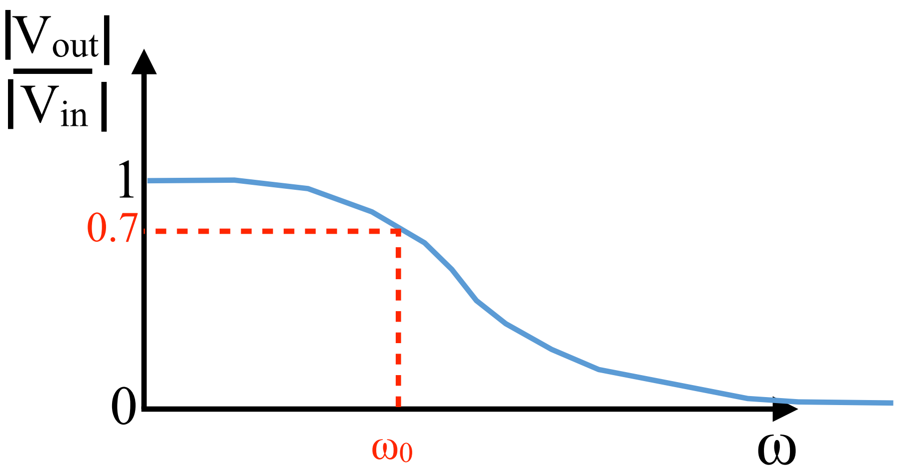
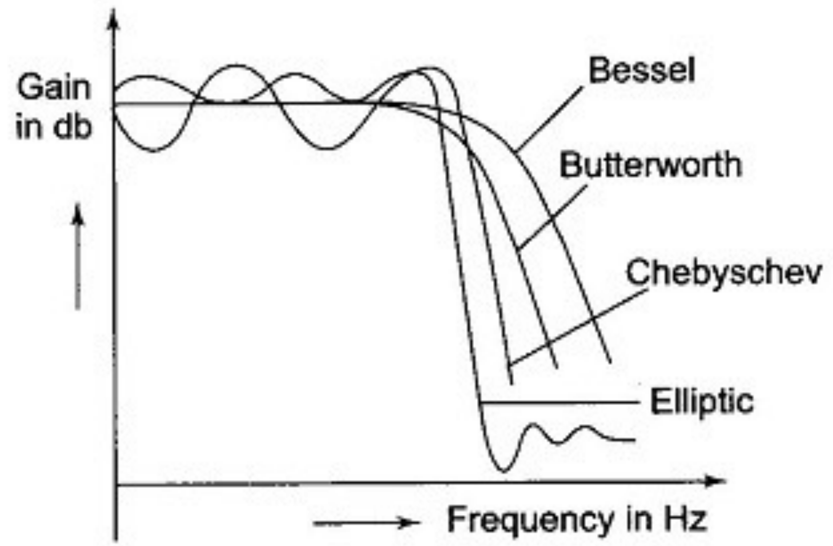
PHYS127AL Lecture 16

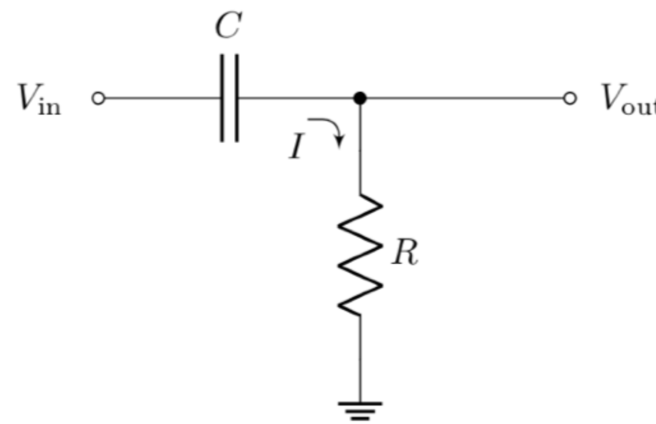
David Stuart, UC Santa Barbara

Active filters





Review: Frequency response function for a high-pass filter



$$\tilde{V}_{\rm out} = \tilde{I}\tilde{X}_R = \tilde{I}R = \frac{\tilde{V}_{\rm in}}{R+\tilde{X}_C}R = \tilde{V}_{\rm in}\frac{R}{R+\tilde{X}_C}$$

$$\tilde{V}_{\rm out} = \tilde{V}_{\rm in}\left[\frac{R}{R-j/\omega C}\right] = \tilde{V}_{\rm in}\left[\frac{R}{R-j/\omega C}\right]\left[\frac{R+j/\omega C}{R+j/\omega C}\right]$$

$$\tilde{V}_{\rm out} = \tilde{V}_{\rm in}\frac{R^2+jR/\omega C}{R^2+1/\omega^2 C^2} = \tilde{V}_{\rm in}\frac{1+j/\omega RC}{1+1/\omega^2 R^2 C^2}$$

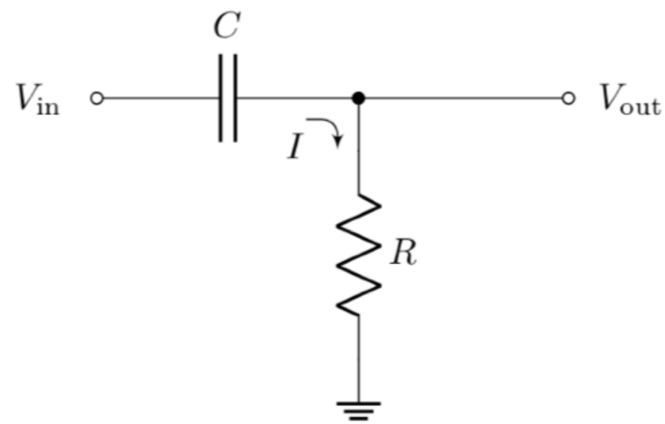
$$|\tilde{V}_{\rm out}| = |\tilde{V}_{\rm in}|\left|\frac{1+j\omega RC}{1+\omega^2 R^2 C^2}\right|$$

$$\frac{|\tilde{V}_{\rm out}|}{|\tilde{V}_{\rm in}|} = \left|\frac{1+j/\omega RC}{1+1/\omega^2 R^2 C^2}\right| = \sqrt{\left[\frac{1+j/\omega RC}{1+1/\omega^2 R^2 C^2}\right]\left[\frac{1-j/\omega RC}{1+1/\omega^2 R^2 C^2}\right]}$$

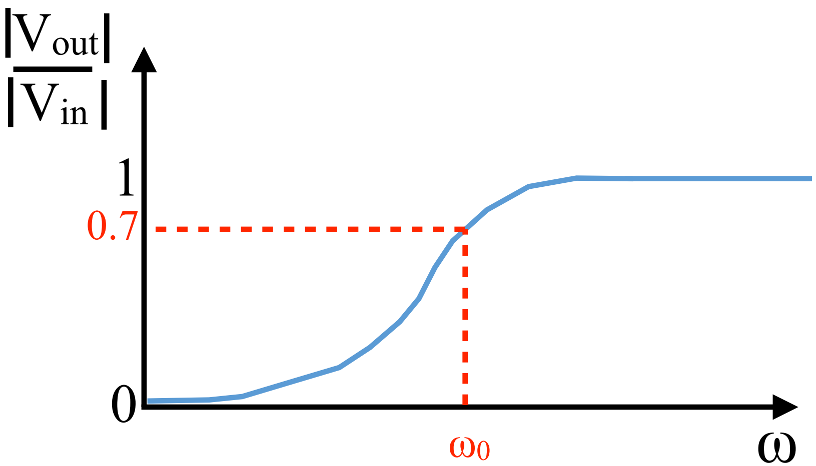
$$\frac{|\tilde{V}_{\rm out}|}{|\tilde{V}_{\rm in}|} = \sqrt{\frac{1+1/\omega^2 R^2 C^2}{(1+1/\omega^2 R^2 C^2)^2}} = \frac{\sqrt{1+1/\omega^2 R^2 C^2}}{1+1/\omega^2 R^2 C^2} = \frac{1}{\sqrt{1+1/\omega^2 R^2 C^2}} = \frac{\omega RC}{\sqrt{1+\omega^2 R^2 C^2}}$$

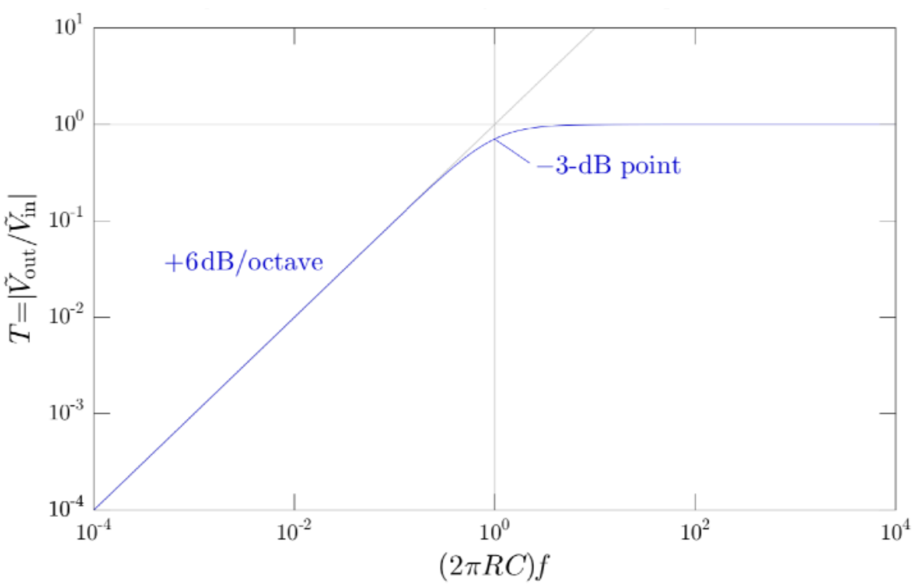
Review: Frequency response function for a high-pass filter

$$\frac{|\tilde{V}_{\text{out}}|}{|\tilde{V}_{\text{in}}|} = \frac{1}{\sqrt{1+1/\omega^2R^2C^2}} = \frac{\omega RC}{\sqrt{1+\omega^2R^2C^2}}$$



$V_{out} \rightarrow 0$ as $\omega \rightarrow 0$ and $V_{out} \rightarrow V_{in}$ as $\omega \rightarrow \infty$.





Can characterize the frequency scale with

$$\omega^2 = 1/R^2C^2 \Rightarrow \omega = 1/RC$$

$$\frac{|\tilde{V}_{\text{out}}|}{|\tilde{V}_{\text{in}}|} = \frac{1}{\sqrt{2}} = -3\text{ dB}$$

Review: Frequency response function for a high-pass filter

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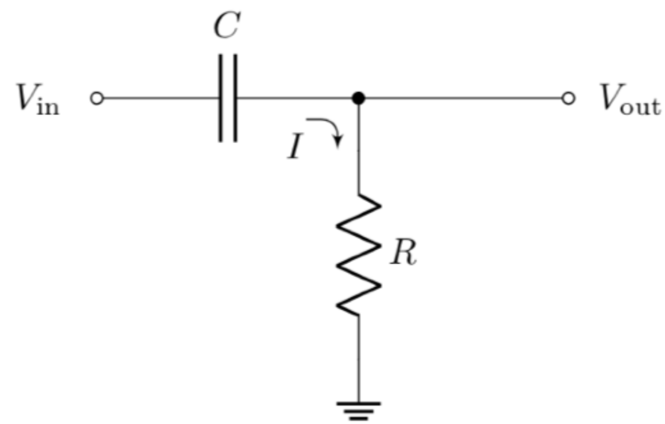

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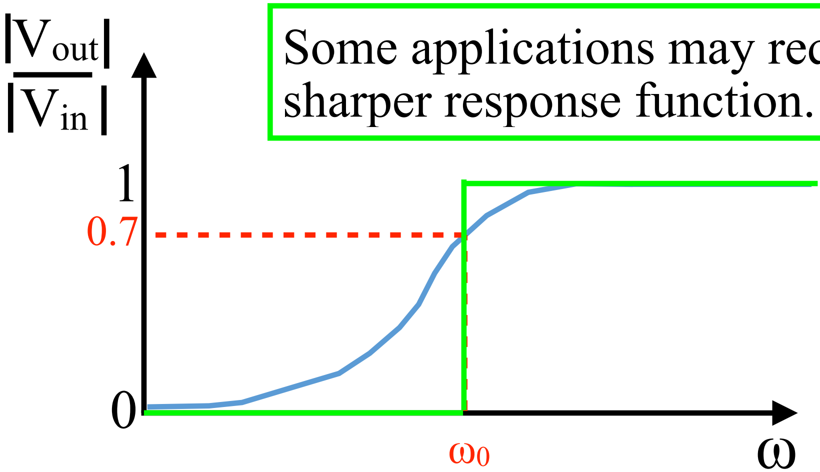
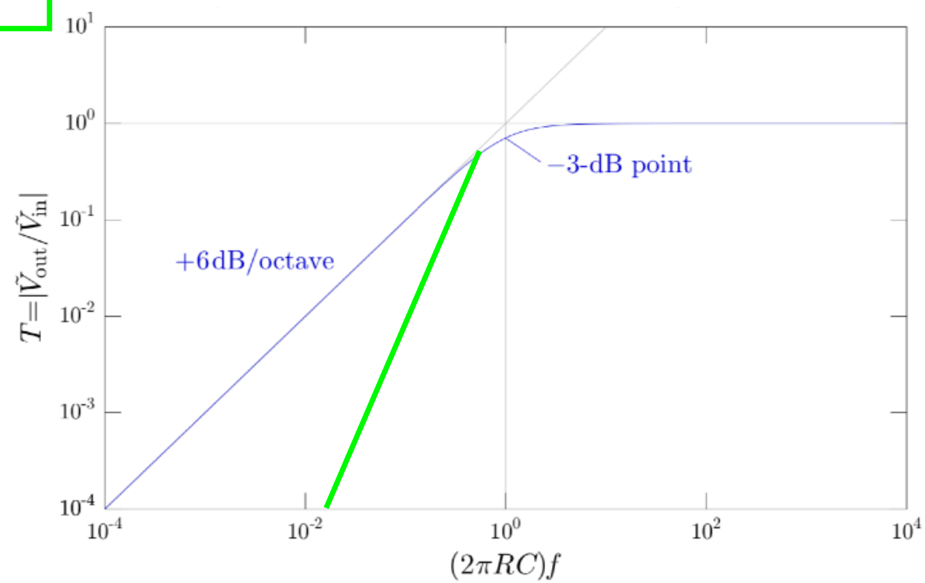


Some applications may require a sharper response function.



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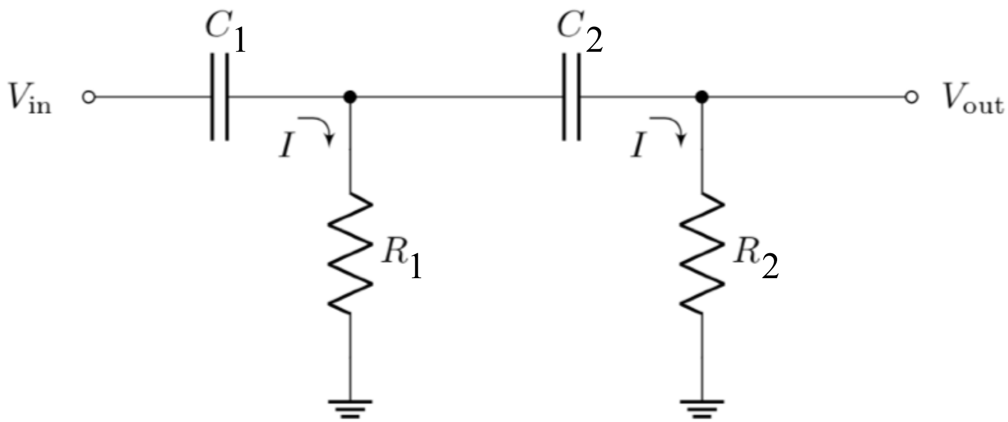
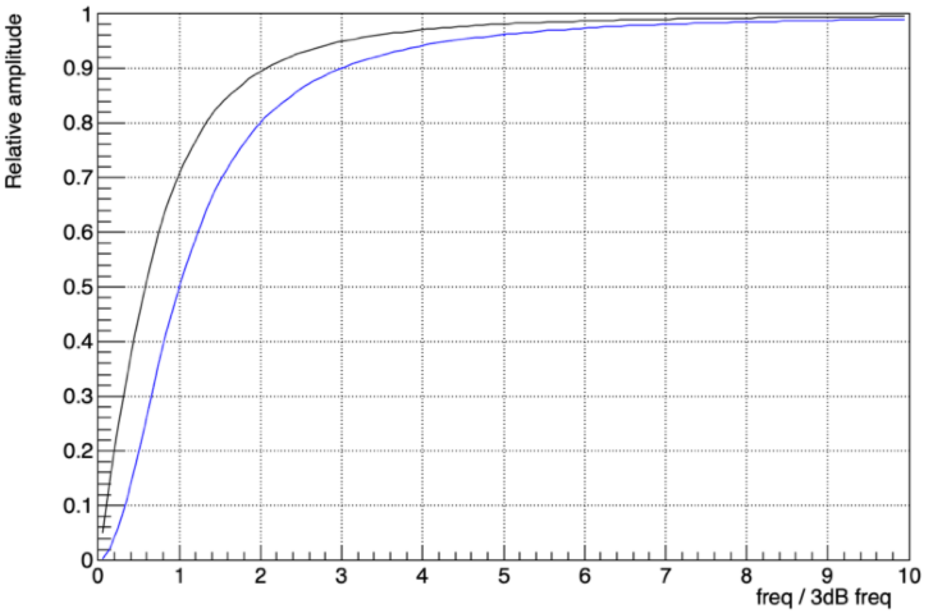
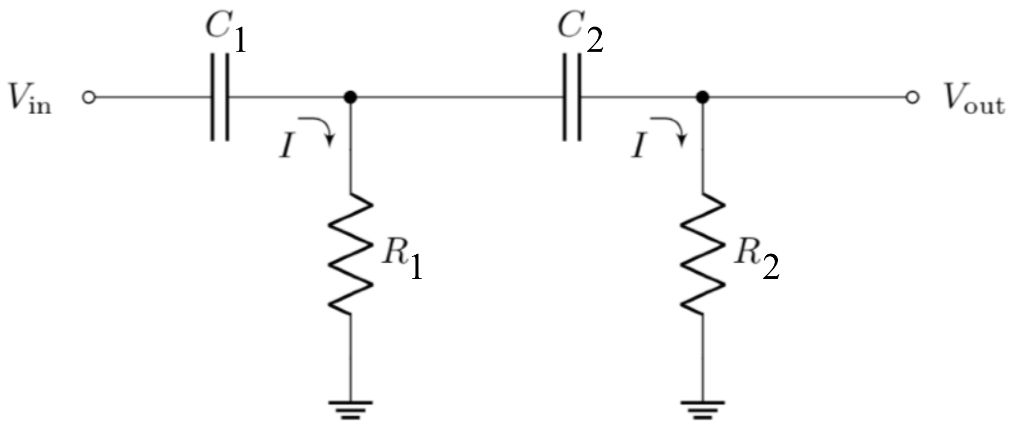
Sharpening the response function



This improved the low-end frequency response, but we lose more at the high end.



Sharpening the response function



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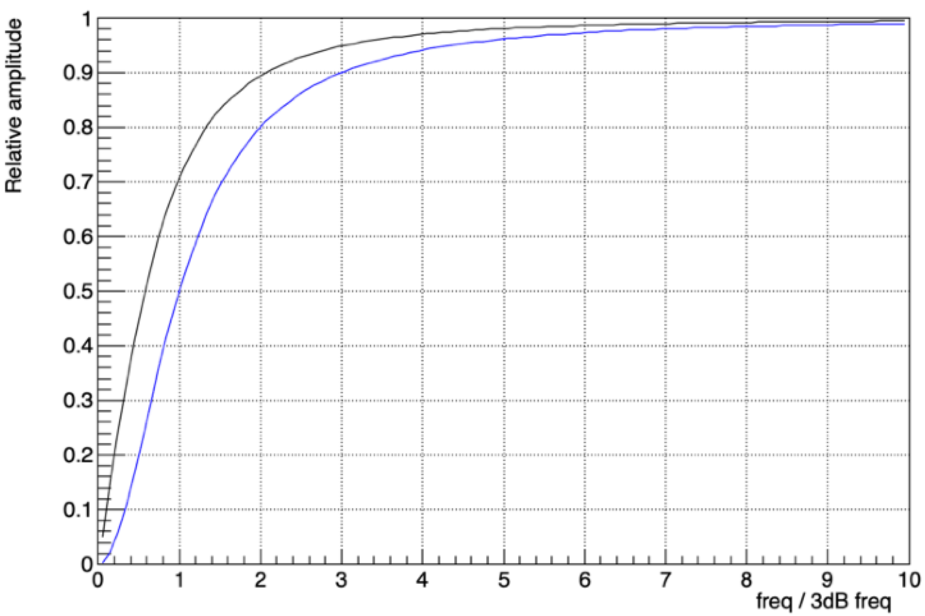

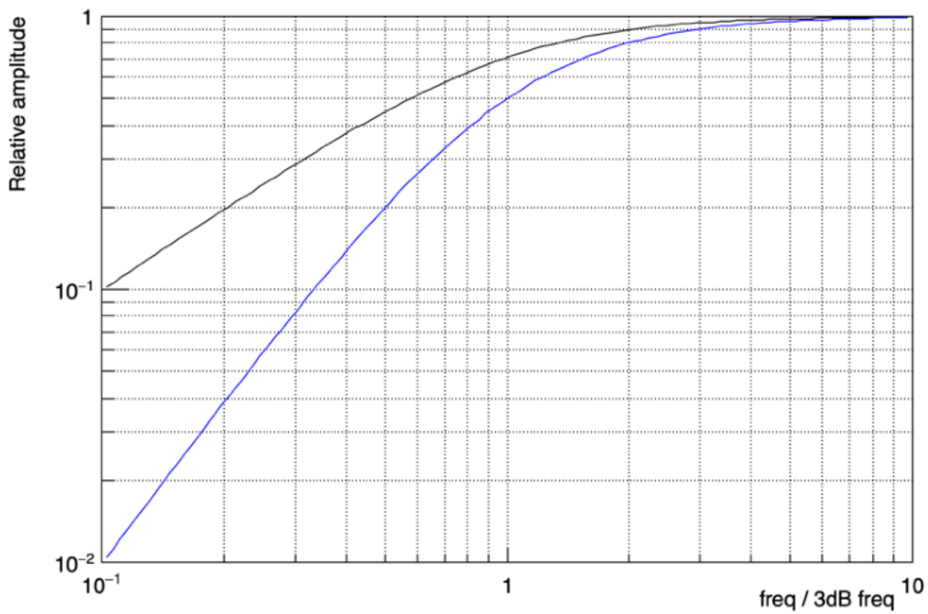

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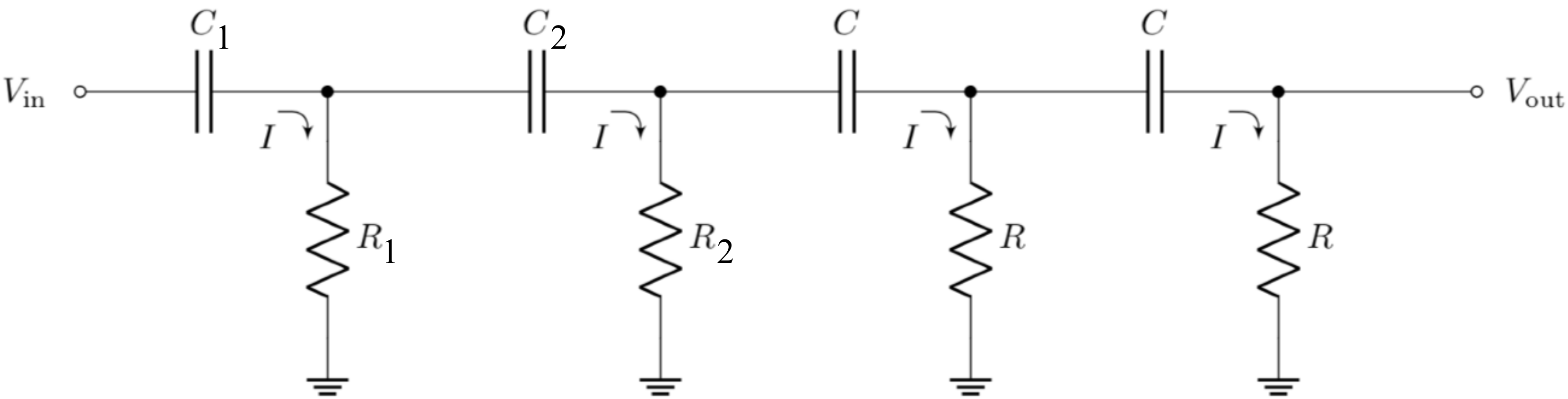
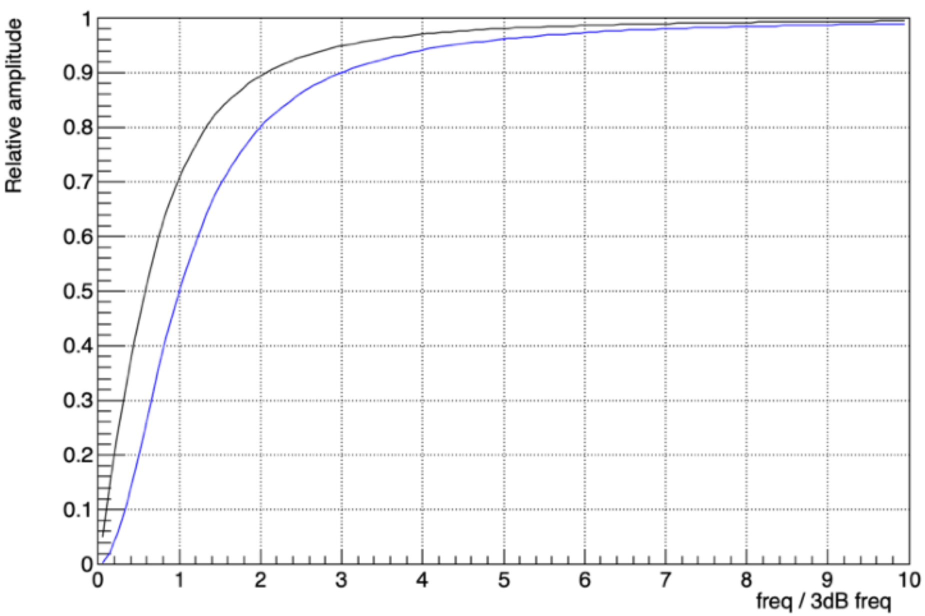
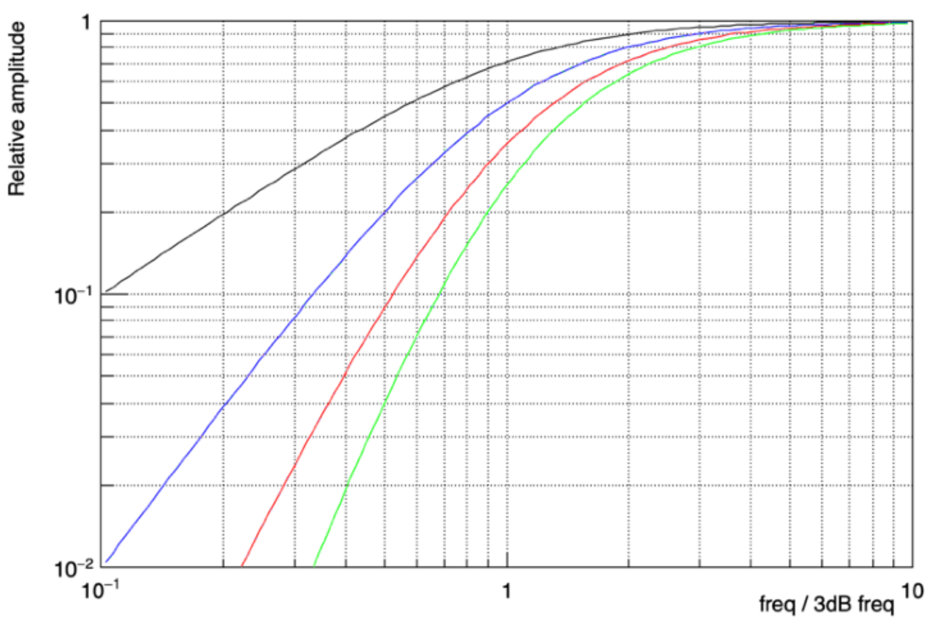


This improved the low-end frequency response, but we lose more at the high end.

We could add more stages to further suppress the low end.





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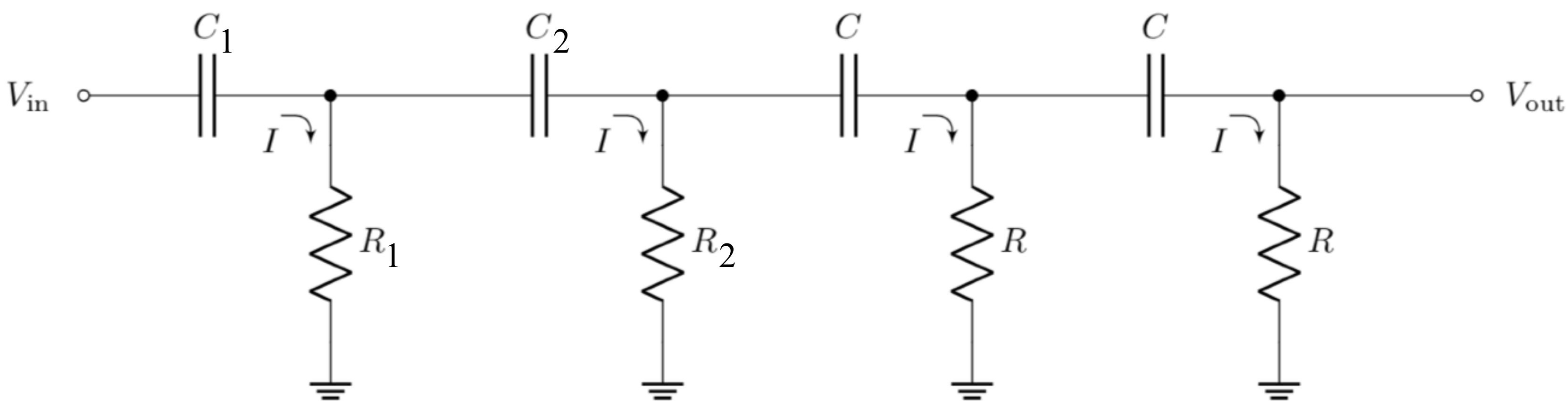

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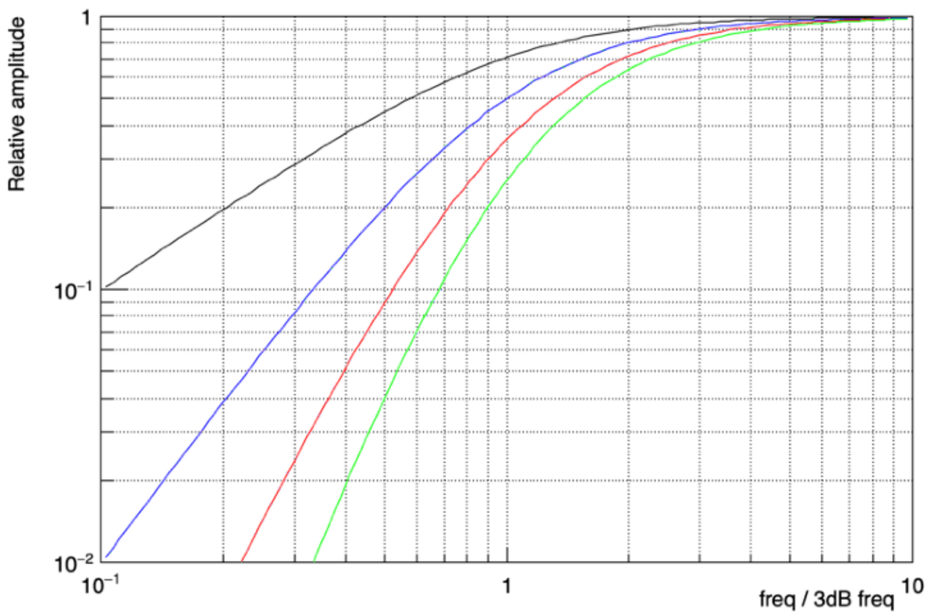
Two problems: lose the high end and need $(x10)^4$ impedance increases.



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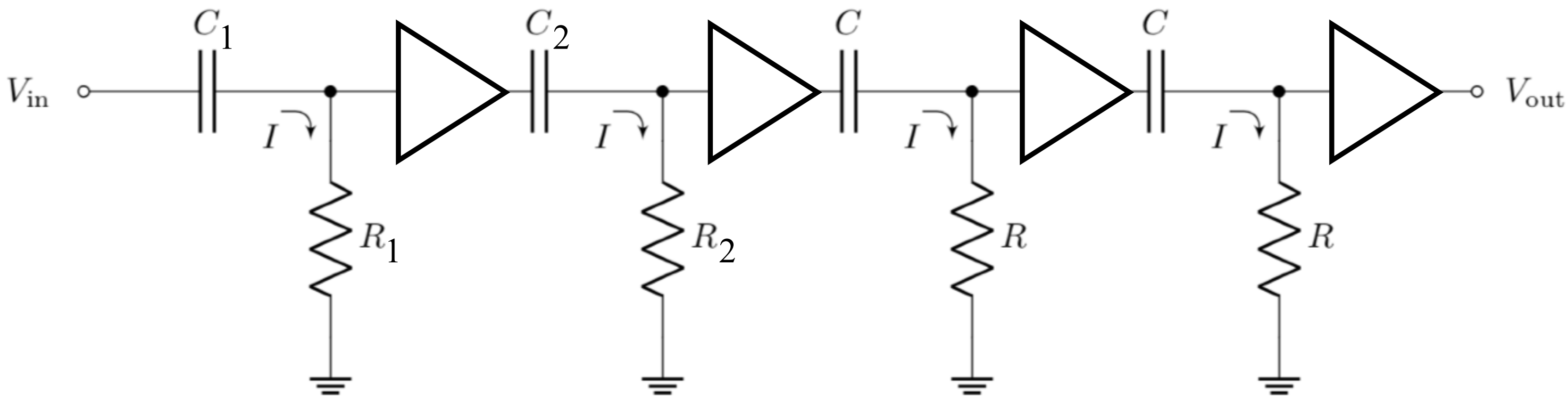

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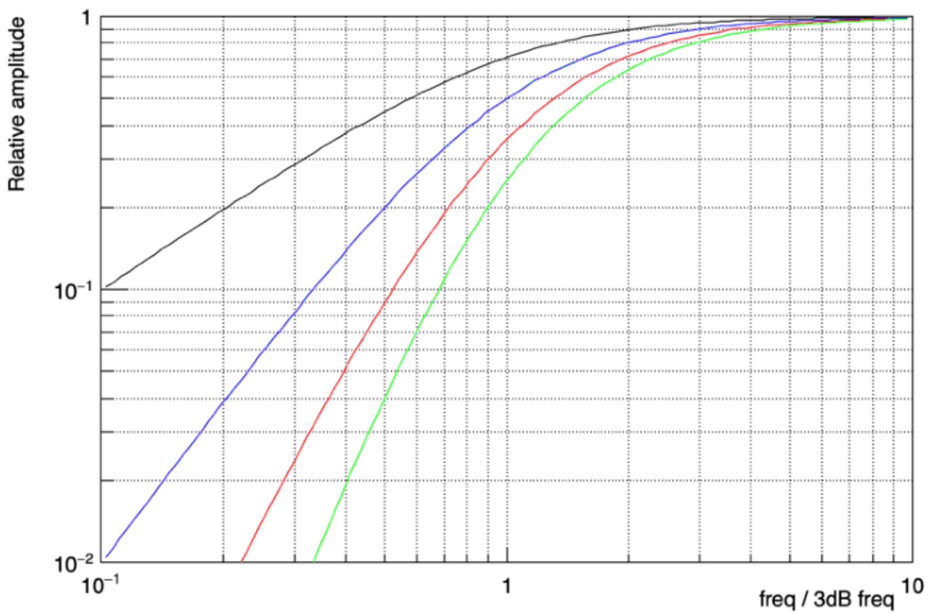
Fix the impedance with op-amp buffers.



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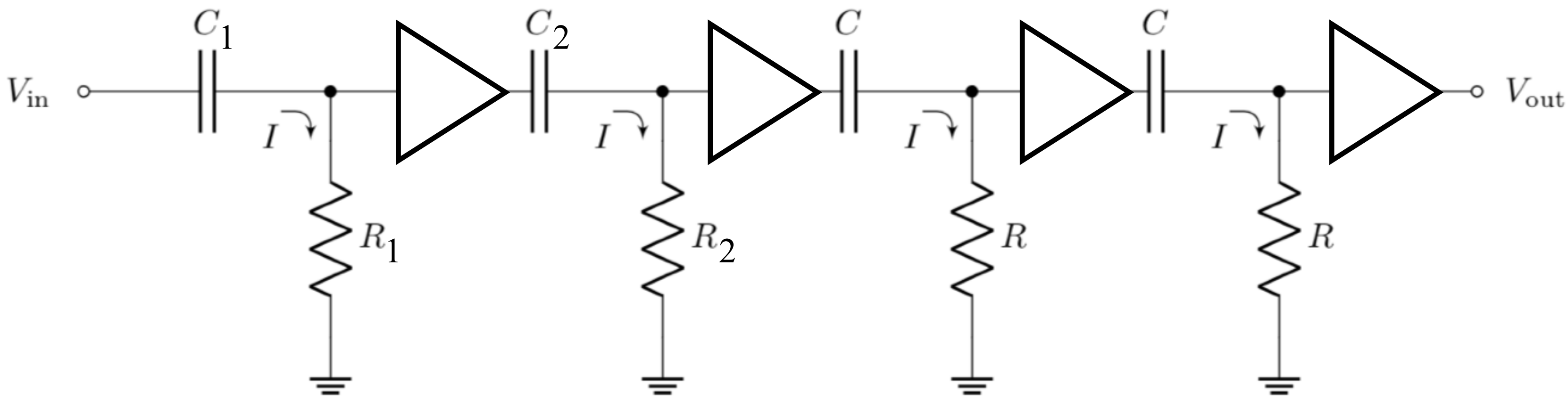

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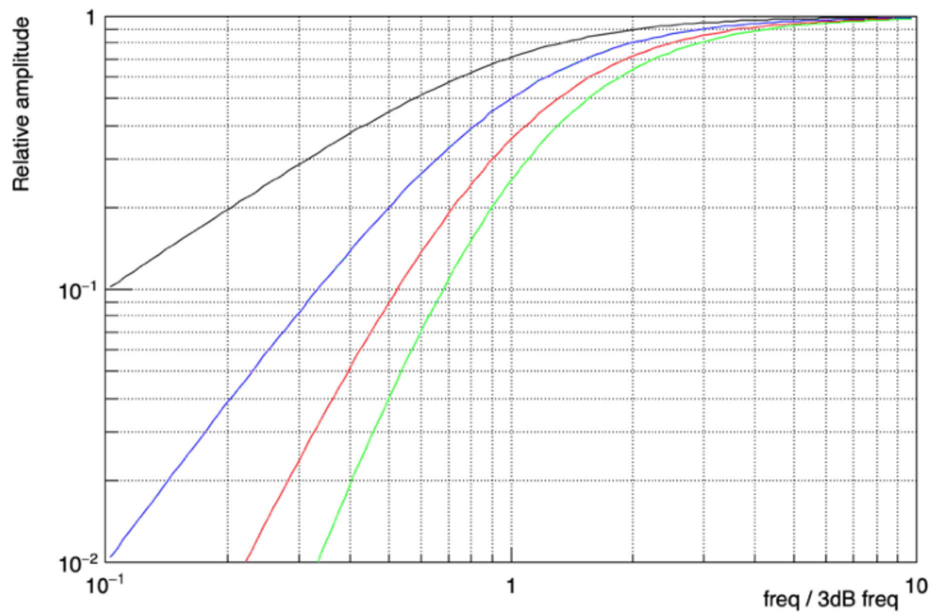
Fix the impedance with op-amp buffers.

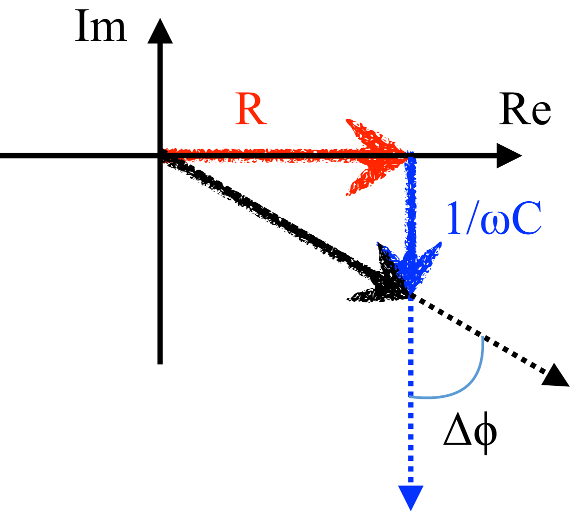
We could regain the high end by putting gain into the op-amp, and ideally make the gain be frequency dependent.

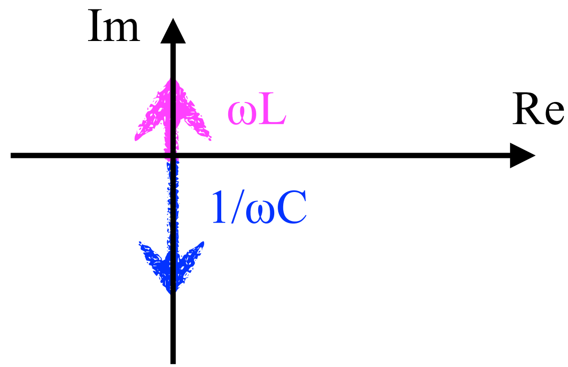


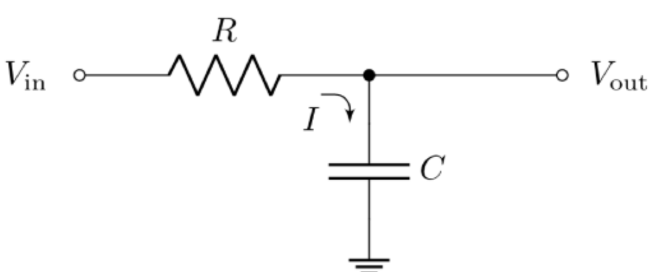
Sharpening the response function

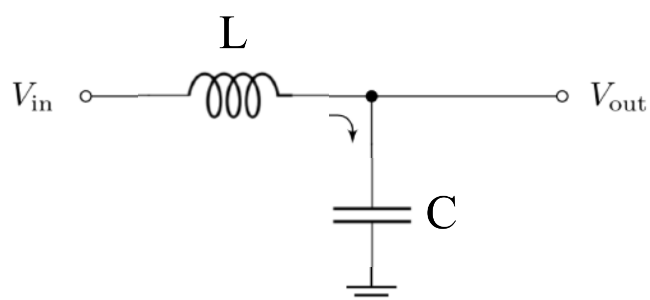
Another problem is that each stage introduces a phase shift that could build up.

We could avoid the phase shift with an LC filter instead of RC.









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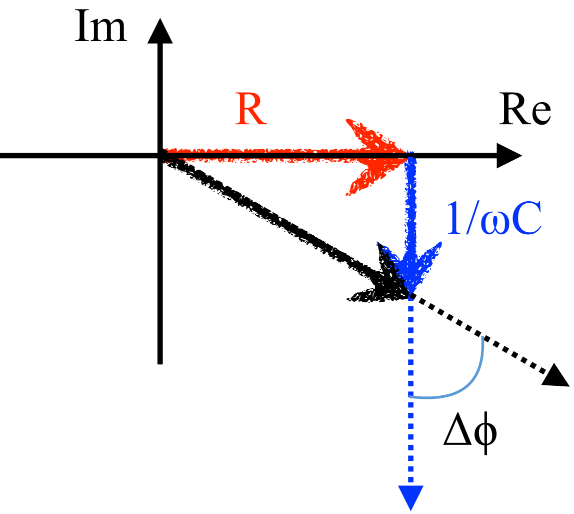
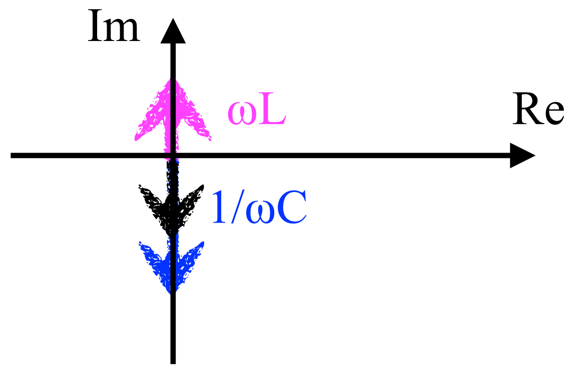
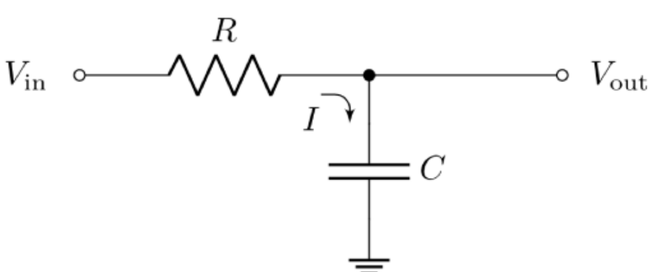
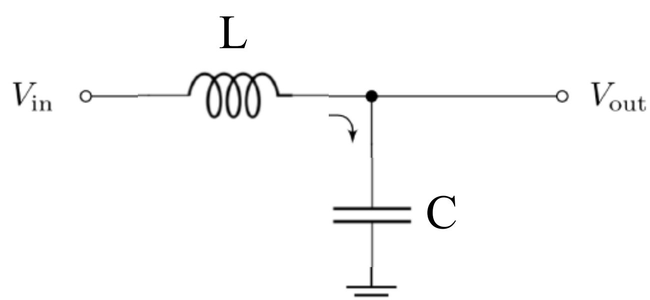








Shrinking an inductor

The problem with inductors is that they are physically huge.

Resistors and capacitors can be made small (~μm) with photolithography.

It would be nice to emulate an inductance with tiny components (like R, C, and op-amps)

$X_L = j\omega L$ while $X_C = -j/\omega C$.

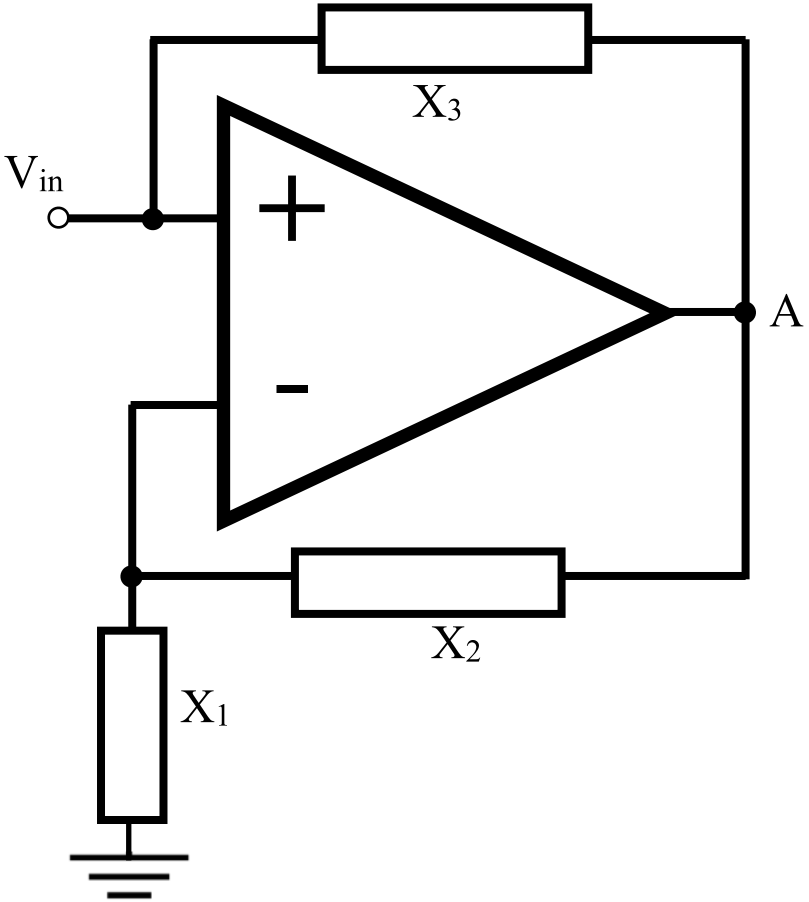
To convert a capacitance to an inductance we need to *invert* the frequency dependence and *negate* the impedance. (Negative impedance means that a higher voltage reduces the current.)

We can do that with a "negative impedance converter".

Negative impedance converter

The problem with inductors is that they are physically huge.

A negative impedance converter helps provide the inductor emulation.



$V_A = ?$

Negative impedance converter

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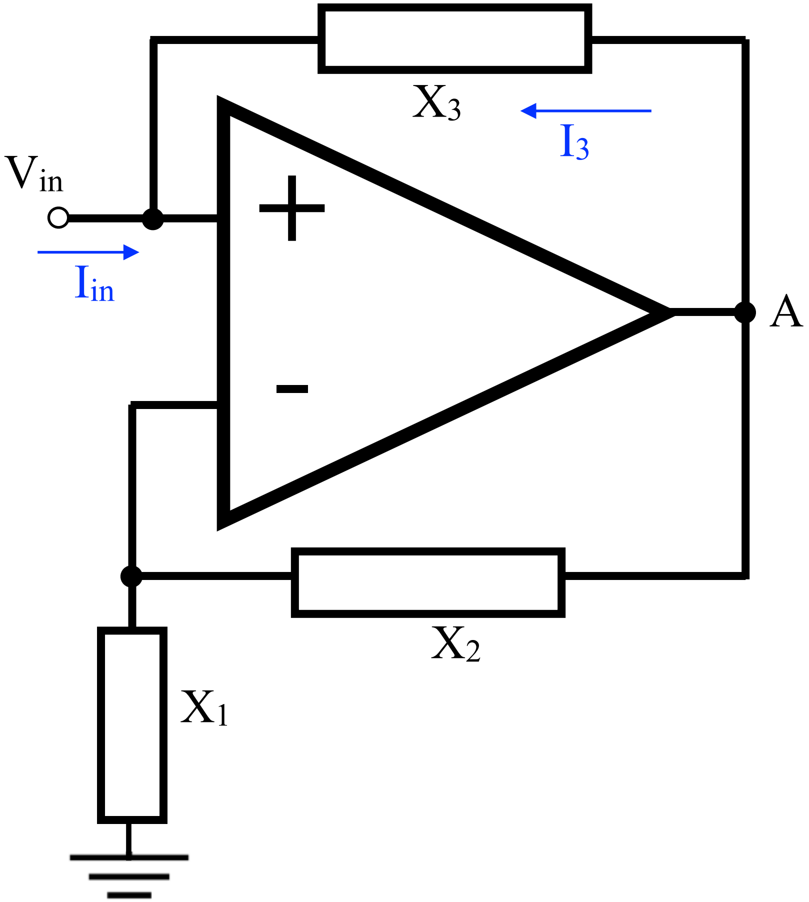

$V_A = V_{in}\,(1 + X_2/X_1)$

$I_3 = (V_A - V_{in})/X_3 \;= (V_{in} + V_{in}\,X_2/X_1 - V_{in})/X_3$

$= V_{in}\,X_2/(X_1X_3)$

I_3 flows *from* A *into* the input, so $I_{in} = -I_3$.

Negative impedance converter

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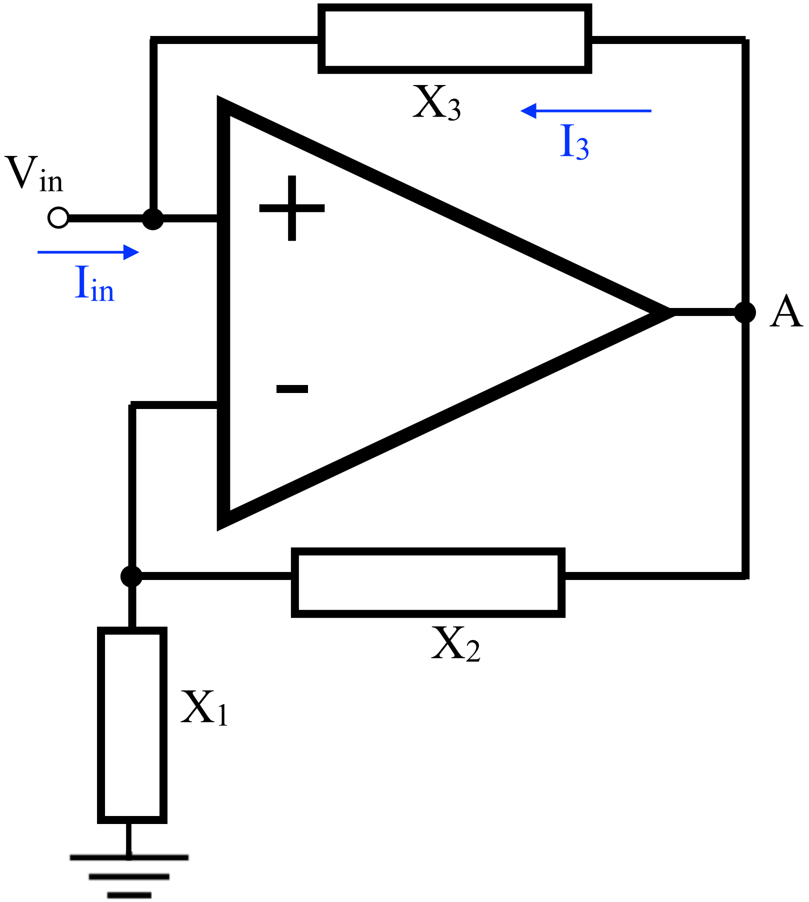

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$X_{in} = \Delta V_{in} / \Delta I_{in} = \Delta V_{in} /(-\Delta V_{in} X_2/(X_1X_3))$

$X_{in} = - X_1 X_3 / X_2$

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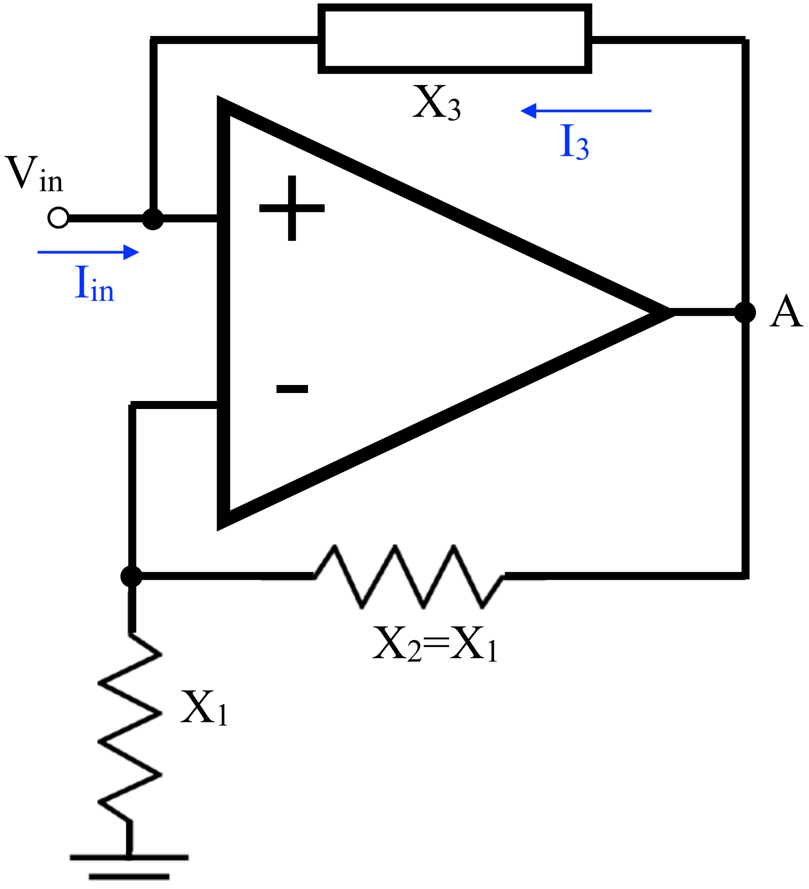

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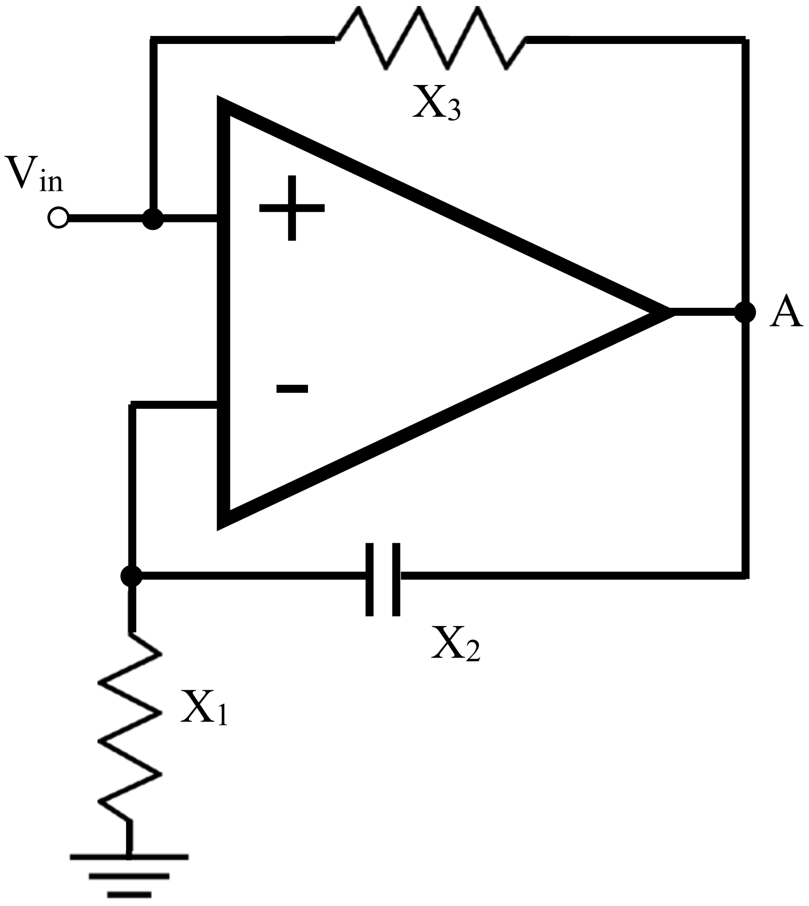

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I_3 flows *from* A *into* the input, so $I_{in} = -I_3$.

$X_{in} = \Delta V_{in}/\Delta I_{in} = \Delta V_{in}/(-\Delta V_{in}X_2/(X_1X_3))$

$X_{in} = -X_1X_3/X_2$

$X_{in} = -RR/(-j/\omega C) = R^2\omega C/j$

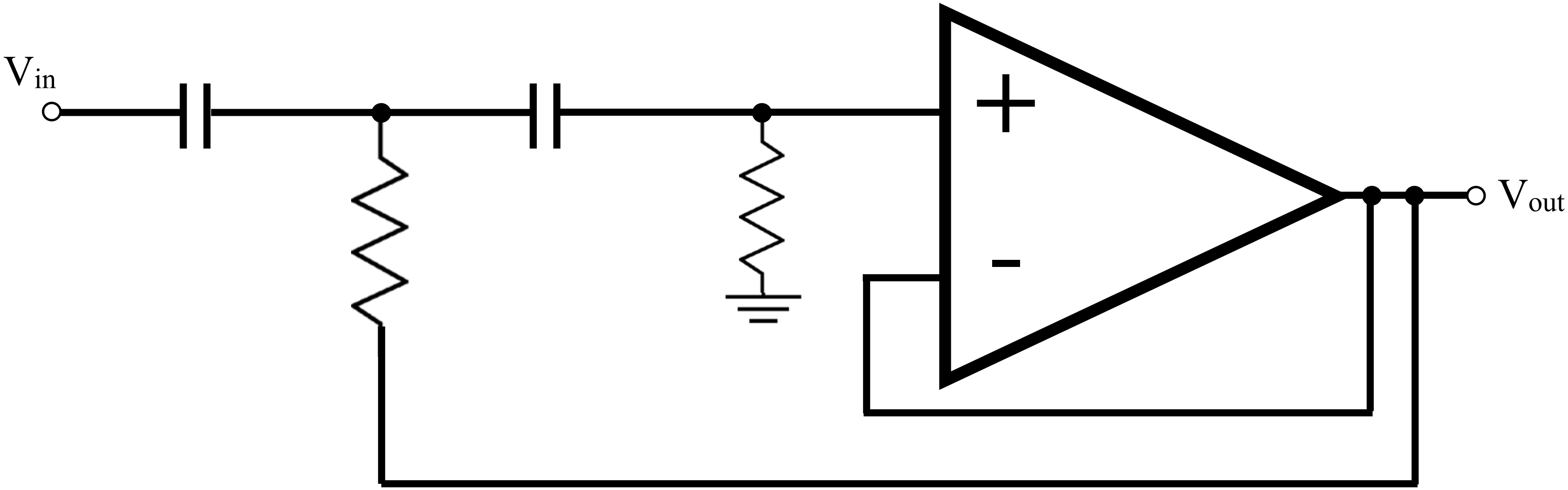
$X_{in} = -j\omega CR^2$

Combine this with previous, plug it in using the fact that *ground is just a reference*.

$X = j\omega CR^2$ which is like an $L = CR^2$.

Sallen-Key filter configuration

Can combine R's, C's, and op-amps in general configuration.

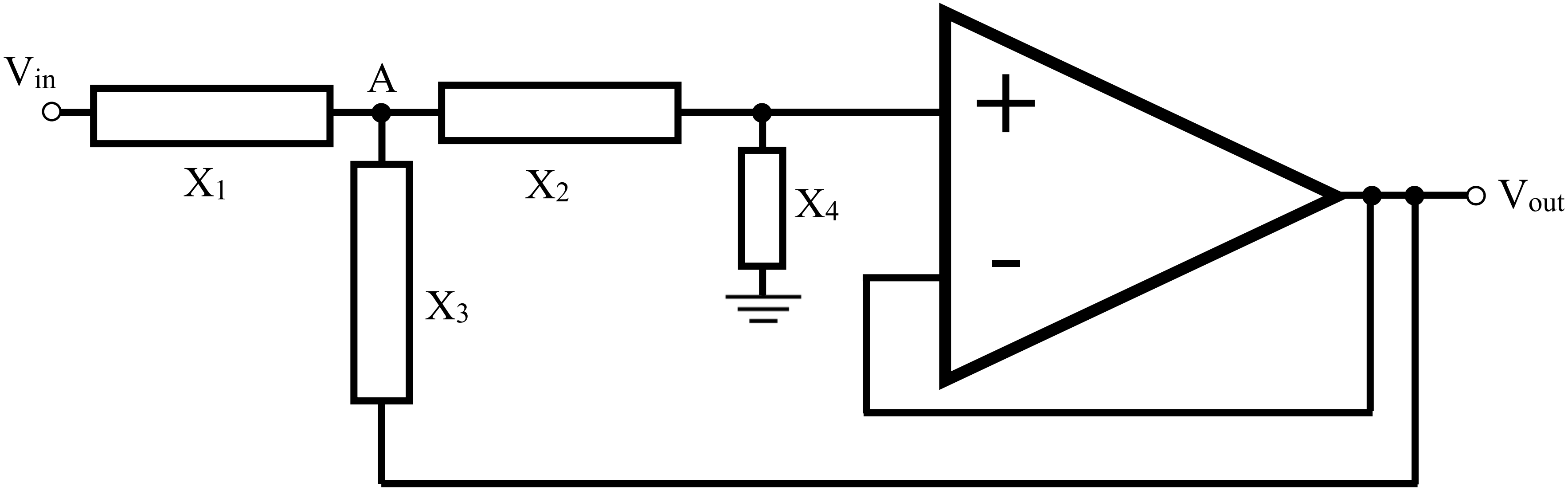


Analyzing the V_{out} vs V_{in} behavior can be done with the golden rules.

But let's do that more generally.

Voltage-controlled voltage source

Can combine R's, C's, and op-amps in general configuration.



Analyzing the V_{out} vs V_{in} behavior can be done with the golden rules and Ohm's law.

$V_+ = ?$

$V_A = ?$

$V_A - V_+ = ?$

$V_+ = ?$

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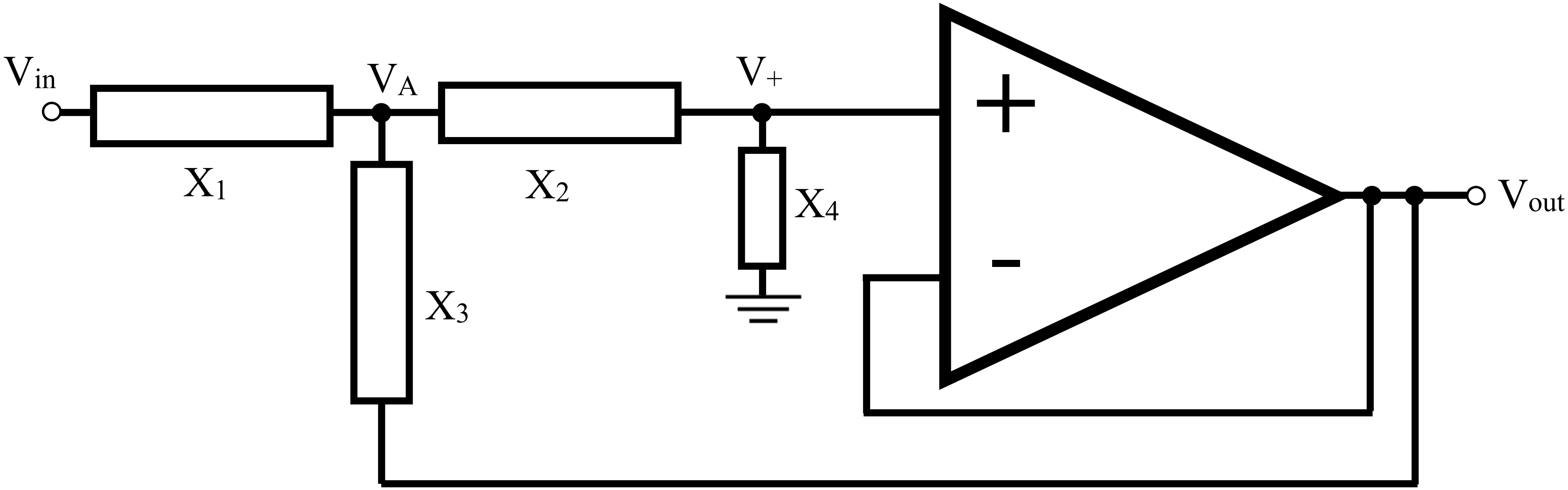

Analyzing the V_{out} vs V_{in} behavior can be done with the golden rules and Ohm's law.

$V_+ = V_{out}$

$V_A = V_{in} - I_1 X_1$

$V_A - V_+ = I_2 X_2$

$V_+ = I_4 X_4 = I_2 X_4$

$V_A - V_{out} = I_3 X_3$

$V_+ = V_A X_4 / (X_2+X_4)$

$$\frac{V_{out}}{V_{in}} = \frac{X_3 X_4}{X_1 X_2 + X_3 (X_1 + X_2) + X_3 X_4}$$

You can choose any mix of R and C (or even L with NIC) to get whatever relationship you want.

Voltage-controlled voltage source

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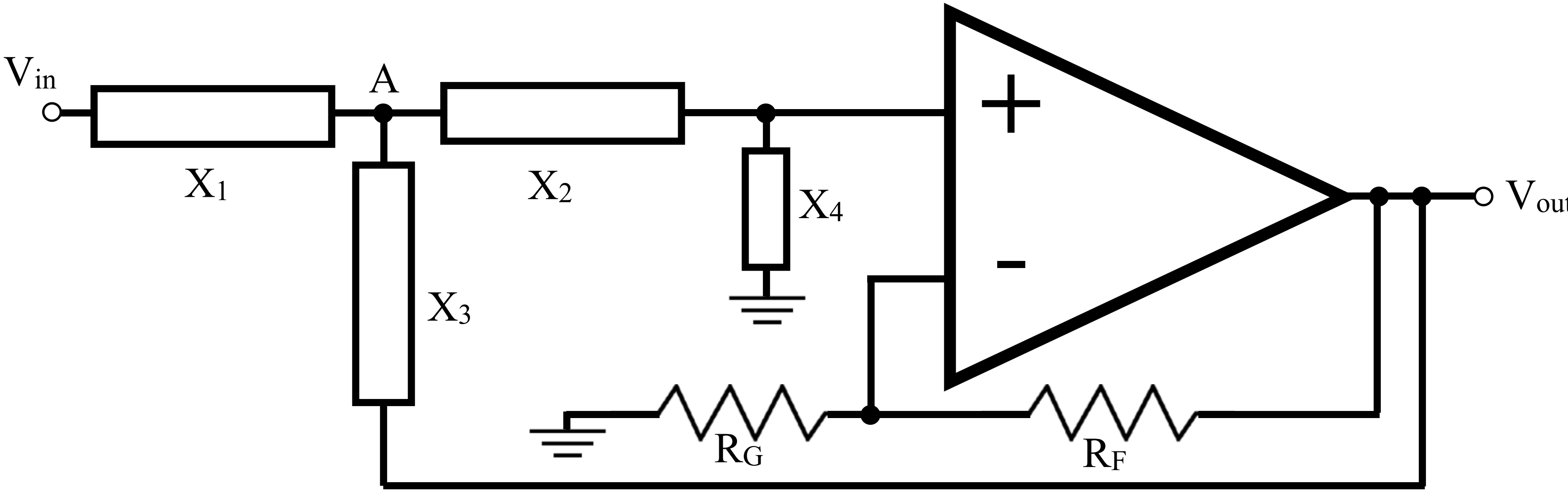

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$V_A - V_{out} = I_3 X_3$

$V_+ = V_A X_4 / (X_2+X_4)$

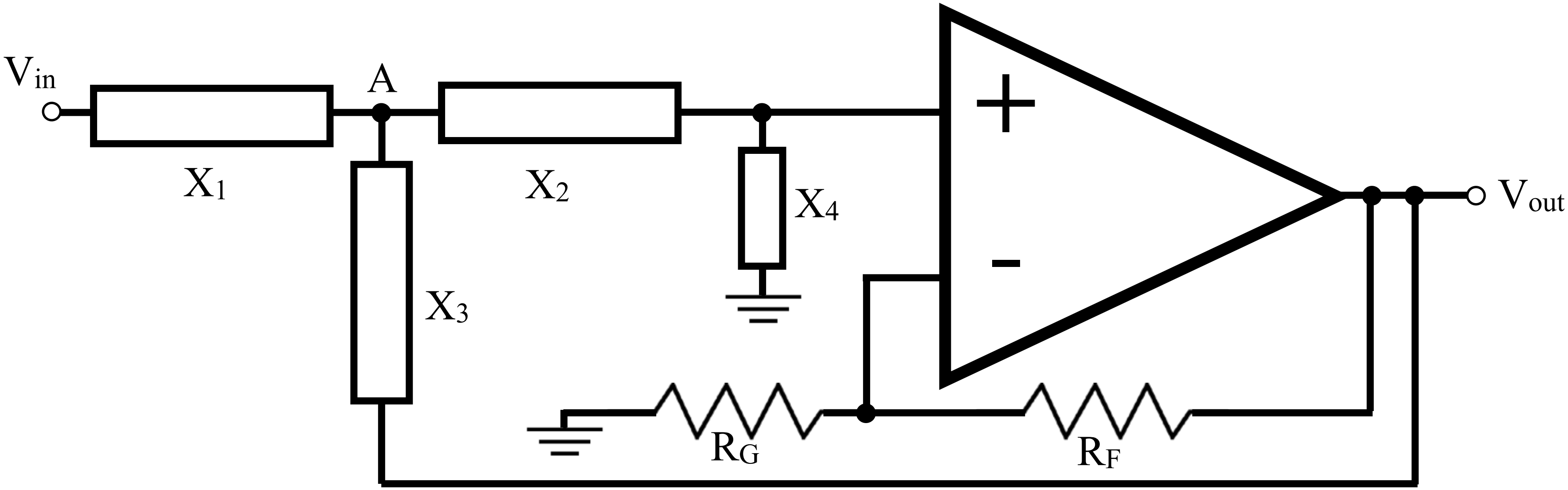
$$\frac{V_{out}}{V_{in}} = \frac{X_3 X_4}{X_1 X_2 + X_3 (X_1 + X_2) + X_3 X_4}$$

You can choose any mix of R and C (or even L with NIC) to get whatever relationship you want.

We could also add amplification.

Voltage-controlled voltage source

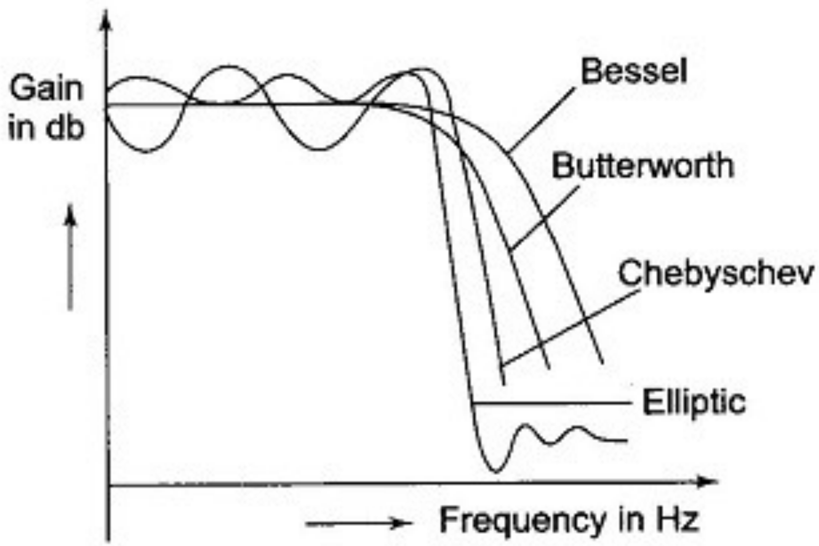
Can combine R's, C's, and op-amps in general configuration.



Can vary X1 - X4 and gain to get a variety of different response types.

You will not be likely to build your own active filter.

Can buy them to match specs.



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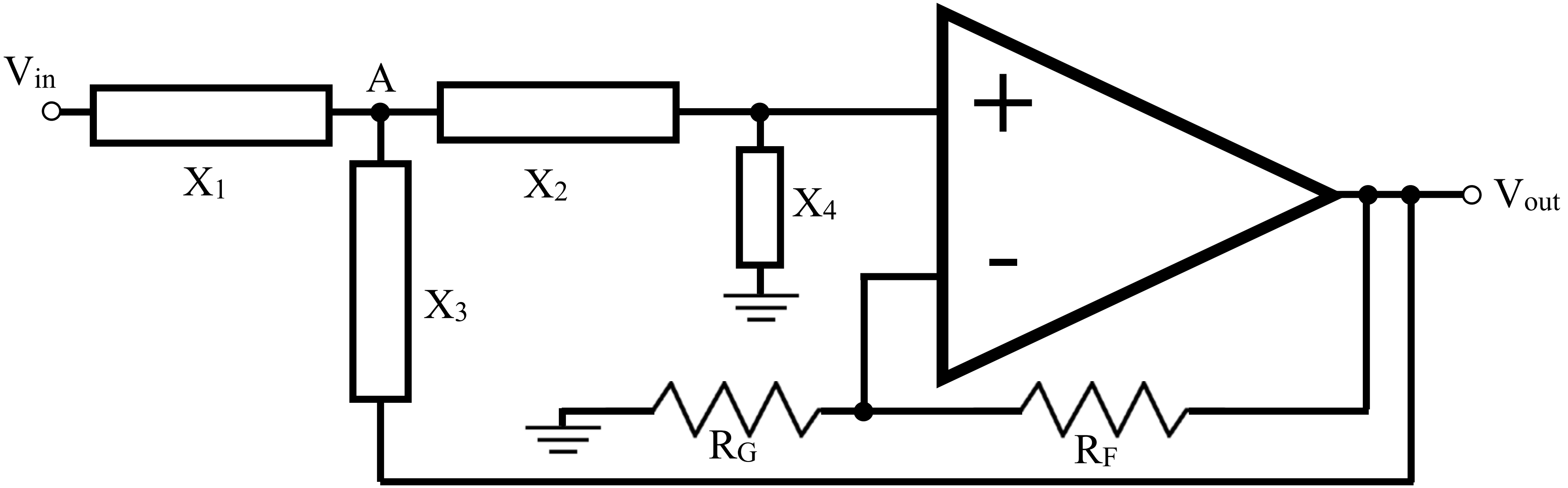

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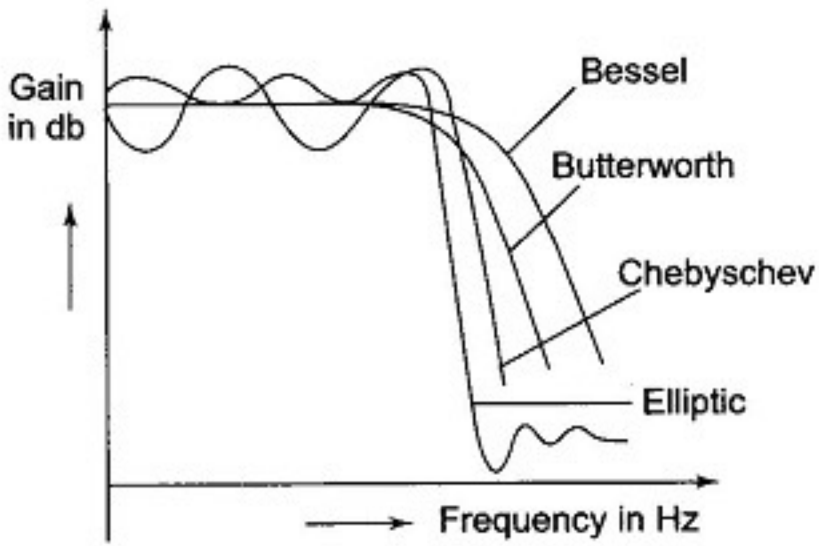
You will not be likely to build your own active filter.

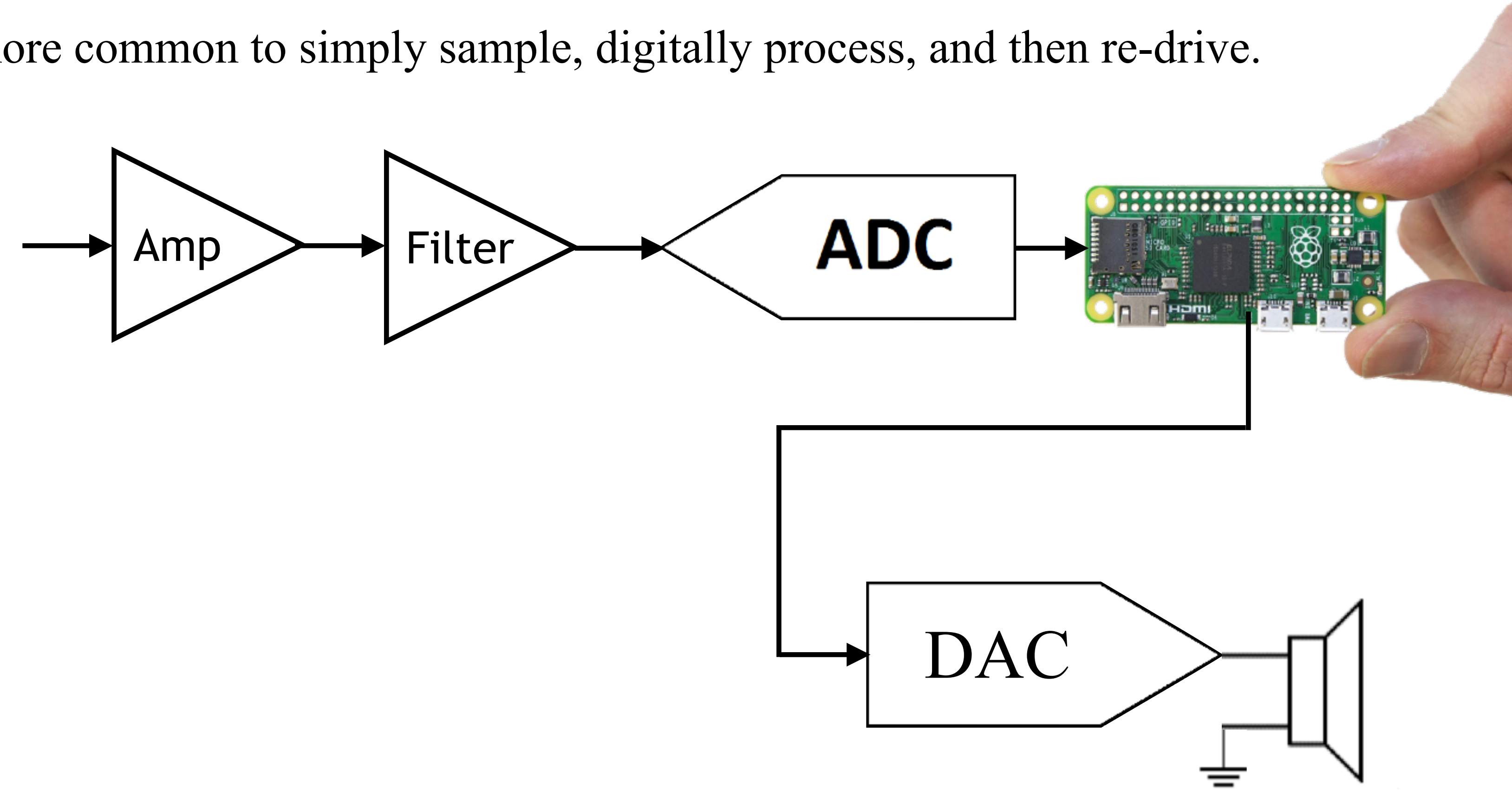
Can buy them to match specs.

But they can cost $5 - $10.



Software or firmware digital signal processing

It is getting more common to simply sample, digitally process, and then re-drive.

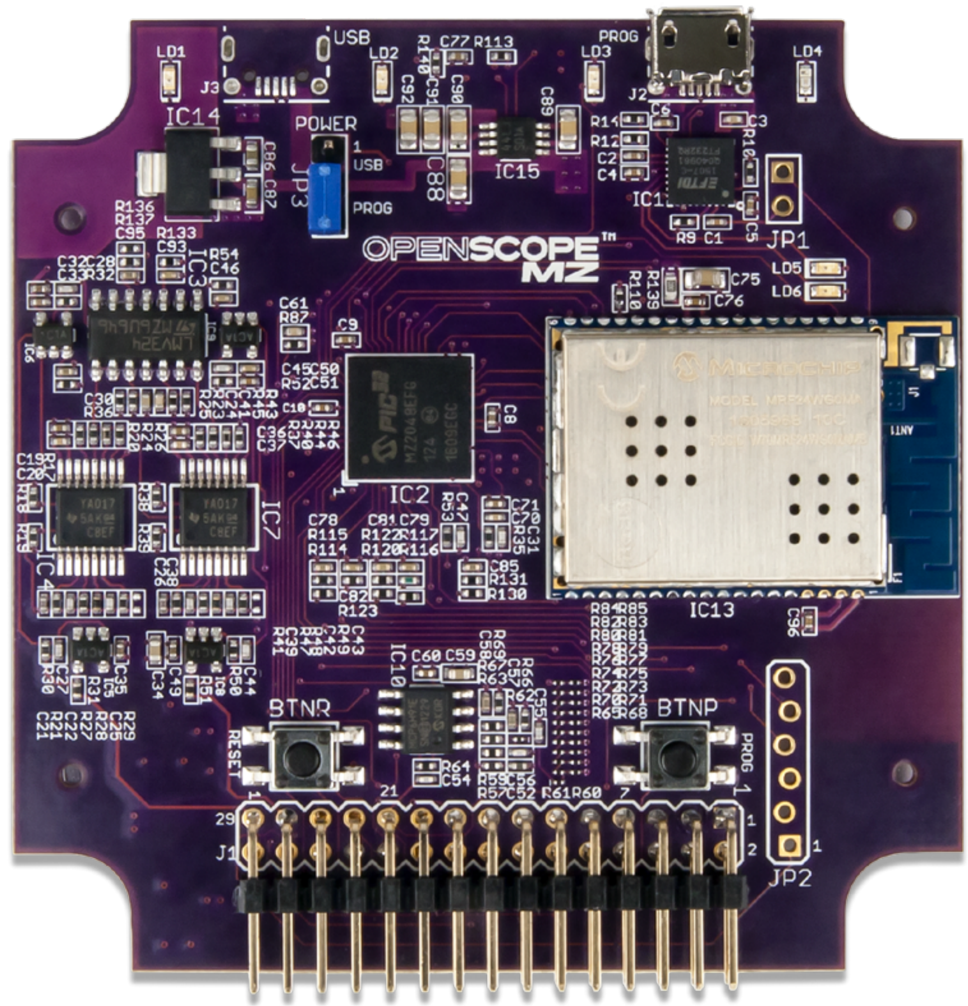


Software or firmware digital signal processing

It is getting more common to simply sample, digitally process, and then re-drive.

Instead of a full operating system, you can just use a micro controller, like the OpenScope and AD2.

PIC = peripheral interface controller



Software or firmware digital signal processing

It is getting more common to simply sample, digitally process, and then re-drive.

For processing a lot of parallel data, can use a Field Programmable Gate Array (FPGA) which can process hundreds of inputs at O(GHz) in parallel.

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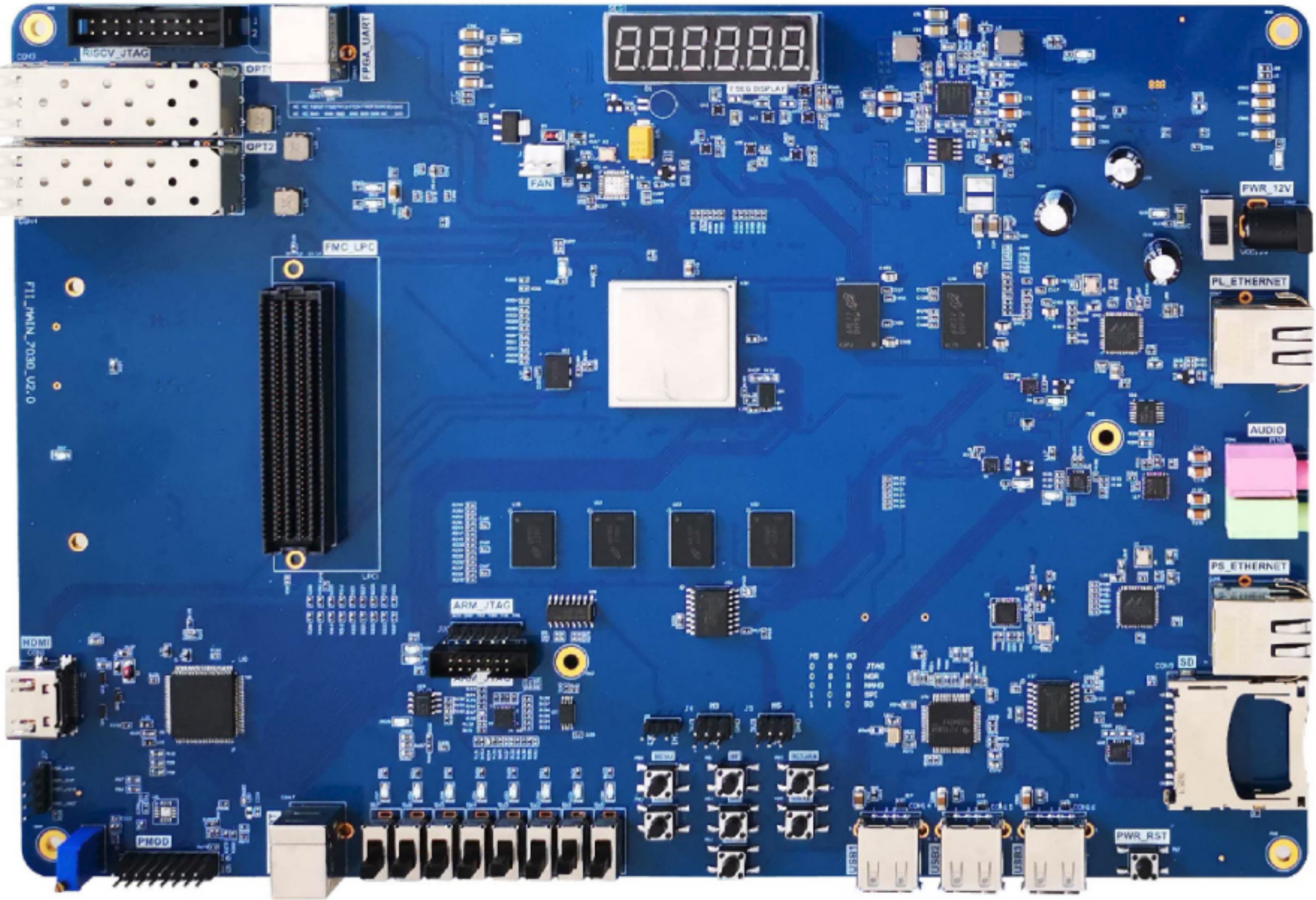
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FPGA_UART
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OPT2
FAN
FMC_LPC
FII_MAIN_7030_V2.0
PWR_12V
PL_ETHERNET
AUDIO
PS_ETHERNET
SD
HDMI
ARM_JTAG
PMOD
USB1
USB2
USB3
PWR_RST

Software or firmware digital signal processing

It is getting more common to simply sample, digitally process, and then re-drive.

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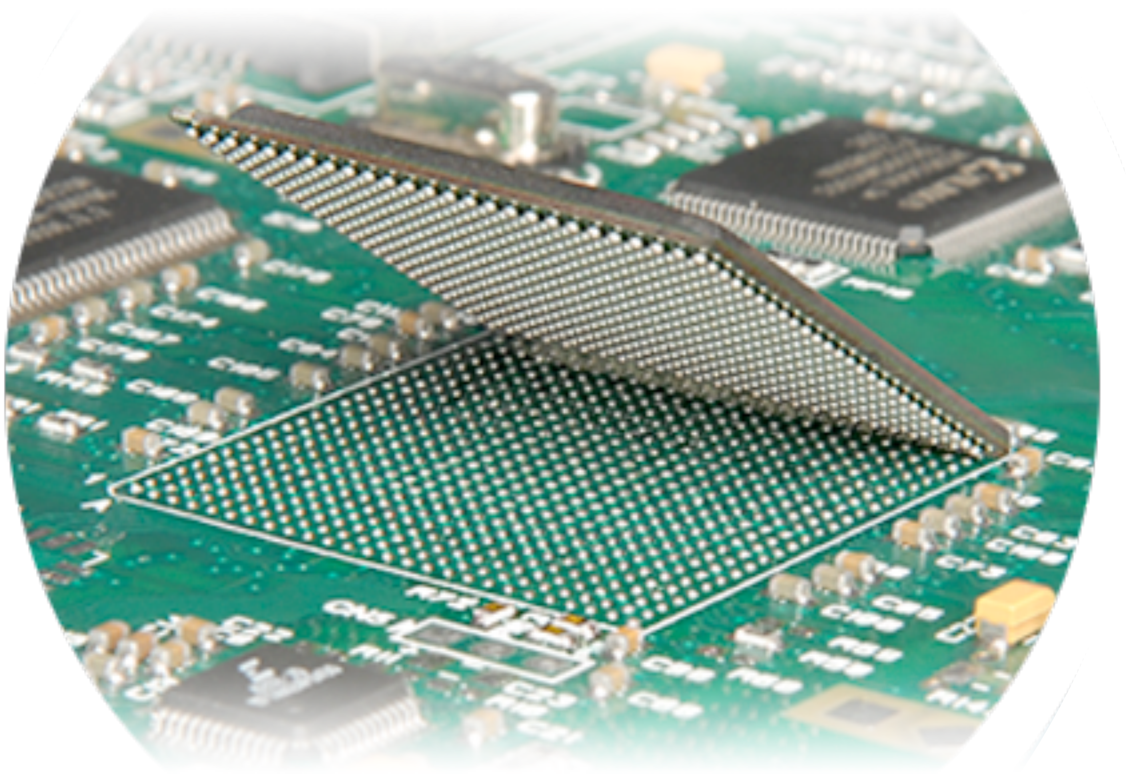
Many inputs, so have a 2D grid of connections with sub-mm spacing.



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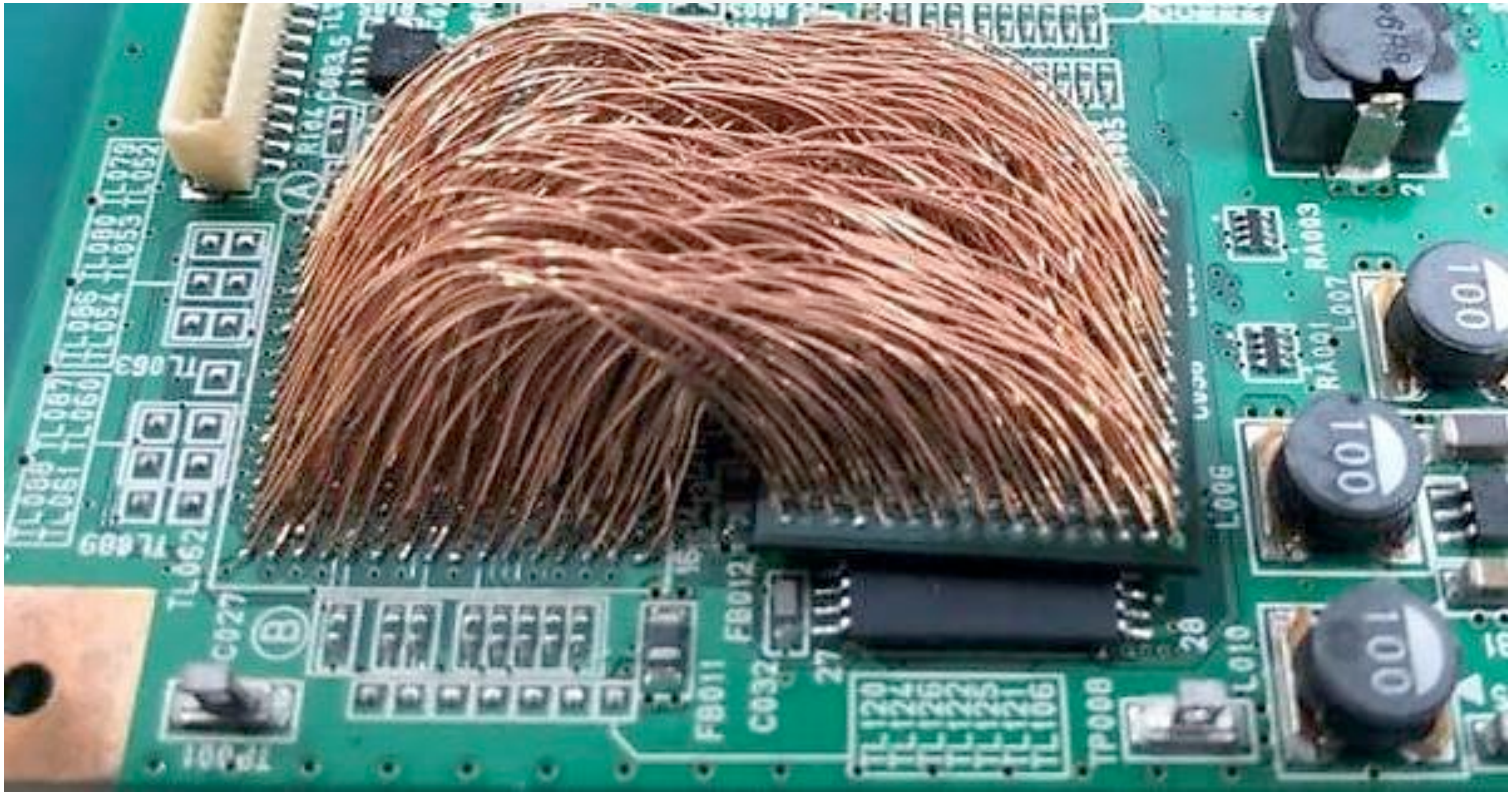

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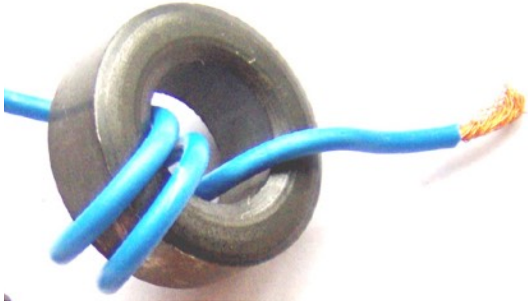
But "better is the enemy of good."

You can often just think about it and "add a cap" or an inductor to make it work.



As a hint toward next time: What does this circuit do?