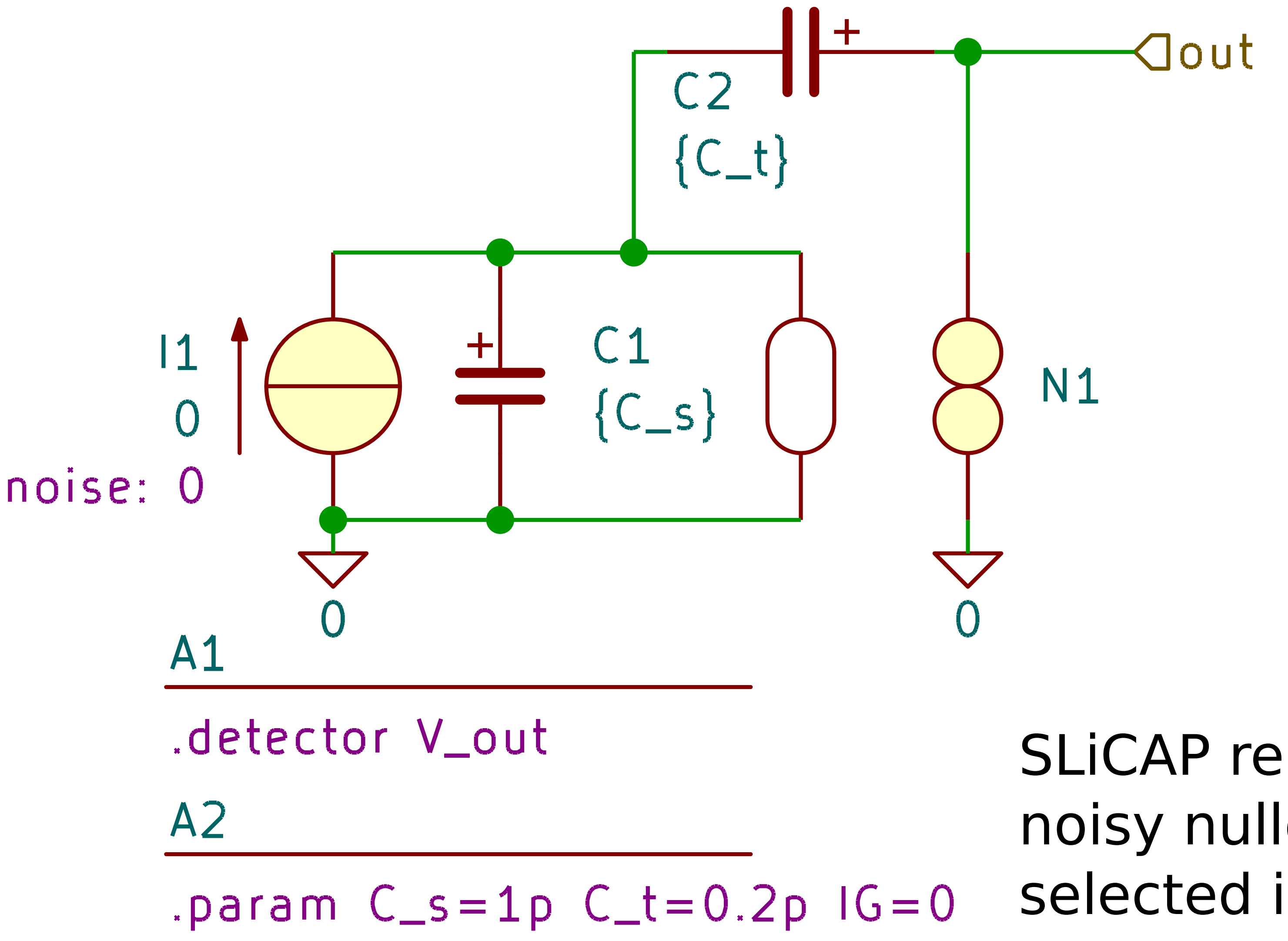
term	**coefficient**
$\frac{1}{c_{iss}}$	$\alpha = \int_{f_{min}}^{f_{max}} \frac{K_F \chi f^{-A_F} (C_s+C_t)^2}{C_{OX} C_t^2}\, df$
$\frac{1}{g_m}$	$\beta = \int_{f_{min}}^{f_{max}} \frac{4\Gamma T k n (C_s+C_t)^2}{C_t^2}\, df$
$\frac{c_{iss}}{g_m}$	$\gamma = \int_{f_{min}}^{f_{max}} \frac{8\Gamma T k n (C_s+C_t)}{C_t^2}\, df$
$\frac{c_{iss}^2}{g_m}$	$\delta = \int_{f_{min}}^{f_{max}} \frac{4\Gamma T k n}{C_t^2}\, df$
1	$\epsilon = 0$

If we ignore flicker noise:

$$c_{\mathrm{issOpt}} = \sqrt{\frac{\beta}{\delta}} = C_s + C_t = 1.2\ \mathrm{pF}$$

$$v_{n_{\mathrm{out}}}^2 = \frac{16kTn\Gamma}{g_m}\left(\frac{C_s+C_t}{C_t}\right)^2 (f_{\max} - f_{\min})$$

SLiCAP design automation



1. Select CMOS process and fit EKV parameters to BSIM
2. Create KiCAD amplifier circuit with nullor as controller
3. Define noise requirements (frequency range and budgets)
4. Define technology requirements
   (channel type, minimum and maximum geometry)
5. Define circuit requirements
   (inversion coefficient or gm/ID ratio, and current budget)
6. Run the design automation script
7. Select one valid option for design

SLiCAP replaces the nullor with an N-channel or a P-channel noisy nullor and evaluates W, L, and I_{DS} for six scenarios for the selected inversion coefficient or gm/ID ratio:

1. Mininum noise at maximum inversion level
2. Minimum current to meet the noise specification
3. Minimum cut-off frequency to meet the noise specification
4. Minimum product of g_m and c_{iss} to meet the noise specification
5. Minimum area at a given current budget to meet the noise specification
6. Maximum area at a given current budget to meet the noise specification