Structured Electronic Design

EE3C11

Noise in Electronic Circuits

Anton J.M. Montagne

(c) 2020 A.J.M. Montagne

Noise mechanisms

(c) 2020 A.J.M. Montagne

Noise mechanisms

Thermal noise

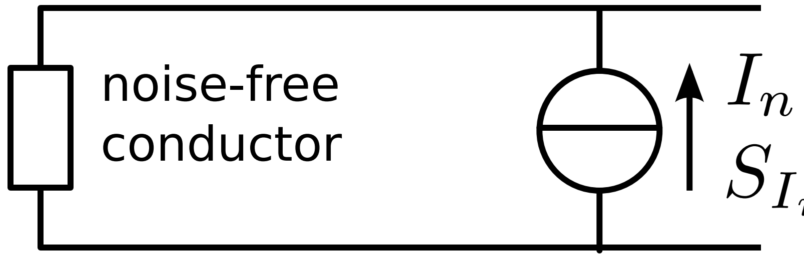
Noise in conductors caused by thermal (Brownian) motion (Brown 1828).
Experimetally detected by Johnson (1928) and explained by Nyquist (1928).

Noise mechanisms

Thermal noise

Noise in conductors caused by thermal (Brownian) motion (Brown 1828).
Experimetally detected by Johnson (1928) and explained by Nyquist (1928).

$G = \frac{1}{R}$



I_n

$S_{I_n} = 4kTG \; [A^2/\mathrm{Hz}]$

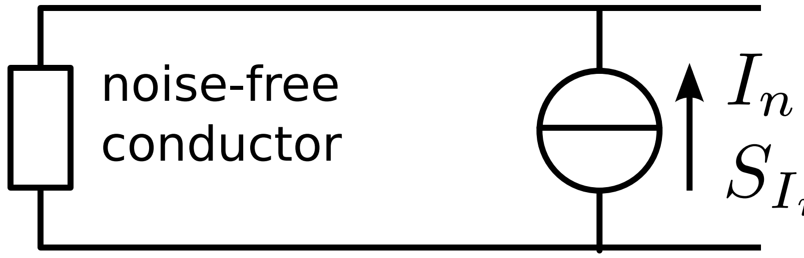
(c) 2020 A.J.M. Montagne

Noise mechanisms

Thermal noise

Noise in conductors caused by thermal (Brownian) motion (Brown 1828).
Experimetally detected by Johnson (1928) and explained by Nyquist (1928).

$G = \frac{1}{R}$

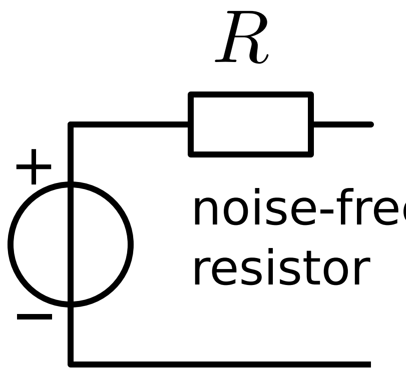


I_n

$S_{I_n} = 4kTG\ [A^2/\mathrm{Hz}]$

V_n

$S_{V_n} = 4kTR\ [V^2/\mathrm{Hz}]$



Noise mechanisms

Thermal noise

Noise in conductors caused by thermal (Brownian) motion (Brown 1828).
Experimetally detected by Johnson (1928) and explained by Nyquist (1928).

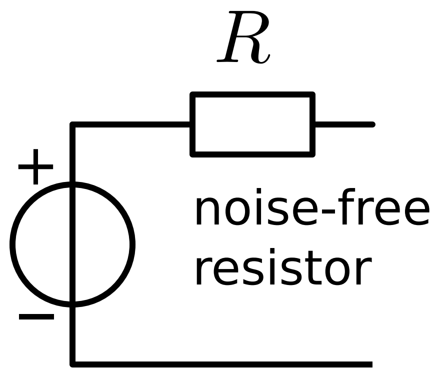
$G = \frac{1}{R}$

I_n

$S_{I_n} = 4kTG\ [A^2/\mathrm{Hz}]$

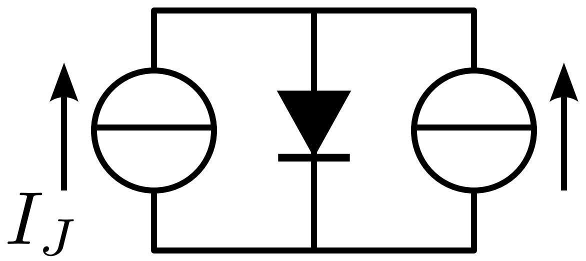
V_n

$S_{V_n} = 4kTR\ [V^2/\mathrm{Hz}]$



Shot noise

Noise current associated with a DC current through a junction.



I_n

$S_{I_n} = 2qI_J$

Noise mechanisms

Thermal noise

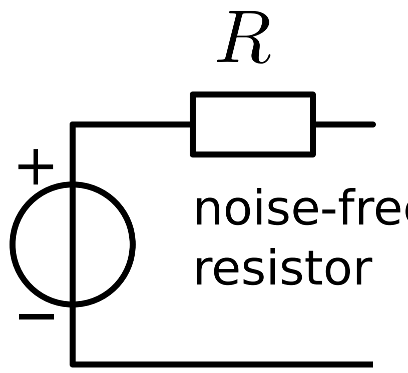
Noise in conductors caused by thermal (Brownian) motion (Brown 1828).
Experimetally detected by Johnson (1928) and explained by Nyquist (1928).

$G = \frac{1}{R}$

I_n

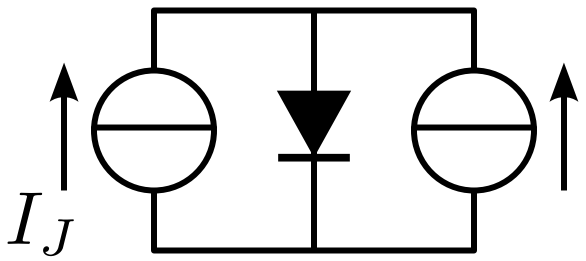
$S_{I_n} = 4kTG \; [A^2/\mathrm{Hz}]$ $\quad S_{V_n} = 4kTR \; [V^2/\mathrm{Hz}]$

V_n



Shot noise

Noise current associated with a
DC current through a junction.



I_n

$S_{I_n} = 2qI_J$

Excess noise

Noise current resulting from fluctuations in conduction mechanism.

Noise mechanisms

Thermal noise

Noise in conductors caused by thermal (Brownian) motion (Brown 1828).
Experimetally detected by Johnson (1928) and explained by Nyquist (1928).

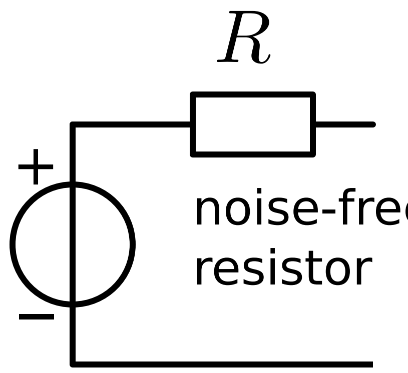
$G = \frac{1}{R}$

I_n

$S_{I_n} = 4kTG\ [A^2/\mathrm{Hz}]$

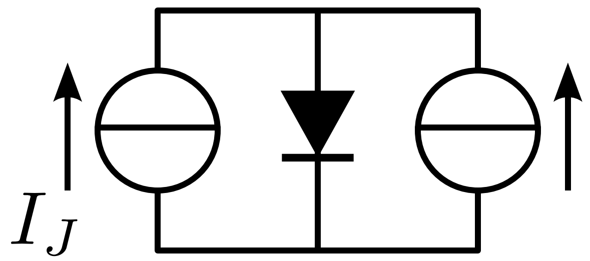
V_n

$S_{V_n} = 4kTR\ [V^2/\mathrm{Hz}]$



Shot noise

Noise current associated with a DC current through a junction.



I_n

$S_{I_n} = 2qI_J$

Excess noise

Noise current resulting from fluctuations in conduction mechanism.

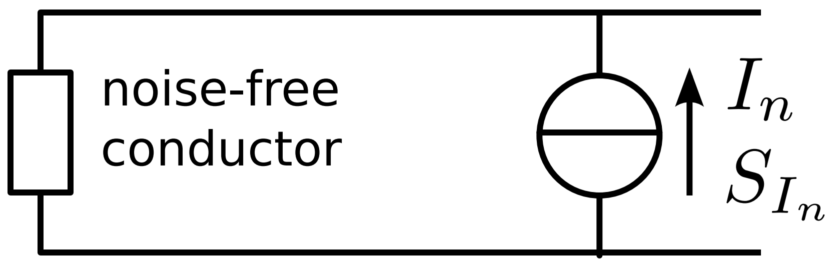
In junctions $S_{I_n} = K\frac{I_J^\alpha}{f}$

Noise mechanisms

Thermal noise

Noise in conductors caused by thermal (Brownian) motion (Brown 1828).
Experimetally detected by Johnson (1928) and explained by Nyquist (1928).

$G = \frac{1}{R}$



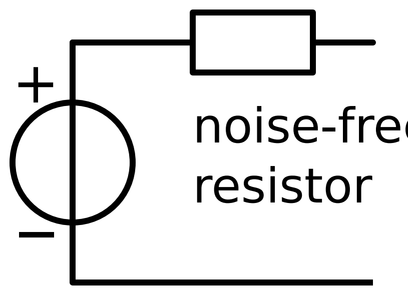
I_n

$S_{I_n} = 4kTG \; [A^2/\mathrm{Hz}]$

V_n

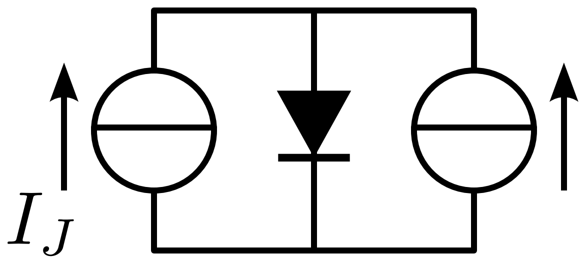
$S_{V_n} = 4kTR \; [V^2/\mathrm{Hz}]$

R



Shot noise

Noise current associated with a DC current through a junction.



I_J

I_n

$S_{I_n} = 2qI_J$

Excess noise

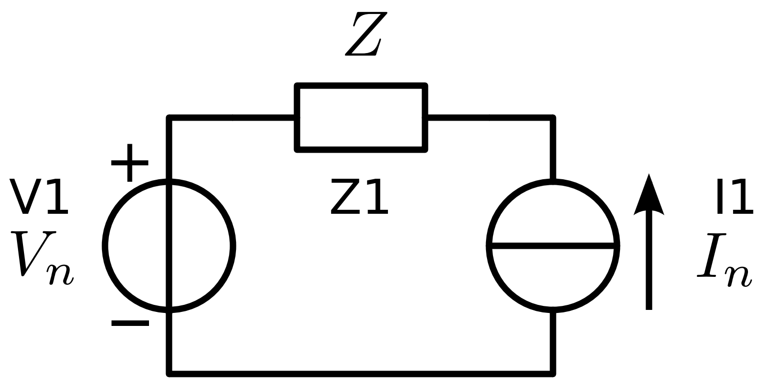
Noise current resulting from fluctuations in conduction mechanism.

In junctions $S_{I_n} = K\frac{I_J^{\alpha}}{f}$

In resistors $S_{V_n} = K\frac{V_R^2}{f}$

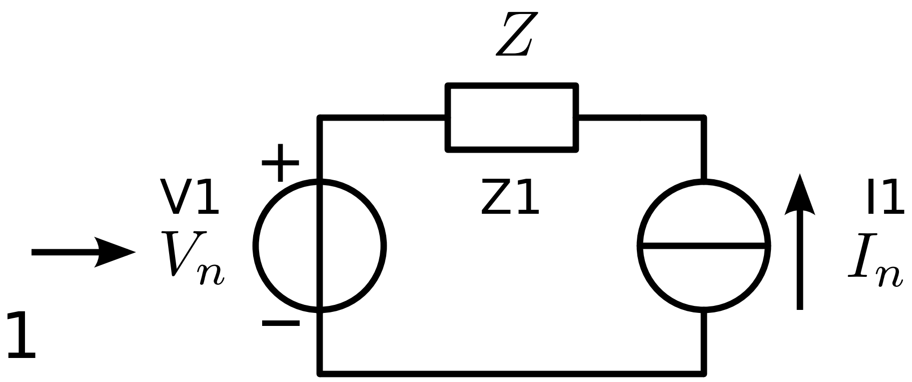
Drawing conventions

Drawing conventions



Drawing conventions

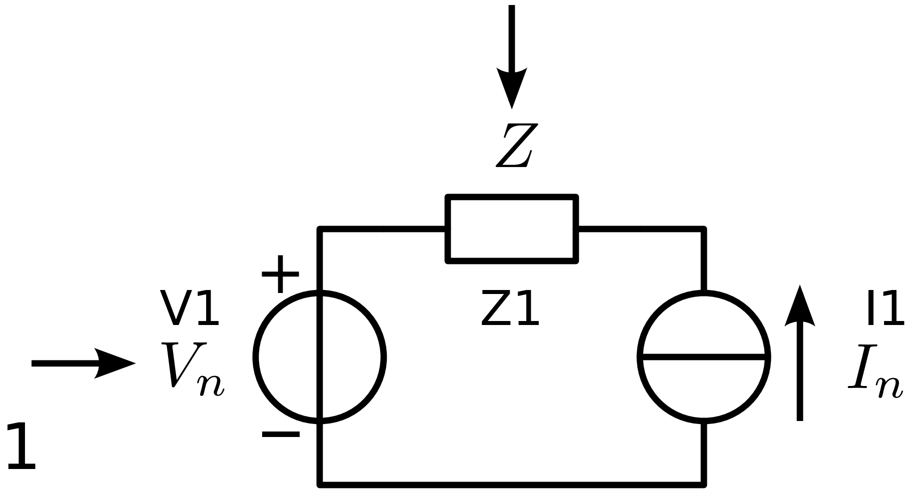
Fourier Transform of noise voltage of V1



Drawing conventions

Complex impedance of Z1

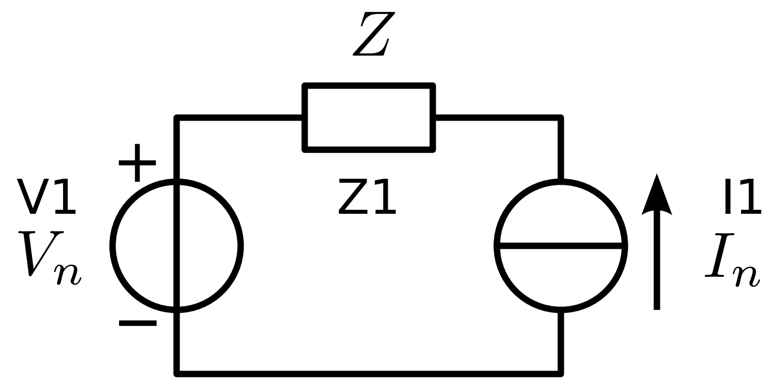
Fourier Transform of noise voltage of V1



Drawing conventions

Complex impedance of Z1

Fourier Transform of noise voltage of V1

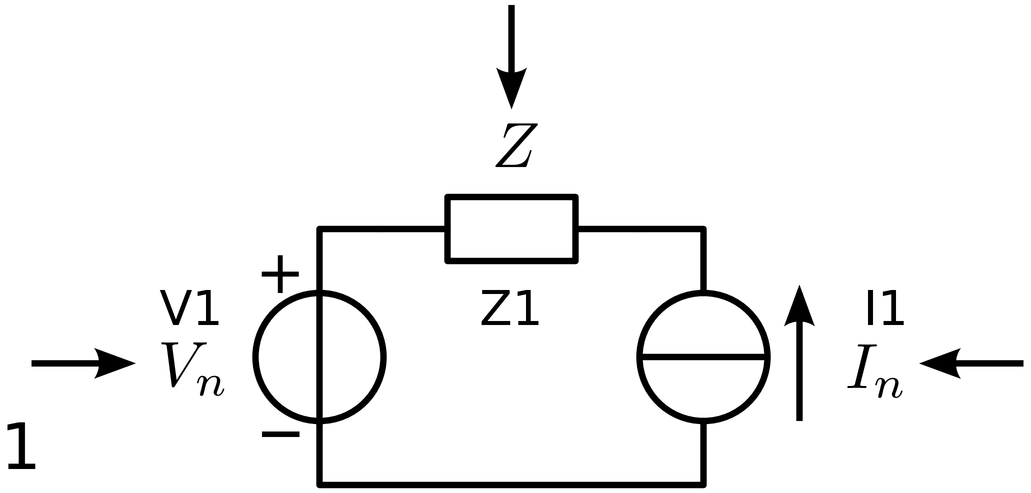


Fourier Transform of noise current of I1

Drawing conventions

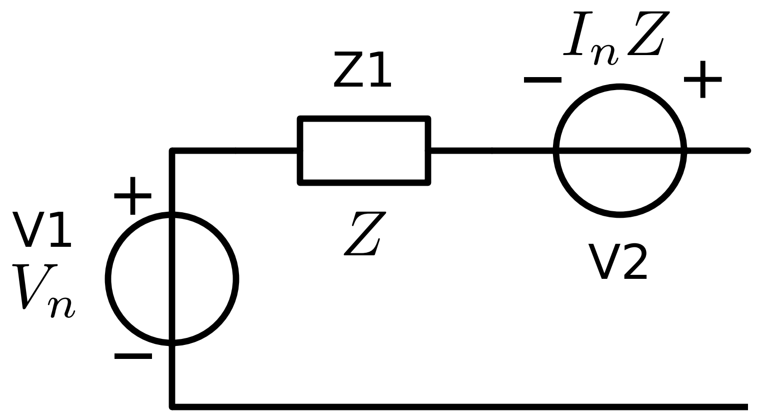
Complex impedance of Z1

Fourier Transform of noise voltage of V1



Fourier Transform of noise current of I1

Equivalent circuit after Norton-Thevenin Transformation

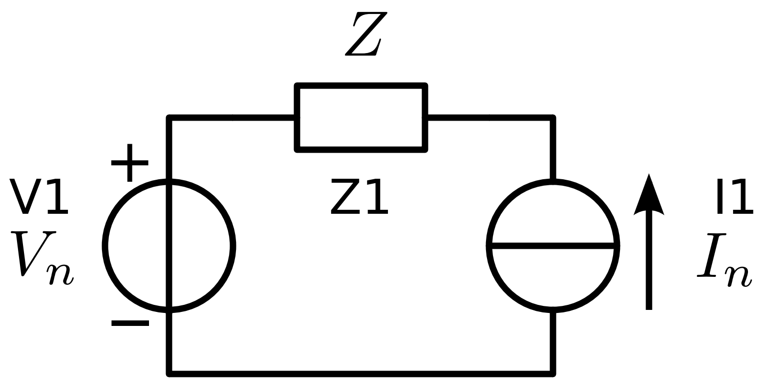


(c) 2020 A.J.M. Montagne

Drawing conventions

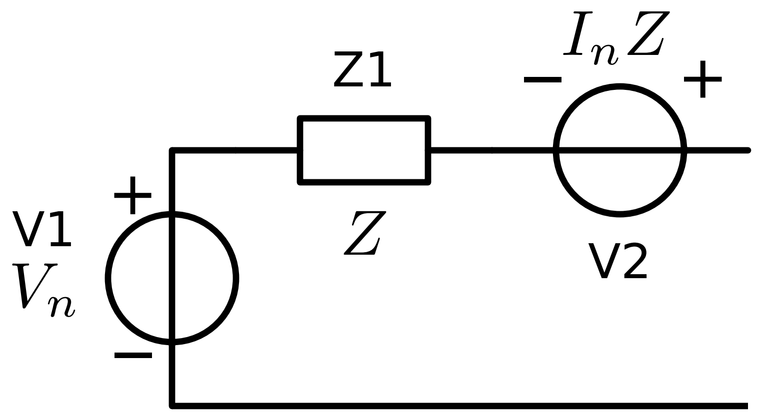
Complex impedance of Z1

Fourier Transform of noise voltage of V1



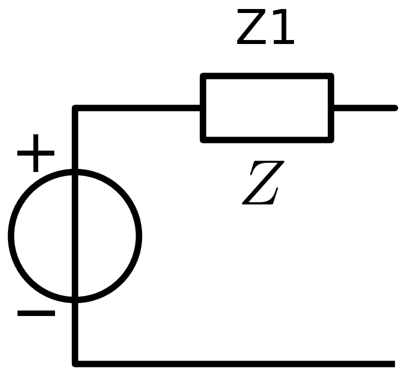
Fourier Transform of noise current of I1

Equivalent circuit after Norton-Thevenin Transformation



Equivalent circuit in which the voltage of V3 represents the total noise voltage

$V_{n,tot} = V_n + Z\,I_n$



Noise parameters

Noise parameters

Equivalent noise bandwidth of a system

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system:

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system:

$$B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega [\mathrm{Hz}]$$

(c) 2020 A.J.M. Montagne

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system:

$$B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega [\mathrm{Hz}]$$

Noise temperature

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system: $B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega[\mathrm{Hz}]$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B:

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system: $B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega [\mathrm{Hz}]$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B: $T_n = \frac{P}{kB}$

(c) 2020 A.J.M. Montagne

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system:

$$B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega [\mathrm{Hz}]$$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B:

$$T_n = \frac{P}{kB}$$

Signal-to-noise ratio

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system: $B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega[\mathrm{Hz}]$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B: $T_n = \frac{P}{kB}$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power:

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system:

$$B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega [\mathrm{Hz}]$$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B:

$$T_n = \frac{P}{kB}$$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power:

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$$

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system:

$$B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega [\mathrm{Hz}]$$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B:

$$T_n = \frac{P}{kB}$$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power:

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$$

Noise figure

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system:

$$B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega[\mathrm{Hz}]$$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B:

$$T_n = \frac{P}{kB}$$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power:

$$SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$$

Noise figure

dB measure for deterioration of the signal-to-noise ratio by a system:

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system: $B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega[\mathrm{Hz}]$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B: $T_n = \frac{P}{kB}$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power: $SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$

Noise figure

dB measure for deterioration of the signal-to-noise ratio by a system: $F = SNR_{\mathrm{input}} - SNR_{\mathrm{output}}$

(c) 2020 A.J.M. Montagne

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system: $B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega[\mathrm{Hz}]$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B: $T_n = \frac{P}{kB}$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power: $SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$

Noise figure

dB measure for deterioration of the signal-to-noise ratio by a system: $F = SNR_{\mathrm{input}} - SNR_{\mathrm{output}}$

Dynamic range

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system: $B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega[\mathrm{Hz}]$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B: $T_n = \frac{P}{kB}$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power: $SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$

Noise figure

dB measure for deterioration of the signal-to-noise ratio by a system: $F = SNR_{\mathrm{input}} - SNR_{\mathrm{output}}$

Dynamic range

dB ratio of maximum signal power and the noise power in the absence of a signal:

(c) 2020 A.J.M. Montagne

Noise parameters

Equivalent noise bandwidth of a system

Bandwidth of a brickwall filter with pass-band gain equal to the maximum magnitude of the system transfer that would produce the same output noise power as the system: $B_n = \frac{1}{2\pi}\int_0^\infty \left|\frac{H(j\omega)}{H_{\max}}\right|^2 d\omega[\mathrm{Hz}]$

Noise temperature

Apparent temperature of a noise source with available noise power P over bandwidth B: $T_n = \frac{P}{kB}$

Signal-to-noise ratio

dB ratio of (weighted) signal power and (weighted) noise power: $SNR = 10\log_{10}\left(\frac{P_{signal}}{P_{noise}}\right)$

Noise figure

dB measure for deterioration of the signal-to-noise ratio by a system: $F = SNR_{\mathrm{input}} - SNR_{\mathrm{output}}$

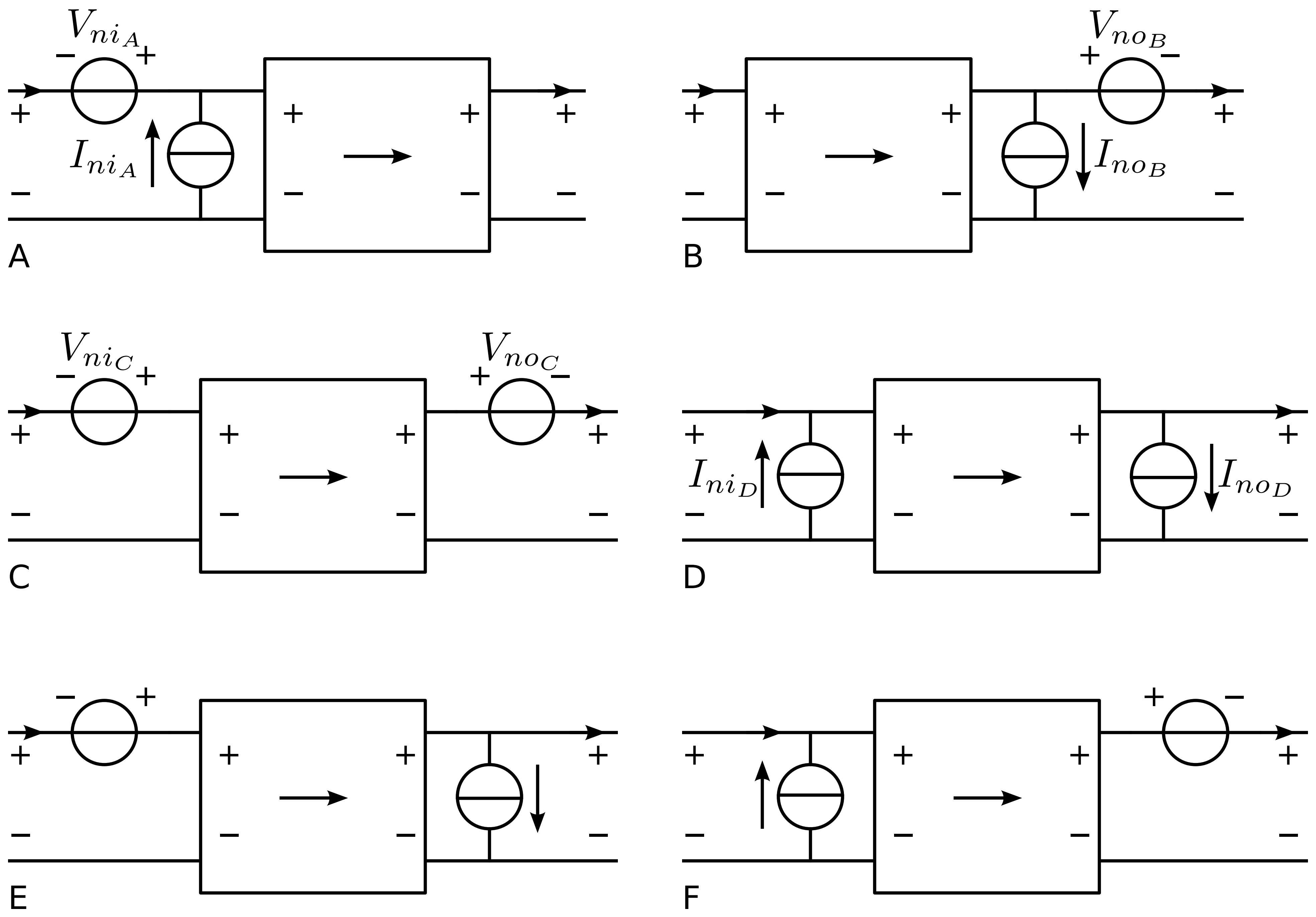
Dynamic range

dB ratio of maximum signal power and the noise power in the absence of a signal: $D = 10\log_{10}\left(\frac{P_{s,max}}{P_{n,min}}\right)$

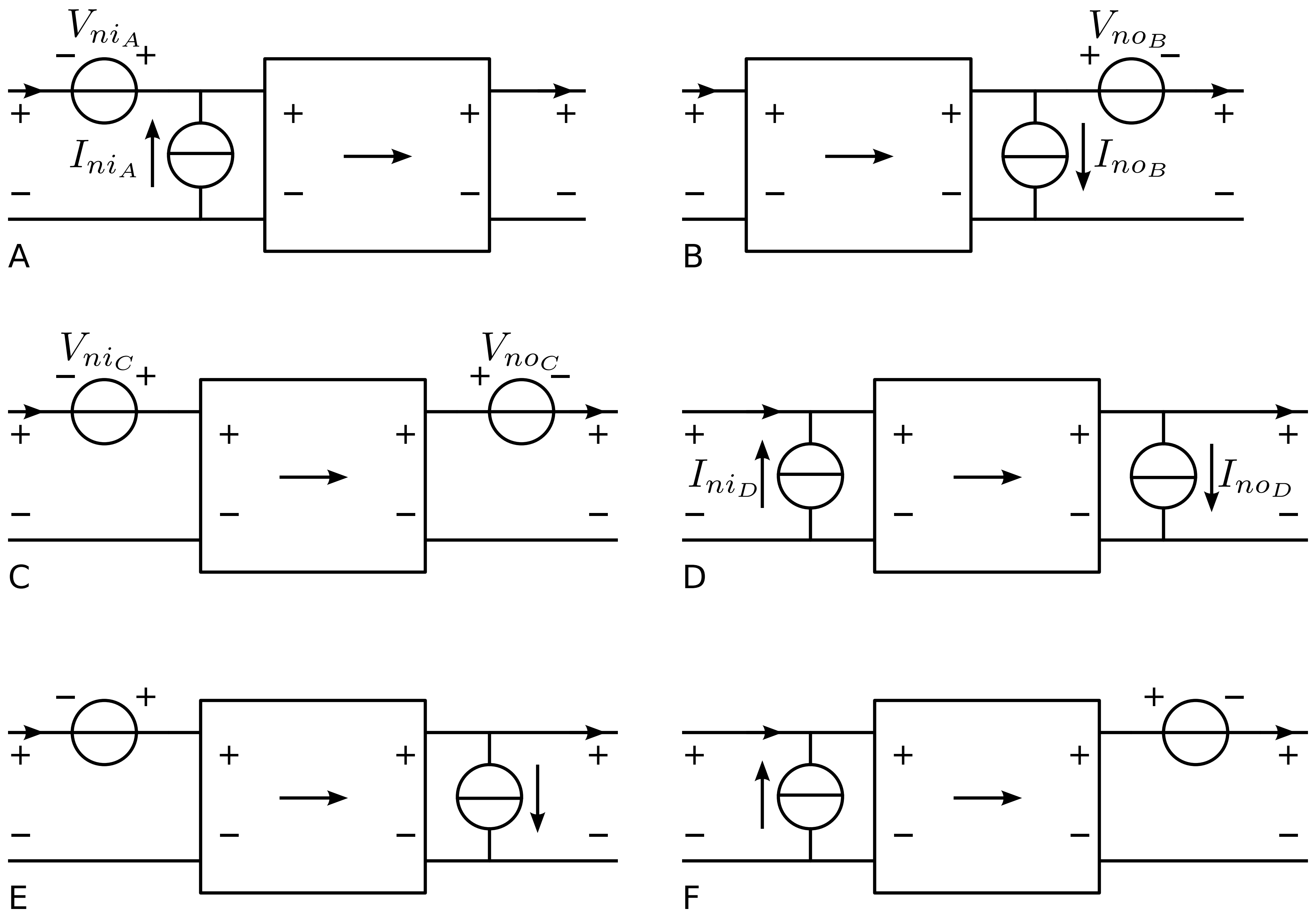
(c) 2020 A.J.M. Montagne

Noisy two-ports

Noisy two-ports



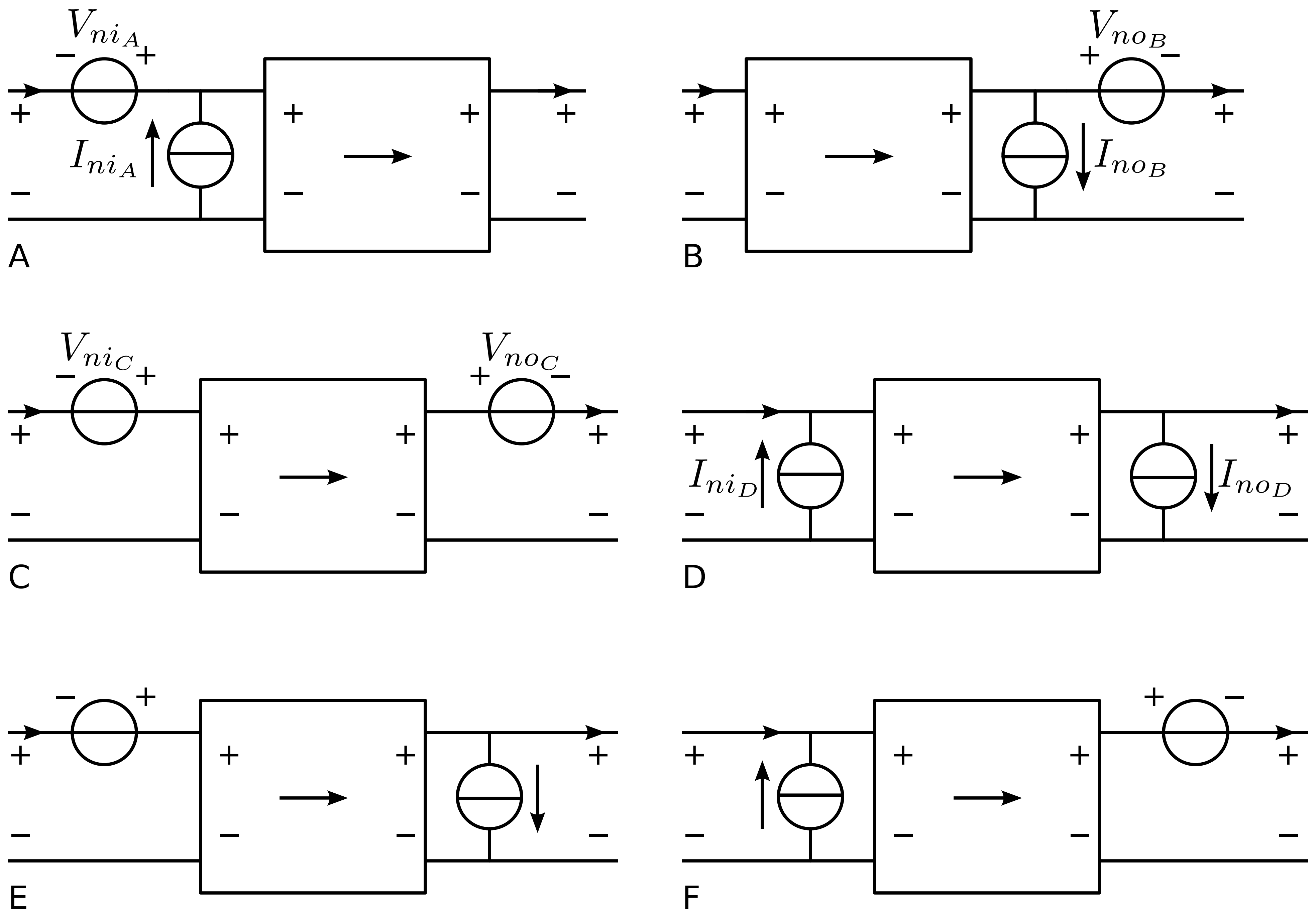
Noisy two-ports



Noise representation

- A noise-free two-port with
  two noise sources
- Six representations:
  4 port variables:
  * two independent variables
  * two dependent variables

Noisy two-ports



Noise representation

- A noise-free two-port with two noise sources
- Six representations:
  4 port variables:
  * two independent variables
  * two dependent variables

Can be translated into each other

- Example 2.9
- Example 19.2

Amplifier noise measurement

Amplifier noise measurement

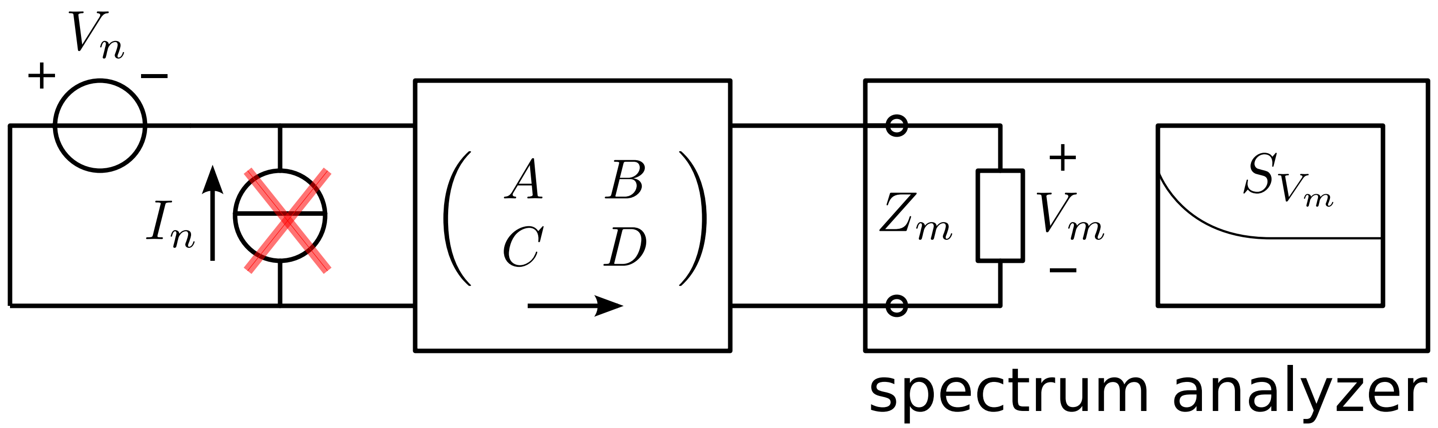
- Measure spectrum of the output noise for open and shorted input
- Calculate input noise sources from load impedance and A,B,C,D.

(c) 2020 A.J.M. Montagne

Amplifier noise measurement

- Measure spectrum of the output noise for open and shorted input
- Calculate input noise sources from load impedance and A,B,C,D.

Shorted input:
Input noise current does not contribute to amplifier output noise

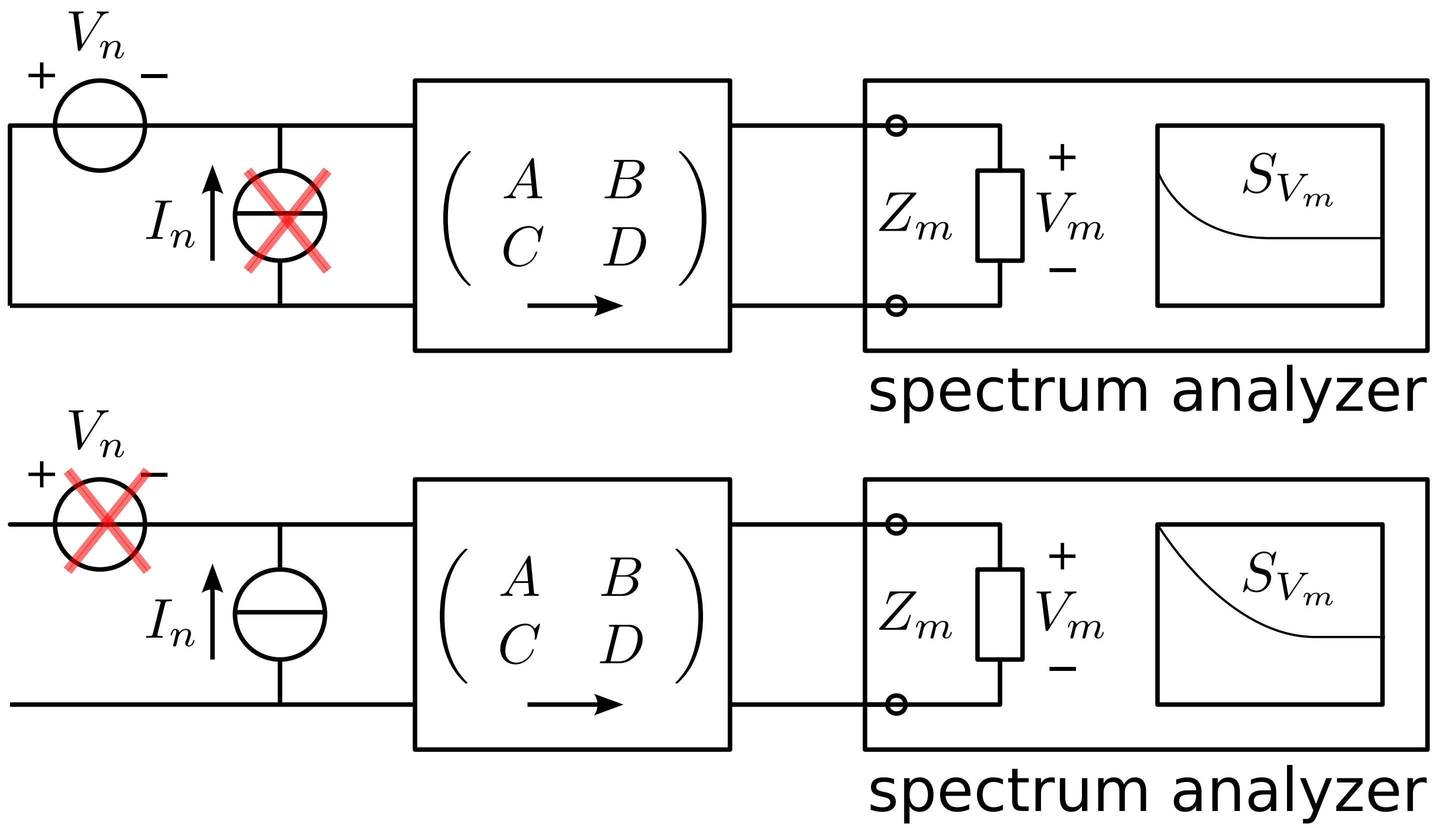


Amplifier noise measurement

- Measure spectrum of the output noise for open and shorted input
- Calculate input noise sources from load impedance and A,B,C,D.

Shorted input:
Input noise current does not contribute to amplifier output noise

Open input:
Input noise voltage does not contribute to amplifier output noise



Amplifier noise design

Amplifier noise design

Equivalent-input noise description is convenient at early stages of the design.

Amplifier noise design

Equivalent-input noise description is convenient at early stages of the design.

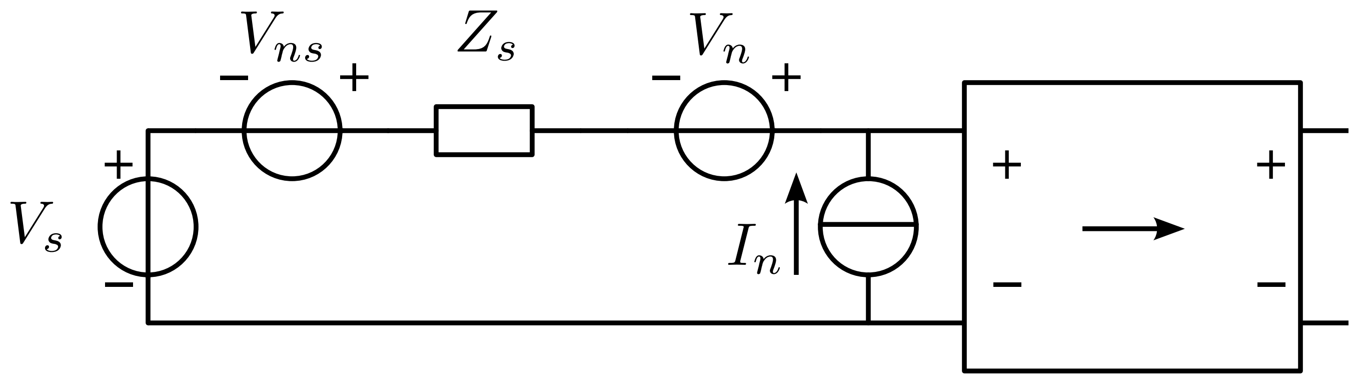
Budgets for equivalent input noise sources can be determined
without knowledge of amplifier circuit.

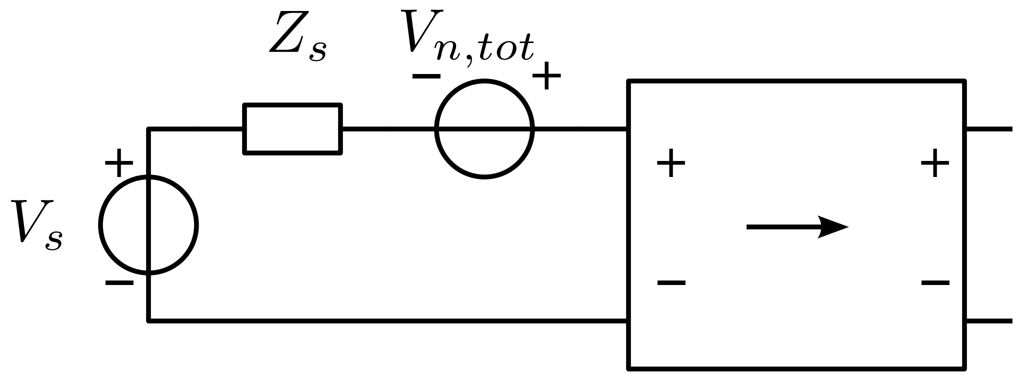
(c) 2020 A.J.M. Montagne

Amplifier noise design

Equivalent-input noise description is convenient at early stages of the design.

Budgets for equivalent input noise sources can be determined without knowledge of amplifier circuit.



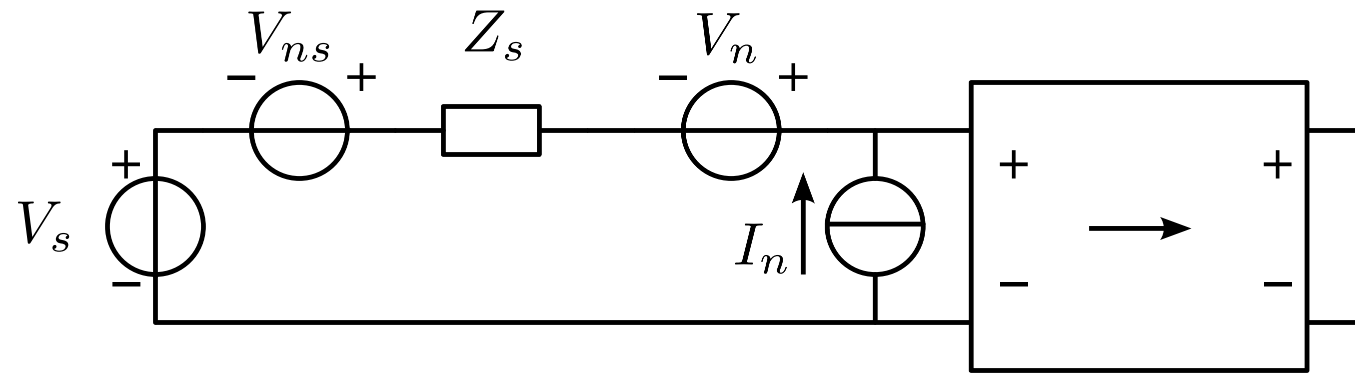


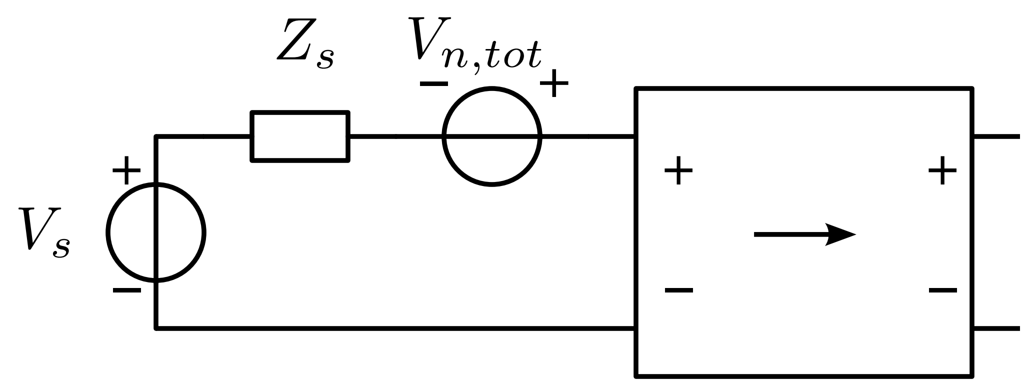
$$S_{V_{n,tot}} = S_{V_{ns}} + S_{V_n} + S_{I_n}|Z_s|^2$$

Amplifier noise design

Equivalent-input noise description is convenient at early stages of the design.

Budgets for equivalent input noise sources can be determined without knowledge of amplifier circuit.





$$S_{V_{n,tot}} = S_{V_{ns}} + S_{V_n} + S_{I_n}|Z_s|^2$$

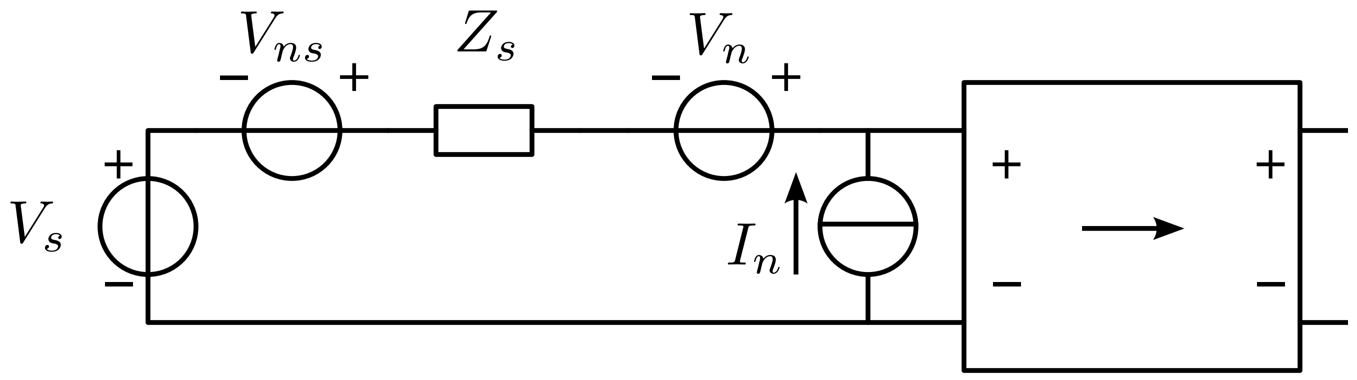
Noise figure

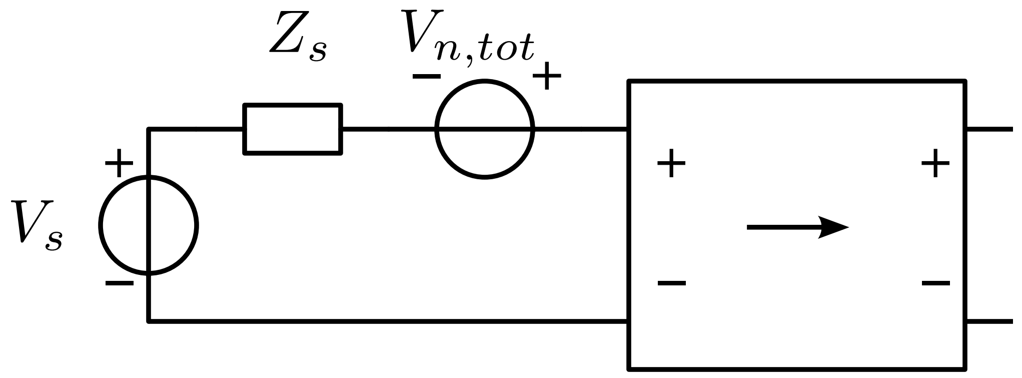
equivalent-input notation:

Amplifier noise design

Equivalent-input noise description is convenient at early stages of the design.

Budgets for equivalent input noise sources can be determined without knowledge of amplifier circuit.





$$S_{V_{n,tot}} = S_{V_{ns}} + S_{V_n} + S_{I_n}|Z_s|^2$$

Noise figure

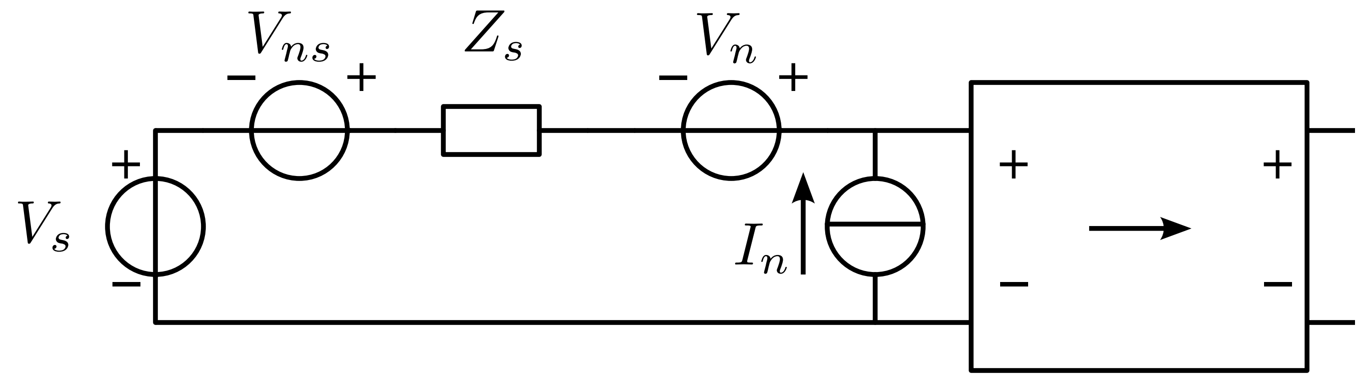
equivalent-input notation:

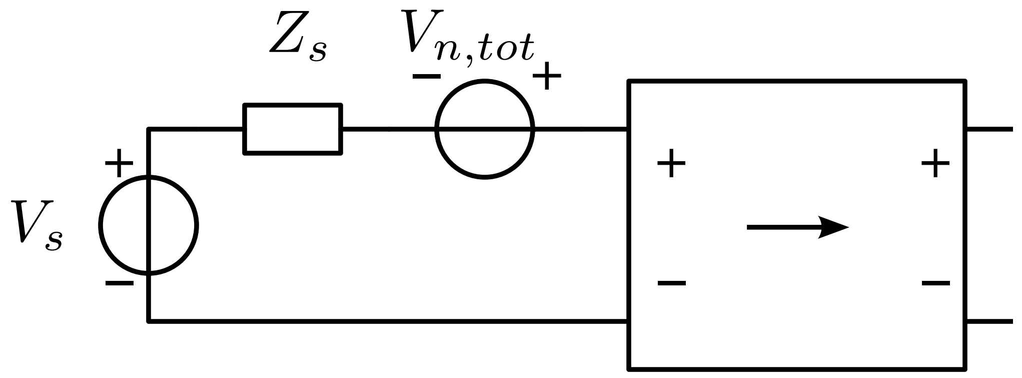
$$F = \frac{\int_0^\infty S_{V_{n,tot}}|W(f)|^2 df}{\int_0^\infty S_{V_{ns}}|W(f)|^2 df}$$

Amplifier noise design

Equivalent-input noise description is convenient at early stages of the design.

Budgets for equivalent input noise sources can be determined without knowledge of amplifier circuit.





$$S_{V_{n,tot}} = S_{V_{ns}} + S_{V_n} + S_{I_n}|Z_s|^2$$

Noise figure

equivalent-input notation:

$$F = \frac{\int_0^\infty S_{V_{n,tot}}|W(f)|^2 df}{\int_0^\infty S_{V_{ns}}|W(f)|^2 df}$$

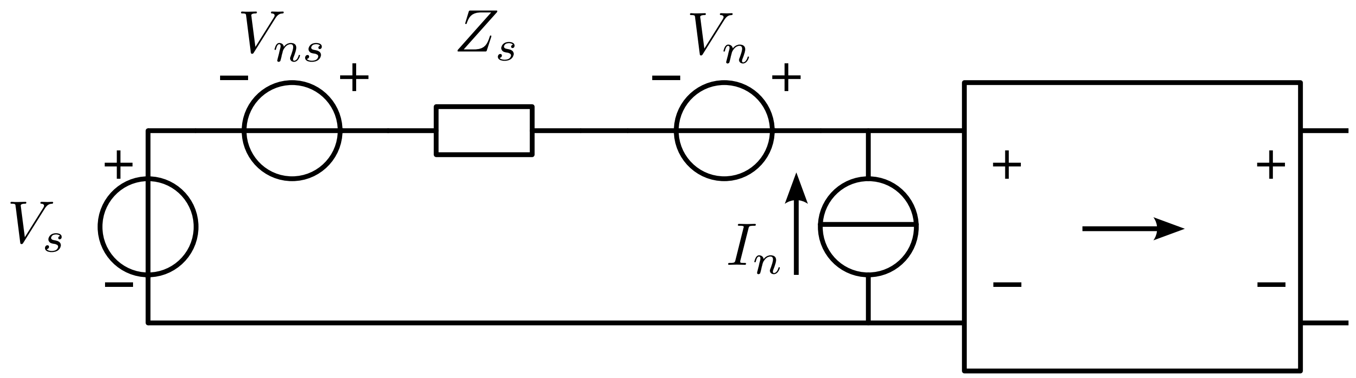
$|W(f)|^2$

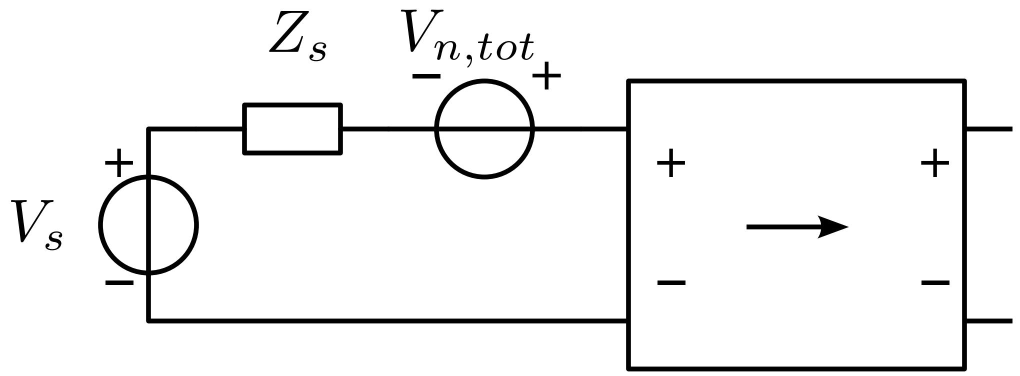
Squared magnitude of weighting function that models the sensitivity of the observer as a function of frequency

Amplifier noise design

Equivalent-input noise description is convenient at early stages of the design.

Budgets for equivalent input noise sources can be determined without knowledge of amplifier circuit.





$$S_{V_{n,tot}} = S_{V_{ns}} + S_{V_n} + S_{I_n}|Z_s|^2$$

Noise figure

equivalent-input notation:

$$F = \frac{\int_0^\infty S_{V_{n,tot}} |W(f)|^2 df}{\int_0^\infty S_{V_{ns}} |W(f)|^2 df}$$

$|W(f)|^2$

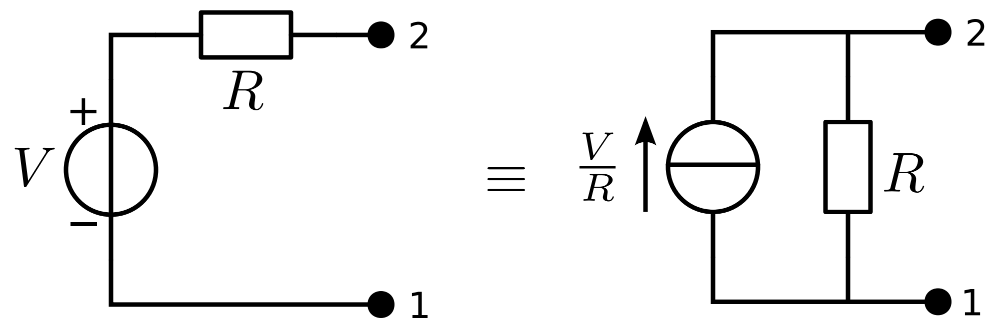
Squared magnitude of weighting function that models the sensitivity of the observer as a function of frequency

(c) 2020 A.J.M. Montagne

Source transformation techniques

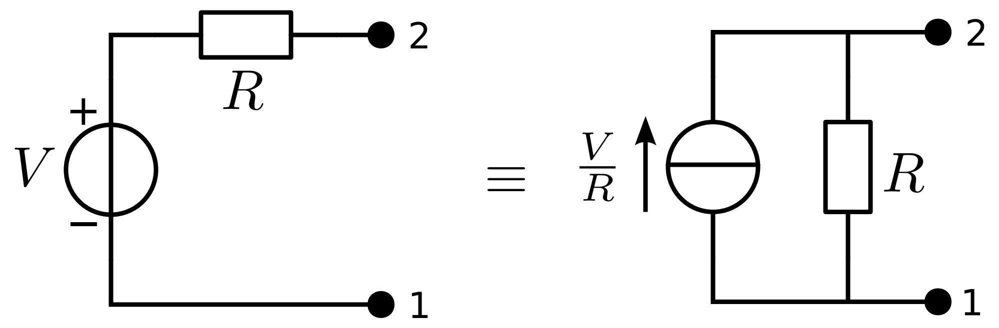
Source transformation techniques

Thévenin / Norton equivalent networks

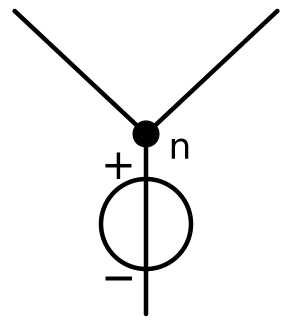


Source transformation techniques

Thévenin / Norton
equivalent networks

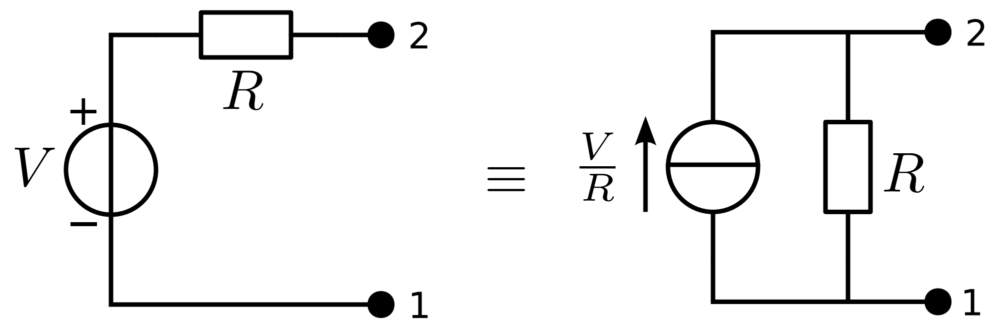


Blakesley voltage shift

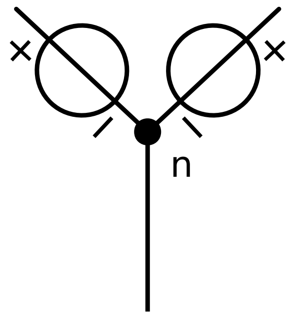


Source transformation techniques

Thévenin / Norton equivalent networks

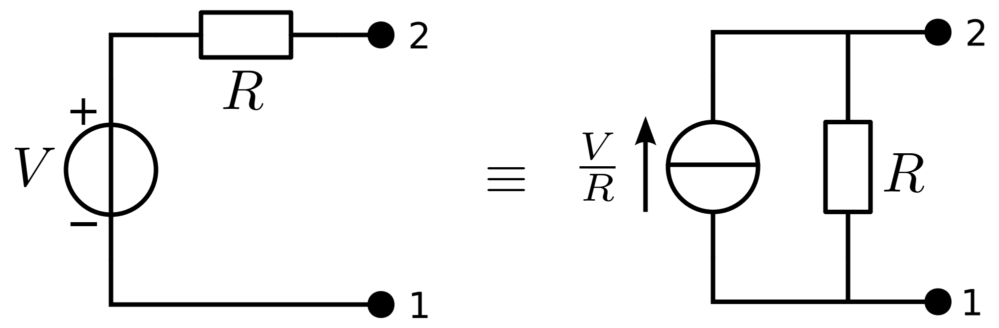


Blakesley voltage shift

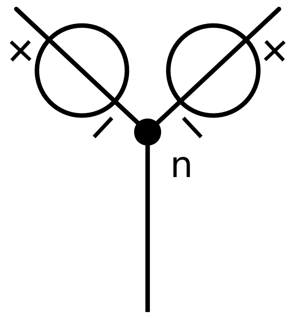


Source transformation techniques

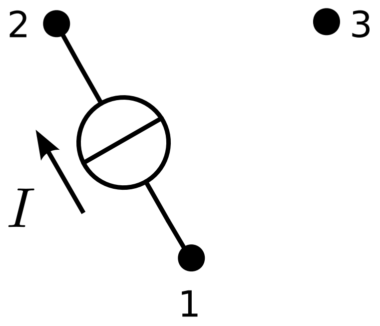
Thévenin / Norton
equivalent networks



Blakesley voltage shift

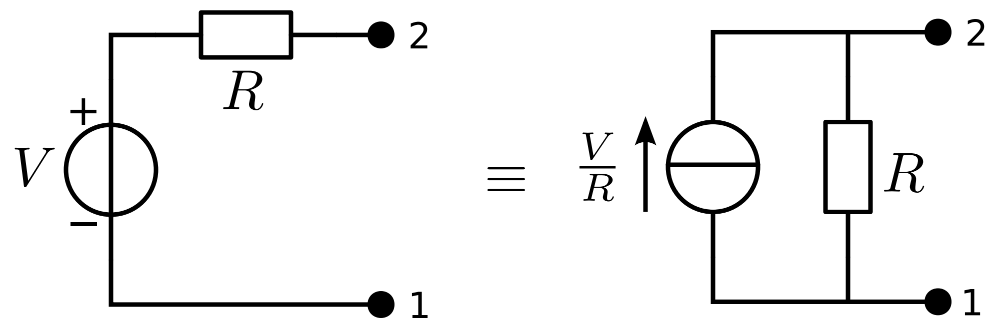


Current split / redirect

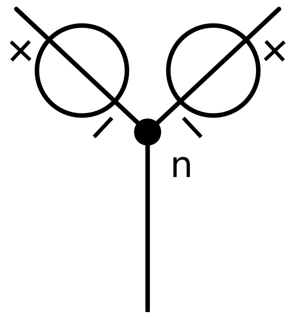


Source transformation techniques

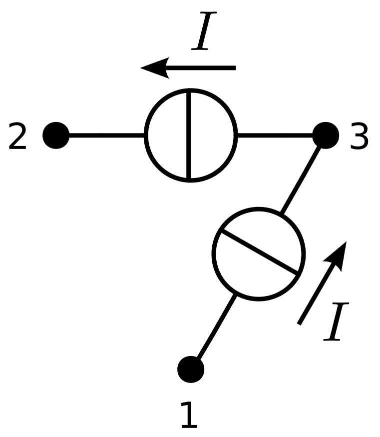
Thévenin / Norton equivalent networks



Blakesley voltage shift

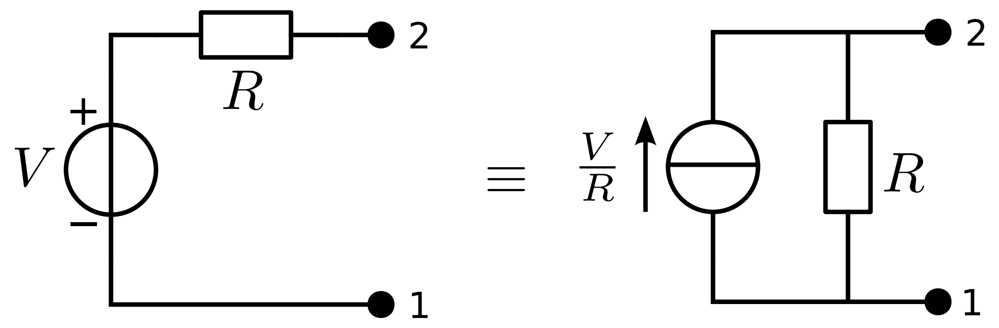


Current split / redirect

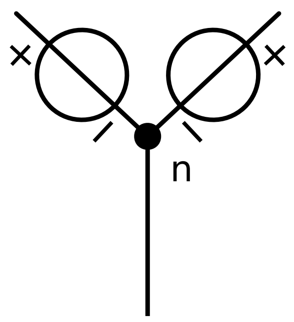


Source transformation techniques

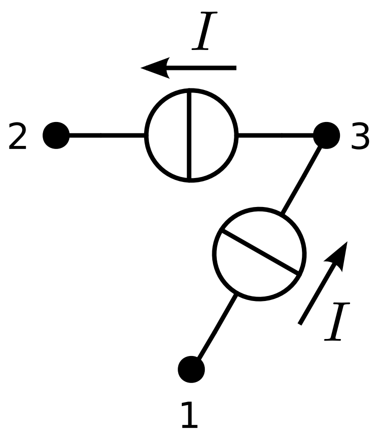
Thévenin / Norton
equivalent networks



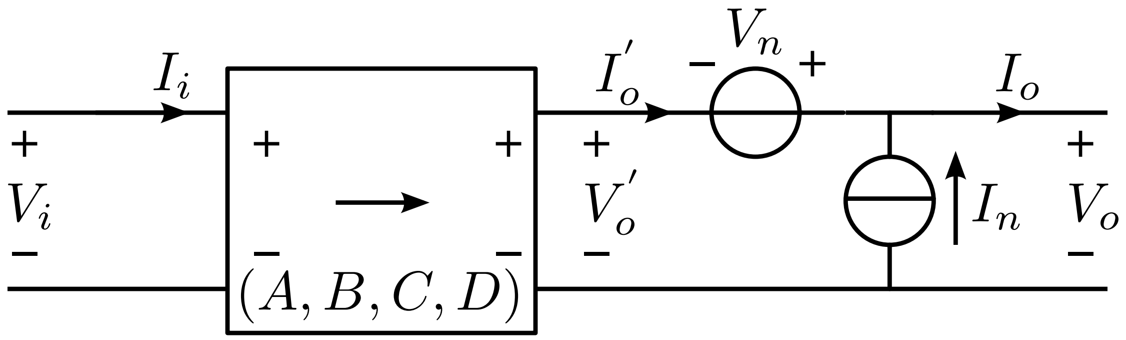
Blakesley voltage shift

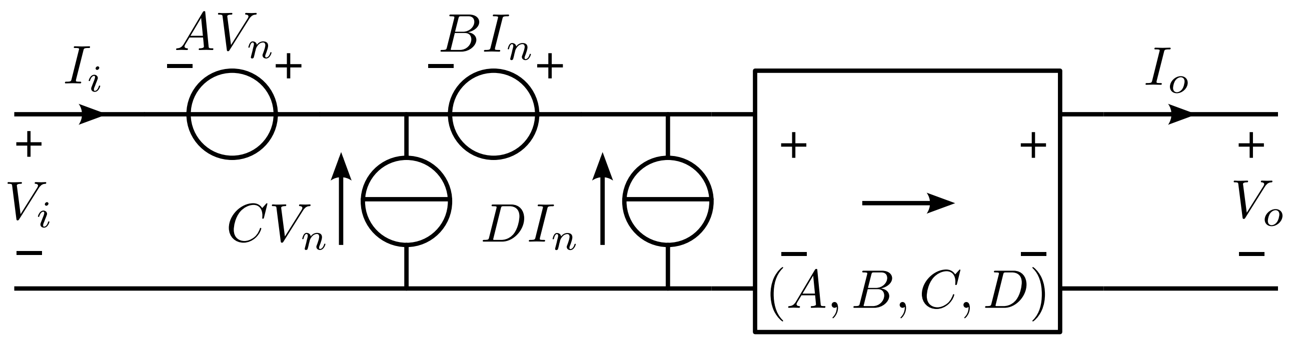


Current split / redirect

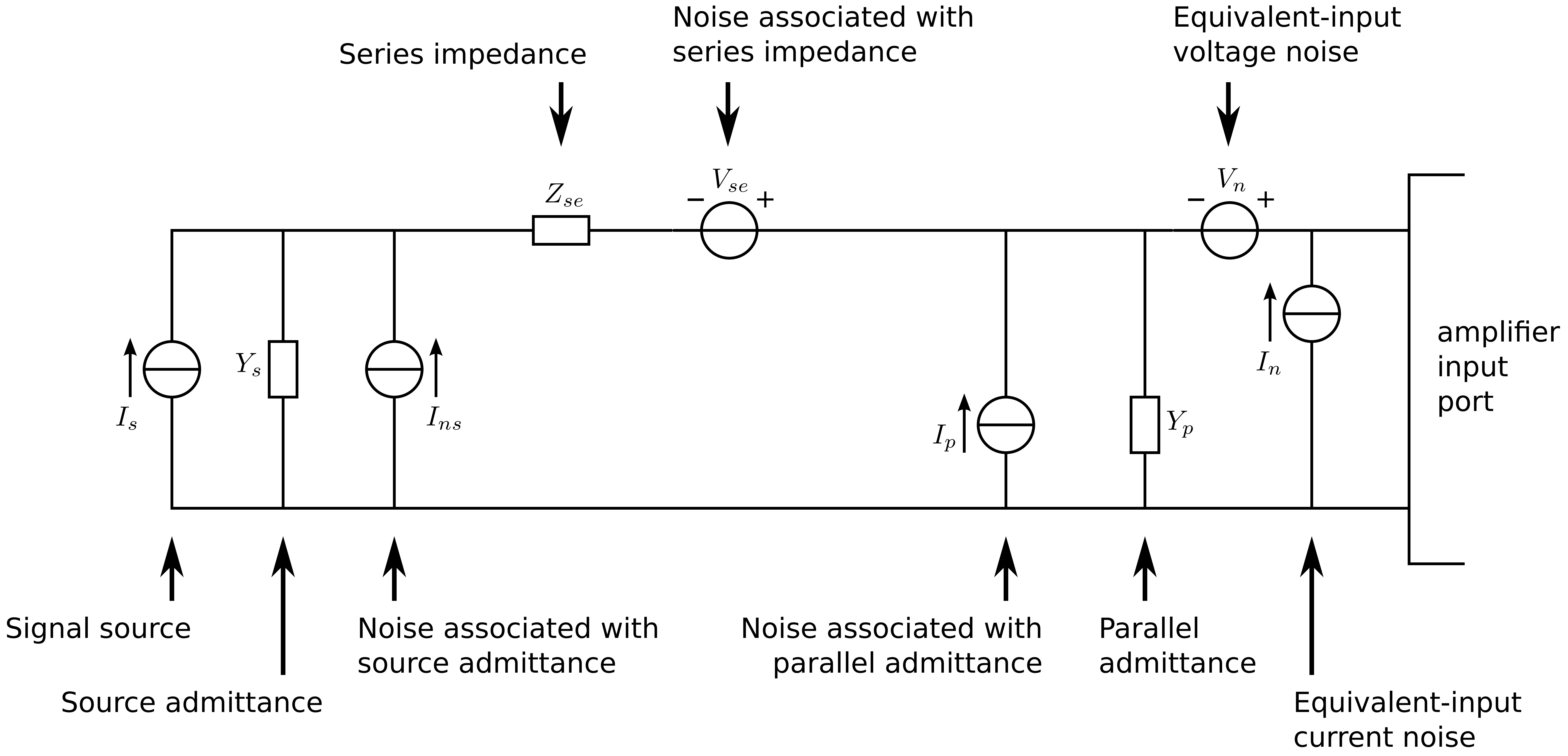


Equivalent two-port representations

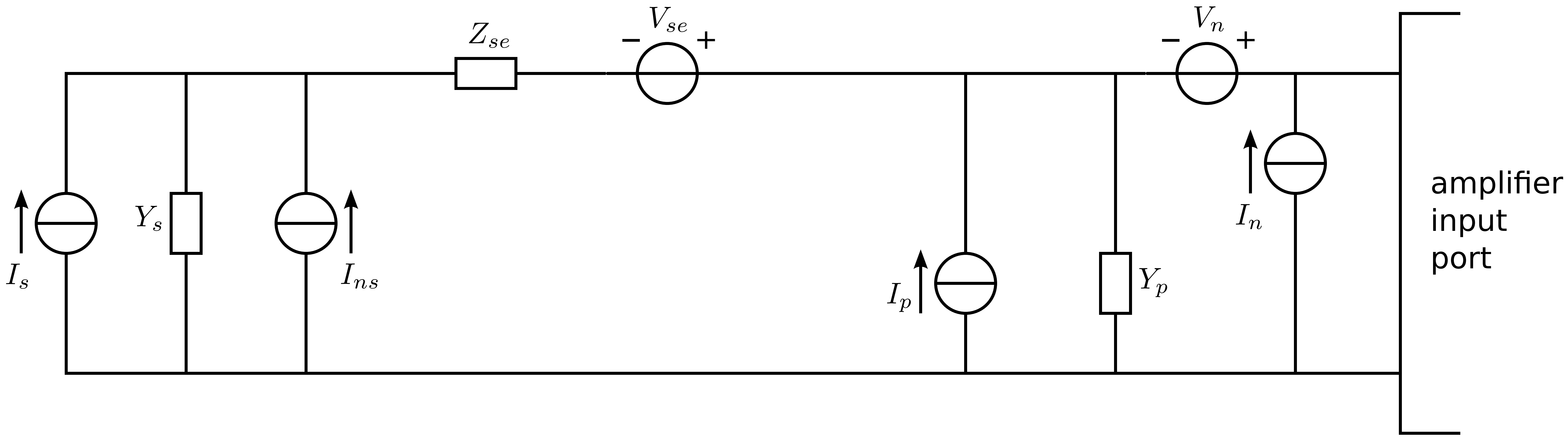




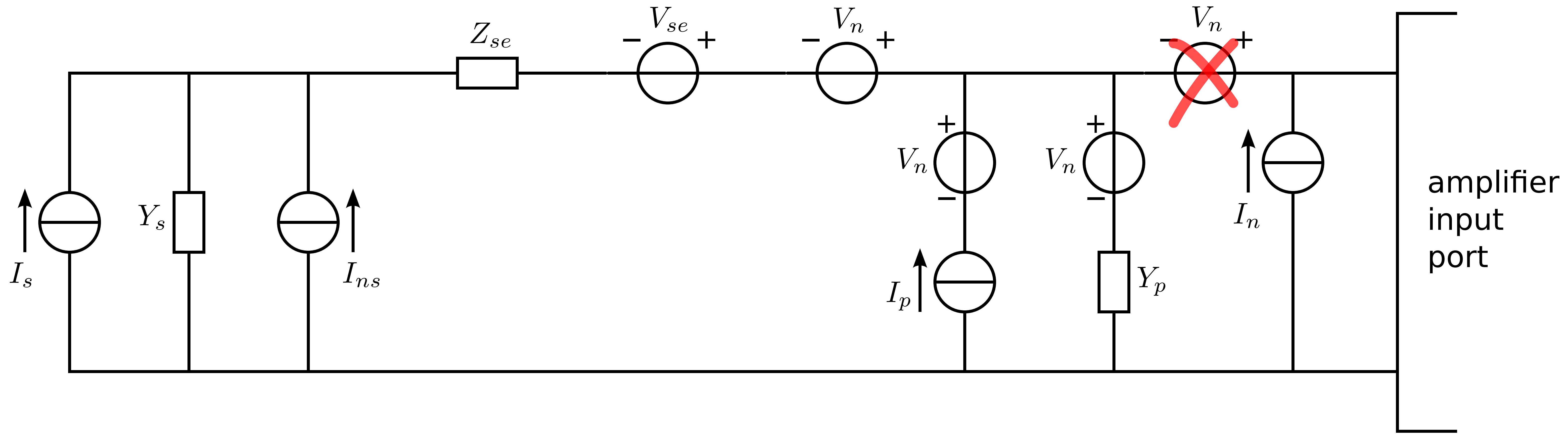
Impedances in the signal path



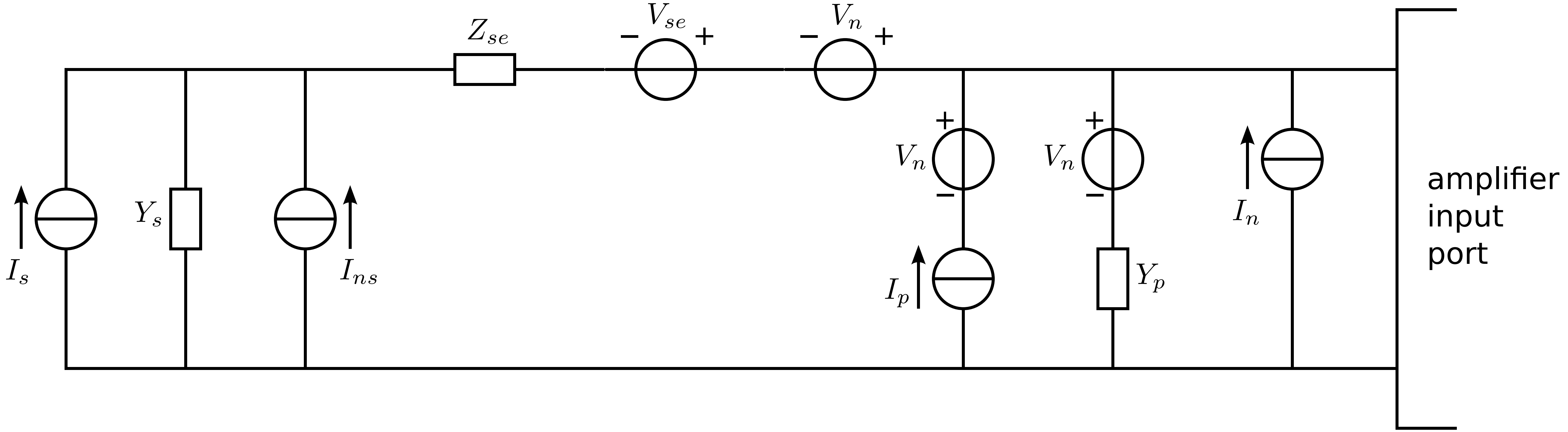
Impedances in the signal path



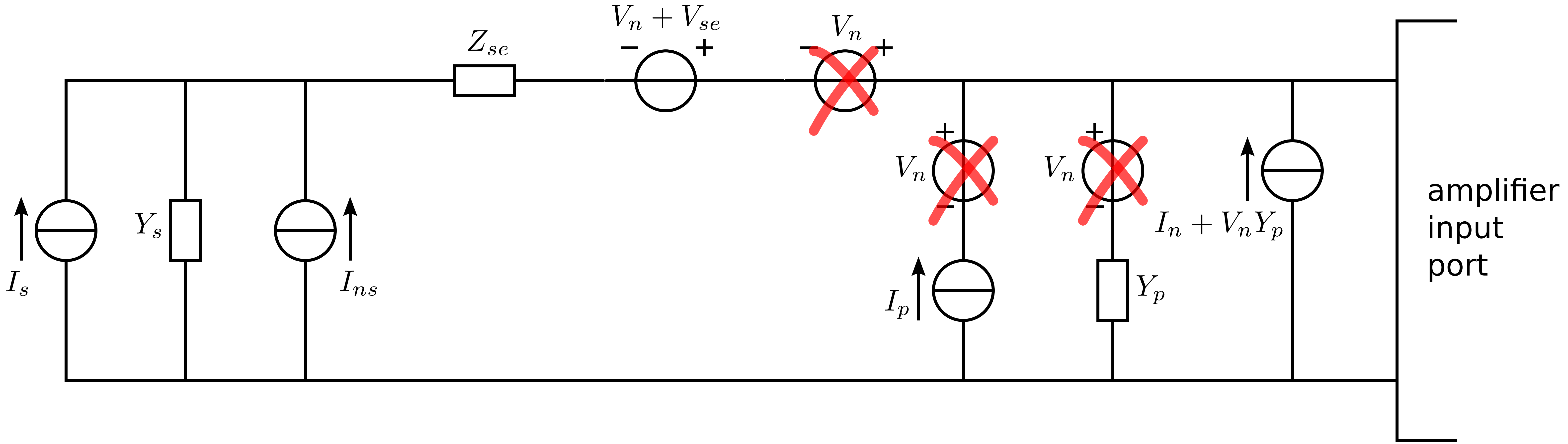
Impedances in the signal path



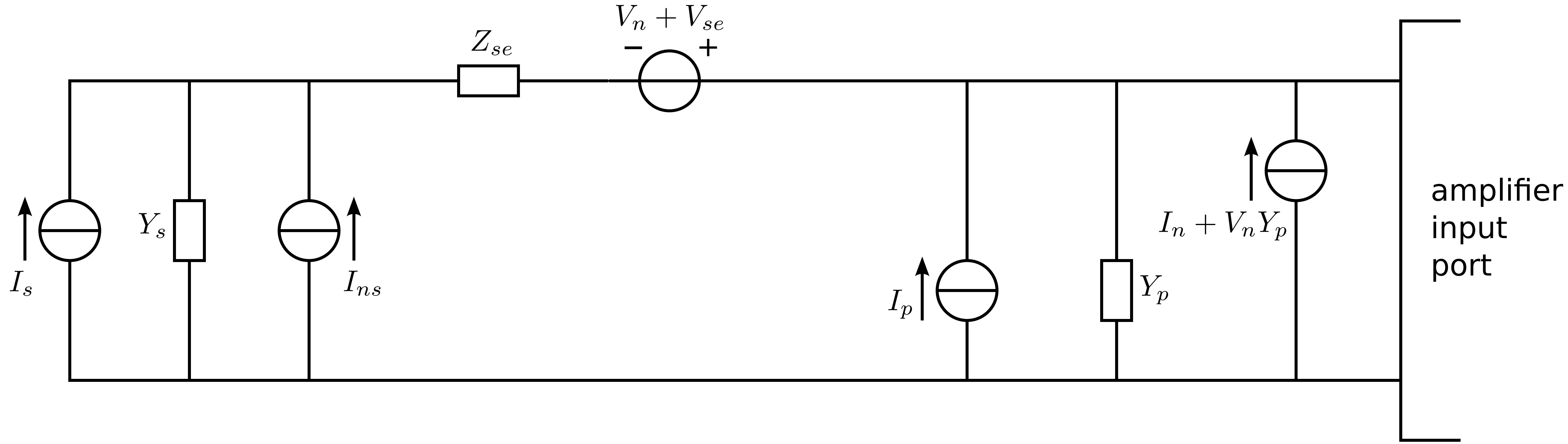
Impedances in the signal path



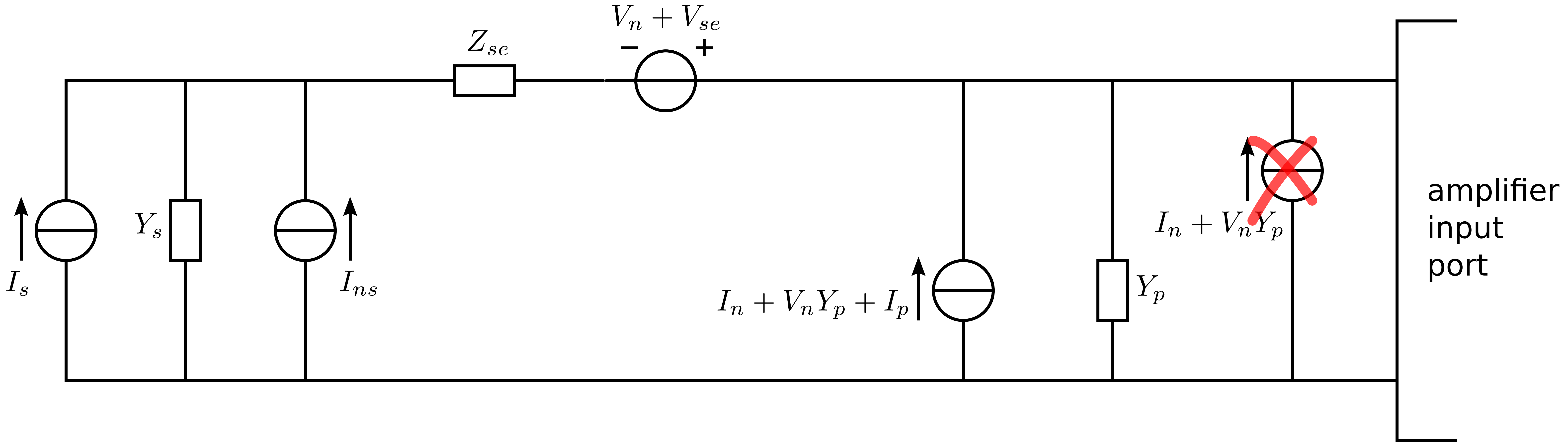
Impedances in the signal path



Impedances in the signal path

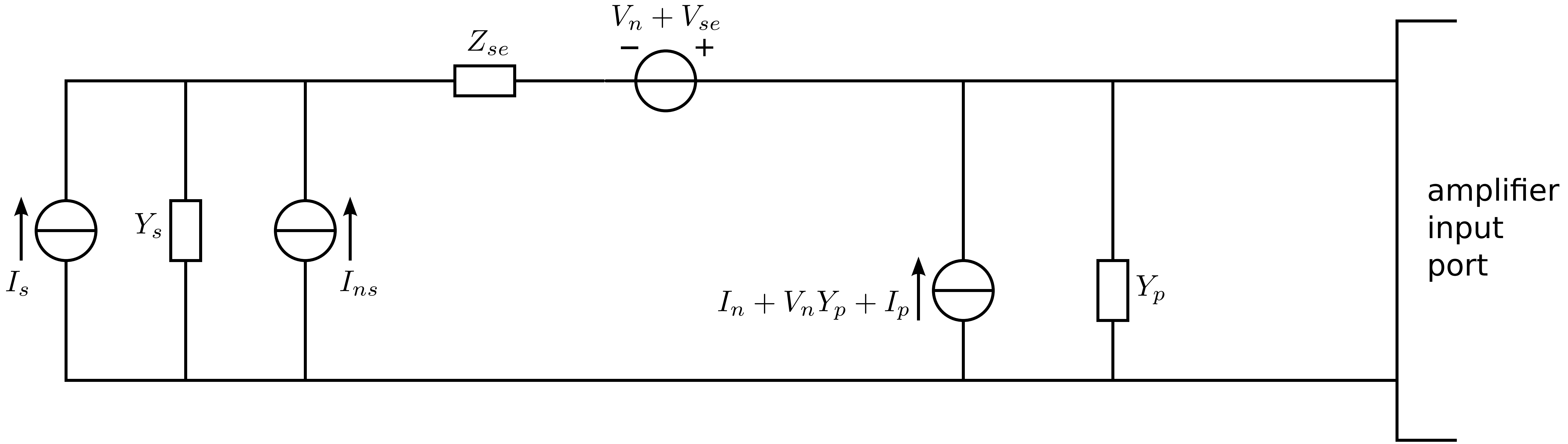


Impedances in the signal path

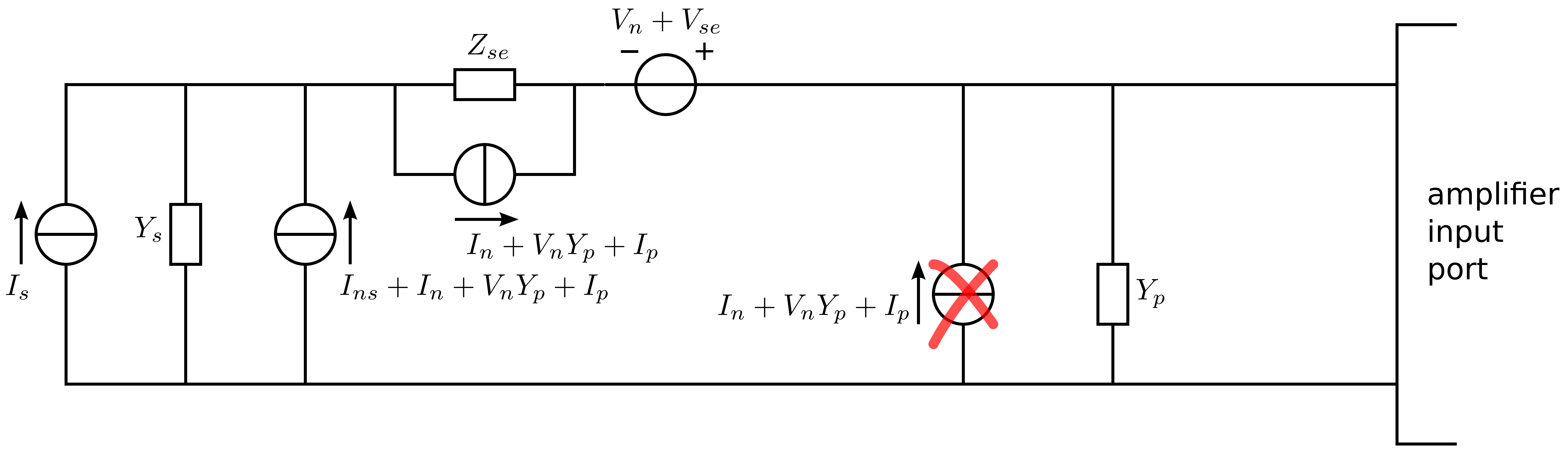


(c) 2020 A.J.M. Montagne

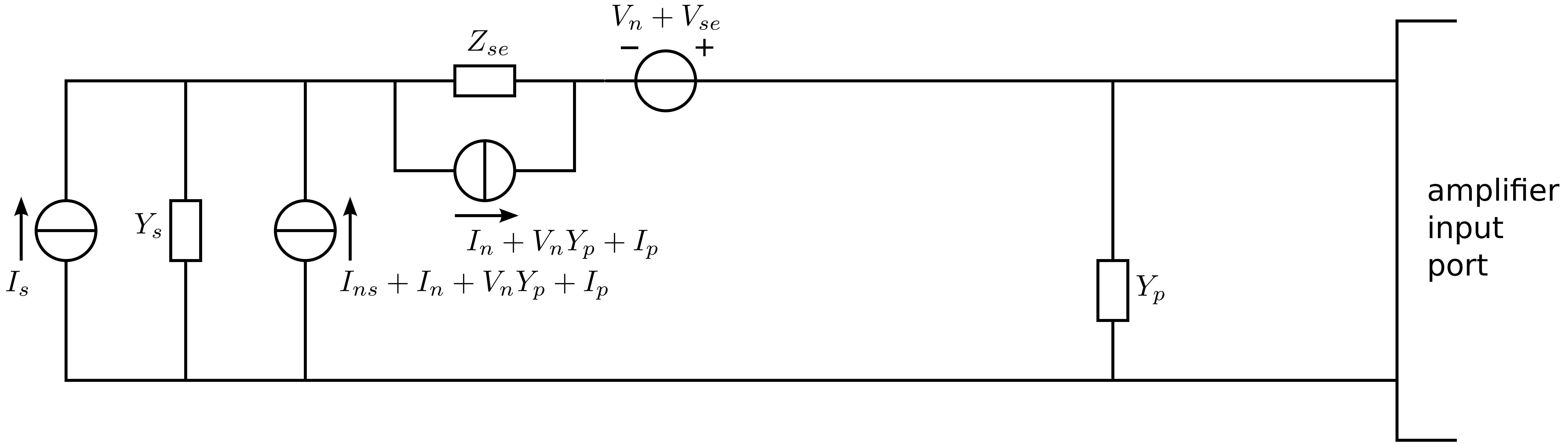
Impedances in the signal path



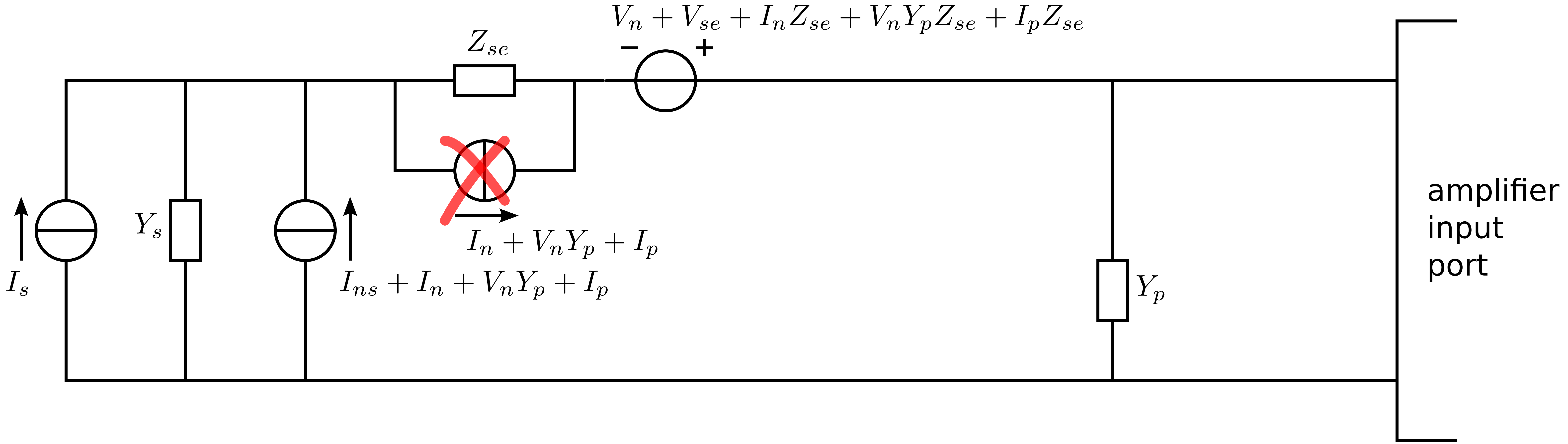
Impedances in the signal path



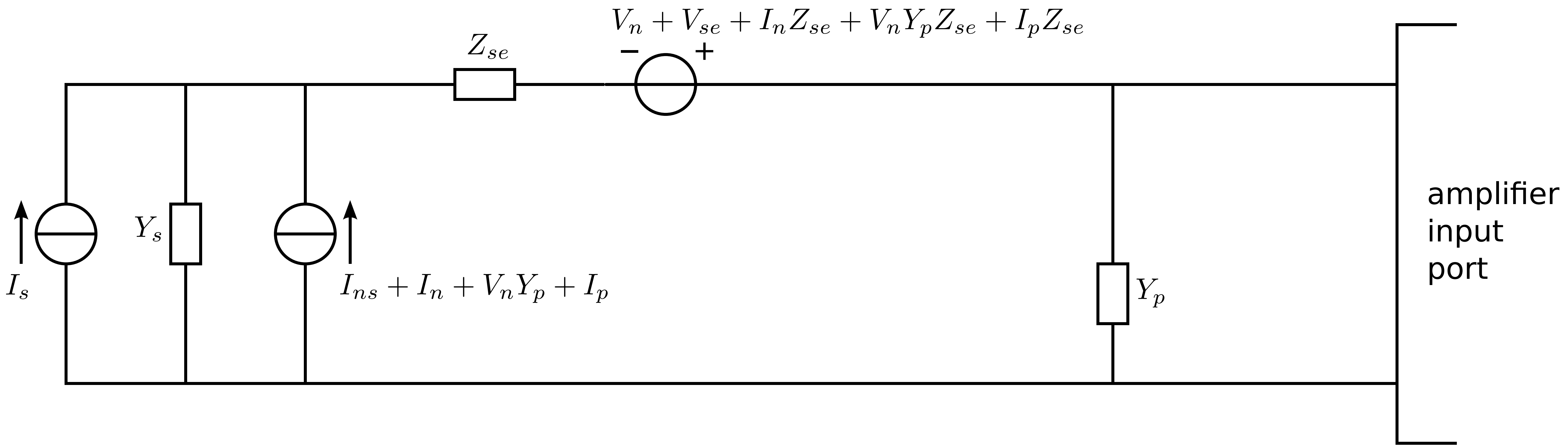
Impedances in the signal path



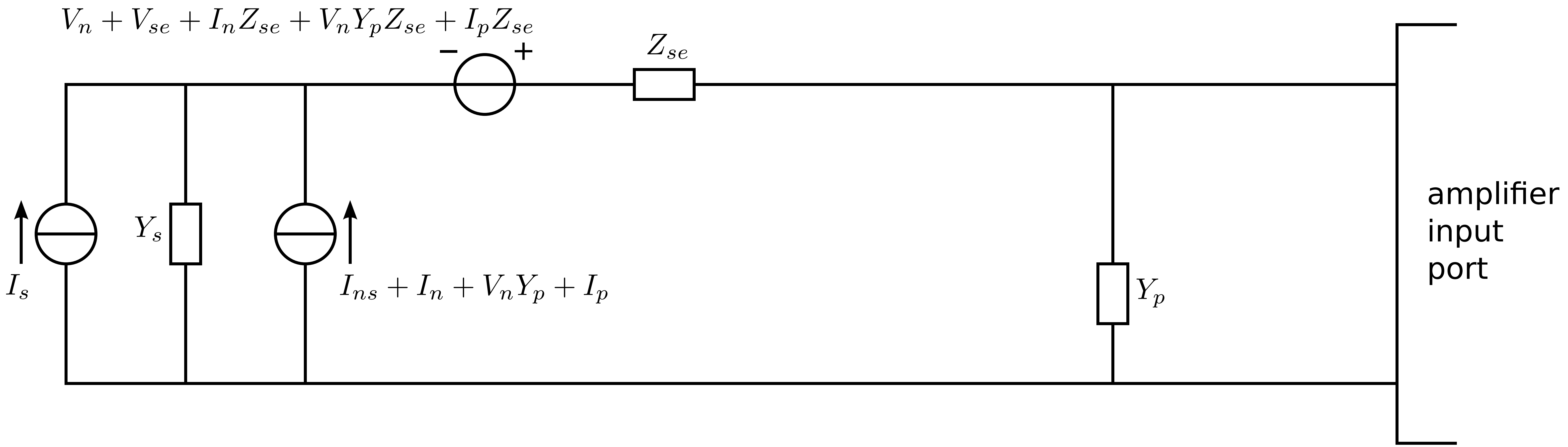
Impedances in the signal path



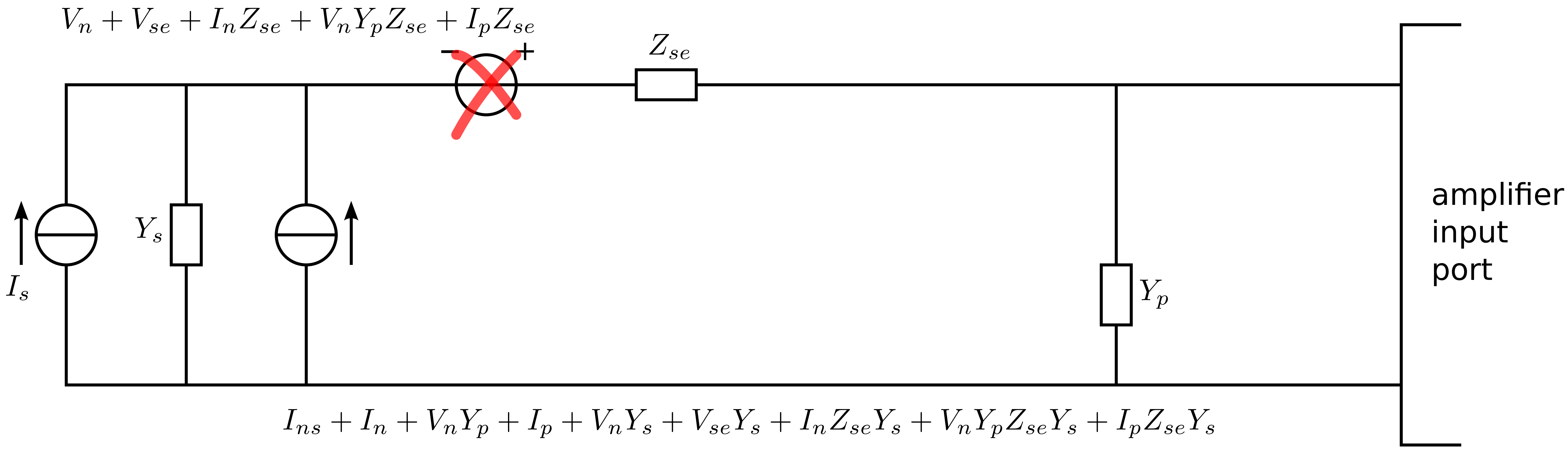
Impedances in the signal path



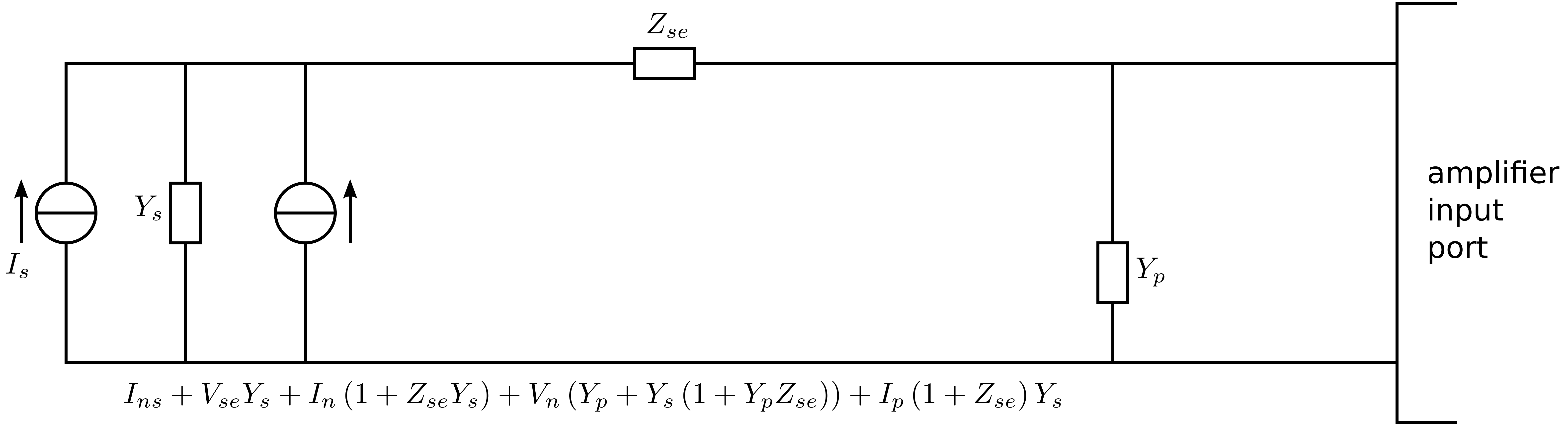
Impedances in the signal path



Impedances in the signal path

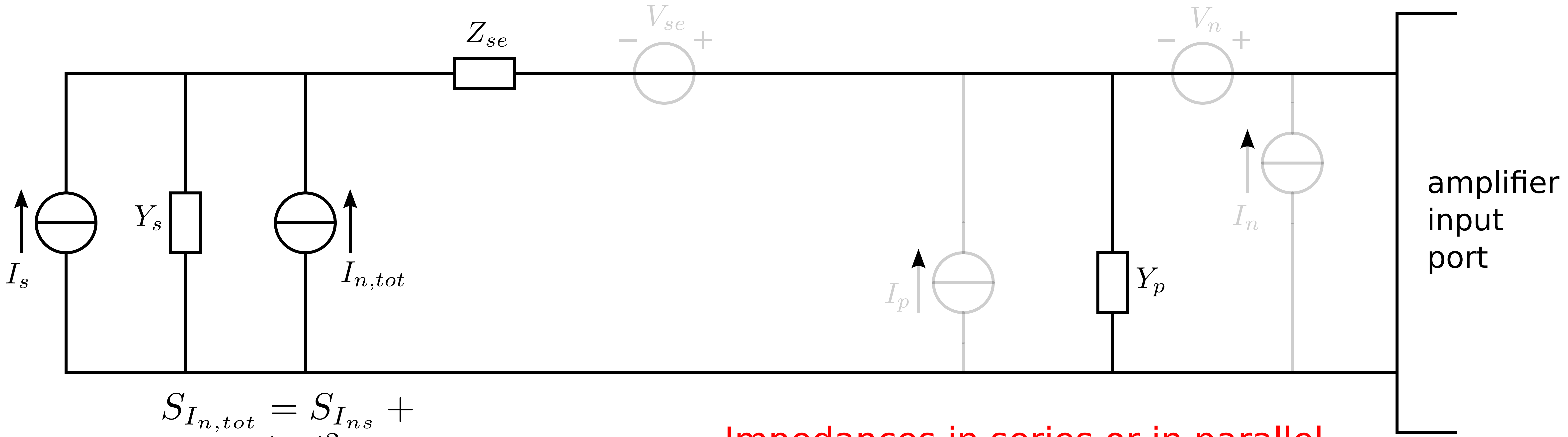


Impedances in the signal path



(c) 2020 A.J.M. Montagne

Impedances in the signal path



$$
\begin{aligned}
S_{I_{n,tot}} &= S_{I_{ns}} + \\
&+ S_{V_{se}} |Y_s|^2 + \\
&+ S_{I_n} |1 + Z_{se} Y_s|^2 + \\
&+ S_{V_n} |Y_p + Y_s (1 + Y_p Z_{se})|^2 + \\
&+ S_{I_p} |1 + Z_{se} Y_s|^2
\end{aligned}
$$

Impedances in series or in parallel with the signal path increase the influence of noise sources further in the signal path

Design conclusions

Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

Gererally, they increase the influence of existing noise sources

(c) 2020 A.J.M. Montagne

Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

(c) 2020 A.J.M. Montagne

Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

Only in narrow-band applications they may improve the noise performance:

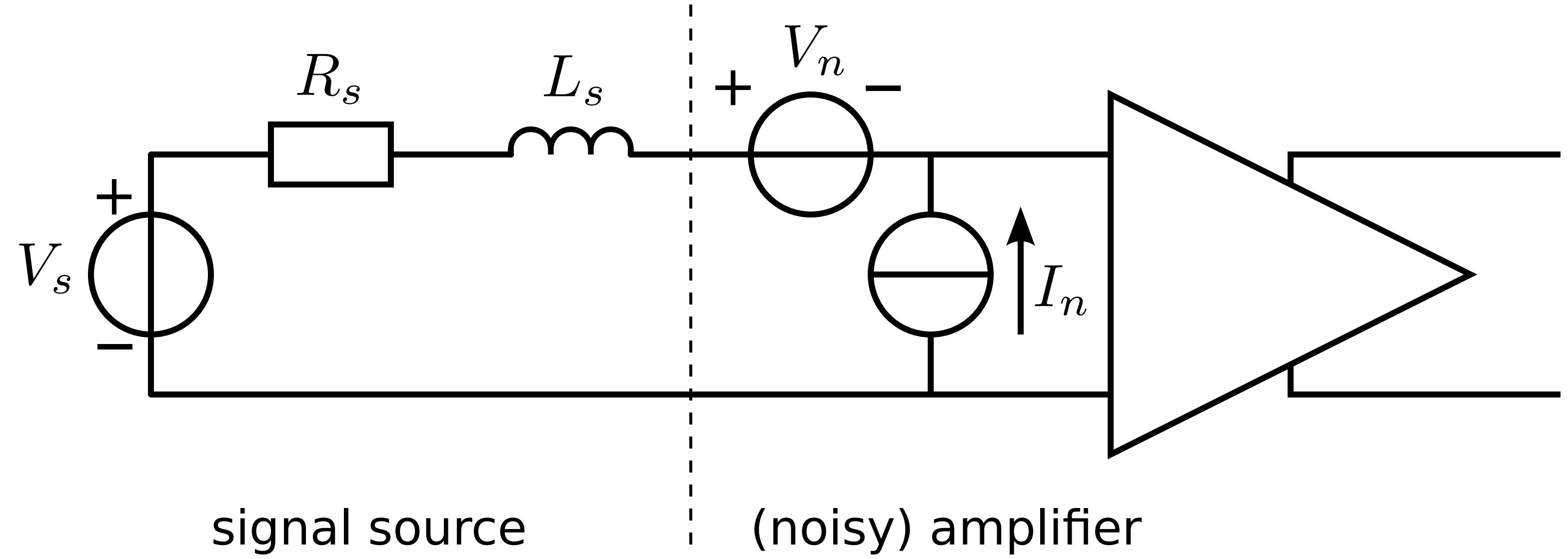
Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

Only in narrow-band applications they may improve the noise performance:



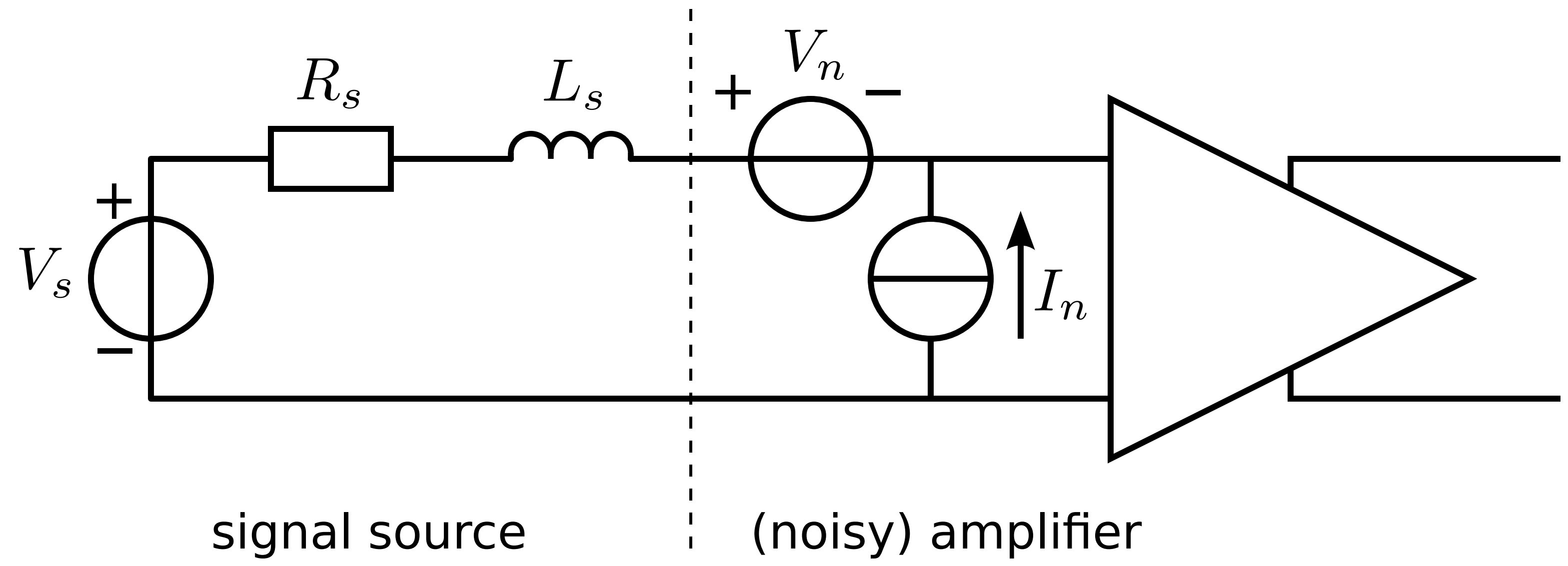
Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

Only in narrow-band applications they may improve the noise performance:



$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + (\omega L_s)^2\right)$$

(c) 2020 A.J.M. Montagne

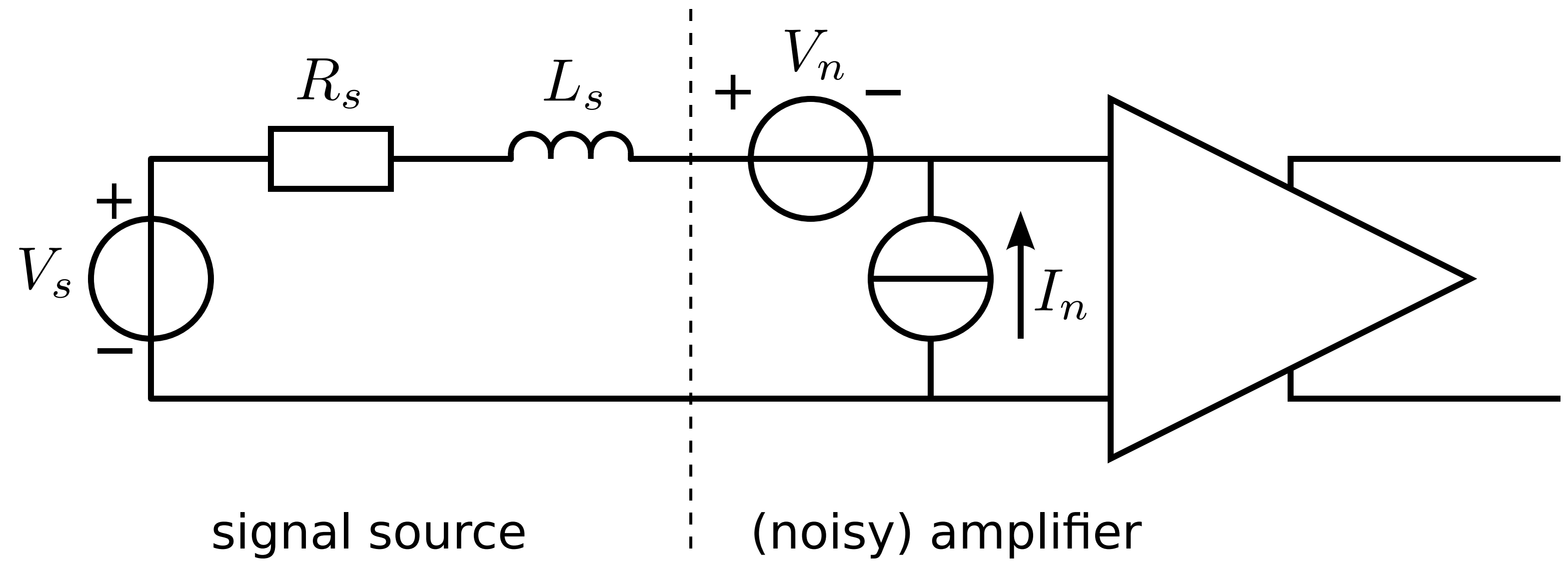
Design conclusions

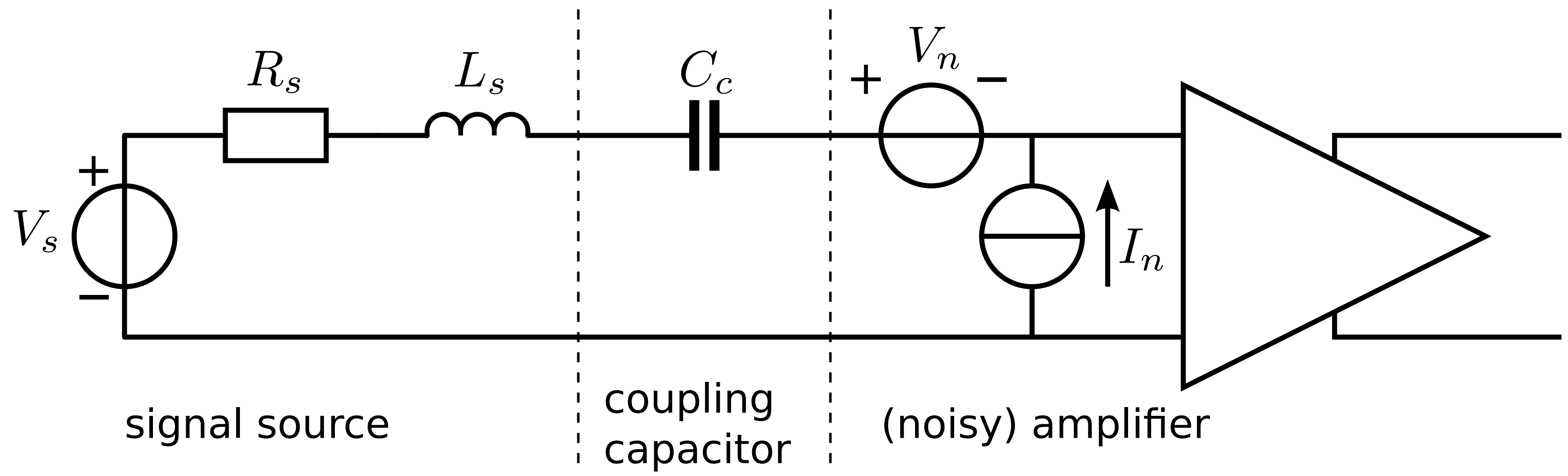
Insertion of impedances in series or in parallel with the signal path should be avoided

Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

Only in narrow-band applications they may improve the noise performance:





$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + (\omega L_s)^2\right)$$

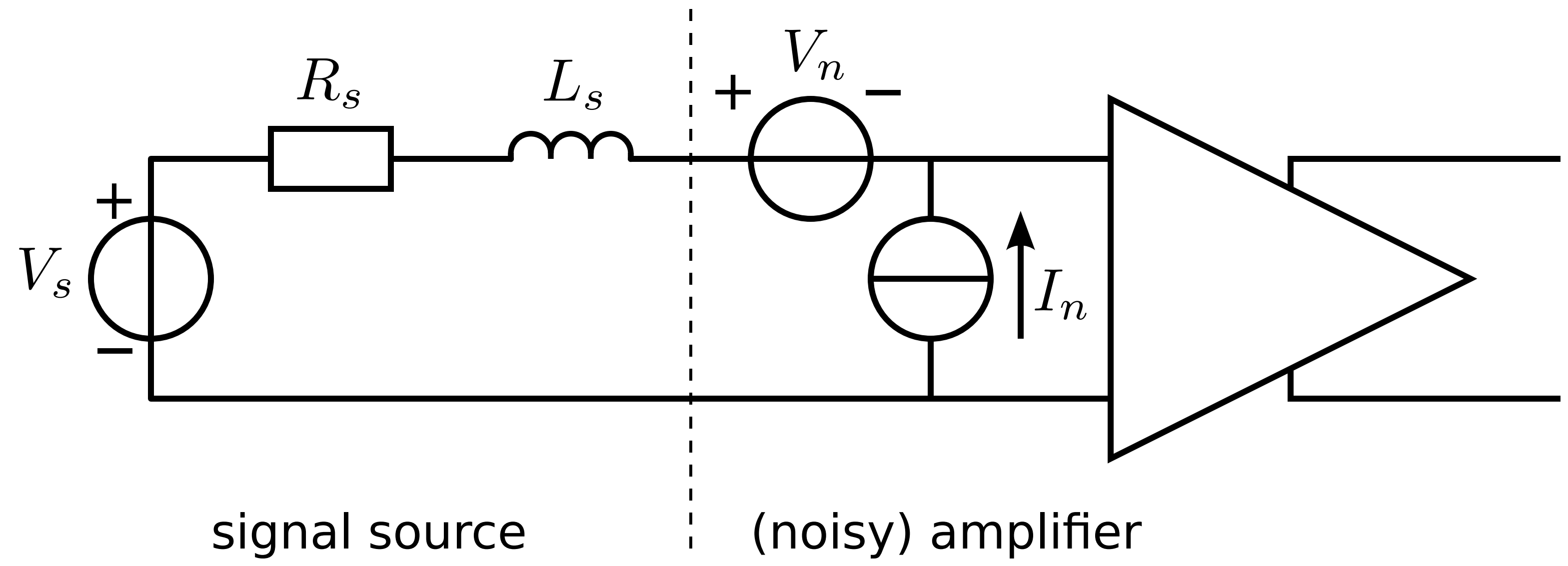
Design conclusions

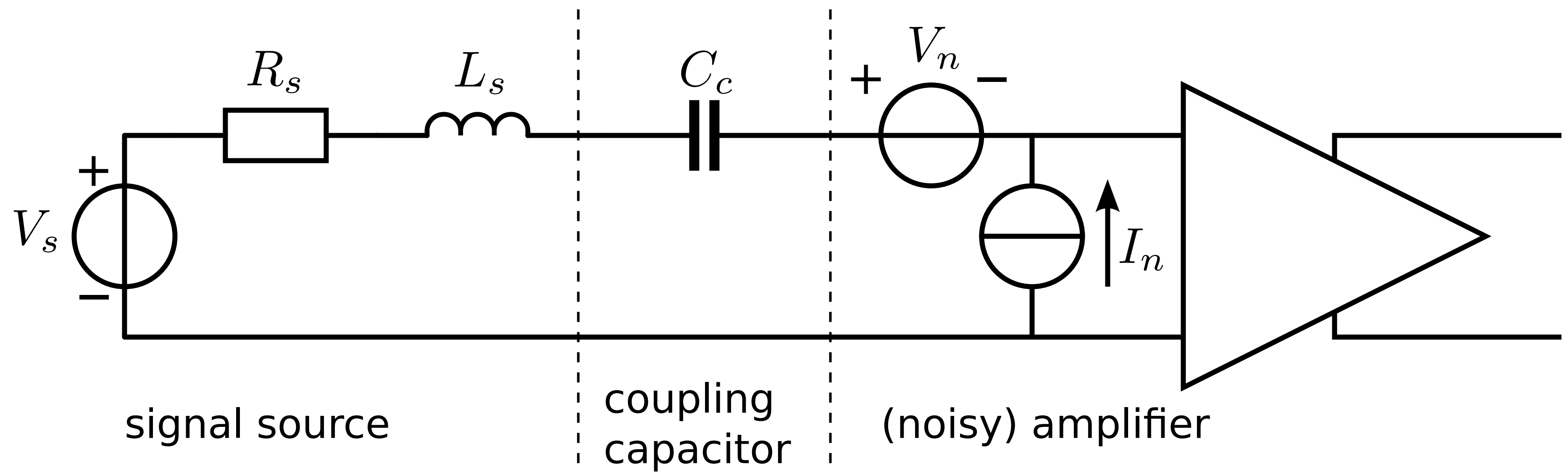
Insertion of impedances in series or in parallel with the signal path should be avoided

Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

Only in narrow-band applications they may improve the noise performance:





$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + (\omega L_s)^2\right)$$

$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + \left(\omega L_s - \frac{1}{\omega C_c}\right)^2\right)$$

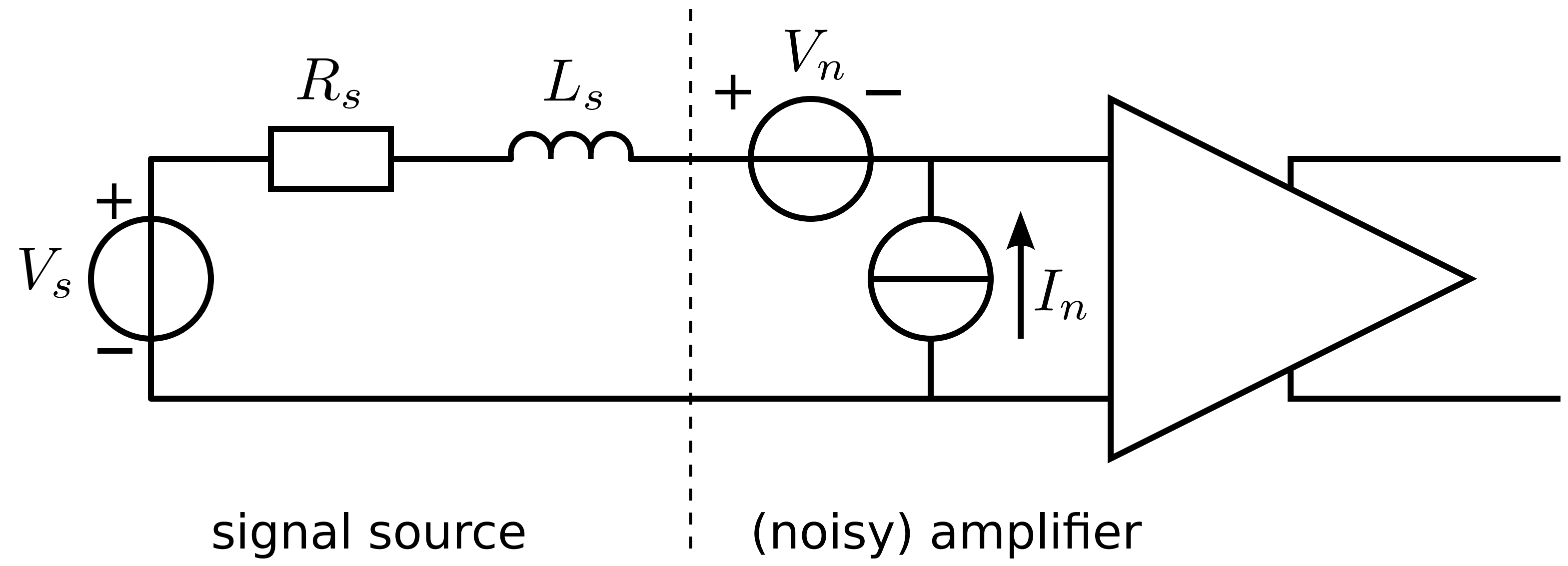
Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

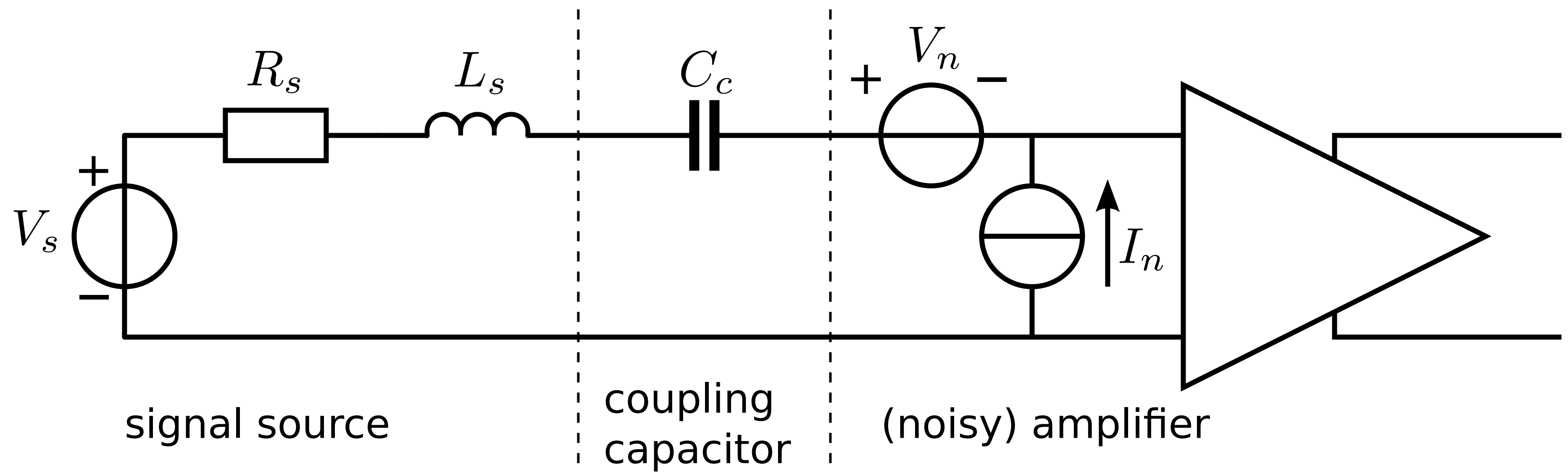
Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

Only in narrow-band applications they may improve the noise performance:



$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + (\omega L_s)^2\right)$$



$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + \left(\omega L_s - \frac{1}{\omega C_c}\right)^2\right)$$

Strong reduction of contribution of I_n
to the total source-referred noise if $\omega L_s \approx \frac{1}{\omega C_c}$

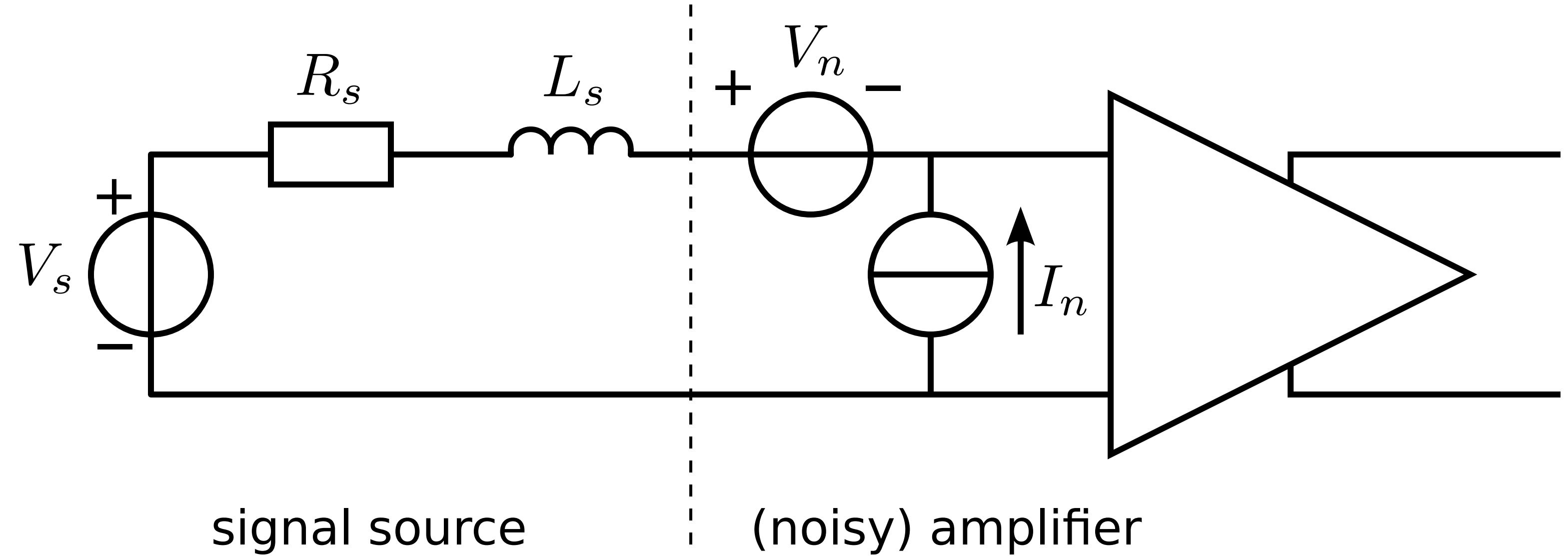
Design conclusions

Insertion of impedances in series or in parallel with the signal path should be avoided

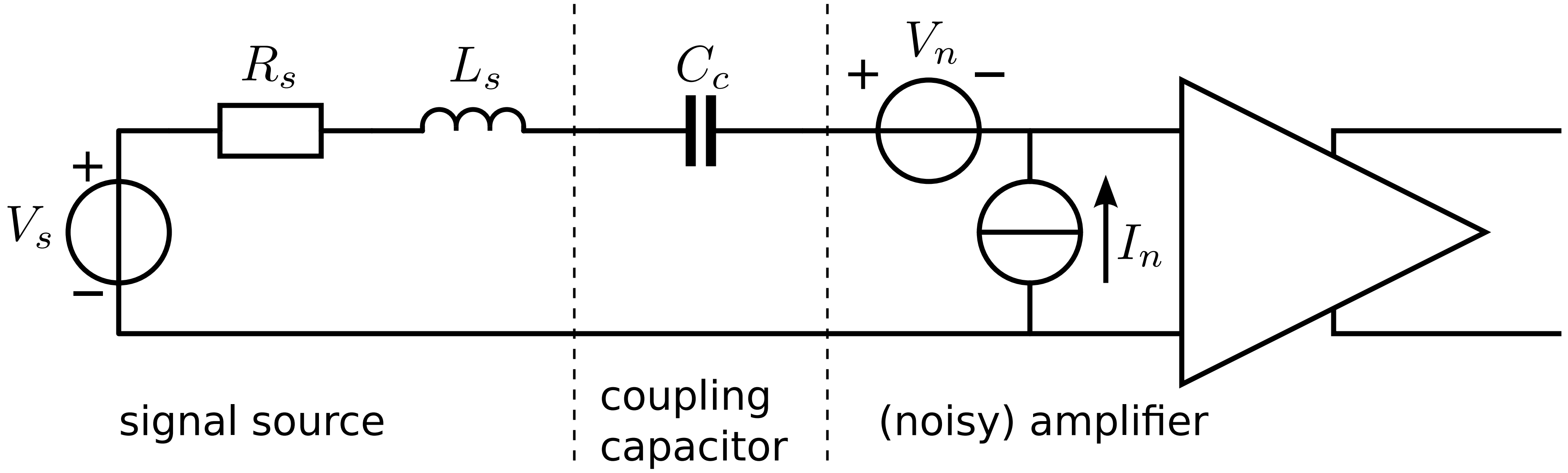
Gererally, they increase the influence of existing noise sources

If these impedances have a nonzero real part they contribute noise themselves

Only in narrow-band applications they may improve the noise performance:



$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + (\omega L_s)^2\right)$$



$$S_{Vn_{tot}} = 4kTR_s + S_{V_n} + S_{I_n}\left(R_s^2 + \left(\omega L_s - \frac{1}{\omega C_c}\right)^2\right)$$

Strong reduction of contribution of I_n
to the total source-referred noise if $\omega L_s \approx \frac{1}{\omega C_c}$