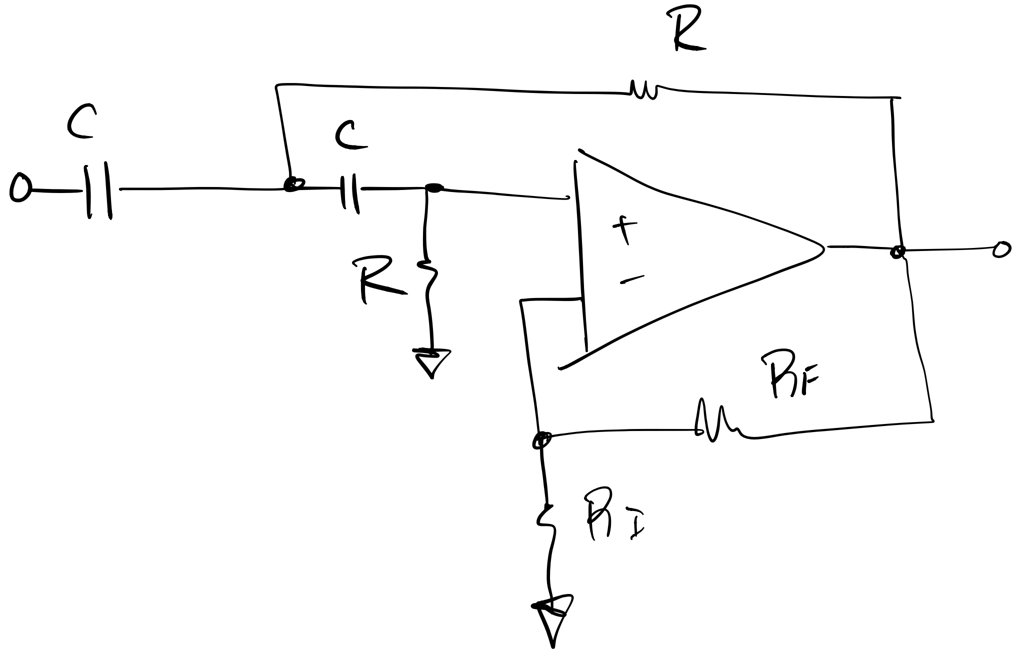
Active High-Pass Filter

.. simply reverse caps and resistors!



- same design procedure and equations as low pass!
  .. just remember that

$$FSF_{(\text{high-pass})} = \frac{f_c}{f_o}$$

ex: design 2nd-order Bessel HPF w/ $f_{-3dB} = 800$ Hz using S-K E.C. configuration

∴ need f_o to design filter!

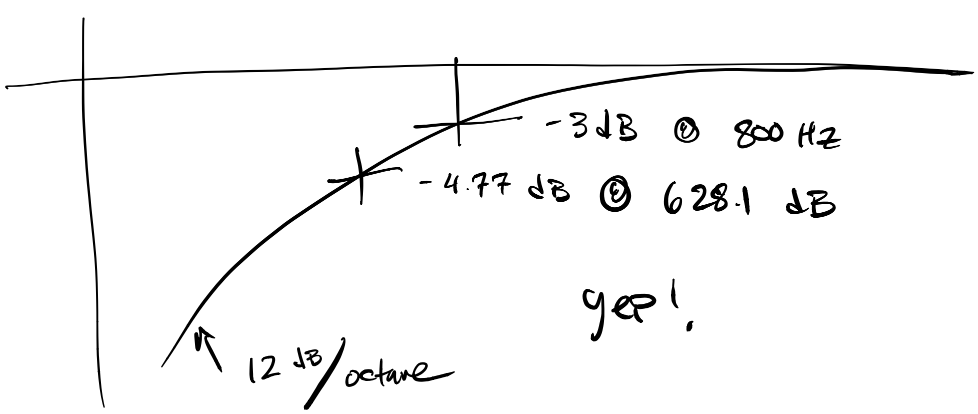
$$FSF = \frac{f_c}{f_o} \rightarrow f_o = \frac{f_c}{FSF} = \frac{800}{1.2736}$$

Bessel!!!

$$f_o = 628.1 \text{ Hz}$$

reality check: $Q_{Bessel} = \frac{1}{\sqrt{3}} = 0.577$

$\longrightarrow$ -4.77 dB @ f_o



yep!

∴ pick $C = 100\text{ nF}$

then $R = \dfrac{1}{2\pi f_0 C} = \dfrac{1}{2\pi \cdot 628.1 \cdot 100 \times 10^{-9}}$

$R = 2534$ → use $2.55k$ 1%

nearest E96!

∴ now we set A_v to get the desired Q

$A_v = 3 - \dfrac{1}{Q} = 3 - \dfrac{1}{1/\sqrt{3}}$

$= 1.268 = 1 + \dfrac{R_F}{R_I}$

∴ $\dfrac{R_F}{R_I} = 0.268$

Pick $R_F = 10k$ 1%

then $R_I = 37321$

use $37.4\ k\Omega$ 1%

∴ what if R was too small in initial computation?

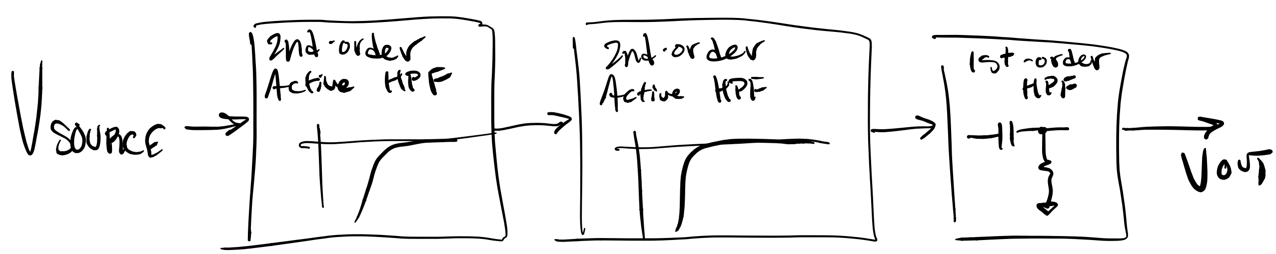
∴ lower C to raise R!

∴ OK, great... but what if we need <u>steeper</u> than 2nd-order; say, for anti-aliasing filter?

∴ the key: <u>cascade</u> the required number of 1st and 2nd-order filters to get the order you want!

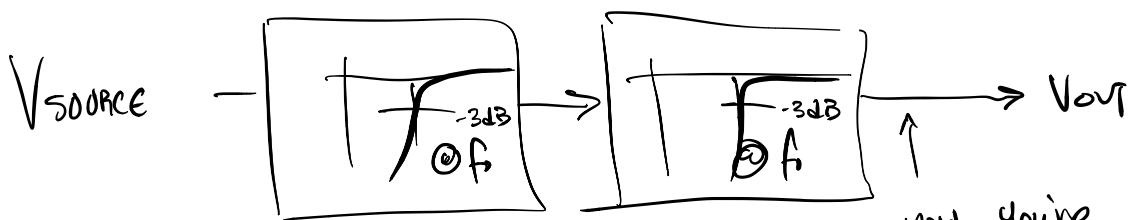
ex: 5th-order high-pass filter

block diagram:



∴ to make this work, each active filter must have <u>specific</u> f_0 and Q to acheive the correct <u>overall</u> -3dB point and Q!

example: if you cascade two Butterworth 2nd-order HPFs, you will <u>not</u> get a Butterworth 4th-order HPF!



now you're <u>-6dB</u> at f_0

→ that's not Butterworth, it's Linkwitz-Reilly!!!...

∴ the solution: a <u>table</u> that gives FSF and Q for each filter section in terms of a final -3dB cutoff, f_c

Table 1. Butterworth Filter Table

FILTER ORDER	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5	
	FSF	Q	FSF	Q	FSF	Q	FSF	Q	FSF	Q
2	1.000	0.7071								
3	1.000	1.0000	1.000							
4	1.000	0.5412	1.000	1.3065						
5	1.000	0.6180	1.000	1.6181	1.000					
6	1.000	0.5177	1.000	0.7071	1.000	1.9320				
7	1.000	0.5549	1.000	0.8019	1.000	2.2472	1.000			
8	1.000	0.5098	1.000	0.6013	1.000	0.8999	1.000	2.5628		
9	1.000	0.5321	1.000	0.6527	1.000	1.0000	1.000	2.8802	1.000	
10	1.000	0.5062	1.000	0.5612	1.000	0.7071	1.000	1.1013	1.000	3.1969

Table 2. Bessel Filter Table

FILTER ORDER	Stage 1		Stage 2		Stage 3		Stage 4		Stage 5	
	FSF	Q	FSF	Q	FSF	Q	FSF	Q	FSF	Q
2	1.2736	0.5773								
3	1.4524	0.6910	1.3270							
4	1.4192	0.5219	1.5912	0.8055						
5	1.5611	0.5635	1.7607	0.9165	1.5069					
6	1.6060	0.5103	1.6913	0.6112	1.9071	1.0234				
7	1.7174	0.5324	1.8235	0.6608	2.0507	1.1262	1.6853			
8	1.7837	0.5060	2.1953	1.2258	1.9591	0.7109	1.8376	0.5596		
9	1.8794	0.5197	1.9488	0.5894	2.0815	0.7606	2.3235	1.3220	1.8575	
10	1.9490	0.5040	1.9870	0.5380	2.0680	0.6200	2.2110	0.8100	2.4850	1.4150

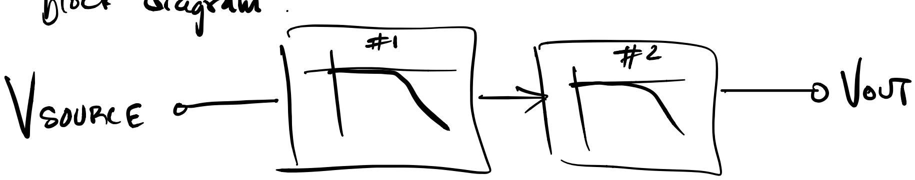
1% Resistor Table (E96)

100	102	105	107	110	113	115	118	121	124	127	130
133	137	140	143	147	150	154	158	162	165	169	174
178	182	187	191	196	200	205	210	215	221	226	232
237	243	249	255	261	267	274	280	287	294	301	309
316	324	332	340	348	357	365	374	383	392	402	412
422	432	442	453	464	475	487	499	511	523	536	549
562	576	590	604	619	634	649	665	681	698	715	732
750	768	787	806	825	845	866	887	909	931	953	976

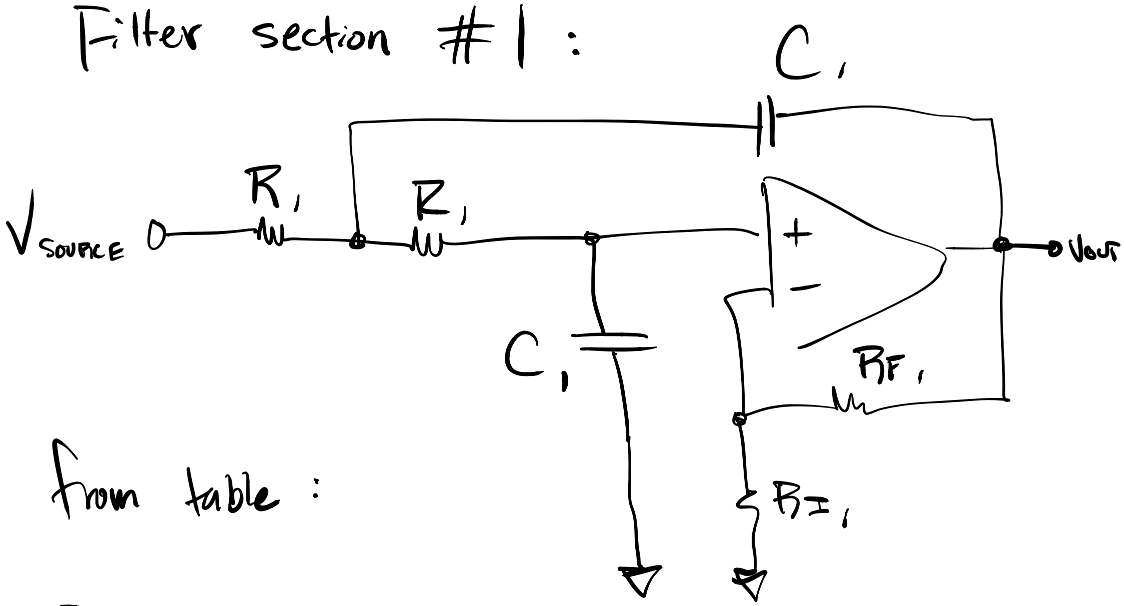
ex: design 4th-order Butterworth low-pass filter w/ f_c = 500 Hz

∴ this requires two 2nd-order Sallen-Key active low-pass filters in cascade

block diagram:



Filter section #1 :



from table :

$FSF_1 = 1.000$

$Q_1 = 0.5412$ ← weird value!

$$FSF_{(\text{low-pass})} = \frac{f_0}{f_c}$$

$\therefore$ $f_{0_1} = FSF_1 \cdot f_c = 1.000 \cdot 500 = 500\ Hz$

pick $C_1 = 1\ \mu F$

then $R_1 = \frac{1}{2\pi \cdot 500 \cdot 1\times10^{-6}} = 318.3\ \Omega$

too low!

try $C_1 = 100\ nF$

→ then $R_1 = 3183$ ✓

use $R_1 = 3.16\ k\Omega$ 1%

$$A_{v1} = 3 - \frac{1}{Q_1} = 3 - \frac{1}{0.5412} = 1.152$$

$$1.152 = 1 + \frac{R_{F1}}{R_{I1}}$$

then $\frac{R_{F1}}{R_{I1}} = 0.152$

pick $R_{F1} = 10\ k\Omega\ 1\%$

then $R_{I1} = 65789$ use $66.5\ k\Omega\ 1\%$

Filter section #2:

from table, $FSF_2 = 1.000$, $Q_2 = 1.3065$

$\Downarrow$

again, weird!

$$f_{o2} = FSF_2\, f_c = 1.000 \cdot 500 = 500\ Hz$$

pick $C_2 = 100nF$ $\Rightarrow$ then $R_2 \approx 3.16\ k\Omega\ 1\%$

$$A_{v2} = 3 - \frac{1}{Q_2} = 3 - \frac{1}{1.3065} = 2.235$$

$$2.235 = 1 + \frac{R_{F2}}{R_{I2}}$$

$$\frac{R_{F2}}{R_{I2}} = 1.235$$

pick $R_{F2} = 10\ k\Omega\ 1\%$

then $R_{I2} = 8097$

use $8.06\ k\Omega\ 1\%$

Note: $Q_1 = 0.5412$

therefore, $20 \log_{10}(.5412) = -5.333 \text{ dB}$ @ f_0

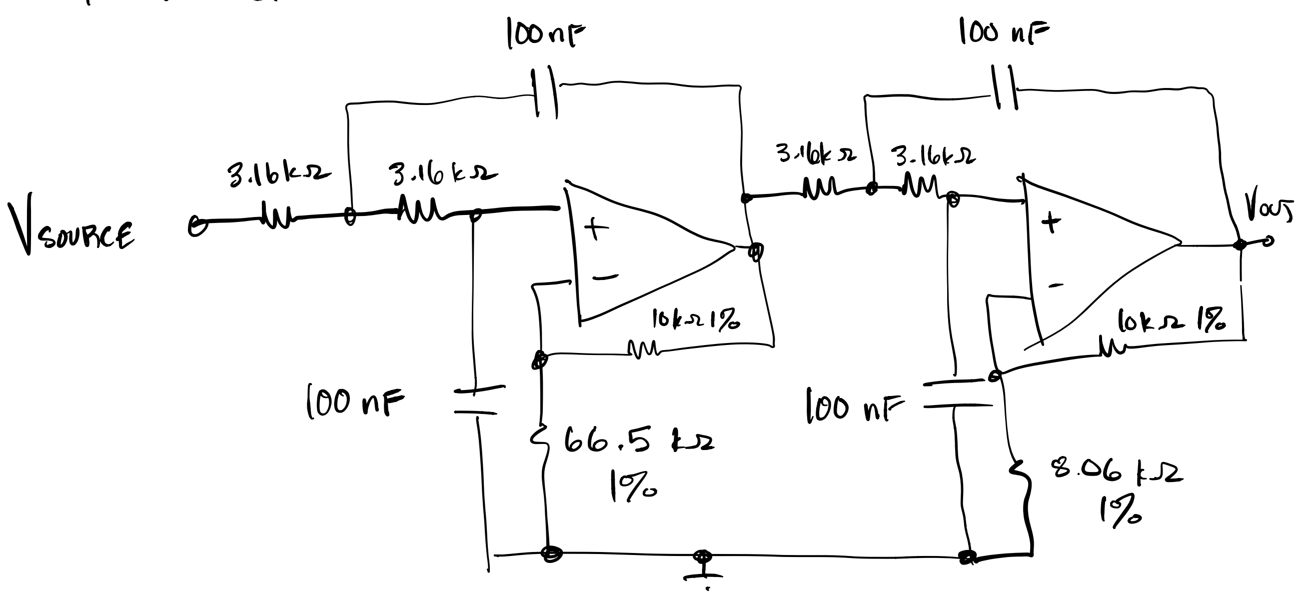
$Q_2 = 1.3065$

$20 \log_{10}(1.3065) = +2.322 \text{ dB}$ @ f_0

$-5.333 + 2.322 \simeq -3\text{dB} \rightarrow$ Butterworth!

.. another check: $0.5412 \cdot 1.3065 = 0.707$

Final circuit:



∴ need to check passband gain!

$A_{v_1} = 1.152$

$A_{v_2} = 2.235$

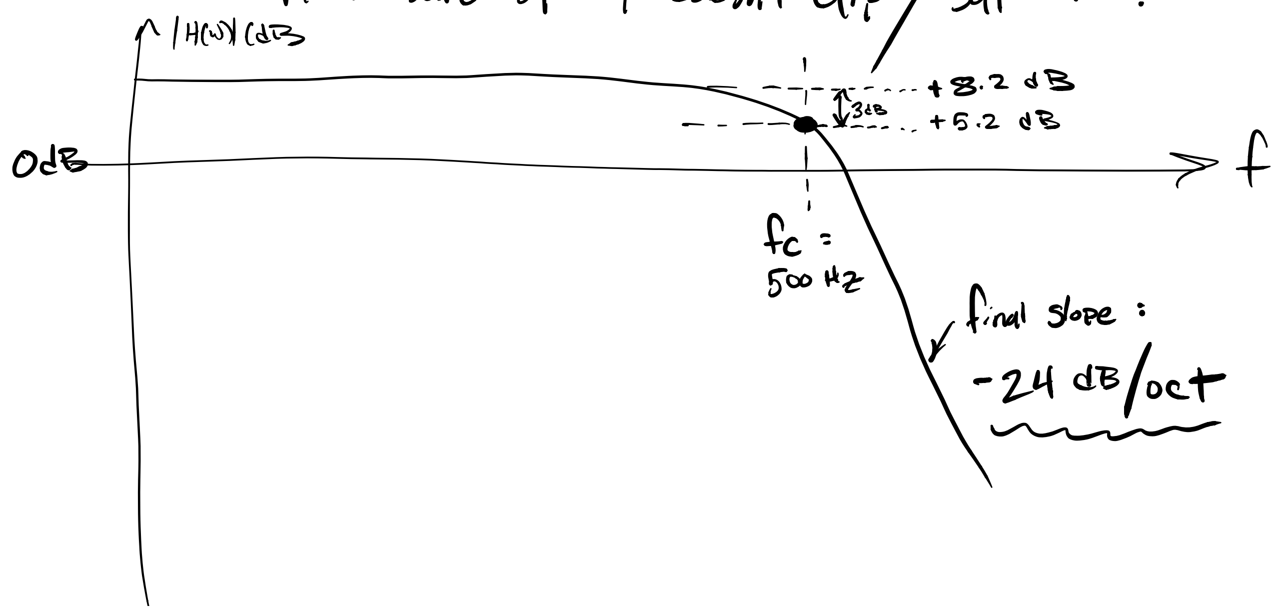
$\therefore A_v \text{(midband)} = 1.152 \cdot 2.235 = 2.575$

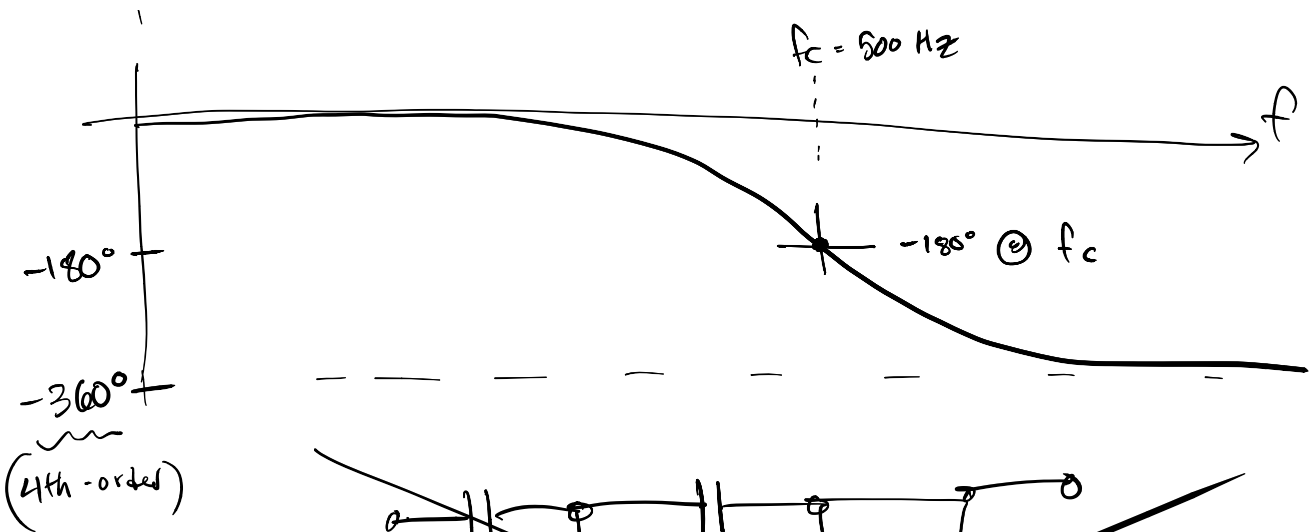
$20 \log_{10} 2.575 = +8.2 \text{ dB}$

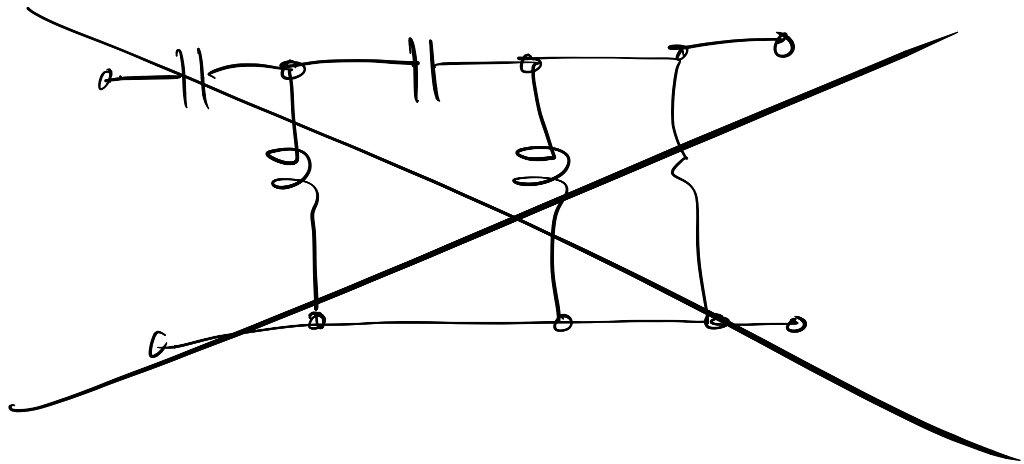
∴ our signal is amplified +8.2 dB in order to get right Q values in filters

∴ usually not a problem!

∴ make sure op-amp doesn't clip / saturate!



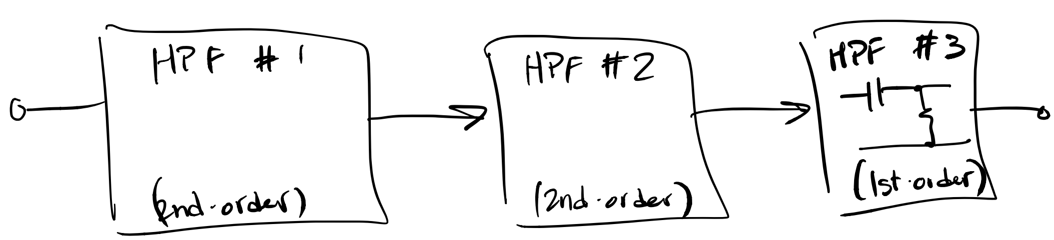




homework: design 5th-order Bessel HPF

w/ f_{-3dB} = 90 Hz

hint:



-- don't forget to compute passband gain in dB and sketch carefully! -- simulate in LTSPICE!!!