ROCHESTER INSTITUTE OF TECHNOLOGY
MICROELECTRONIC ENGINEERING

Feedback in Electronic Circuits

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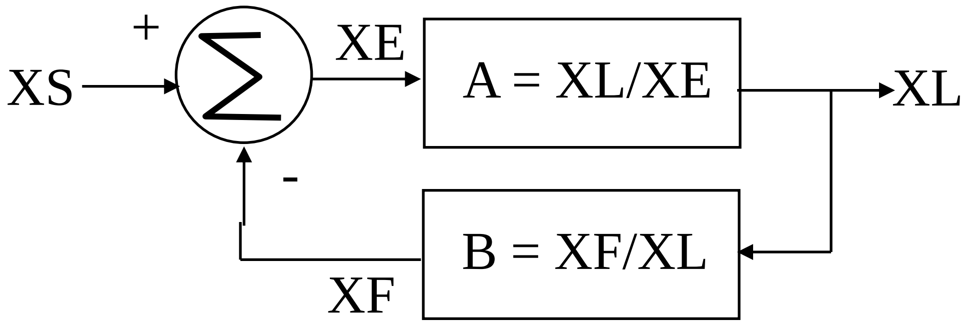
INTRODUCTION



Consider the feedback amplifier shown.

$$XL = A\,XE = A\,(XS - XF) = A\,(XS - BXL)$$
$$= A\,XS - A\,B\,XL \text{ or } XL(1+AB) = A\,XS$$

$$Af = XL/XS = A/(1+AB)$$

In this analysis, A is defined as the gain of the amplifier without feedback, known as the open loop gain, B is the gain of the feedback network, T= -AB is known as the loop gain, and Af is the gain of the amplifier with feedback, known as the closed loop gain.

INTRODUCTION

NEGATIVE FEEDBACK: If the loop gain is negative for any circuit then that circuit has negative feedback. For negative feedback the closed loop gain is:

$$Af = \frac{A}{1 + AB}$$

POSITIVE FEEDBACK: If the loop gain is positive for any circuit then that circuit has positive feedback. Af = A / (1 – AB). Note that if AB = 1 the gain Af = infinity and the circuit will oscillate. That is no input is needed. Which is useful if you want an oscillator.

We will continue by discussing only negative feedback.

NEGATIVE FEEDBACK DECREASES SENSITIVITY

Decrease in Sensitivity – Suppose A changes by x%. How much would Af change? To answer this question lets compute the sensitivity of Af with respect to A:

Sensitivity symbol (not integral)

$$S_{A}^{Af} = \frac{\text{Incremental change in Af}}{\text{Incremental change in A}} = \frac{\Delta Af\ /Af}{\Delta A\ /A}$$

$$\Delta Af = \frac{\delta Af}{\delta A}\,\Delta A = \frac{\delta\left(\frac{A}{1+AB}\right)}{\delta A}\,\Delta A = \frac{1}{(1+AB)^2}\,\Delta A$$

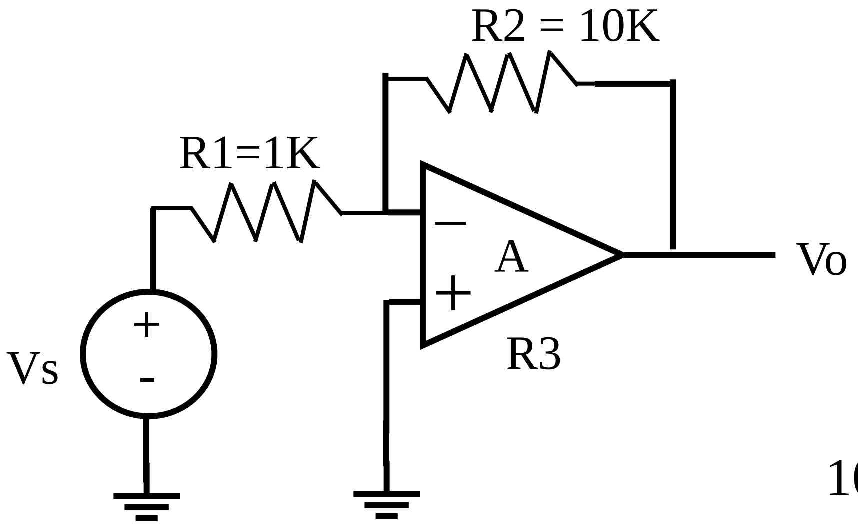
$$\frac{\Delta Af}{Af} = \frac{\frac{1}{(1+AB)^2}\,\Delta A}{Af} = \frac{\frac{1}{(1+AB)^2}\,\Delta A}{\frac{A}{(1+AB)}} = \frac{1}{(1+AB)}\,\frac{\Delta A}{A}$$

$$\boxed{S_{A}^{Af} = \frac{1}{(1+AB)}}$$

So we see that the sensitivity of the gain Af to changes in gain A is less than 1 which is an improvement over an amplifier without feedback.

NEGATIVE FEEDBACK DECREASES SENSITIVITY

Decrease in Sensitivity –



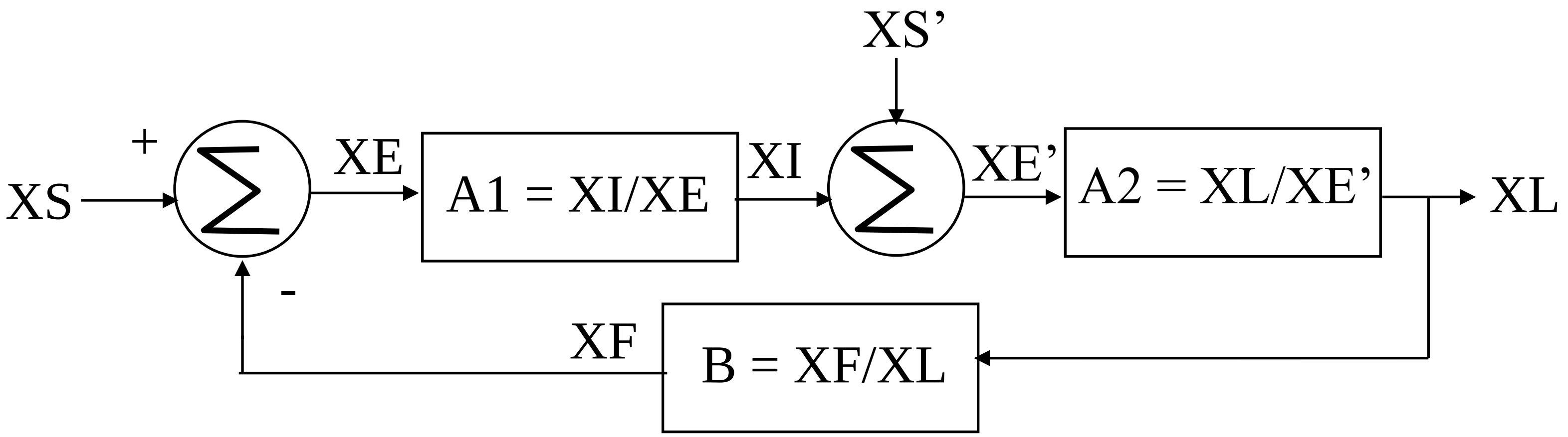
$10^4 < A < 10^5$

The gain without feedback, A, is large but not precise (may change from one op amp to the next).

The gain with feedback, A_f, is –R2/R1 = -10 which is precise (and lower than A)

NEGATIVE FEEDBACK DECREASES DISTORTION

Reduction in Distortion: Suppose and amplifier consists of two stages, A1 and A2 such that A = A1 A2 and that distortion is modeled as the addition of an unwanted signal XS' as shown in the figure below.



XL = A2 XE' = A2 (XI +XS')

XL = A2(A1XE +XS') = A2 (A1(XS-XF) + XS')

XL = A2(A1(XS-BXL) + XS')

NEGATIVE FEEDBACK DECREASES DISTORTION

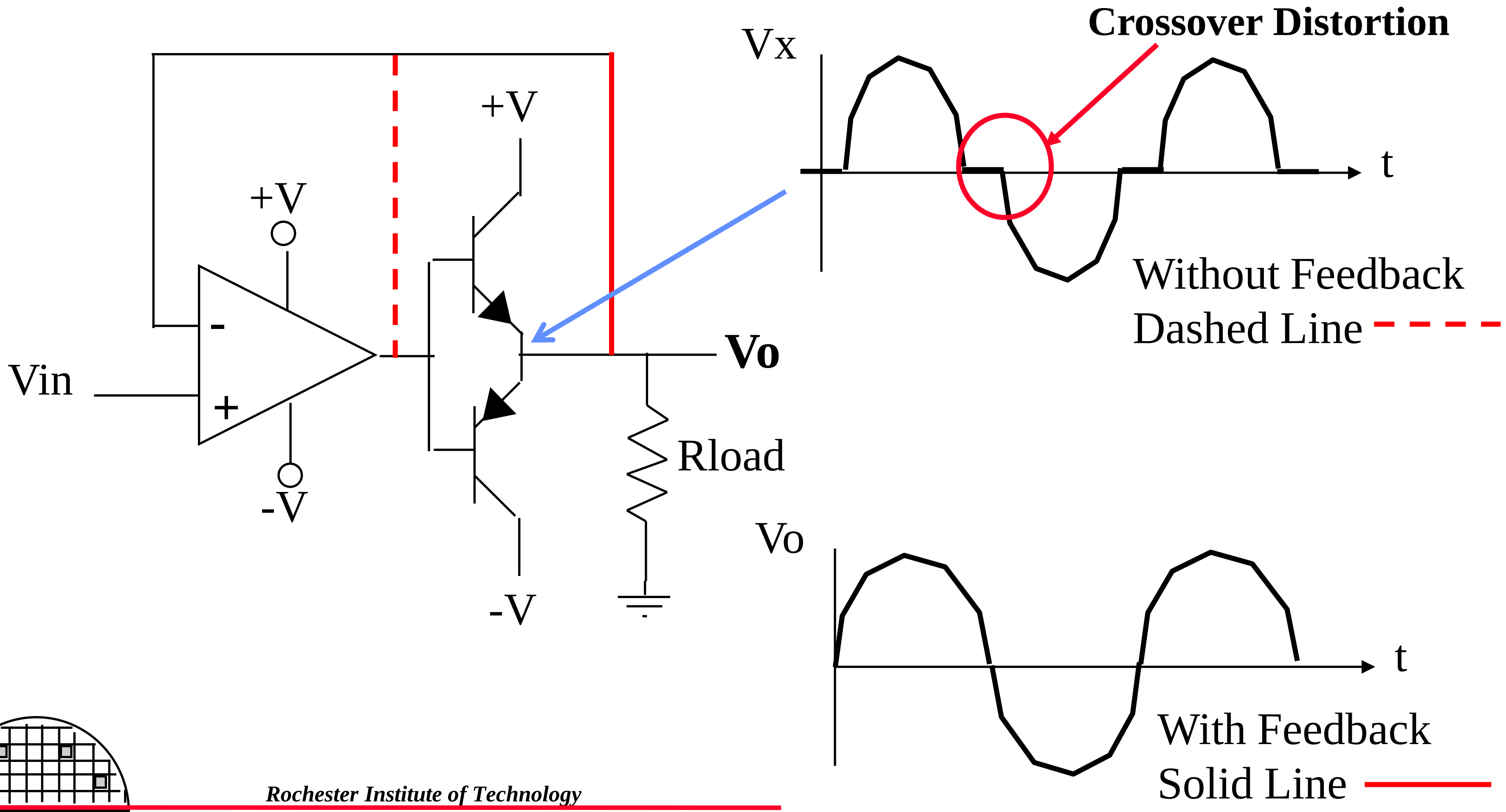
$$XL = A2\ XE' = A2\ (XI + XS')$$
$$XL = A2(A1XE + XS') = A2\ (A1(XS - XF) + XS')$$
$$XL = A2(A1(XS - BXL) + XS')$$

$$XL = A2A1XS - A2A1BXL + A2XS'$$

$$XL = \frac{A1A2}{(1 + A1A2B)} \left(XS + \frac{XS'}{A1} \right)$$

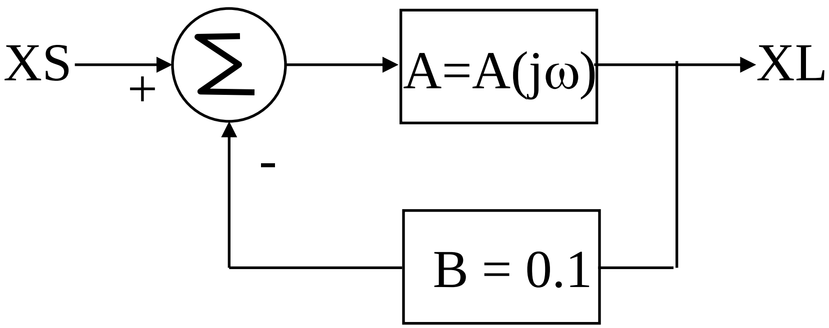
If Xs' were some unwanted signal, say distortion, we could decrease the effect of Xs' by introducing it as close as possible to the output of the amplifier. In other words make A, as large as possible, use feedback to achieve the desired gain and also reduce distortion introduced after A1. In many amplifiers distortion is introduced in the output stage, (crossover, etc.)

NEGATIVE FEEDBACK DECREASES DISTORTION



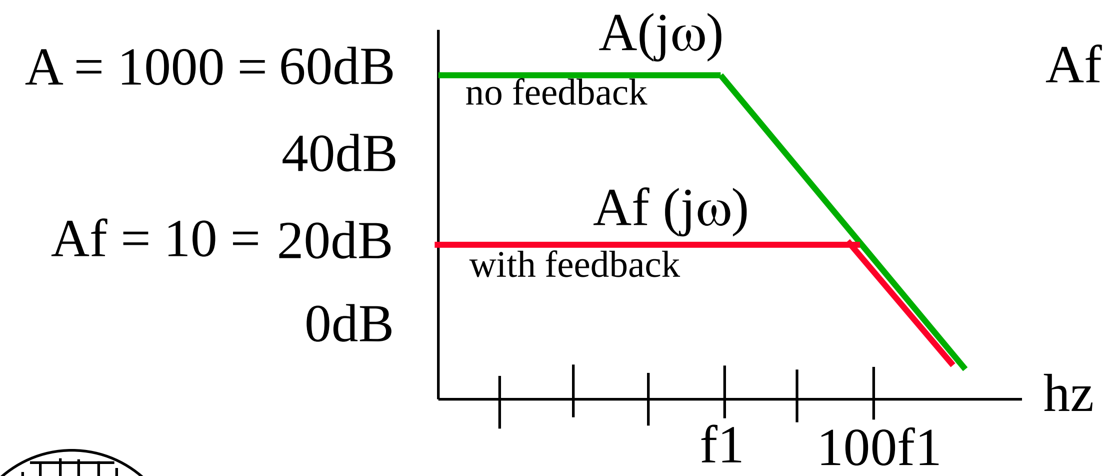
NEGATIVE FEEDBACK INCREASES BANDWITDTH

Bandwidth is the frequency range where the amplifier gain is flat.



$$A(j\omega) = \frac{1000}{1 + j\, f/f1}$$

Let f1 = 1000 hz



$$Af(jw) = \frac{A}{1+AB} = \frac{\dfrac{1000}{1+jf/f1}}{1+\dfrac{100}{1+jf/f1}}$$

$$= \frac{1000}{1+jf/f1 + 100}$$

$$Af(jw) = \frac{1000}{101} \quad \frac{1}{1+jf/(101\ f1)}$$

SUMMARY OF ADVANTAGES OF NEGATIVE FEEDBACK

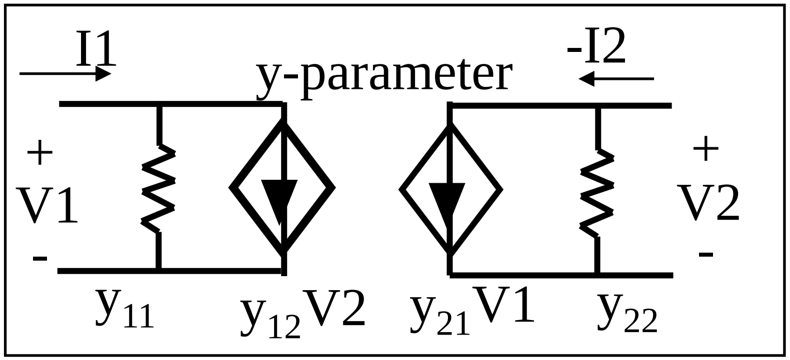
Negative feedback reduces the gain of an amplifier compared to the gain without feedback:

However, an amplifier with negative feedback has the following improvements

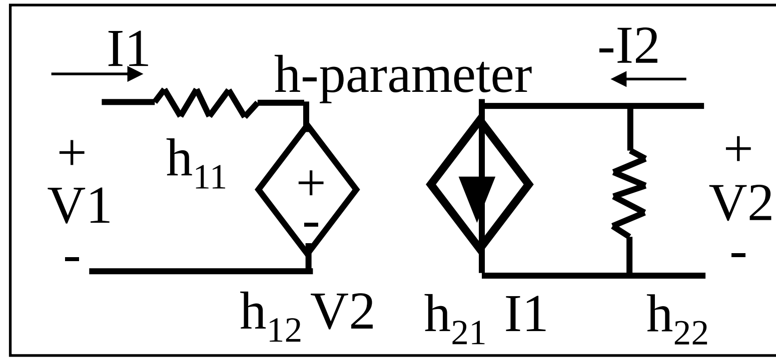
1. The gain with feedback is less sensitive to the amplifier gain value itself
2. Feedback can reduce unwanted distortion.
3. Feedback increases the bandwidth

REVIEW OF TWO PORT EQUIVALENT CIRCUITS

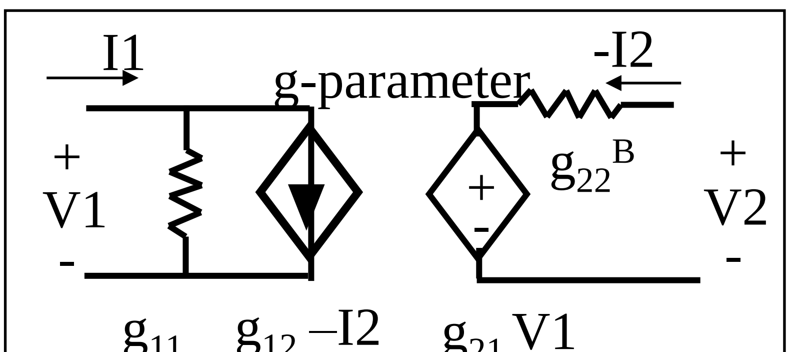
$$I1 = y_{11}\,V1 + y_{12}\,V2$$
$$I2 = y_{21}\,V1 + y_{22}\,V2$$



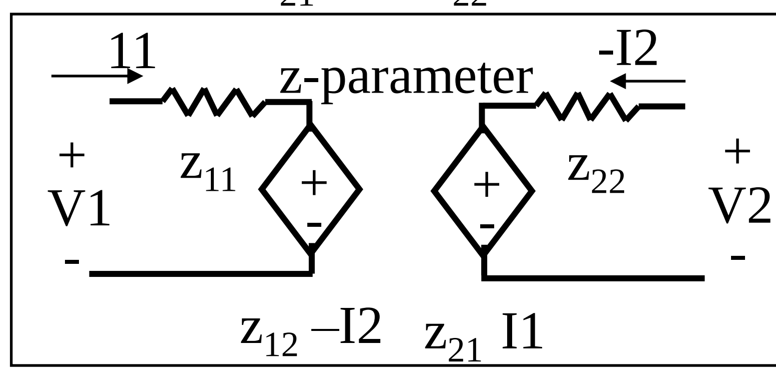
$$V1 = h_{11}\,I1 + h_{12}\,V2$$
$$I2 = h_{21}\,I1 + h_{22}\,V2$$



$$I1 = g_{11}\,V1 + g_{12}\,V2$$
$$I2 = g_{21}\,V1 + g_{22}\,V2$$



$$V1 = z_{11}\,I1 + z_{12}\,V2$$
$$I2 = z_{21}\,I1 + z_{22}\,V2$$



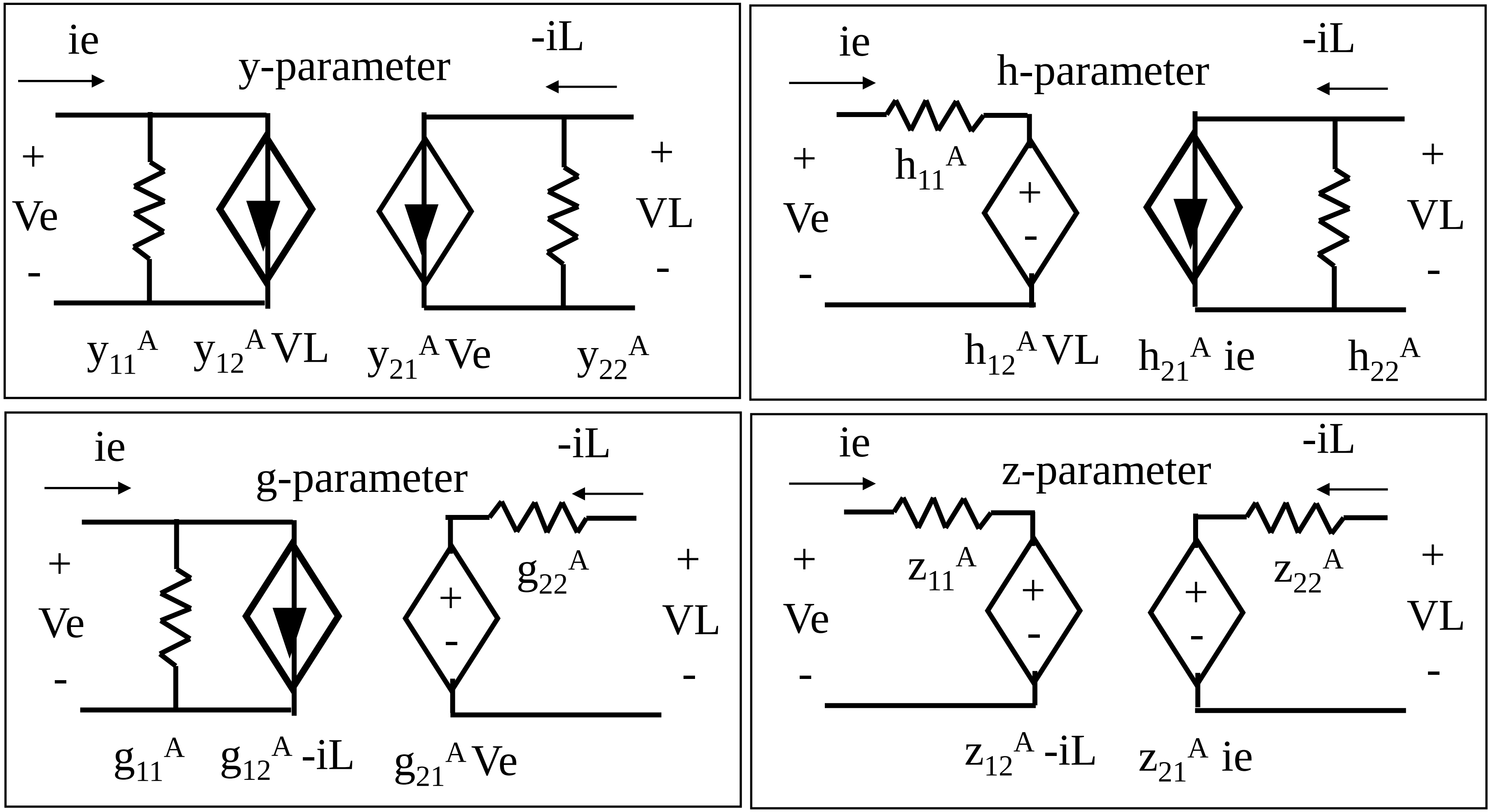
GENERALIZED APPROACH

A Generalized Approach for the Analysis of Feedback Amplifiers:

The components of a feedback amplifier are:

1. An Amplifier (y,g,h,z parameter two-port model)
2. A Feedback Network (y,g,h,z parameter two-port model)
3. A Sampling Network (series or parallel connections)
4. A Mixing or Comparing Network (connections)
5. A Load (a resistor)
6. A Source (Thevenin or Norton equivalent)

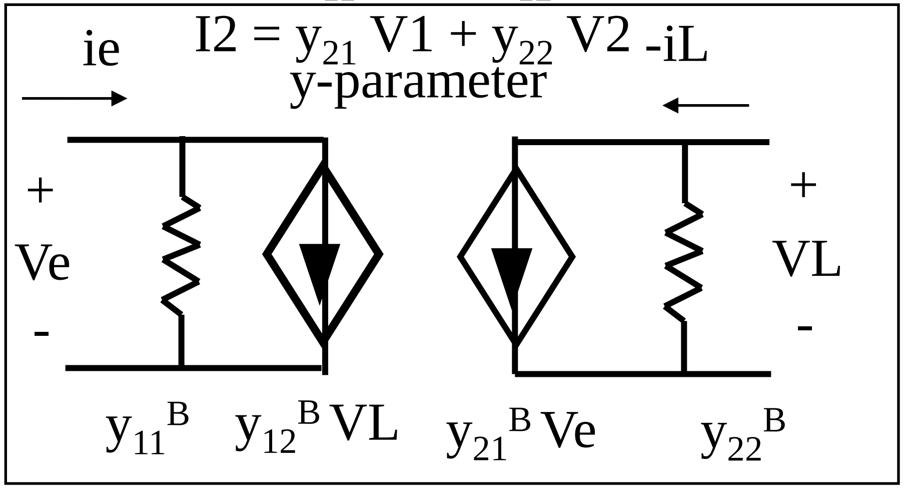
AMPLIFIER MODELS

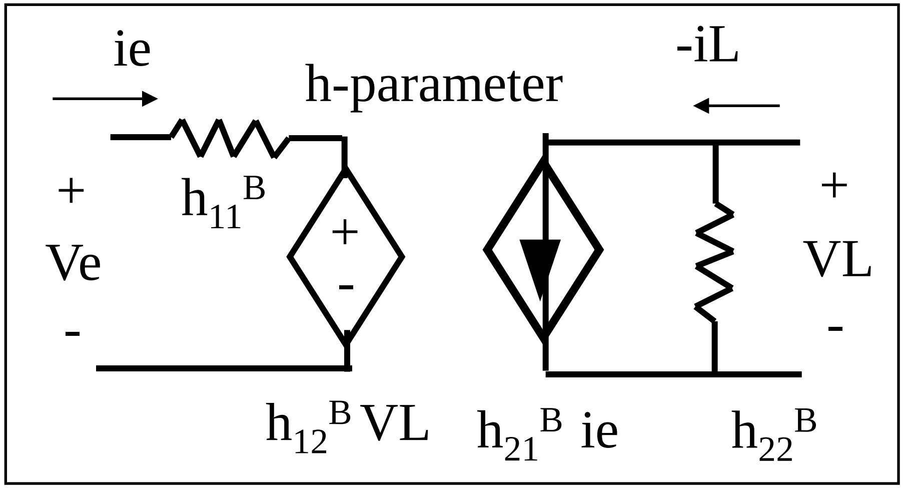


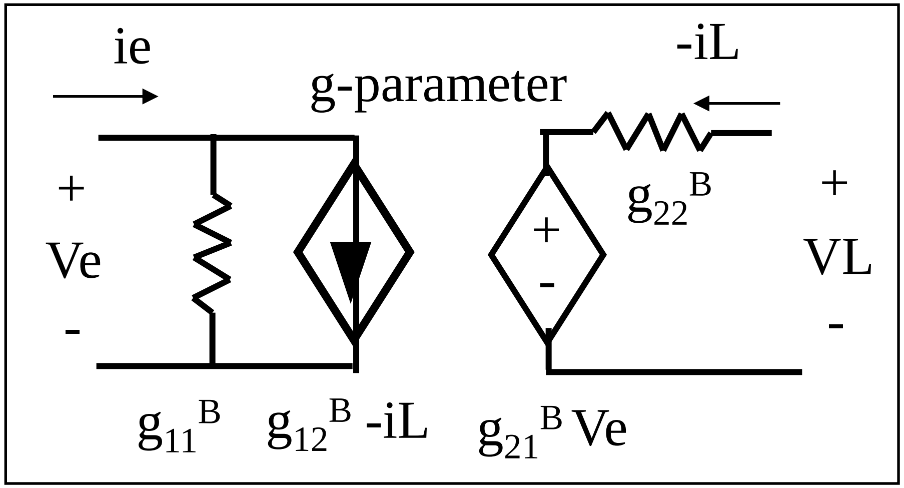
FEEDBACK NETWORK MODELS

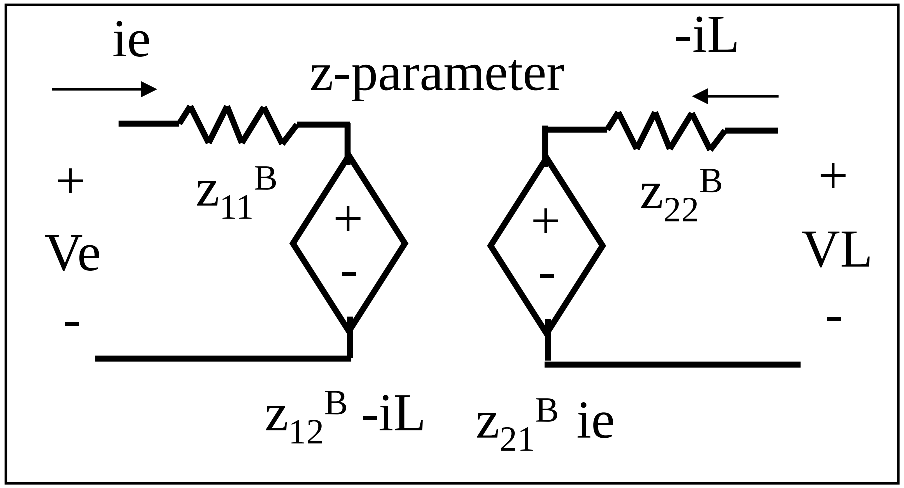
$I1 = y_{11}\ V1 + y_{12}\ V2$

$I2 = y_{21}\ V1 + y_{22}\ V2$









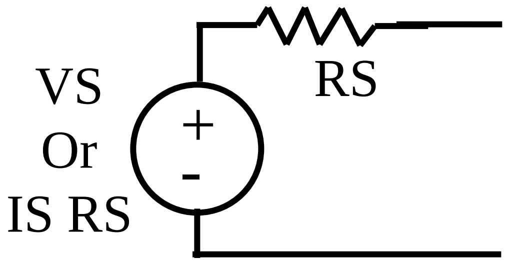
SAMPLING, MIXING, LOAD, SOURCE

3. The sampling network consists of the wires used to connect the feedback network to the amplifier. Sampling can be done in parallel (voltage sampling) or in series (current sampling) with the load.

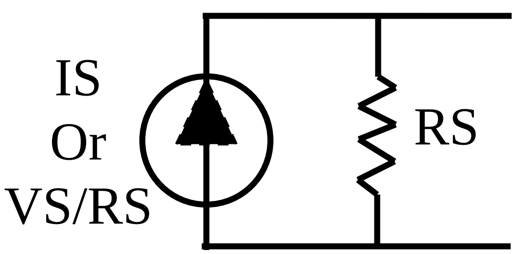
4. The mixing network consists of the wires used to connect the feedback network to the amplifier. Mixing can be in parallel (shunt) or series with the source.

5. The load is a resistor connected to the output of the amplifier.

6. The source is represented by its Thevinin or Norton equivalent circuit.



Thevinin

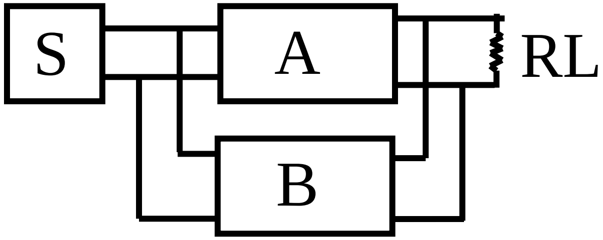


Norton

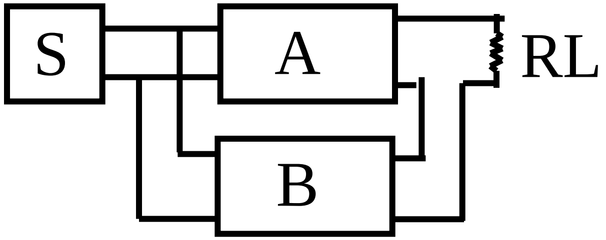
FEEDBACK AMPLIFIER CONFIGURATIONS

Since A and B are being considered as two-port networks there are four ways in which these two-port networks can be connected to provide feedback as shown below:

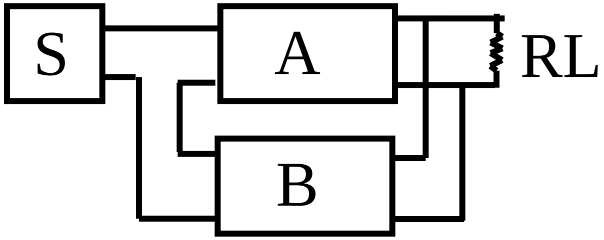
Voltage-Shunt Feedback
(use y parameters)



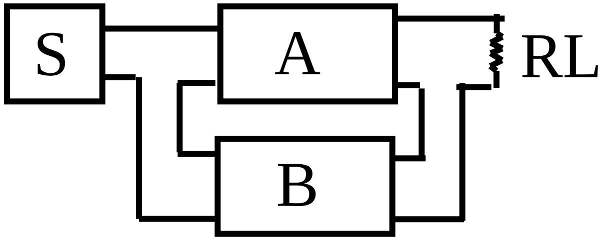
Current-Shunt Feedback
(use g parameters)



Voltage-Series Feedback
(use h parameters)

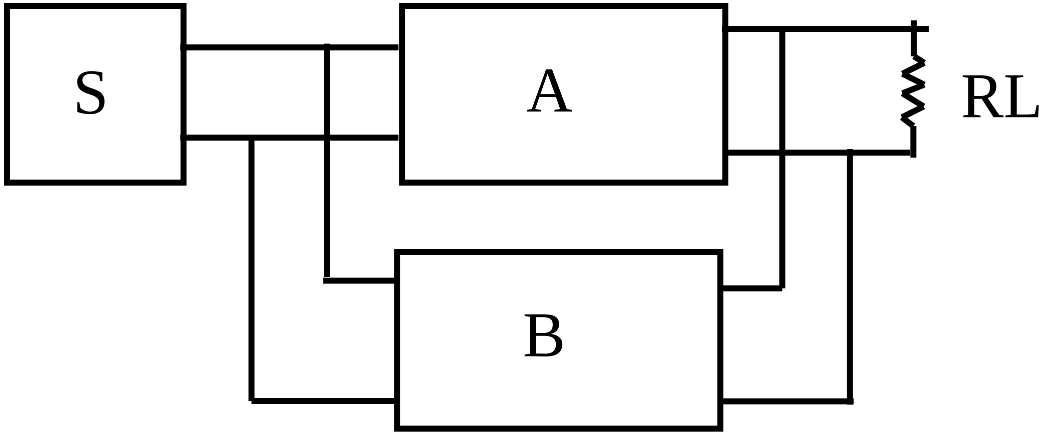


Current-Series Feedback
(use z parameters)



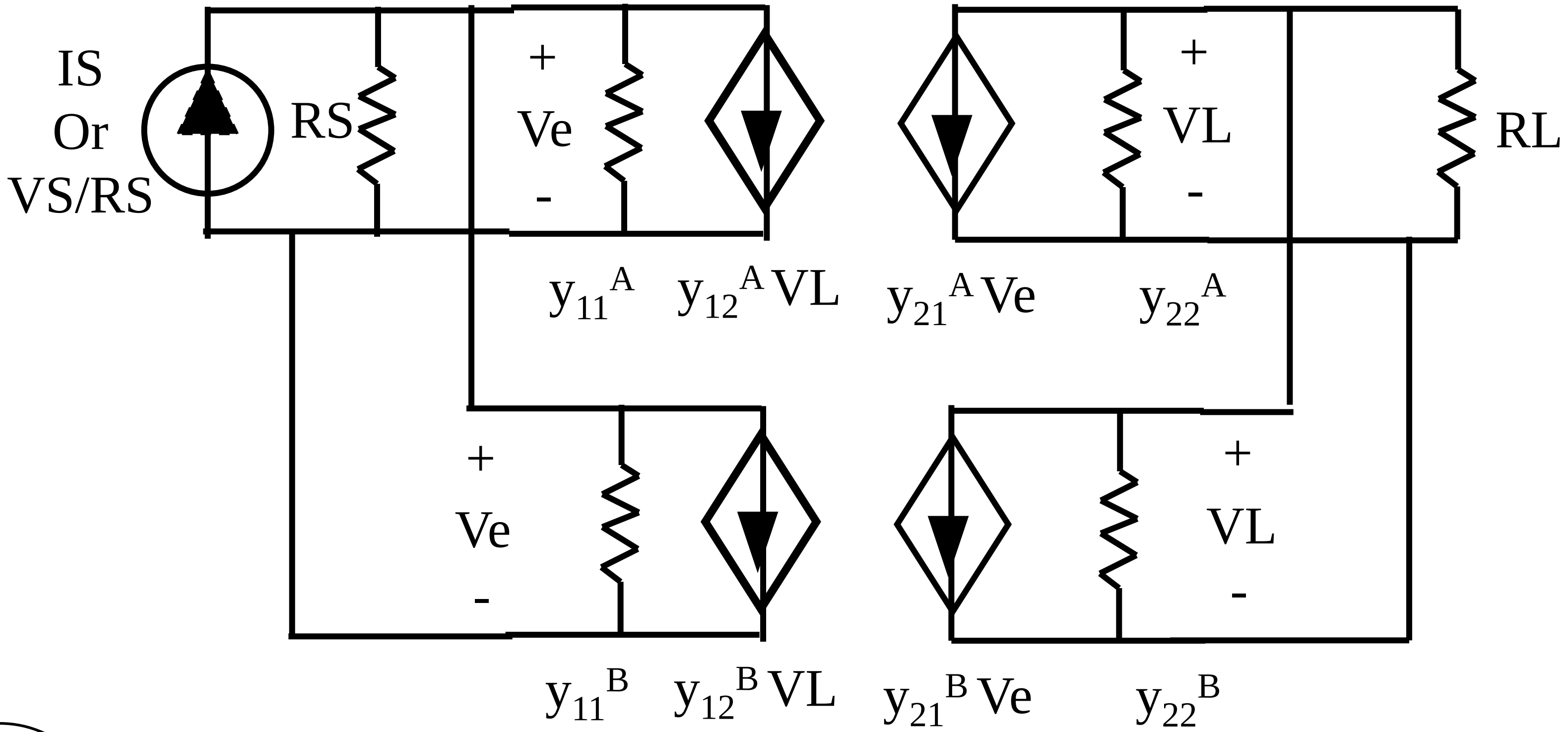
VOLTAGE-SHUNT FEEDBACK

Since **voltage – shunt** feedback implies parallel connections for the sampling and mixing networks. We will select, y-parameter two port models and a Norton model for the source. The resulting equivalent circuit can be greatly simplified by combining parallel current sources and parallel conductances.



VOLTAGE-SHUNT FEEDBACK

Select y-parameters and Norton equivalent circuits for voltage-shunt feedback:



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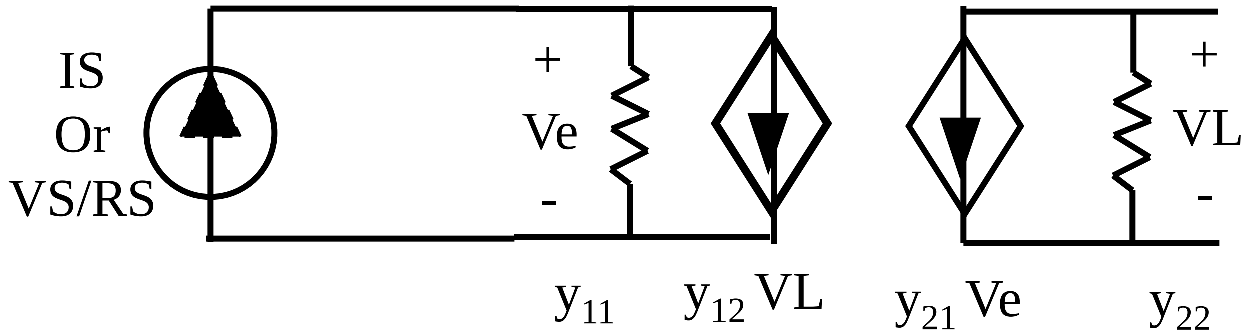
SIMPLIFIED VOLTAGE-SHUNT FEEDBACK

From the previous page we combine current sources in parallel and conductances in parallel. (the equivalent circuit is simplified)



$$y_{11} = y_{11}^{A} + y_{11}^{B} + 1/Rs$$

$$y_{22} = y_{22}^{A} + y_{22}^{B} + 1/RL$$

$$y_{12} = y_{12}^{A} + y_{12}^{B}$$

$$y_{21} = y_{21}^{A} + y_{21}^{B}$$

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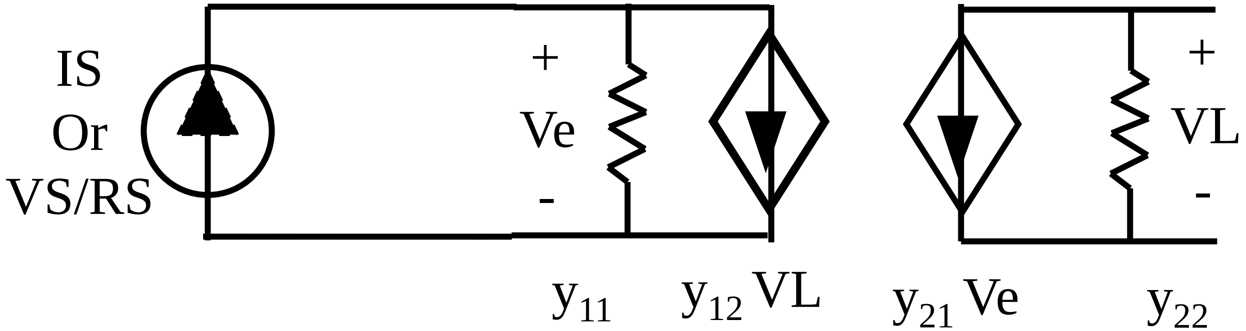
ANALYSIS OF VOLTAGE-SHUNT FEEDBACK



KCL gives $IS = y_{11}\,Ve + y_{12}\,VL$

$0 = y_{21}\,Ve + y_{22}\,VL$ this eqn gives $Ve = -y_{22}VL/y_{21}$

$IS = y_{11}(-y_{22}VL/y_{21}) + y_{12}\,VL = [-y_{11}y_{22}/y_{21} + y_{12}]VL$

$$VL/IS = \frac{1}{[y_{12}-y_{11}y_{22}/y_{21}]}$$

$$VL/IS = \frac{\dfrac{-y_{21}}{y_{11}y_{22}}}{1 + \dfrac{-y_{12}y_{21}}{y_{11}y_{22}}} \quad \Rightarrow \quad Af = \frac{A}{1 + AB}$$

ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

A_{Rf} = VL/IS is the gain with feedback : Notice that the gain with feedback, Af, for voltage-shunt feedback has units of ohms (Ω). Af is not a voltage gain, it is not a current gain, it is a transresistance.

Suppose we wanted a voltage gain instead of transresistance. Recall that IS came from the Norton equivalent of the source. Thus VS = IS RS

$$A_{Rf} = VL/IS$$

$$A_{Vf} = VL/VS = (VL/IS)\ (1/RS) = A_{Rf}\ (1/RS)$$

$$A_{If} = IL/VS = (VL/IS)\ (1/RL) = A_{Rf}\ (1/RL)$$

ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

$A_R = \dfrac{-y_{21}}{y_{11}y_{22}}$ is the gain of the feedback amplifier with the feedback disabled. A_R is not the gain of the feedback amplifier with the feedback disconnected.

$$A_{Rf} = \left. \frac{\dfrac{-y_{21}}{y_{11}y_{22}}}{1 + \dfrac{-y_{12}y_{21}}{y_{11}y_{22}}} \right|_{y_{12} = 0} = \frac{-y_{21}}{y_{11}y_{22}}$$

ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

$B = y_{12}$: this quantity is very important for estimating the gain of the amplifier with feedback

$$A_{Rf} \sim \frac{1}{B} = \frac{1}{y_{12}}$$

This approximation is good as y_{21} goes to infinity

$$A_{Rf} = \frac{\dfrac{-y_{21}}{y_{11}y_{22}}}{1 + \dfrac{-y_{12}y_{21}}{y_{11}y_{22}}}$$

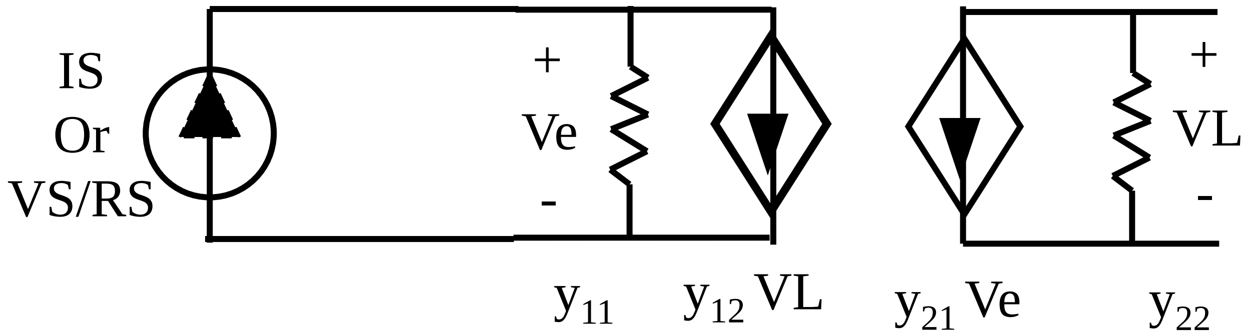
Exact gain

$$T = -BA = \frac{y_{12}y_{21}}{y_{11}y_{22}}$$

is the loop gain T

ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

Input Admittance, $Y_{If} = IS/Ve$



$IS = y_{11}\,Ve + y_{12}\,VL$

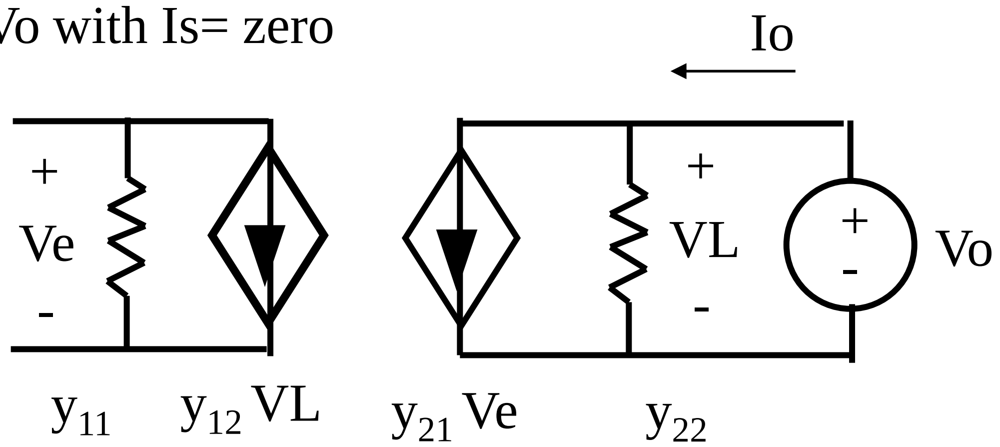
$0 = y_{21}\,Ve + y_{22}\,VL \longrightarrow VL = -y_{21}/y_{22}\,Ve$

$$IS = y_{11}\,Ve + y_{12}\left(-y_{21}/y_{22}\,Ve\right) = y_{11}\,Ve\left(1 - \frac{y_{12}y_{21}}{y_{11}y_{22}}\right)$$

$$Y_{If} = IS/Ve = y_{11}\left(1 - \frac{y_{12}y_{21}}{y_{11}y_{22}}\right) = y_{11}\left(1 - T\right)$$

ANALYSIS OF VOLTAGE-SHUNT FEEDBACK

Output Admittance, Y_{Of} = Io/Vo with Is= zero



$0 = y_{11}\,Ve + y_{12}\,Vo$

$Io = y_{21}\,Ve + y_{22}\,Vo$

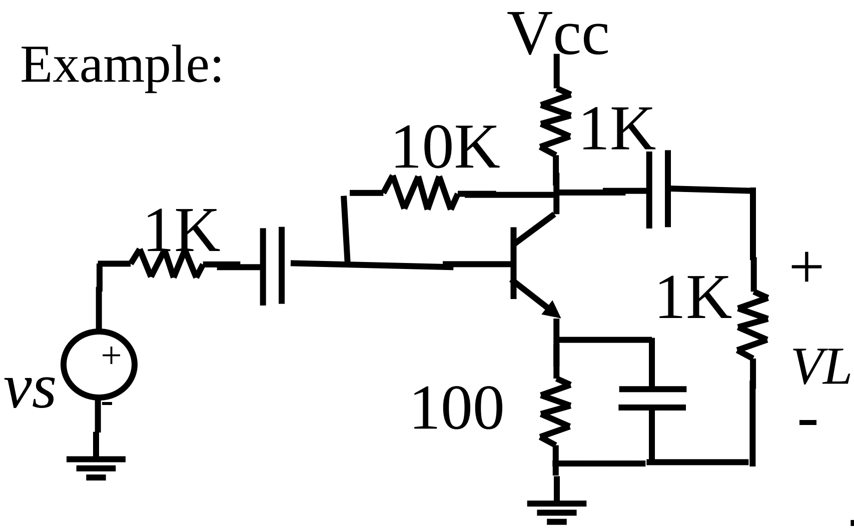
$\rightarrow Ve = -y_{12}/y_{11}\,Vo$

$$Io = y_{21}\left[-y_{12}/y_{11}\,Vo\right] + y_{22}\,Vo = y_{22}\,Vo\left(1 - \frac{y_{12}y_{21}}{y_{11}y_{22}}\right)$$

$$Y_{Of} = Io/Vo = y_{22}\left(1 - \frac{y_{12}y_{21}}{y_{11}y_{22}}\right) = y_{22}\left(1 - T\right)$$

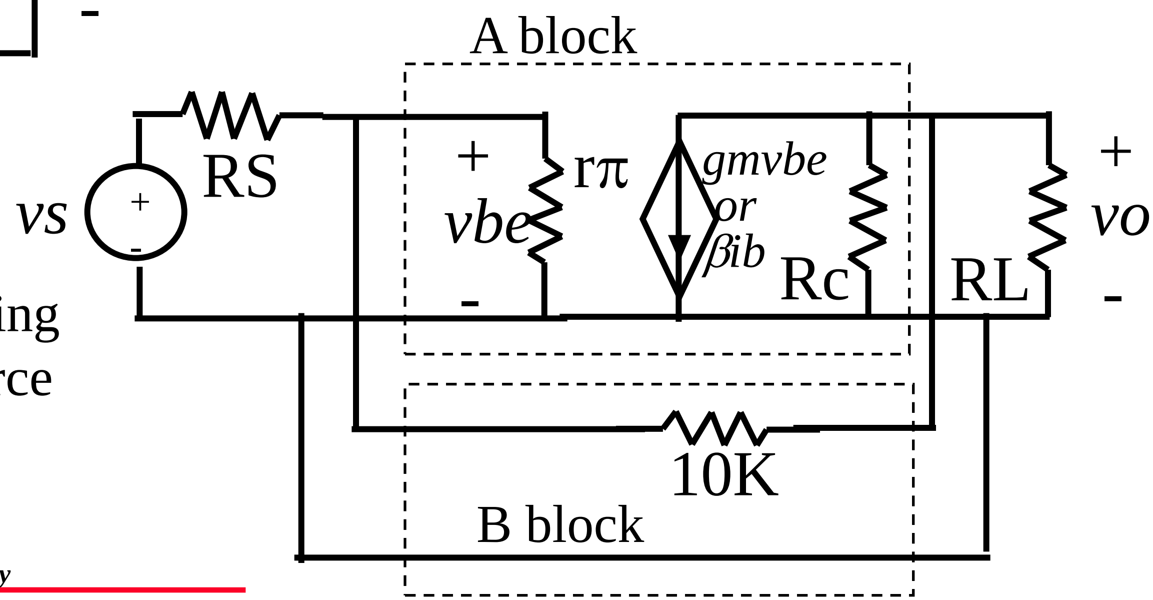
EXAMPLE VOLTAGE-SHUNT FEEDBACK

Example:



Assume DC analysis is good
β = 100, VA=infinite, rπ=1K

ac eq. ckt



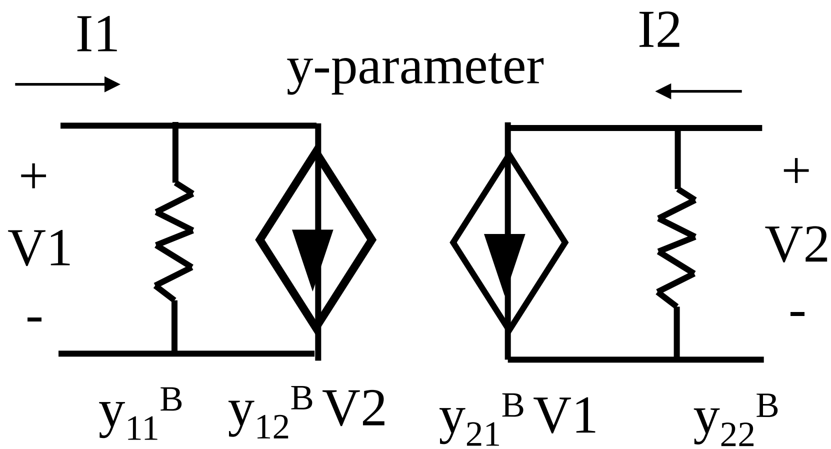
1. Identify A block, B block mixing network, sampling network, source and load.

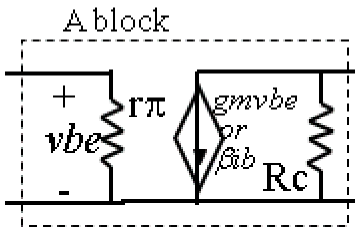
EXAMPLE VOLTAGE-SHUNT FEEDBACK

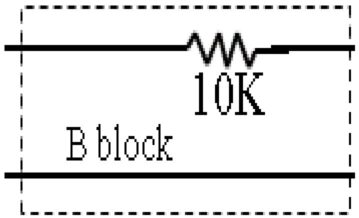
2. Find two port parameters for A block and B block.

$I1 = y_{11}\ V1 + y_{12}\ V2$

$I2 = y_{21}\ V1 + y_{22}\ V2$







y_{11}^{A} = 1/1K = 1E-3
y_{12}^{A} = 0 (almost always)
y_{21}^{A} = gm=B/rπ=0.1
y_{22}^{A} = 1/1K = 1E-3

y_{11}^{B} = 1/10K = 1E-4
y_{12}^{B} = -1/10K = -1E-4
y_{21}^{B} = -1/10K = -1E-4
y_{22}^{B} = 1/10K = 1E-4

EXAMPLE VOLTAGE-SHUNT FEEDBACK

3. Find the combined parameters

$y_{11} = y_{11}^{A} + y_{11}^{B} + 1/RS$	= 1e-3 + 1e-4 + 1e-3	= 2.1e-3
$y_{12} = y_{12}^{A} + y_{12}^{B}$	= 0 + -1e-4	= -1e-4
$y_{21} = y_{21}^{A} + y_{21}^{B}$	= 0.1 -1e-4	= 0.0999=0.1
$y_{22} = y_{22}^{A} + y_{22}^{B} + 1/RL$	=1e-3 + 1e-4 + 1e-3	= 2.1e-3

4. Compute quantities of interest

4.1 Gain with feedback (transresistance)

$$A_{Rf} = \frac{\dfrac{-y_{21}}{y_{11}y_{22}}}{1 + \dfrac{-y_{12}y_{21}}{y_{11}y_{22}}} = \frac{\dfrac{-0.1}{(2.1e\text{-}3)(2.1e\text{-}3)}}{1 + \dfrac{-0.1(-1e\text{-}4)}{(2.1e\text{-}3)(2.1e\text{-}3)}} = -6940 \text{ ohms}$$

4.2 Voltage gain with feedback

$$A_{Vf} = A_{Rf}\,(1/RS) = -6940\,(1/1000) = -6.94$$

EXAMPLE VOLTAGE-SHUNT FEEDBACK

4.3 Current Gain with Feedback

$$A_{If} = A_{Rf}\ (1/RL) = -6940\ (1/1000) = -6.94$$

4.4 Approximate Gain

$$A_{Rf} \sim = 1/y_{12} = -1/1e\text{-}4 = -10000 \text{ ohms}$$
$$A_{Vf} \sim = -10000\ (1/RS) = -10$$
$$A_{If} \sim = -10000\ (1/RL) = -10$$

4.5 Loop gain = T = $\dfrac{y_{12}y_{21}}{y_{11}y_{22}}$ = (-1e-4)(0.1)/(2.1e-3)(2.1e-3) = -2.27

EXAMPLE VOLTAGE-SHUNT FEEDBACK

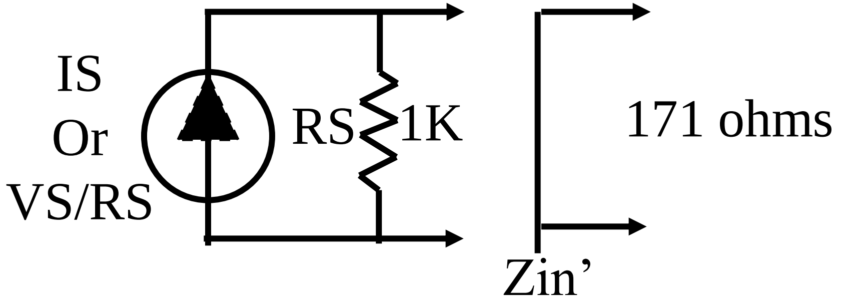
4.6 Input admittance $YIf = y_{11}\,(1 - T) = y_{11}\left(1 - \dfrac{y_{12}y_{21}}{y_{11}y_{22}}\right)$

$YIf = (2.1e\text{-}3)(1 - -2.27) = 6.86\ mS$

Input impedance ZIf = 1/YIf = 146 ohms

Note: this ZIf = 146 ohms is equal to the 1Kohm RS in parallel with Zin' the amplifier input impedance.

So 1000//Zin' = 146 therefore we can find Zin' = 171 ohms



EXAMPLE VOLTAGE-SHUNT FEEDBACK

4.7 Output Impedance Zof = 1/Yof

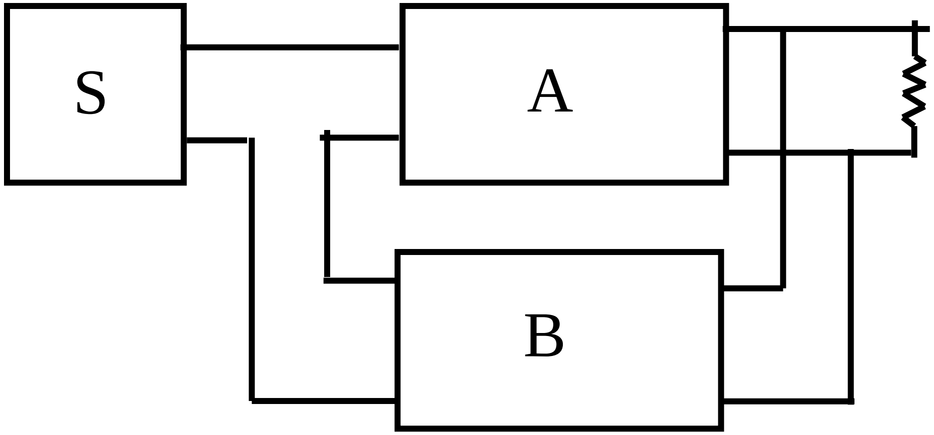
$Yof = y_{22}\ (1\text{-}T) = y_{22}\ (1\text{- -}2.27) = 6.86\ mS$

Zof = 1 / Yof = 146 ohms

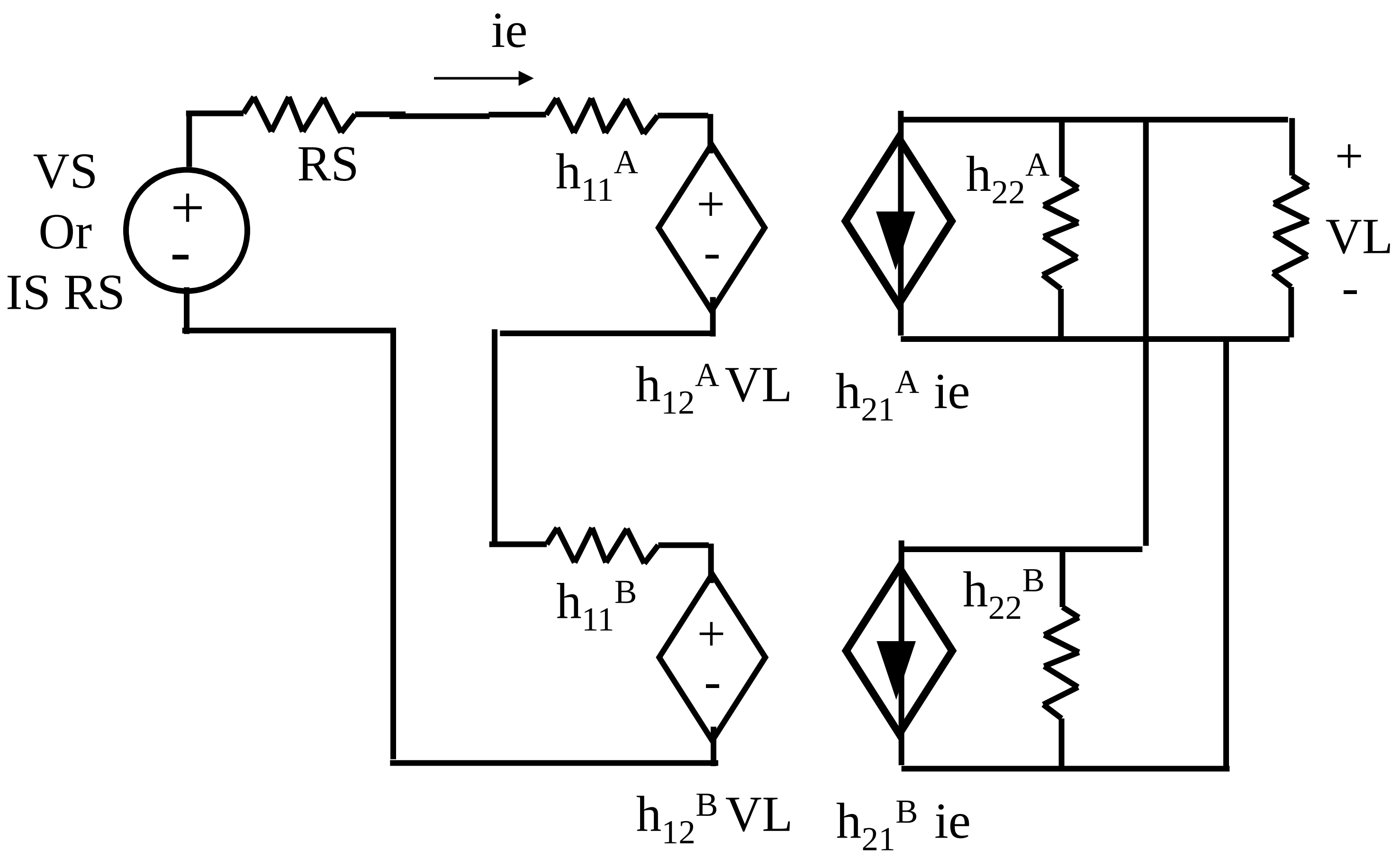
Note: this 146 includes the 1000 ohm RL
so Zo’ (without RL) is = 171 ohms

VOLTAGE SERIES FEEDBACK

Since **voltage – series** feedback implies parallel connection at the load and series connection at the source, we will select, h-parameter two port models and a Thevenin model for the source. The resulting equivalent circuit can be greatly simplified by combining appropriate components



VOLTAGE SERIES FEEDBACK



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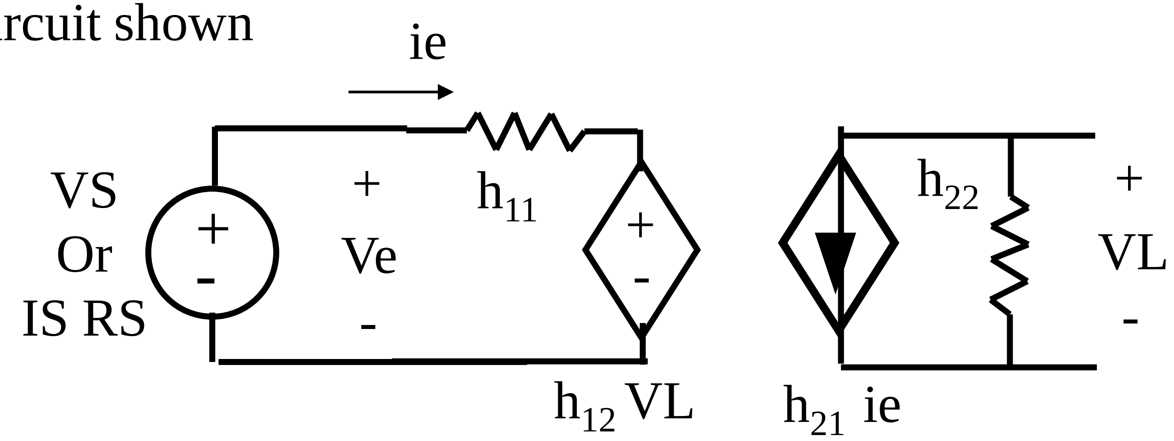
SIMPLIFIED VOLTAGE-SERIES FEEDBACK

From the previous page we combine appropriate components to get the equivalent circuit shown



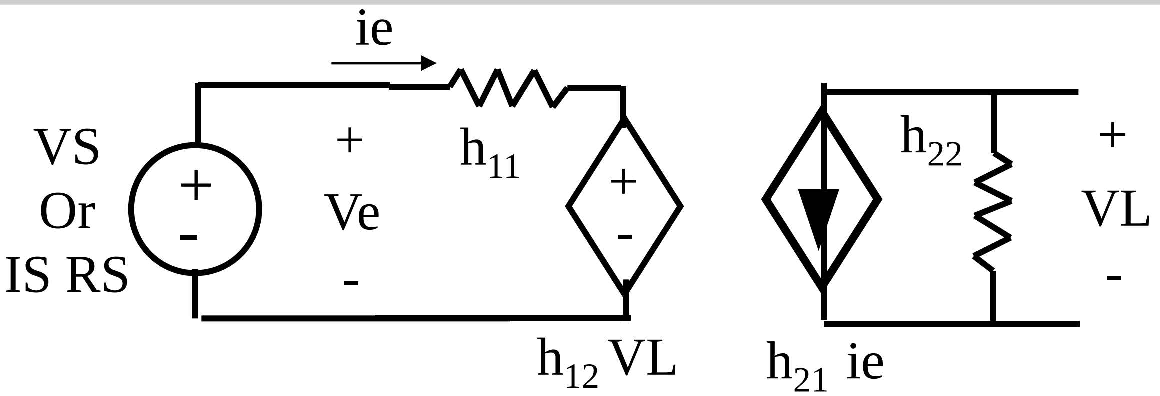
$$h_{11} = h_{11}^A + h_{11}^B + Rs$$

$$h_{22} = h_{22}^A + h_{22}^B + 1/RL$$

$$h_{12} = h_{12}^A + h_{12}^B$$

$$h_{21} = h_{21}^A + h_{21}^B$$

ANALYSIS OF VOLTAGE-SERIES FEEDBACK



KVL gives $VS = h_{11}\, ie + h_{12}\, VL$

KCL gives $0 = h_{21}\, ie + h_{22}\, VL$ this eqn gives $ie = -h_{22} VL / h_{21}$

$$VS = h_{11}(-h_{22}VL/h_{21}) + h_{12}\, VL = [-h_{11}h_{22}/h_{21} + h_{12}]VL$$

$$VL/VS = \frac{1}{[h_{12} - h_{11}h_{22}/h_{21}]}$$

$$VL/VS = \frac{\dfrac{-h_{21}}{h_{11}h_{22}}}{1 + \dfrac{-h_{12}h_{21}}{h_{11}h_{22}}} \Rightarrow Af = \frac{A}{1 + AB}$$

VOLTAGE SERIES FEEDBACK

Gain with Feedback

$$A_{Vf} = \frac{\dfrac{-h_{21}}{h_{11}h_{22}}}{1 + \dfrac{-h_{12}h_{21}}{h_{11}h_{22}}}$$

This is a voltage gain (other gains can be found)

Gain with Feedback Disabled

$$A_V = \frac{-h_{21}}{h_{11}h_{22}}$$

Approximate Gain

$$B \sim= \frac{1}{h_{12}}$$

Loop Gain

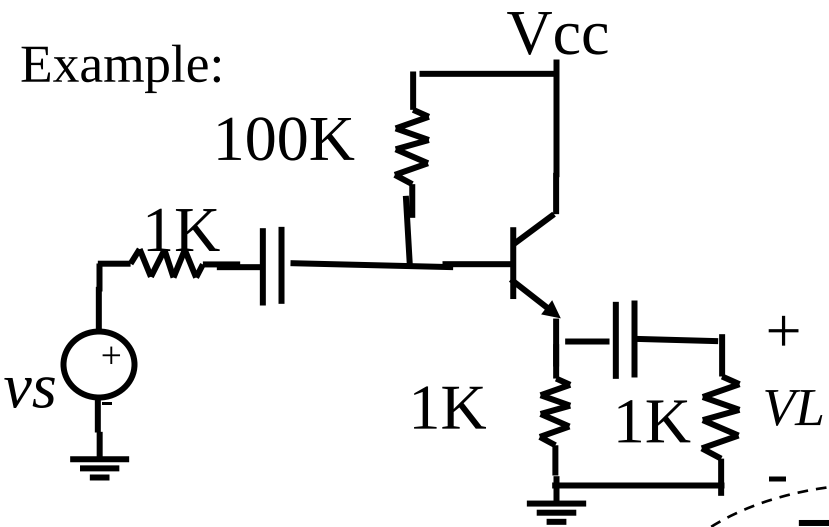
$$T = \frac{h_{12}h_{21}}{h_{11}h_{22}}$$

Input Impedance $ZIf = h_{11}\,(1-T)$

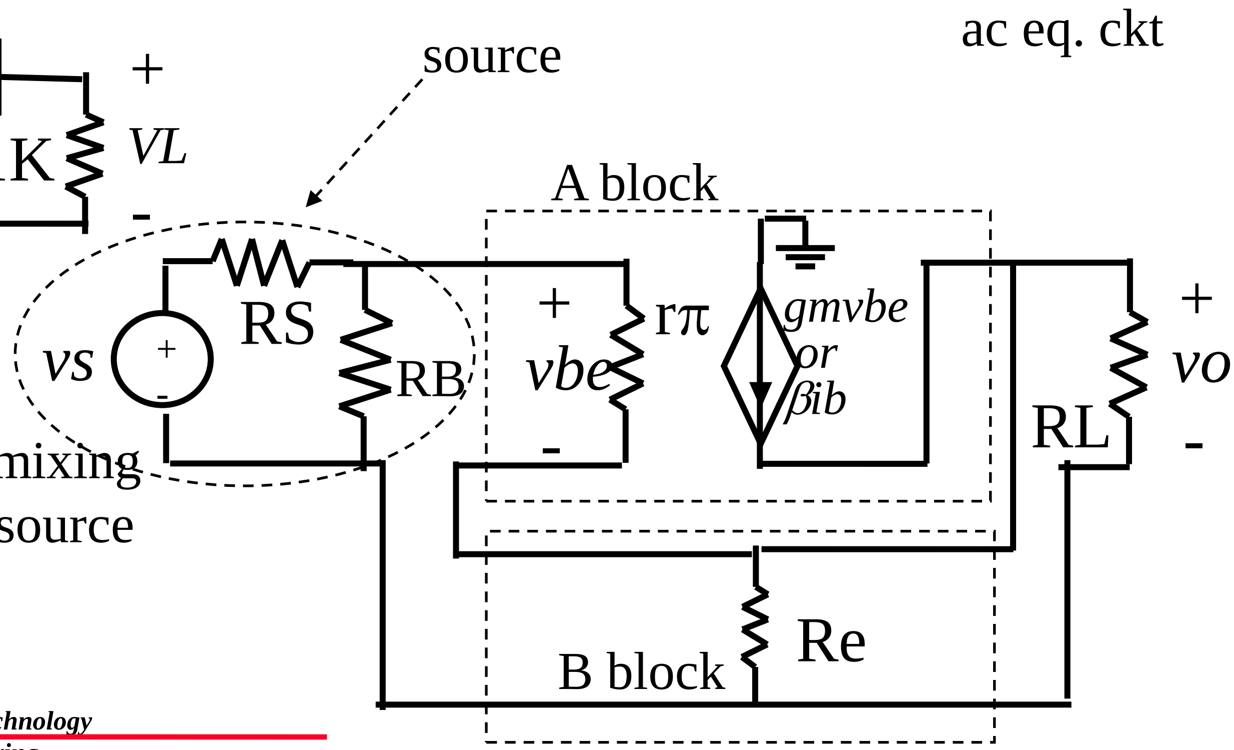
Output Admittance $Yof = h_{22}\,(1-T)$

EXAMPLE VOLTAGE-SERIES FEEDBACK

Example:



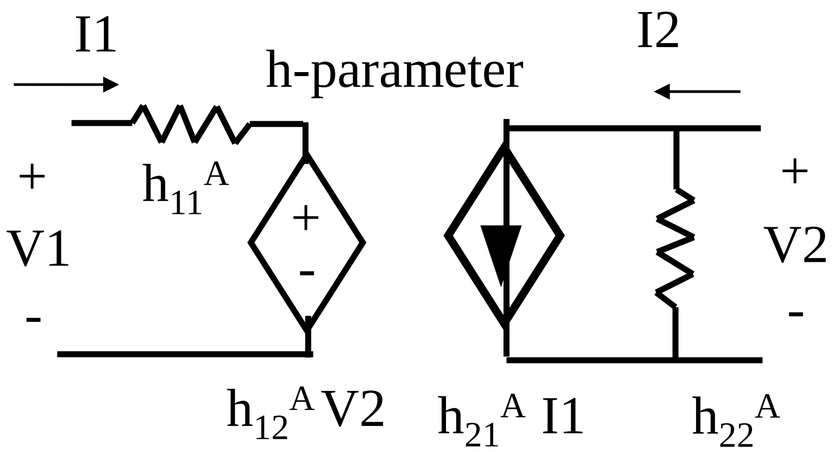
Assume DC analysis is good
β = 100, VA=infinite, rπ=1K



1. Identify A block, B block mixing network, sampling network, source and load.

EXAMPLE VOLTAGE-SERIES FEEDBACK

2. Find two port parameters for A block and B block.



$V1 = h_{11}\ I1 + h_{12}\ V2$
$I2 = h_{21}\ I1 + h_{22}\ V2$

$h_{11}^A = r\pi = 1000$
$h_{12}^A = 0$
$h_{21}^A = \beta = -100$
$h_{22}^A = 1/ro = 0$

$h_{11}^B = 0$
$h_{12}^B = 1$
$h_{21}^B = -1$
$h_{22}^B = 1/Re = 1E\text{-}3$

EXAMPLE VOLTAGE-SERIES FEEDBACK

3. Find the combined parameters

$h_{11} = h_{11}^{A} + h_{11}^{B} + RS//RB$	$= 1000 + 0 + 1000$	$= 2000$
$h_{12} = h_{12}^{A} + h_{12}^{B}$	$= 0 + 1$	$= 1$
$h_{21} = h_{21}^{A} + h_{21}^{B}$	$= -100 - 1$	$= -101$
$h_{22} = h_{22}^{A} + h_{22}^{B} + 1/RL$	$= 0 + 1e\text{-}3 + 1e\text{-}3$	$= 2e\text{-}3$

4. Compute quantities of interest

4.1 Gain with feedback (Voltage Gain)

$$A_{Vf} = \frac{\dfrac{-h_{21}}{h_{11}h_{22}}}{1 + \dfrac{-h_{12}h_{21}}{h_{11}h_{22}}} = \frac{\dfrac{101}{(2000)(2e\text{-}3)}}{1 + \dfrac{(101)(1)}{(2000)(2e\text{-}3)}} = 0.962$$

EXAMPLE VOLTAGE-SERIES FEEDBACK

4.2 Approximate Voltage Gain

$$A_{Vf} \sim = 1/h_{12} = 1$$

4.3 Loop gain = T = $\dfrac{h_{12}h_{21}}{h_{11}h_{22}}$ = (-101)(1)/(2000)(2e-3) = -25.3

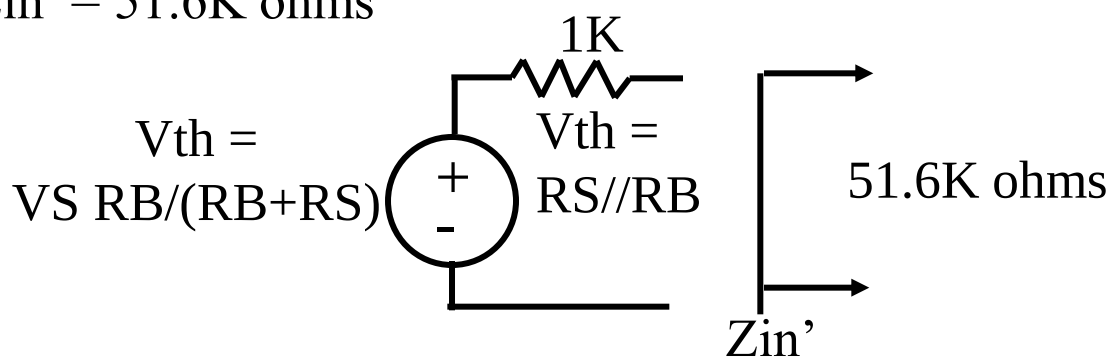
EXAMPLE VOLTAGE-SERIES FEEDBACK

4.4 Input impedance $ZIf = h_{11}(1- T) = h_{11}\left(1 - \frac{h_{12}h_{21}}{h_{11}h_{22}}\right)$

$ZIf = (2000)(1- -25.3) = 52.6Kohm$

Note: this ZIf = 52.6K ohms is equal to the 1Kohm RS//RB in series with Zin' the amplifier input impedance.

So Zin' = 51.6K ohms



EXAMPLE VOLTAGE-SERIES FEEDBACK

4.5 Output Impedance Zof = 1/Yof

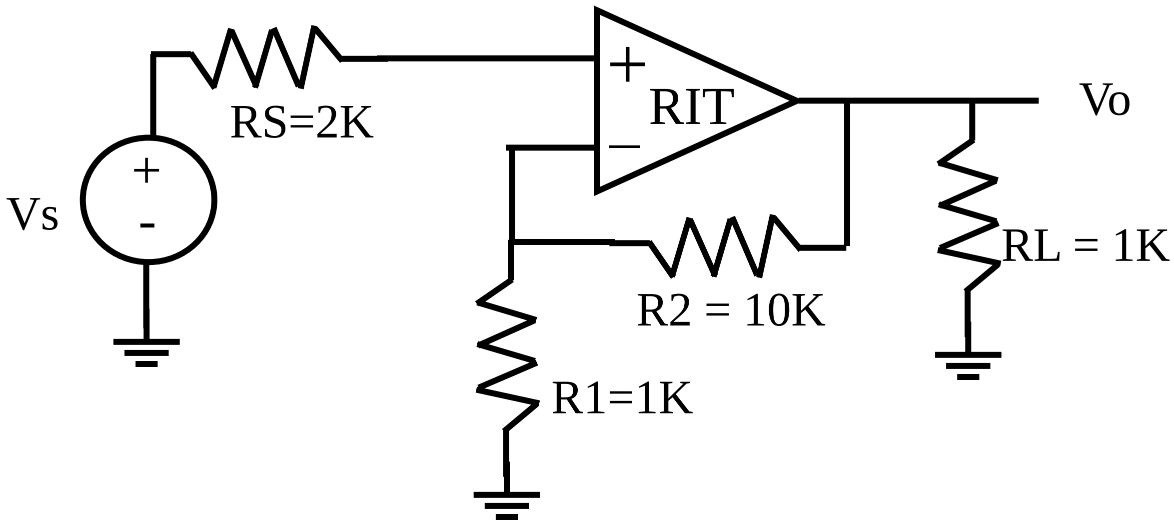
$Yof = h_{22}$ (1-T) = 2E-3 (1- -25.3) = 50.6 mS

Zof = 1 / Yof = 19.8 ohms

Note: this 19.8 includes the 1000 ohm RL
so Zo' (without RL) is = 20.1 ohms

EXAMPLE RIT OP AMP

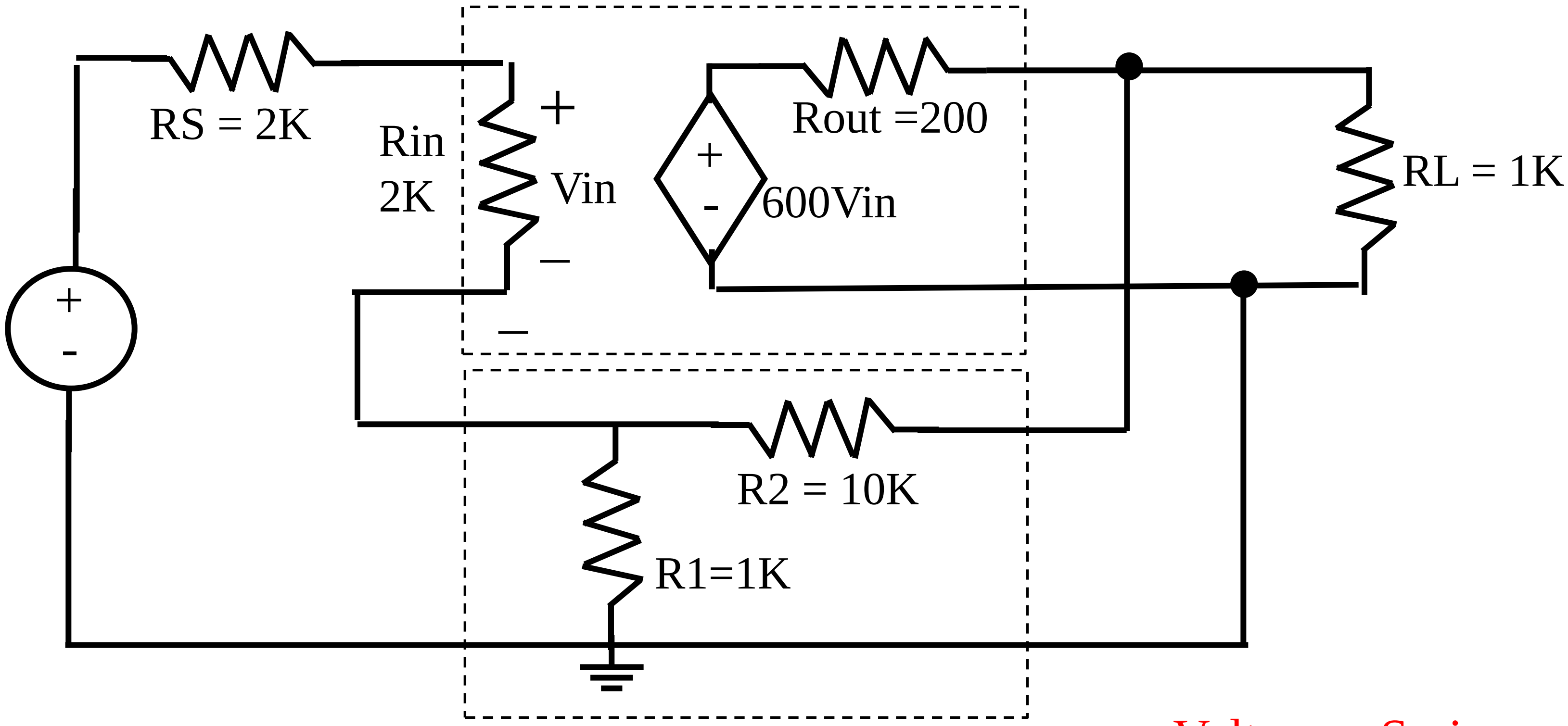
Lets use feedback to get the exact voltage gain, approximate voltage gain, input impedance and output impedance for the circuit below. The Op Amp is the one you built in lab with a differential amplifier, level shift stage and output stage. The overall voltage gain was 600 V/V and the differential input resistance was ~2K ohms. The output resistance was ~200 ohms.



Identify the feedback and make sure it is negative feedback.

EXAMPLE RIT OP AMP

The small signal ac equivalent circuit of the feedback amplifier on the previous page is:



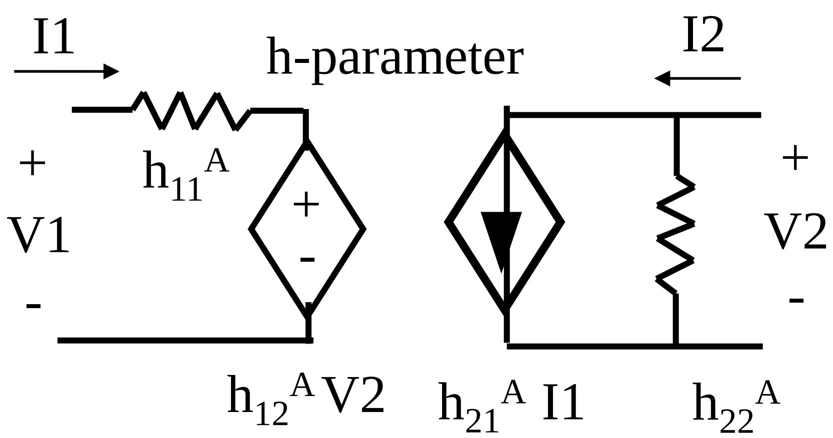
Voltage – Series
h - parameters

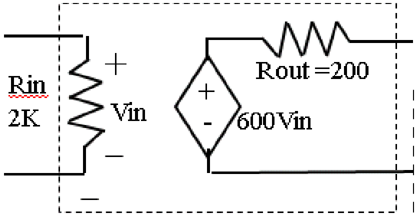
EXAMPLE VOLTAGE-SERIES FEEDBACK

Find two port parameters for A block and B block.

$V1 = h_{11}\ I1 + h_{12}\ V2$

$I2 = h_{21}\ I1 + h_{22}\ V2$





$h_{11}{}^{A} = 2K$

$h_{12}{}^{A} = 0$

$h_{21}{}^{A} = -6000$

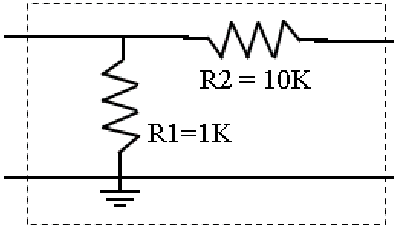
$h_{22}{}^{A} = 1/200 = 5E\text{-}3$

$h_{11}{}^{B} = 1K//10K = 909$

$h_{12}{}^{B} = 1/11 = 0.0909$

$h_{21}{}^{B} = -\ 0.0909$

$h_{22}{}^{B} = 1/11K = 9.09E\text{-}5$



EXAMPLE VOLTAGE-SERIES FEEDBACK

Find the combined parameters

$h_{11} = h_{11}^A + h_{11}^B + RS$ = 2000 + 909 + 2000 = 4909

$h_{12} = h_{12}^A + h_{12}^B$ = 0 + 0.0909 = 0.0909

$h_{21} = h_{21}^A + h_{21}^B$ = -6000 = -6000

$h_{22} = h_{22}^A + h_{22}^B + 1/RL$ = 1/200+1/11K + 1/1K = 6.091E-3

Compute quantities of interest

1. Exact Gain with feedback (Voltage Gain)

$$A_{Vf} = \frac{\dfrac{-h_{21}}{h_{11}h_{22}}}{1 + \dfrac{-h_{12}h_{21}}{h_{11}h_{22}}} = \frac{\dfrac{- -6000}{(4909)(6.091e\text{-}3)}}{1 + \dfrac{(- -6000)(0.0909)}{(4909)(6.09e\text{-}3)}} = 10.4$$

EXAMPLE VOLTAGE-SERIES FEEDBACK

2. Approximate Voltage Gain

$A_{Vf} \sim = 1/h_{12} = 1/0.0909 = 11$ which agrees with ideal op amp theory

3. Loop gain = T = $\dfrac{h_{12}h_{21}}{h_{11}h_{22}} = -18.2$

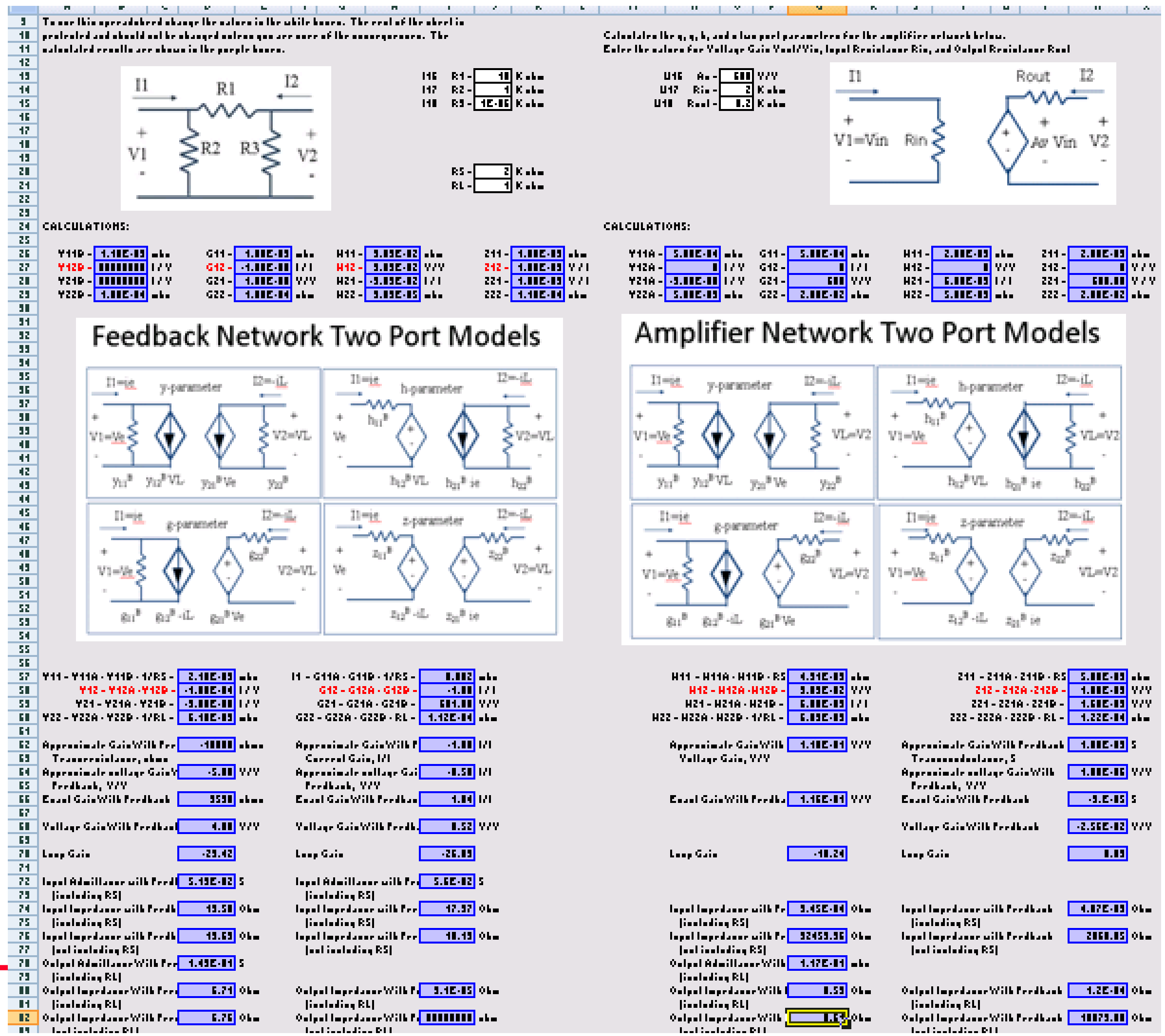
4. Input Impedance $Z_{If} = h_{11}\left(1 - T\right)$

= 4909 (1 - -18.2) = 94.5K
but includes RS
= 94.5K-2K=92.5K without RS

5. Output Impedance $Y_{Of} = h_{22}\left(1 - T\right)$

= 6.09E-3 (1 - -18.2) = 0.117S
but includes RL
Zout = 1/0.117 = 8.53 ohms
but includes RL
Zout=Z'out//RL=8.53 ohms
Z'out = 8.61 ohm without RL

SPREAD SHEET



SUMMARY OF FEEDBACK AMPLIFIERS

Voltage-Shunt

Input Admittance

$$Y_{If} = y_{11}\left(1-T\right)$$

$$Y_{Of} = y_{22}\left(1-T\right)$$

Output Admittance

Loop Gain

$$T = \frac{y_{12}y_{21}}{y_{11}y_{22}}$$

$$A_{Rf} \cong \frac{1}{y_{12}}$$

~ Gain

Exact Gain

$$A_{Rf} = \frac{\dfrac{-y_{21}}{y_{11}y_{22}}}{1+\dfrac{-y_{12}y_{21}}{y_{11}y_{22}}}$$

Transresistance

Voltage Gain

$$A_{Vf} = A_{Rf}\ (1/RS)$$

$$A_{If} = A_{Rf}\ (1/RL)$$

Current Gain

Voltage-Series

Input Impedance

$$Z_{If} = h_{11}\left(1-T\right)$$

$$Y_{Of} = h_{22}\left(1-T\right)$$

Output Admittance

Loop Gain

$$T = \frac{h_{12}h_{21}}{h_{11}h_{22}}$$

$$A_{Vf} \cong \frac{1}{h_{12}}$$

~ Gain

Exact Gain

$$A_{Vf} = \frac{\dfrac{-h_{21}}{h_{11}h_{22}}}{1+\dfrac{-h_{12}h_{21}}{h_{11}h_{22}}}$$

Voltage gain

Voltage Gain

$$A_{Vf} = A_{Vf}$$

$$A_{If} = A_{Vf}\ (RS/RL)$$

Current Gain

SUMMARY OF FEEDBACK AMPLIFIERS

Current-Shunt

Input Admittance

$$Y_{Of} = g_{22}\left(1-T\right)$$

$$Z_{If} = g_{11}\left(1-T\right)$$

Output Impedance

Loop Gain

$$T = \frac{g_{12}g_{21}}{g_{11}g_{22}}$$

$$A_{If} \cong \frac{1}{g_{12}}$$

~ Gain

Exact Gain

$$A_{If} = \frac{\dfrac{-g_{21}}{g_{11}g_{22}}}{1 + \dfrac{-g_{12}g_{21}}{g_{11}g_{22}}}$$

Current Gain

Voltage Gain

$$A_{Vf} = A_{If}\ (-RL/RS)$$

$$A_{If} = A_{If}$$

Current Gain

Current-Series

Input Impedance

$$Z_{Of} = z_{22}\left(1-T\right)$$

$$Z_{If} = z_{11}\left(1-T\right)$$

Output Impedance

Loop Gain

$$T = \frac{z_{12}z_{21}}{z_{11}z_{22}}$$

$$A_{Gf} \cong \frac{1}{z_{12}}$$

~ Gain

Exact Gain

$$A_{Gf} = \frac{\dfrac{-z_{21}}{z_{11}z_{22}}}{1 + \dfrac{-z_{12}z_{21}}{z_{11}z_{22}}}$$

Transconductance

Voltage Gain

$$A_{Vf} = A_{Gf}\ (-RL)$$

$$A_{If} = A_{Gf}\ (RS)$$

Current Gain

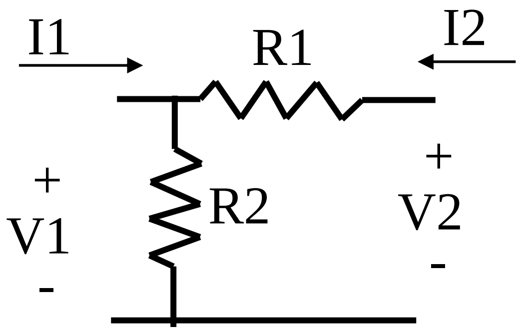
REFERENCES

1. Sedra and Smith, 5.1-5.4
2. Device Electronics for Integrated Circuits, 2nd Edition, Kamins and Muller, John Wiley and Sons, 1986.
3. The Bipolar Junction Transistor, 2nd Edition, Gerald Neudeck, Addison-Wesley, 1989.

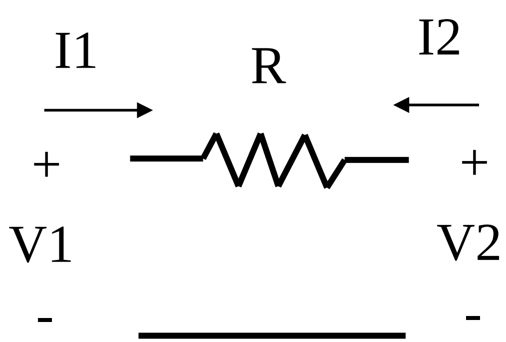
HOMEWORK PROBLEM 1

1. Find all 16 two port parameters for each of the following circuits.

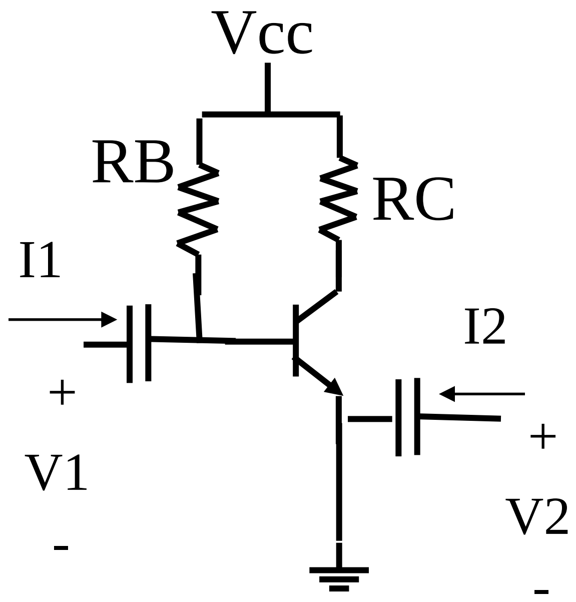
1a)



1b)



1c)



HOMEWORK SOLUTION FOR PROBLEM 1

1a)
y11 = 1/(R1 // R2)
y12 = - 1/R1
y21 = - 1/R1
y22 = 1/R1

z11 = R2
z12 = R2
z21 = R2
z22 = R1 + R2

h11 = R1 // R2
h12 = R2 / (R1+R2)
h21 = -R2 / (R1+R2)
h22 = 1/ (R1+R2)

g11 = 1/R2
g12 = -1
g21 = 1
g22 = R1

1b)
y11 = 1/R
y12 = - 1/R
y21 = - 1/R
y22 = 1/R

z11 = infinity
z12 = infinity
z21 = infinity
z22 = infinity

h11 = R
h12 = 1
h21 = -1
h22 = 0

g11 = 0
g12 = -1
g21 = 1
g22 = R

1c)
y11 = 1/(RB // rπ)
y12 = 0
y21 = gm
y22 = 1/RC

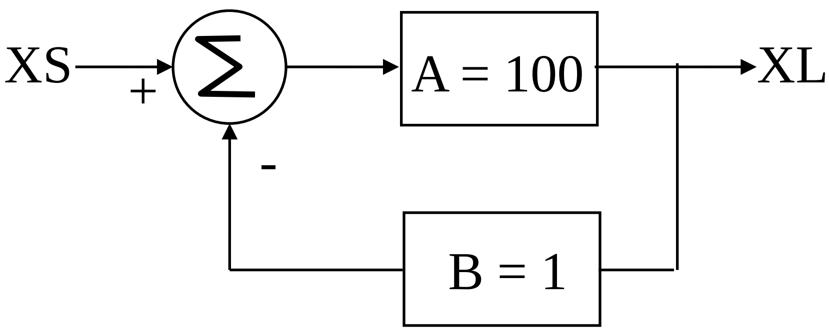
z11 = RB // rπ
z12 = 0
z21 = -β RC
z22 = RC

h11 = (RB // rπ)
h12 = 0
h21 = β
h22 = 1/RC

g11 = 1/(RB // rπ)
g12 = 0
g21 = -gm RC
g22 = RC

HOMEWORK PROBLEM 2 AND SOLUTION

2 a) Find S^{Af}_{A} If A changes by 20% how much does Af change.
b) Redesign the feedback amplifier in a) so that S^{Af}_{A} is reduced by a factor of 100.



Solution:

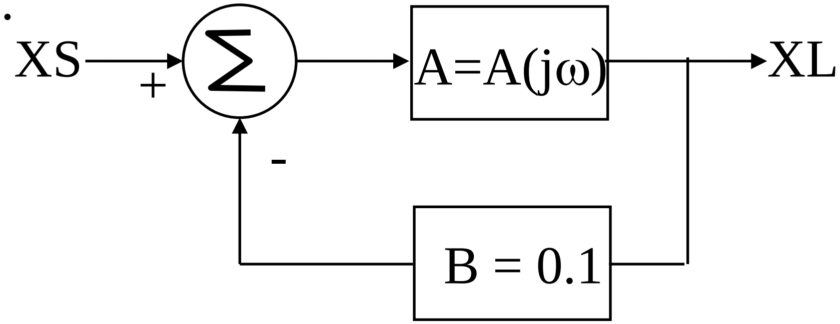
2 a) $S^{Af}_{A} = \dfrac{1}{1 + AB} = 1/101 = .0099$

If A changes by 20% then Af changes by 20% x 0.0099 = 0.198% ~0.2%

b) If we want the sensitivity to be 1/10001 instead of 1/101 then we increase the gain of the amplifier A to 10,000 giving Af = A/(1+AB) = 1 (same as before) and sensitivity = 1/(1+AB) = 0.0001 thus a 20% change in A is 0.002% change in gain with feedback

HOMEWORK PROBLEM 3 AND SOLUTION

3.

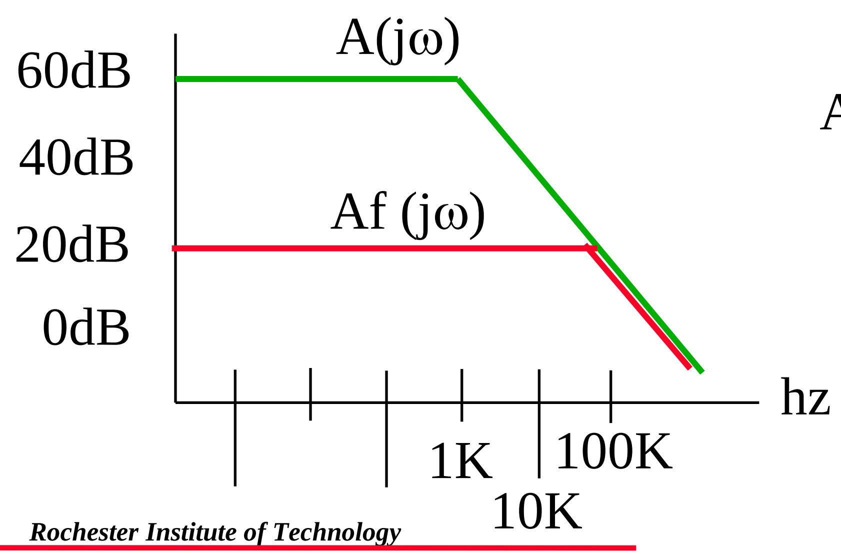


$$A(j\omega) = \frac{1000}{1 + j\, f/f1}$$

Let f1 = 1000 hz

Draw a Bode plot of the amplitude part of the gain function for A (jω) and Af (jω)

Solution:



$$Af = \frac{A}{1+AB} = \frac{\dfrac{1000}{1+jf/1000}}{1+\dfrac{100}{1+jf/1000}}$$

$$= \frac{1000}{1+jf/1000 + 100}$$

$$= \frac{1000}{101} \quad \frac{1}{1+jf/101000}$$

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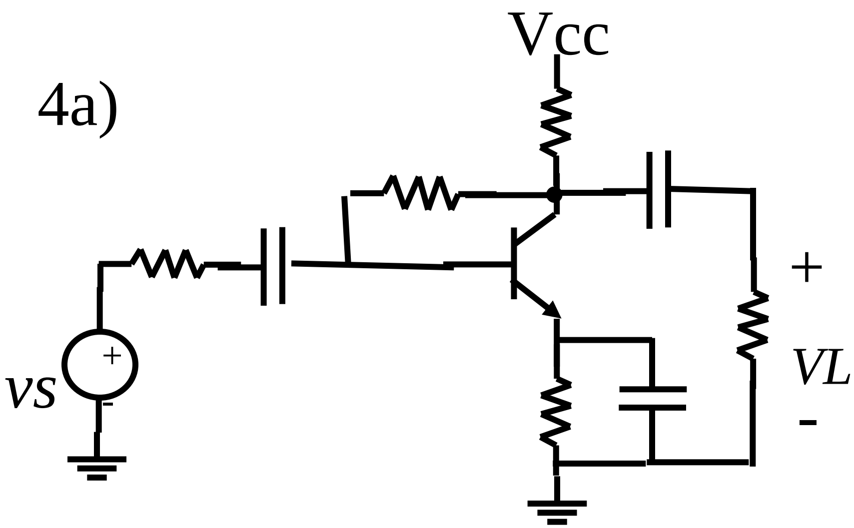
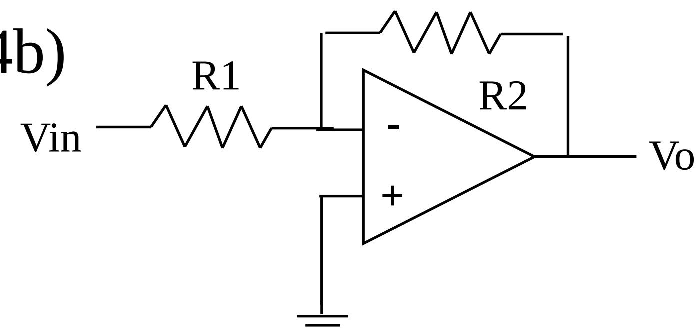
HOMEWORK PROBLEM 4

4) Refer to the feedback amplifiers shown below. For each identify the type of feedback and determine if the feedback is negative or positive.

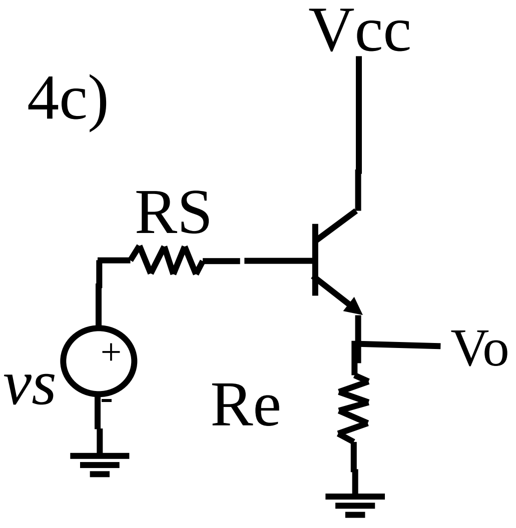
4a)

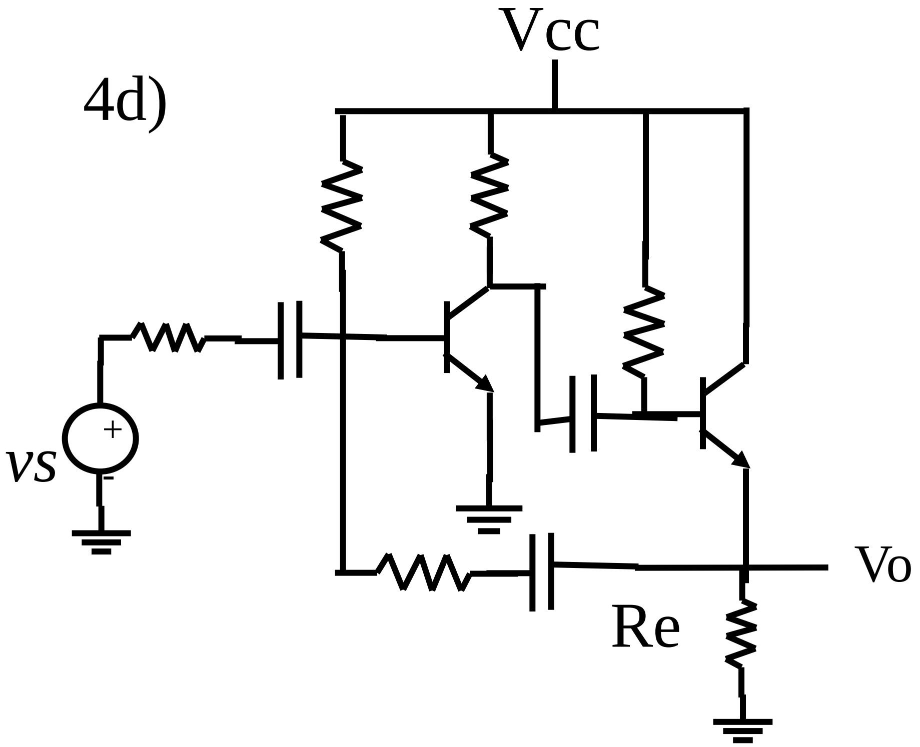


4b)



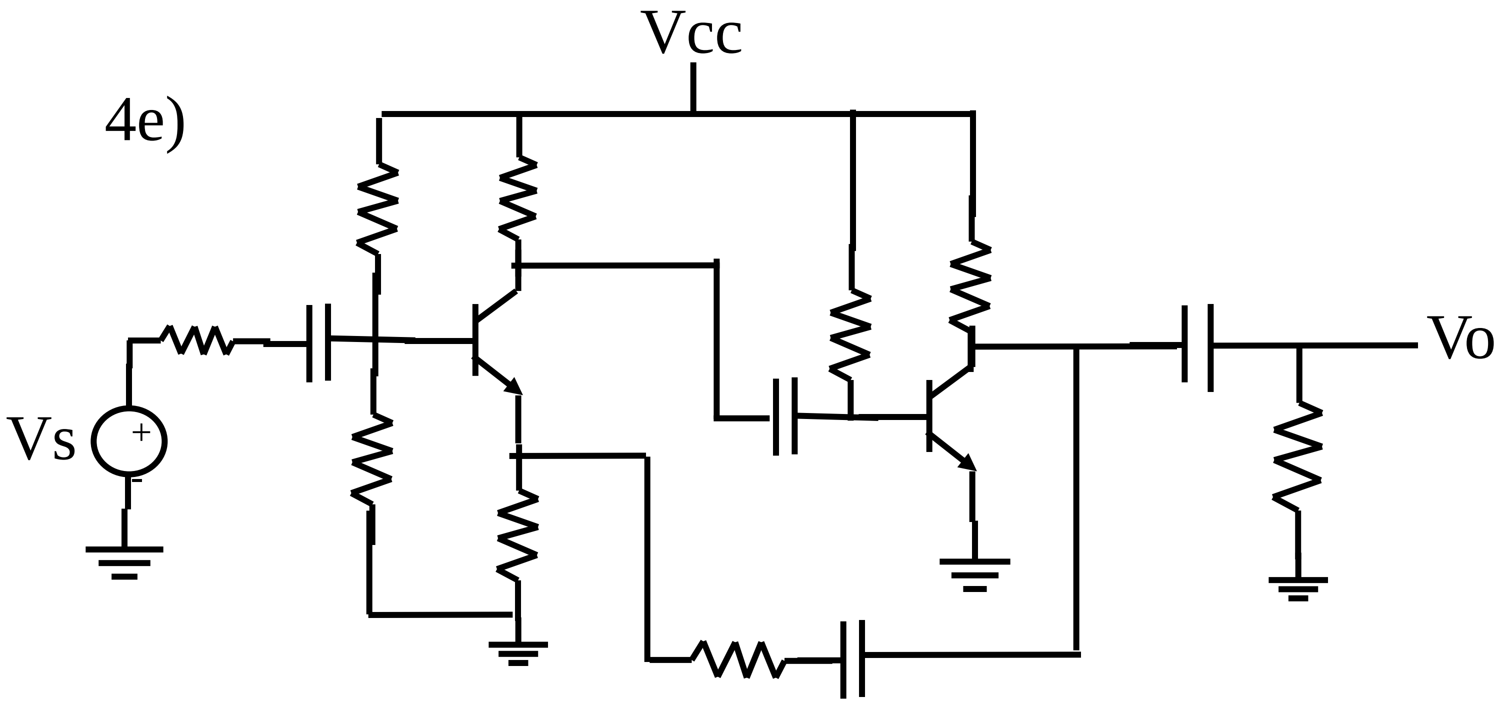
HOMEWORK PROBLEM 4 (CONTINUED)





HOMEWORK PROBLEM 4 (CONTINUED)

4e)



HOMEWORK PROBLEM 4 SOLUTION

4. All are negative feedback
   a. Voltage Shunt
   b. Voltage Shunt
   c. Voltage Series
   d. Voltage Shunt
   e. Voltage Series

HOMEWORK PROBLEM 5

5) For each of the circuits shown in problems 7, 8, and 9, estimate the gain with feedback. Axf ~= 1/ B and B = X12, where X12 is the appropriate combined two port parameters.

Identify the type of gain, transconductance, transresistance, current or voltage.

Convert Axf to voltage gain with feedback, Avf.

HOMEWORK PROBLEM 5 SOLUTION

5a) for the amplifier in problem 6 we have voltage shunt feedback which uses y parameter two port equivalent circuits for the analysis.

$y_{12} = y_{12}^{A} + y_{12}^{B} = 0 - 1/10K$

$A_{Rf} \sim= 1/y_{12} = -10K$ ohms

$A_{Vf} = A_{Rf}\ 1/RS = -10K/600 = -16.7$

5b) for the amplifier in problem 7 we have current shunt feedback which uses g parameter two port equivalent circuits for the analysis.

$g_{12} = g_{12}^{A} + g_{12}^{B} = 0 - 200/(200+10k) = -0.0196$

$A_{If} \sim= 1/g_{12} = -1/0.0196 = -51$

$A_{Vf} = A_{If}\ (-RL)/RS = -51\ (-2K/1K) = 102$

5c) for the amplifier in problem 8 we have voltage series feedback which uses h parameter two port equivalent circuits for the analysis.

$h_{12} = h_{12}^{A} + h_{12}^{B} = 0 + 100/(100+10k) = 0.0099$

$A_{Vf} \sim= 1/h_{12} = 1/0.0099 = -101$

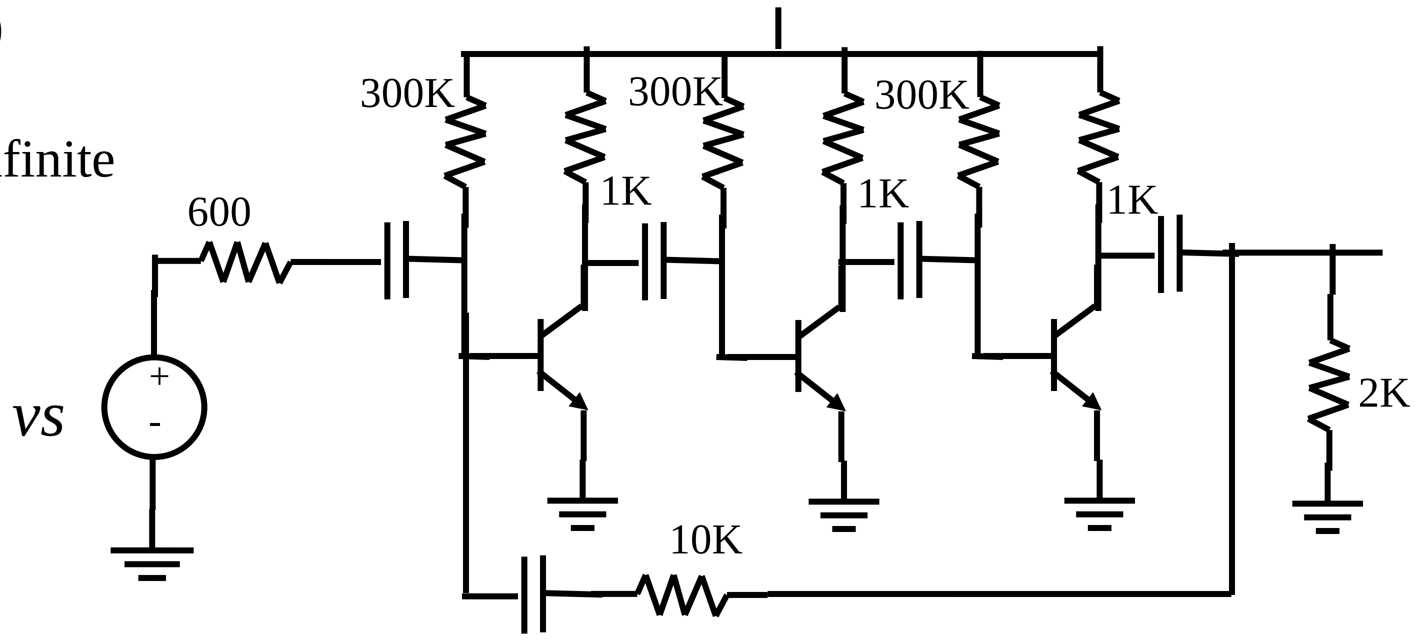
HOMEWORK PROBLEM 6

6) Find the exact gain with feedback for each of the circuit shown below.

$\beta = 100$

$r\pi = 1k$

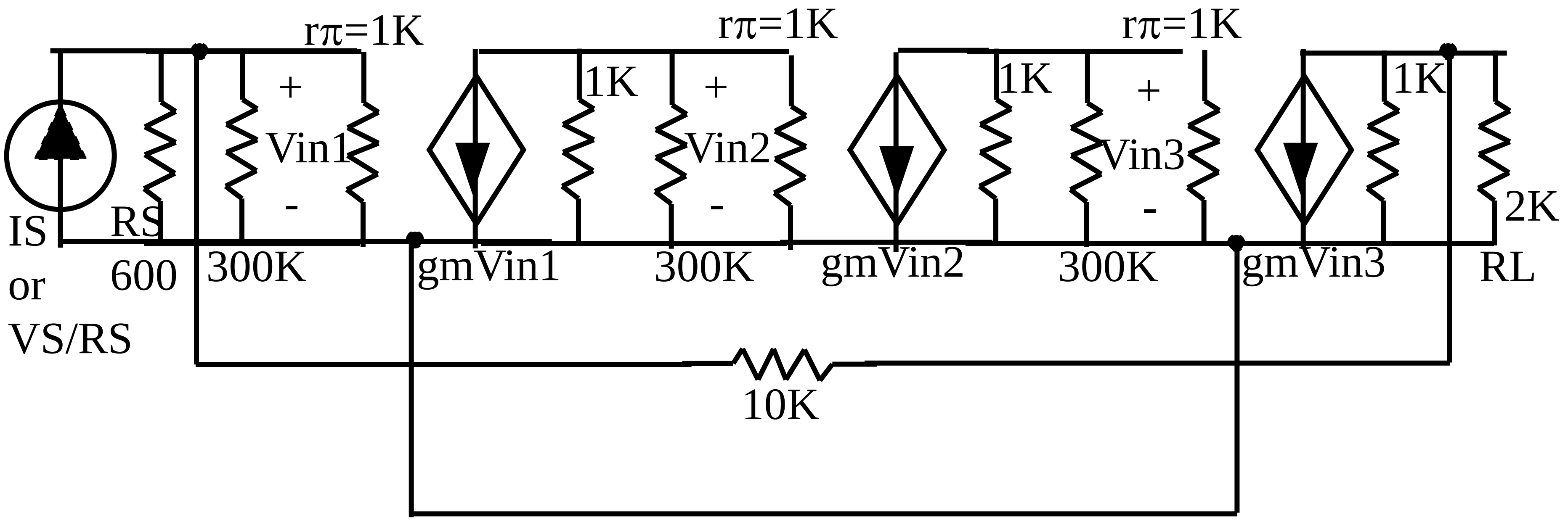
VA = infinite



$gm = Ic/VT = \beta/r\pi = 100/1K = 100mS$

Find the two port parameters for the A and B networks and compute AVf (exactly)

HOMEWORK PROBLEM 6 SOLUTION



y11A=1/(300K//1K)=0.001003 y12A=0 y22A=1/1K=0.001

y21A=-gm3(-gm2(1K//300K//1K))(-gm1(1K//300K//1K) = -250

y11B=1/10K=0.0001 y12B=-1/10K y21B=-1/10K y22A=1/10K

HOMEWORK PROBLEM 6 SOLUTION

Exact Gain

$$A_{Rf} = \frac{\dfrac{-y_{21}}{y_{11}y_{22}}}{1 + \dfrac{-y_{12}y_{21}}{y_{11}y_{22}}}$$

Transresistance

$$Arf = \frac{250/(.00277)(.0016)}{1+(-0.0001)(250)/(.00277)(.0016)} = -9998 \text{ohms}$$

Note: Arf ~ 1/y12 = -10000 ohms

Avf = Arf 1/RS = -9998/600 = - 16.7

y11= y11A+ y11B+1/RS = 0.001+0.0001+0.00167=0.00277

y12 = y12A+ y12B = -0.0001-0 = -0.0001

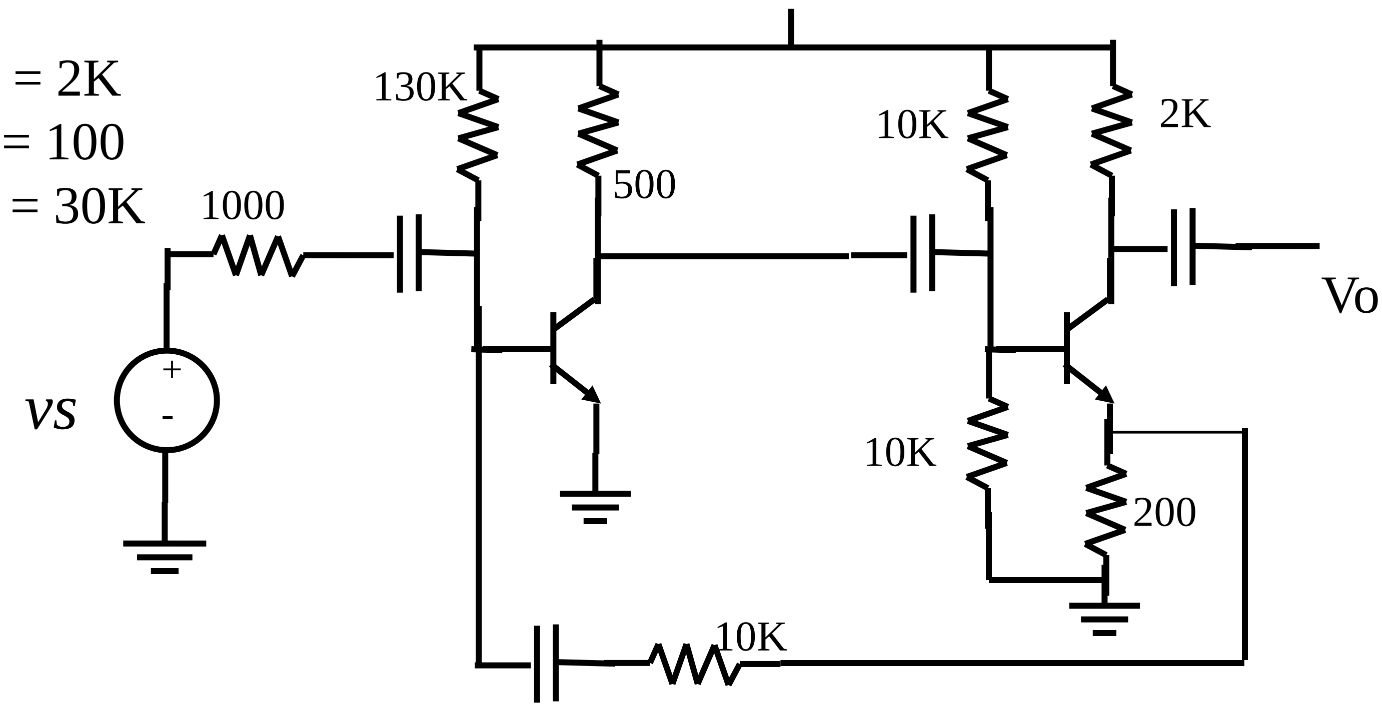
y21= y21A+ y21B = -0.0001-250 = -250

y22 = y22A + y22B + 1/RL = 0.0001+ 0.001 + 0.0005 = 0.0016

HOMEWORK PROBLEM 7

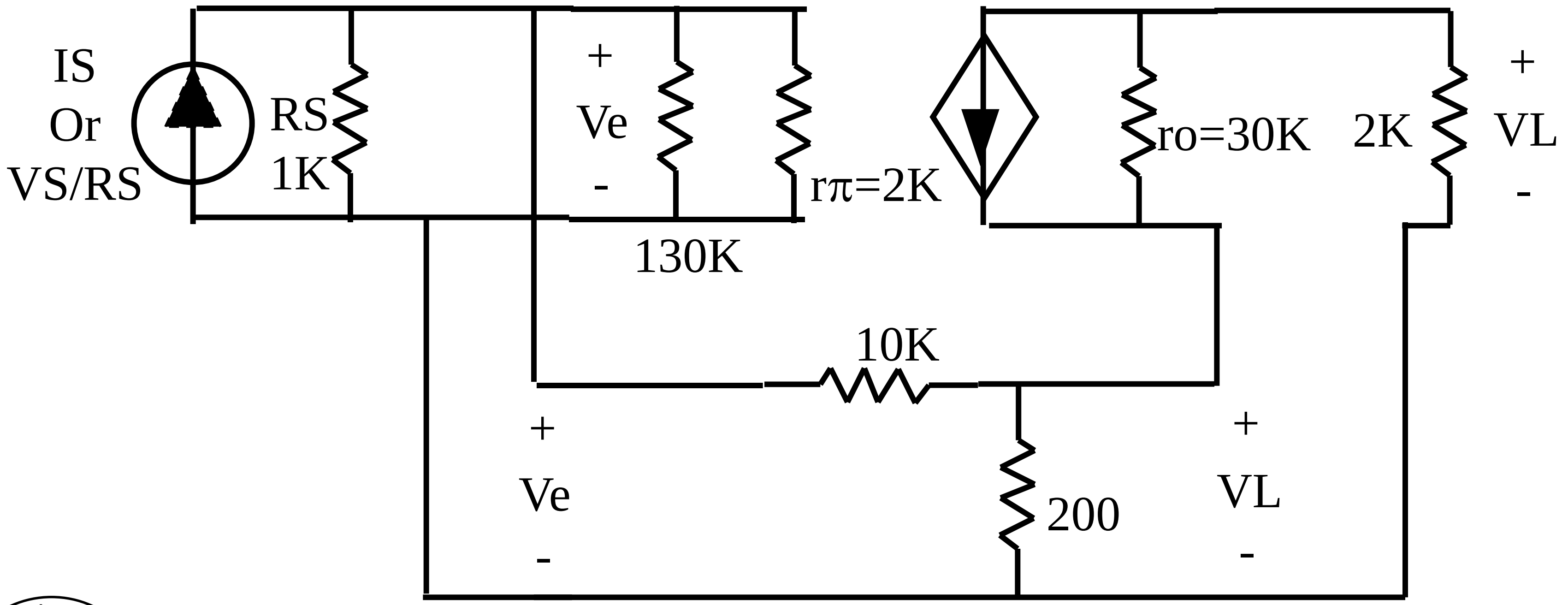
7) Find the exact gain with feedback for the circuit shown below.

rπ = 2K
B = 100
ro = 30K



HOMEWORK PROBLEM 7 SOLUTION

7 cont.) Find the exact gain with feedback for the circuit shown below. The ac equivalent circuit below is useful in separating the B block of the feedback amplifier.



HOMEWORK PROBLEM 7 SOLUTION

7 cont.)

g11A=0.5e-3 g12A=0 g21A=13.7E-3(30K)=3020 g22A=30K

g11B=0.098e-3 g12B=-0.0196 g21B=0.0196 g22B=193

1/RS = 1E-3 RL=2K

g11=g11A+g11B+1/RS = 1.598E-3
g12 = g12A + g12B = -0.0196
g21 = g21A + g21B = 3120
g22 = g22A + g22B + RL = 32.19K

Exact Gain (current gain)

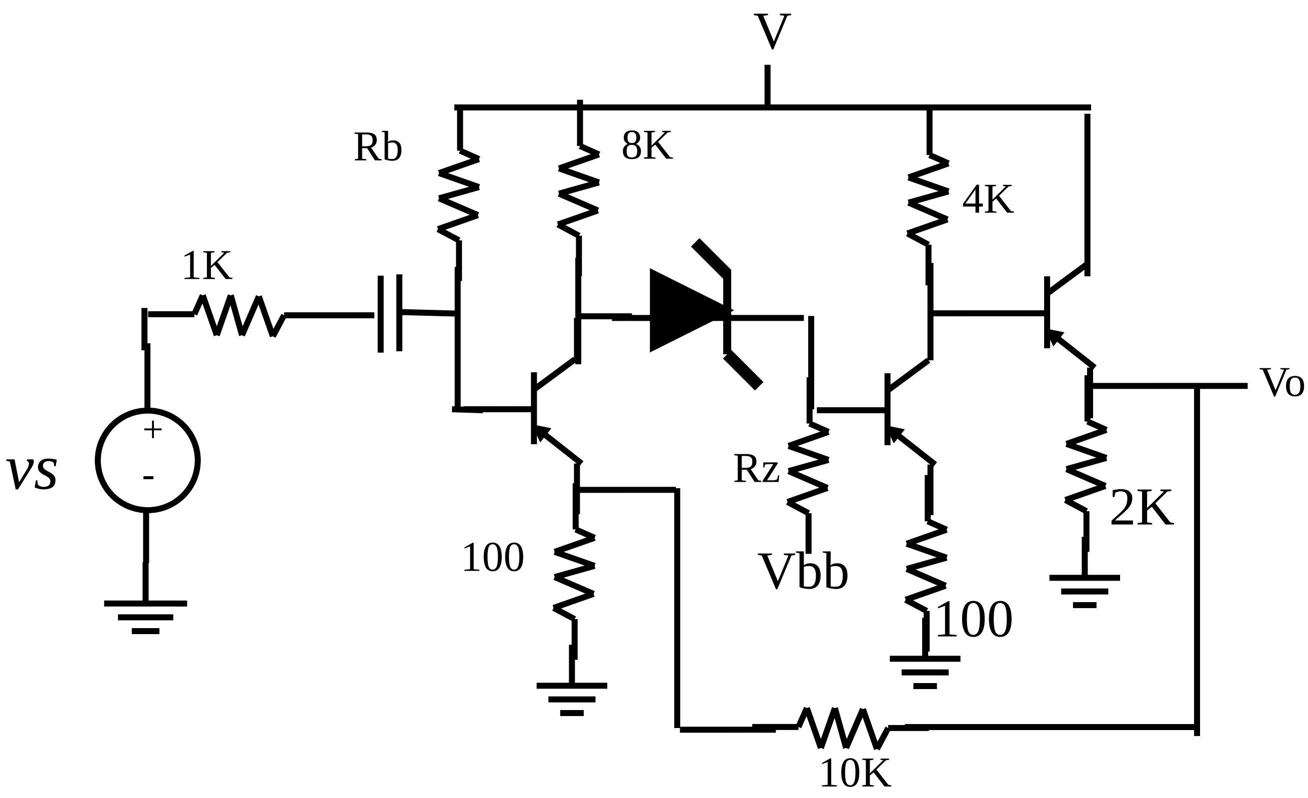
$$A_{If} = \frac{\frac{-g_{21}}{g_{11}g_{22}}}{1 + \frac{-g_{12}g_{21}}{g_{11}g_{22}}} = -27.3$$

Note: Aif ~ 1/g12 = -51

Avf = Aif (-RL)/RS = -27.3 (-2K/1K) = 54.6

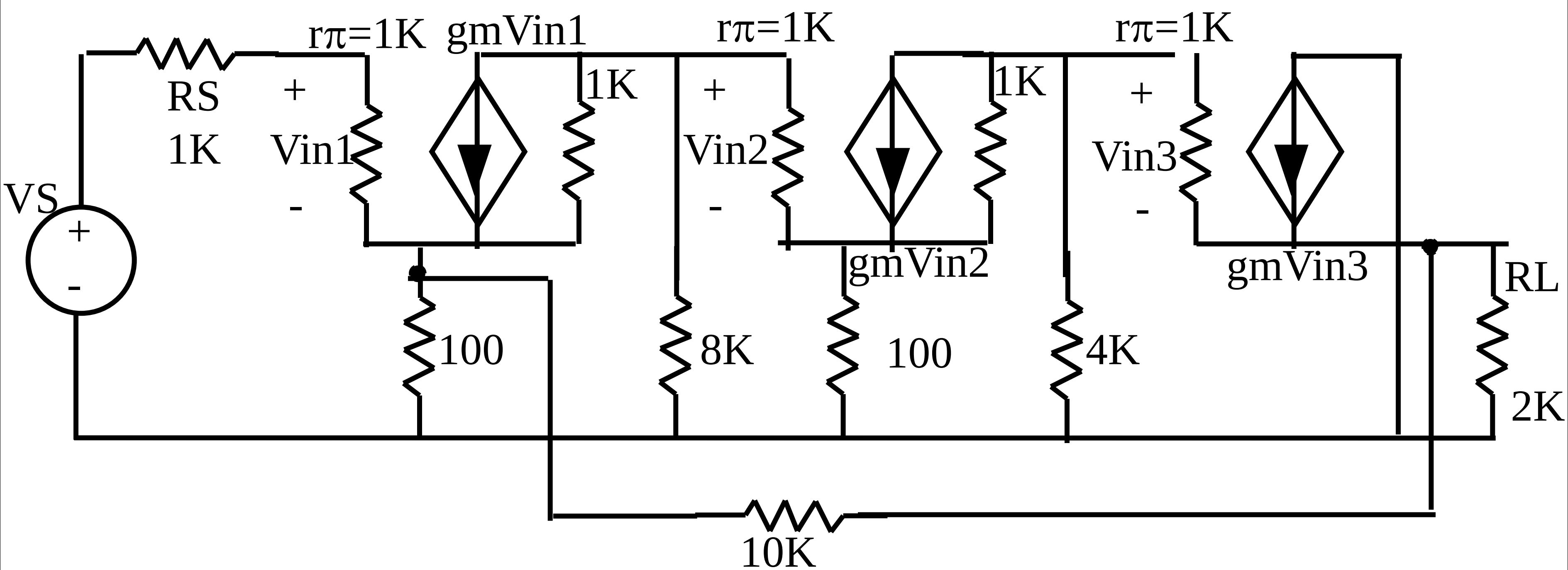
HOMEWORK PROBLEM 8

8) Find the exact gain with feedback for the circuit shown below.



$r\pi$ = 2K
B = 100
ro = infinite
Rb >>1K
Rz >>8K

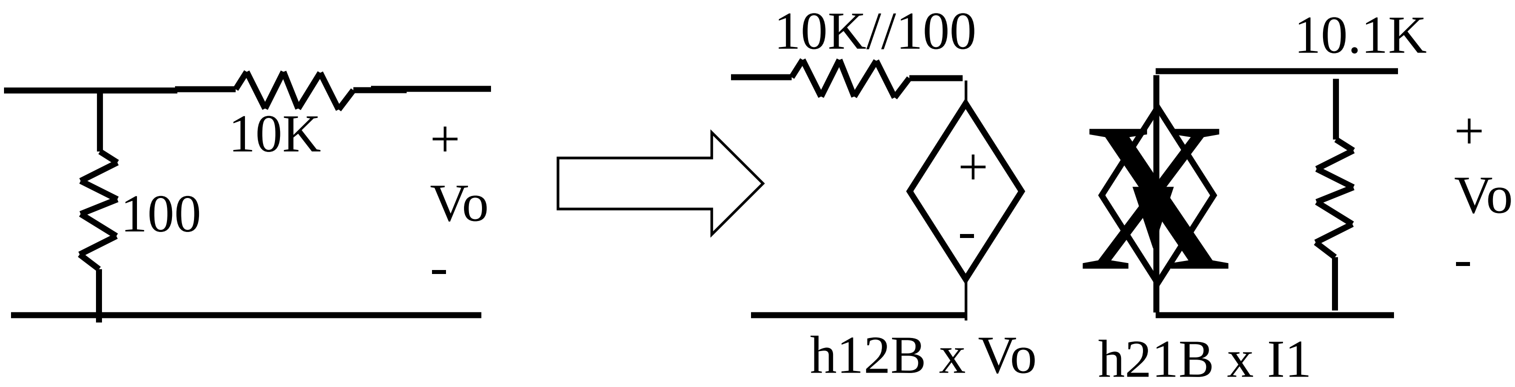
HOMEWORK PROBLEM 8 SOLUTION



Note: the “A” block and “B” block are not completely separate, with proper mixing and sampling networks. The following equivalent circuit can be used

HOMEWORK PROBLEM 8 SOLUTION

First consider the10K and 100 ohm as the "B" block

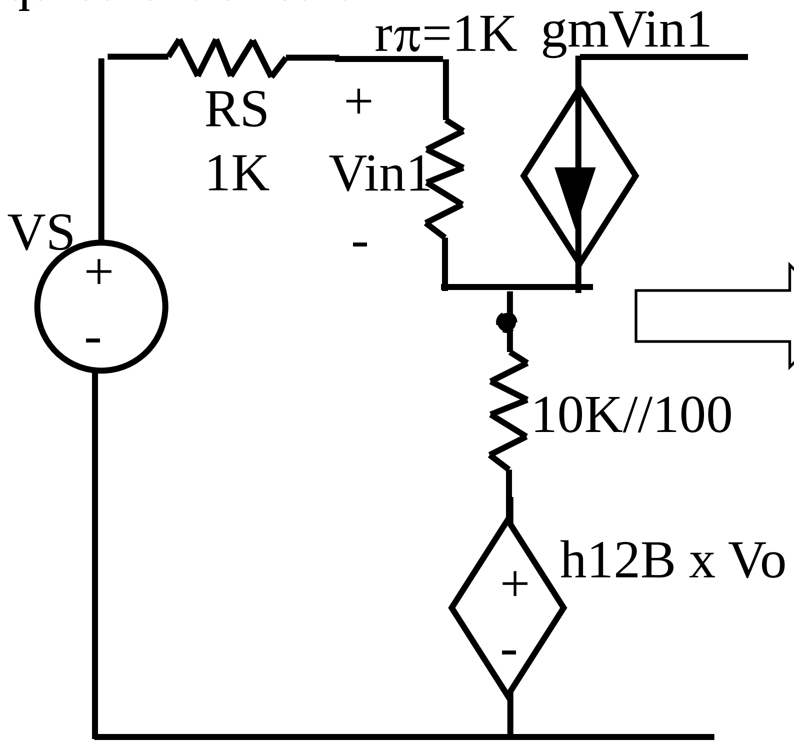


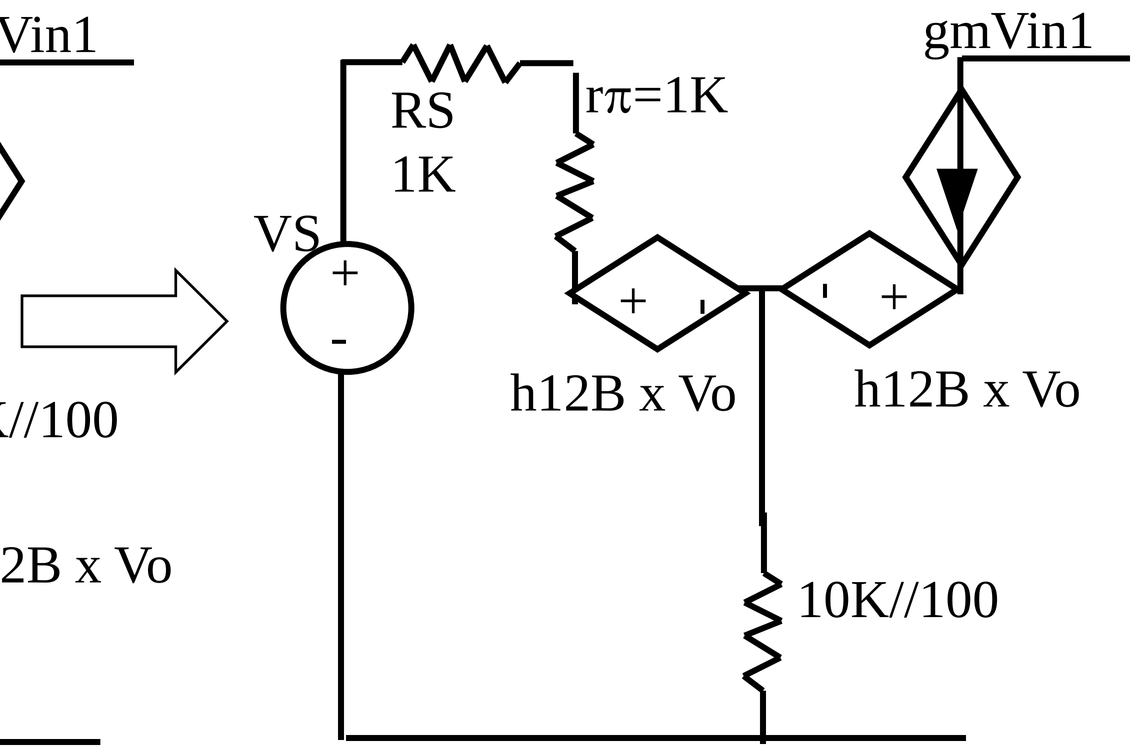
We can not just take the 100 ohm out of the emitter of the first transistor because the transistor will not work correctly in the "A" block,

Note: h21A >> h21B so neglect h21B

HOMEWORK PROBLEM 8 SOLUTION

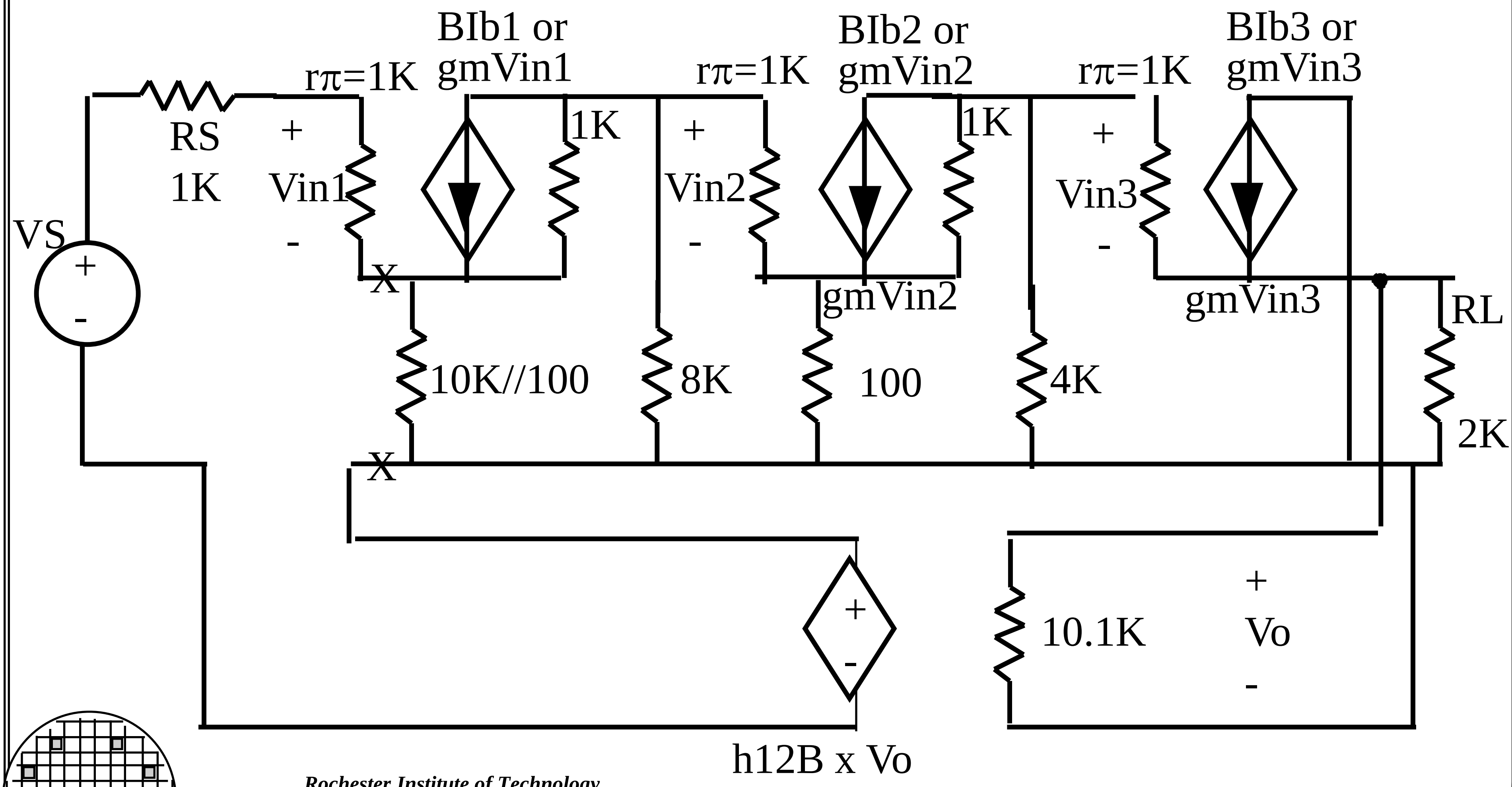
In the emitter of the first transistor put the left hand part of the "B" block 2 port equivalent circuit





Note: the right h12Vo is in series with a current source and can be eliminated.
Note: left h12Vo is in a series loop to left of the two X's (next page) and can be moved anywhere in that loop.

HOMEWORK PROBLEM 8 SOLUTION



HOMEWORK PROBLEM 8 SOLUTION

Finally we have an ac equivalent circuit where the "A" block and "B" block are separate and proper mixing and sampling networks exist.

h11A=rπ + (B+1)10K//100=12K

h12A=0

h22A=1/(2K//(rπ+4K)/(B+1))=0.0173

h21A = 268000

h21A=I2/I1withV2=0

I2 = -(B+1)Ib3 so I2/Ib3 = -(B+1) = -101

Ib3 = -BIb2 (4K/(4K+rp)) so Ib3/Ib2 = -66.7

Ib2 = BIb1 (8K/(8K+(rp+(B+1)100)) so Ib2/Ib1=-39.8

h12A = I2/I1 = I2/Ib3 x Ib3/Ib2 x Ib2/Ib1 = 268000

HOMEWORK PROBLEM 8 SOLUTION

h11B = 0 ,already included
h12B = 100/(100+10K) = 0.0099
h21B = neglected compared to h21 of "A" block
h22B =1/(10K+100) =1/10.1K

RS = 1K

RL = infinite, included in "A" block

h11 = h11A + h11B = 13K
h12 = h12A + h12B = 0 + 0.0099
h21 = h21A + h21B = -268000
h22 = h22A + h22B = 0.0174

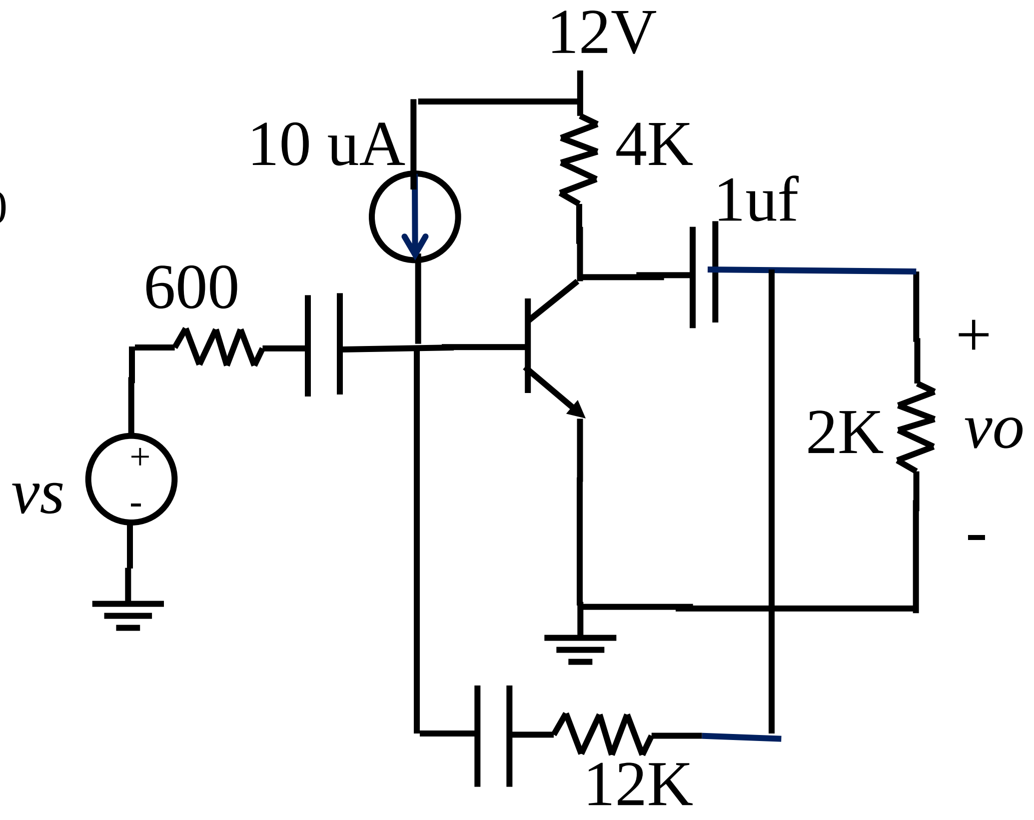
Exact Gain

$$A_{Vf} = \frac{\dfrac{-h_{21}}{h_{11}h_{22}}}{1 + \dfrac{-h_{12}h_{21}}{h_{11}h_{22}}} = \frac{-\dfrac{-268000}{(13K)(0.0099)}}{1 + -\dfrac{-268000(0.0099)}{(13K)(0.0099)}} = 93$$

OLD EXAM QUESTION

Pro 2.

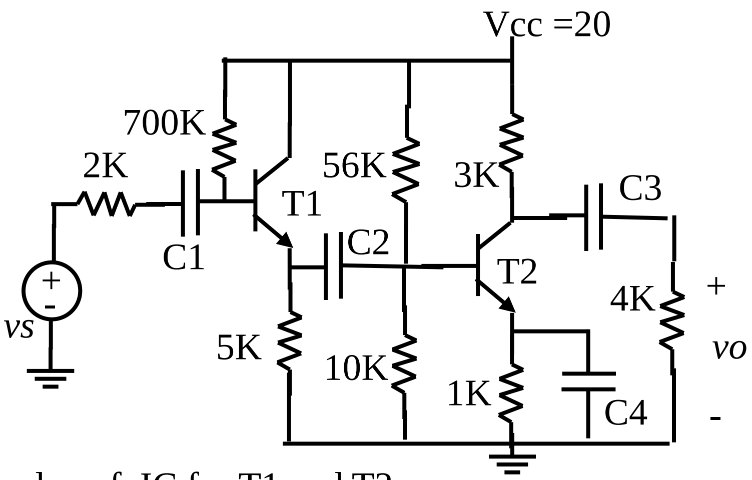
Beta = 150



Find Exact Gain With Feedback, Approximate Gain with Feedback, Voltage Gain, Current Gain, Input Resistance

OLD EXAM QUESTION

Pro 2.



Assume Beta = 150
VA= 100

Calculate dc value of IC for T1 and T2

Calculate gm, rπ and ro for T1 and T2

Calculate the voltage gain *vo/vs*

Pro 3.

For the circuit in problem 2 use a single resistor to provide voltage shunt feedback to stabilize the gain with feedback at ~40 V/V. What value of feedback resistor should be used and show how you would connect it by adding it to the schematic of problem 2.