EE 508
Lecture 23

Filter Synthesis Strategies

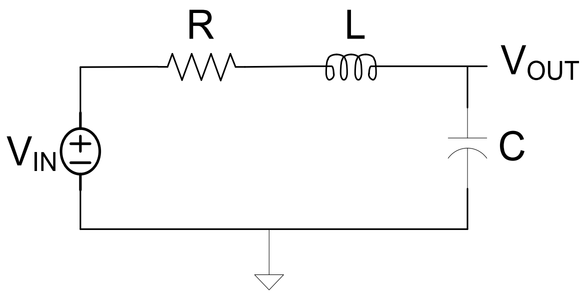
- Integrators

Review from last time

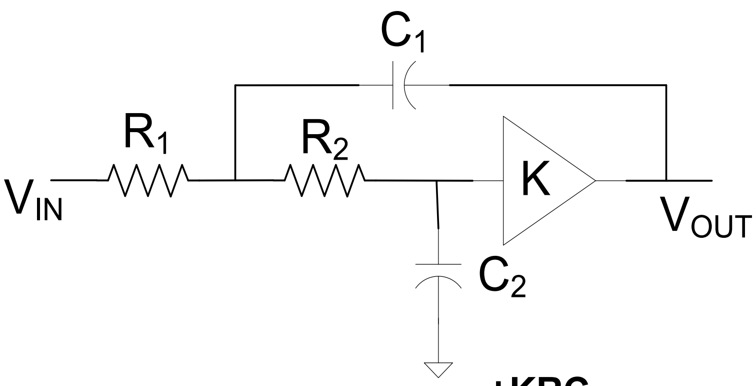
Sensitivity Comparisons

Consider 5 second-order lowpass filters

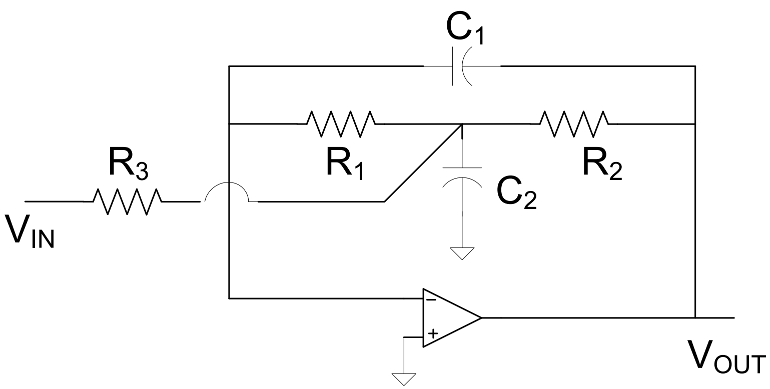
(all can realize same T(s) within a gain factor)



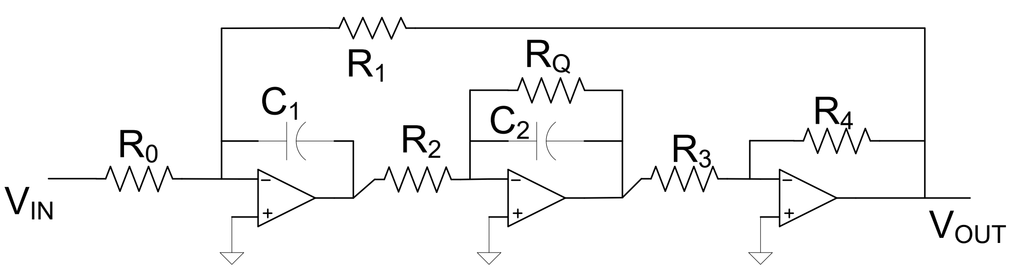
Passive RLC



+KRC



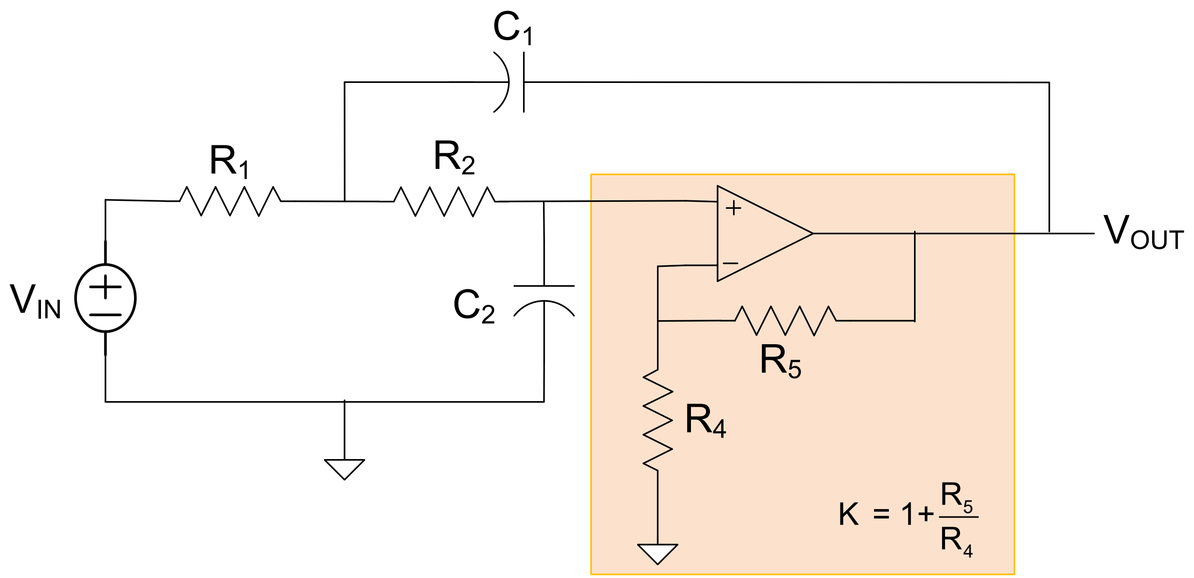
Bridged-T Feedback



Two-Integrator Loop

Review from last time

b) + KRC (a Sallen and Key filter)



$$T(s) = \frac{\dfrac{K}{R_1R_2C_1C_2}}{s^2 + s\left[\left(\dfrac{1}{\sqrt{R_1R_2C_1C_2}}\right)\left(\sqrt{\dfrac{R_1C_1}{R_2C_2}} + \sqrt{\dfrac{R_2C_2}{R_1C_1}} + \sqrt{\dfrac{R_1C_2}{R_2C_1}} - K\sqrt{\dfrac{R_1C_1}{R_2C_2}}\right)\right] + \dfrac{1}{R_1R_2C_1C_2}}$$

$$\omega_0 = \sqrt{\frac{1}{R_1R_2C_1C_2}}$$

$$Q = \frac{1}{\left(\sqrt{\dfrac{R_1C_1}{R_2C_2}} + \sqrt{\dfrac{R_2C_2}{R_1C_1}} + \sqrt{\dfrac{R_1C_2}{R_2C_1}} - K\sqrt{\dfrac{R_1C_1}{R_2C_2}}\right)}$$

How do these five circuits compare?

a) From a passive sensitivity viewpoint?

- If Q is small
- If Q is large

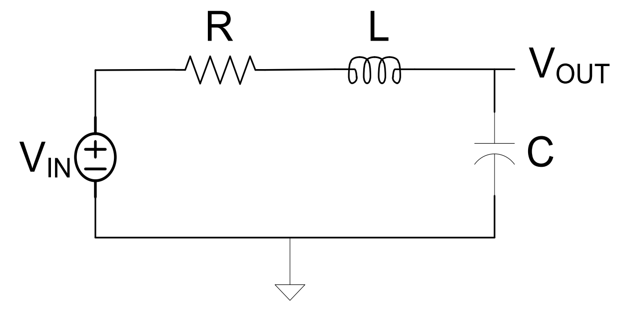
b) From an active sensitivity viewpoint?

- If Q is small
- If Q is large
- If $\tau\omega_0$ is large

Comparison: Calculate all ω_0 and Q sensitivities

Consider passive sensitivities first

a) – Passive RLC



$$S_R^{\omega_0} = 0$$

$$S_L^{\omega_0} = -\frac{1}{2}$$

$$S_C^{\omega_0} = -\frac{1}{2}$$

$$S_R^{Q} = -1$$

$$S_C^{Q} = -\frac{1}{2}$$

$$S_L^{Q} = \frac{1}{2}$$

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

$$\omega_0 = \sqrt{\frac{1}{LC}}$$

Case b1 : +KRC Equal R, Equal C

$$\omega_0 = \sqrt{\frac{1}{R_1 R_2 C_1 C_2}}$$

$$Q = \frac{1}{\left(\sqrt{\frac{R_1 C_1}{R_2 C_2}} + \sqrt{\frac{R_2 C_2}{R_1 C_1}} + \sqrt{\frac{R_1 C_2}{R_2 C_1}} - K\sqrt{\frac{R_1 C_1}{R_2 C_2}}\right)}$$

$$S_{R_1}^{\omega_0} = S_{R_2}^{\omega_0} = S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2}$$

$$S_K^{\omega_0} = 0$$

$$S_{R_1}^{Q} = Q - \frac{1}{2}$$

$$S_{R_2}^{Q} = -Q + \frac{1}{2}$$

$$S_{C_1}^{Q} = 2Q - \frac{1}{2}$$

$$S_{C_2}^{Q} = -2Q + \frac{1}{2}$$

$$S_K^{Q} = 3Q - 1$$

$$Q = \frac{1}{3-K}$$

$$\omega_0 = \frac{1}{RC}$$

If Q_N=10 in +KRC filter, what happens to Q if R_1 increases by 1%? By 10%?

$$S_{R_1}^{Q} = Q - \frac{1}{2}$$

$$\frac{\Delta R_1}{R_1} = 0.01$$

$$\frac{\Delta Q}{Q} \simeq S_{R_1}^{Q} \bullet \frac{\Delta R_1}{R_1} \simeq \left(Q - \frac{1}{2}\right)(0.01) = 9.5 \bullet 0.01 = 0.095$$

$Q_{PREDICT}$=10*(1+0.095)=10.95

Q_{ACTUAL}=11.04

$$\frac{\Delta R_1}{R_1} = 0.1$$

$$\frac{\Delta Q}{Q} \simeq S_{R_1}^{Q} \bullet \frac{\Delta R_1}{R_1} \simeq \left(Q - \frac{1}{2}\right)(0.01) = 9.5 \bullet 0.1 = 0.95$$

$Q_{PREDICT}$=10*(1+0.95)=19.5

Q_{ACTUAL}=105

Sensitivity analysis quite useful if $\frac{\Delta x}{x}$ is small but not accurate when $\frac{\Delta x}{x}$ is large

Effects of R_1 variations on +KRC Filter

$$S_{R_1}^{Q} = Q - \frac{1}{2}$$

	Q	10	
	K	2.9	
Pct Chang	Sens /Var	Predicted	Actual
	Pred	Q	Q
1	0.095	10.95	11.04382
2	0.19	11.9	12.31647
3	0.285	12.85	13.90259
4	0.38	13.8	15.93444
5	0.475	14.75	18.63082
6	0.57	15.7	22.3818
7	0.665	16.65	27.95697
8	0.76	17.6	37.11537
9	0.855	18.55	54.94898
10	0.95	19.5	104.8809
11	1.045	20.45	1053.565
12	1.14	21.4	-132.288
13	1.235	22.35	-62.5303
14	1.33	23.3	-41.0657
15	1.425	24.25	-30.6394
16	1.52	25.2	-24.478
17	1.615	26.15	-20.4088
18	1.71	27.1	-17.5206
19	1.805	28.05	-15.3644
20	1.9	29	-13.6931

	Q	2	
	K	2.5	
Pct Chang	Sens /Var	Predicted	Actual
	Pred	Q	Q
1	0.015	2.03	2.030278
2	0.03	2.06	2.061123
3	0.045	2.09	2.092555
4	0.06	2.12	2.124591
5	0.075	2.15	2.157253
6	0.09	2.18	2.19056
7	0.105	2.21	2.224533
8	0.12	2.24	2.259197
9	0.135	2.27	2.294573
10	0.15	2.3	2.330686
11	0.165	2.33	2.367563
12	0.18	2.36	2.405228
13	0.195	2.39	2.443712
14	0.21	2.42	2.483041
15	0.225	2.45	2.523248
16	0.24	2.48	2.564364
17	0.255	2.51	2.606423
18	0.27	2.54	2.649459
19	0.285	2.57	2.693509
20	0.3	2.6	2.738613

	Q	25	
	K	2.96	
Pct Chang	Sens /Var	Predicted	Actual
	Pred	Q	Q
1	0.245	31.125	33.0588
2	0.49	37.25	48.55531
3	0.735	43.375	90.6151
4	0.98	49.5	637.3774
5	1.225	55.625	-128.087

Case b2 : +KRC Equal R, K=1

$$\omega_0 = \sqrt{\frac{1}{R_1R_2C_1C_2}}$$

$$Q = \frac{1}{\left(\sqrt{\frac{R_1C_1}{R_2C_2}} + \sqrt{\frac{R_2C_2}{R_1C_1}} + \sqrt{\frac{R_1C_2}{R_2C_1}} - K\sqrt{\frac{R_1C_1}{R_2C_2}}\right)}$$

$$S_{R_1}^{\omega_0} = S_{R_2}^{\omega_0} = S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2}$$

$$S_K^{\omega_0} = 0$$

$$S_{R_1}^{Q} = 0$$

$$S_{R_2}^{Q} = 0$$

$$S_{C_1}^{Q} = \frac{1}{2}$$

$$S_{C_2}^{Q} = -\frac{1}{2}$$

$$S_K^{Q} = 2Q^2$$

$$\omega_0 = \frac{1}{RC}$$

$$Q = \frac{1}{2}\sqrt{\frac{C_1}{C_2}}$$

c) Bridged T Feedback

$$\omega_0 = \sqrt{\frac{1}{R_1 R_2 C_1 C_2}}$$

$$Q = \frac{1}{\left(\sqrt{\frac{C_2}{C_1}}\right)\left(\sqrt{\frac{R_1}{R_3}} + \sqrt{\frac{R_2}{R_1}} + \frac{\sqrt{R_1 R_2}}{R_3}\right)}$$

For $R_1 = R_2 = R_3 = R$

$$S_{R_1}^{\omega_0} = S_{R_2}^{\omega_0} = S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2}$$

$$S_{R_3}^{\omega_0} = 0$$

$$S_{R_1}^{Q} = -\frac{1}{6}$$

$$S_{R_2}^{Q} = -\frac{1}{6}$$

$$S_{R_3}^{Q} = \frac{1}{3}$$

$$S_{C_1}^{Q} = -\frac{1}{2}$$

$$S_{C_2}^{Q} = \frac{1}{2}$$

$$\omega_0 = \frac{3Q}{RC_1}$$

$$Q = \frac{1}{3}\sqrt{\frac{C_1}{C_2}}$$

d) 2 integrator loop

$$\omega_0 = \sqrt{\frac{R_4}{R_3} \bullet \frac{1}{R_0 R_2 C_1 C_2}} \qquad Q = \frac{R_Q}{\sqrt{R_0 R_2}} \sqrt{\frac{C_2}{C_1}}$$

For: $R_0 = R_1 = R_2 = R$ $\quad C_1 = C_2 = C$ $\quad R_3 = R_4$

$$S^{\omega_0}_{R_1} = S^{\omega_0}_{R_2} = S^{\omega_0}_{R_3} = S^{\omega_0}_{C_1} = S^{\omega_0}_{C_2} = -\frac{1}{2} \qquad S^{\omega_0}_{R_4} = \frac{1}{2}$$

$$S^{Q}_{R_1} = S^{Q}_{R_2} = S^{Q}_{R_3} = S^{Q}_{C_1} = -\frac{1}{2}$$

$$S^{Q}_{R_4} = S^{Q}_{C_2} = \frac{1}{2}$$

$$S^{Q}_{R_Q} = 1$$

$$S^{Q}_{R_0} = 0$$

$$\omega_0 = \frac{1}{RC}$$

$$Q = \frac{R_Q}{R}$$

d) -KRC passive sensitivities

$$\omega_0 = \sqrt{\frac{1+(R_1/R_3)(1+K)+(R_1/R_4)(1+R_2/R_3+R_2/R_1)}{R_1R_2C_1C_2}}$$

$$Q = \frac{\sqrt{\frac{1+(R_1/R_3)(1+K)+(R_1/R_4)(1+R_2/R_3+R_2/R_1)}{R_1R_2C_1C_2}}}{\left(1+\frac{R_1}{R_3}\right)\left(\frac{1}{R_1C_1}\right)+\left(1+\frac{C_2}{C_1}\right)\left(\frac{1}{R_2C_2}\right)+\left(\frac{1}{R_4C_2}\right)}$$

For $R_1=R_2=R_3=R_4=R$, $C_1=C_2=C$

$$Q = \frac{\sqrt{5+K_0}}{5} \qquad \omega_0 = \frac{\sqrt{5+K}}{R\,C}$$

$$S_{R_1}^{\omega_0} = -\frac{1}{25Q^2} \qquad S_{R_2}^{\omega_0} = -\frac{1}{2}+\frac{1}{25Q^2} \qquad S_{R_3}^{\omega_0} = -\frac{1}{2}+\frac{3}{50Q^2}$$

$$S_{C_1}^{\omega_0} = S_{C_2}^{\omega_0} = -\frac{1}{2} \qquad S_{R_4}^{\omega_0} = -\frac{3}{50Q^2} \qquad S_{K}^{\omega_0} = \frac{1}{2}+\frac{1}{10Q^2}$$

$$S_{R_1}^{Q} = \frac{1}{5}-\frac{1}{25Q^2} \qquad S_{R_2}^{Q} = -\frac{1}{10}+\frac{1}{25Q^2} \qquad S_{R_3}^{Q} = -\frac{3}{10}+\frac{3}{50Q^2}$$

$$S_{R_4}^{Q} = \frac{1}{5}-\frac{3}{50Q^2} \qquad S_{C_2}^{Q} = -\frac{1}{10} \qquad S_{C_1}^{Q} = \frac{1}{10} \qquad S_{K}^{Q} = \frac{1}{2}-\frac{1}{10Q^2}$$

Passive Sensitivity Comparisons

	$\left\| S_x^{\omega_0} \right\|$	$\left\| S_x^{Q} \right\|$
Passive RLC	$\leq \frac{1}{2}$	**1,1/2**
+KRC		
Equal R, Equal C (K=3-1/Q)	**0,1/2**	**Q, 2Q, 3Q**
Equal R, K=1 ($C_1=4Q^2C_2$)	**0,1/2**	**0,1/2, $2Q^2$**
Bridged-T Feedback	**0,1/2**	**1/3,1/2, 1/6**
Two-Integrator Loop	**0,1/2**	**1,1/2, 0**
-KRC	**less than or equal to 1/2**	**less than or equal to 1/2**

Substantial Differences Between (or in) Architectures

How do active sensitivities compare ?

$S_{k}^{\omega_0} = ?$ $S_{k}^{Q} = ?$

Recall $S_x^f = \frac{\partial f}{\partial x} \frac{x}{f}$

so $\frac{\Delta f}{f} \simeq \frac{\Delta x}{x} S_x^f$

but if x is ideally 0, not useful

$\mathcal{S}_x^f = \frac{\partial f}{\partial x}$

$\frac{\Delta f}{f} \simeq \mathcal{S}_x^f \frac{\Delta x}{f}$

Where we are at with sensitivity analysis:

Considered a group of five second-order filters

Passive Sensitivity Analysis

- Closed form expressions were obtained for ω_0 and Q
- Tedious but straightforward calculations provided passive sensitivities directly from the closed form expressions ???

Active Sensitivity Analysis

- Closed form expressions for ω_0 and Q are very difficult or impossible to obtain

If we consider higher-order filters

Passive Sensitivity Analysis

- Closed form expressions for ω_0 and Q are very difficult or impossible to obtain for many useful structures

Active Sensitivity Analysis

- Closed form expressions for ω_0 and Q are very difficult or impossible to obtain

Need some better method for obtaining sensitivities when closed-form expressions are difficult or impractical to obtain or manipulate !!

Relationship between pole sensitivities and ω_0 and Q sensitivities

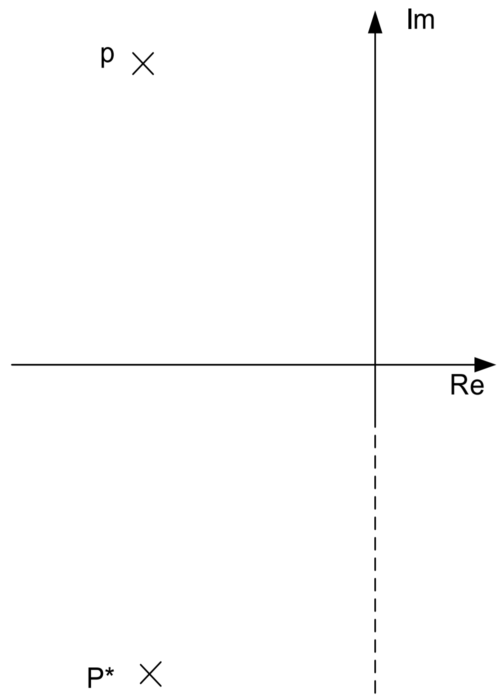
$p = -\alpha + j\beta$

$D_2(s) = (s-p)(s-p^*)$

$D_2(s) = (s+\alpha-j\beta)(s+\alpha+j\beta)$

$D_2(s) = s^2 + s(2\alpha) + (\alpha^2+\beta^2)$

$$D_2(s) = s^2 + s\frac{\omega_0}{Q} + \omega_0^2$$



Relationship between active pole sensitivities and ω_0 and Q sensitivities

Define $D(s)=D_0(s)+\tau D_1(s)$ (from bilinear form of T(s))

Recall: $$\mathcal{S}_\tau^p = \frac{-D_1(p)}{\left.\frac{\partial D(s)}{\partial s}\right|_{s=p,\tau=0}}$$

Theorem: $$\Delta p \cong \tau \mathcal{S}_\tau^p$$

Theorem: $$\Delta\alpha \cong \tau \,\mathrm{Re}\left(\mathcal{S}_\tau^p\right)$$
$$\Delta\beta \cong \tau \,\mathrm{Im}\left(\mathcal{S}_\tau^p\right)$$

Theorem:

$$\frac{\Delta\omega_0}{\omega_0} \cong \frac{1}{2Q}\frac{\Delta\alpha}{\omega_0} + \sqrt{1-\frac{1}{4Q^2}}\,\frac{\Delta\beta}{\omega_0}$$

$$\frac{\Delta Q}{Q} \cong -2Q\left(1-\frac{1}{4Q^2}\right)\frac{\Delta\alpha}{\omega_0} + \sqrt{1-\frac{1}{4Q^2}}\,\frac{\Delta\beta}{\omega_0}$$

Claim: These theorems, with straightforward modification, also apply to other parameters (R, C, L, K, …) where, $D_0(s)$ and $D_1(s)$ will change since the parameter is different

Active Sensitivities

+KRC

Equal-R, Equal-C

$$\omega_o = \frac{1}{RC}, \qquad Q = \frac{1}{3 - K_o}$$

$$\frac{V_o}{V_i} = \frac{\left(3 - \frac{1}{Q}\right)\omega_o^2}{s^2 + s\frac{\omega_o}{Q} + \omega_o^2 + \frac{\left(3 - \frac{1}{Q}\right)}{\mathrm{GB}} s(s^2 + s3\omega_o + \omega_o^2)} \qquad \left(\omega_a \ll \frac{\omega_o}{2Q}\right)$$

$$-\frac{\Delta\alpha}{\omega_o} \cong \frac{1}{2Q}\left(3 - \frac{1}{Q}\right)^2 \frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta\beta}{\omega_o} \cong -\frac{1}{2}\left(3 - \frac{1}{Q}\right)^2 \frac{\left(1 - \frac{1}{2Q^2}\right)}{\sqrt{1 - \frac{1}{4Q^2}}} \frac{\omega_o}{\mathrm{GB}}$$

$$\frac{\Delta\omega_o}{\omega_o} \cong -\frac{1}{2}\left(3 - \frac{1}{Q}\right)^2 \frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta Q}{Q} \cong \frac{1}{2}\left(3 - \frac{1}{Q}\right)^2 \frac{\omega_o}{\mathrm{GB}}$$

Unity-gain, Equal-R

$$\omega_o = \frac{1}{R\sqrt{C_1 C_2}}, \qquad Q = \frac{1}{2}\sqrt{\frac{C_1}{C_2}}$$

$$\frac{V_o}{V_i} = \frac{\omega_o^2}{s^2 + s\frac{\omega_o}{Q} + \omega_o^2 + \frac{s}{\mathrm{GB}}\left[s^2 + s\omega_o\left(2Q + \frac{1}{Q}\right) + \omega_o^2\right]} \qquad \left(\omega_a \ll \frac{\omega_o}{2Q}\right)$$

$$-\frac{\Delta\alpha}{\omega_o} \cong \frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta\beta}{\omega_o} \cong -Q \frac{\left(1 - \frac{1}{2Q^2}\right)}{\sqrt{1 - \frac{1}{4Q^2}}} \frac{\omega_o}{\mathrm{GB}}$$

$$\frac{\Delta\omega_o}{\omega_o} \cong -Q\frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta Q}{Q} \cong Q\frac{\omega_o}{\mathrm{GB}}$$

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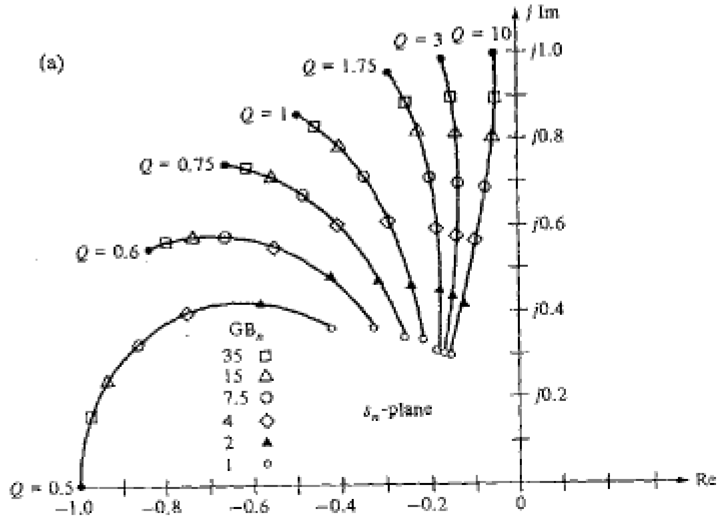
where

$$s_n = \frac{s}{\omega_o}, \qquad \mathrm{GB}_n = \frac{\mathrm{GB}}{\omega_o}.$$

Active Sensitivities

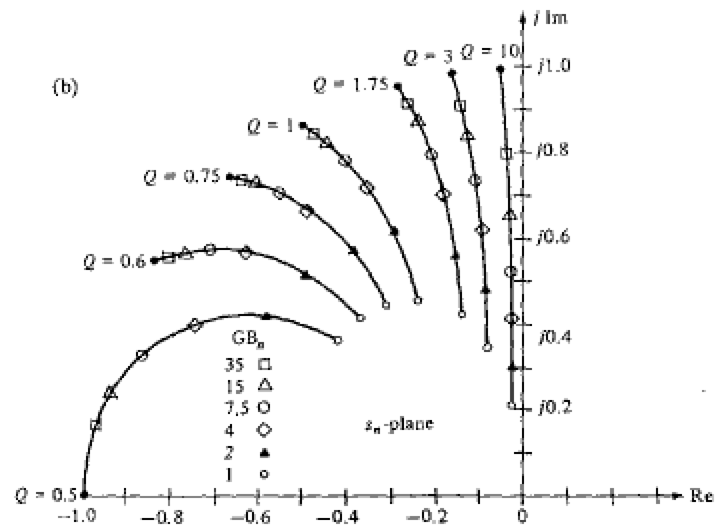
+KRC



◀Fig. 10-5a Plot of upper half-plane root of

$$s_n^3 + s_n^2\left(3+\frac{QGB_n}{3Q-1}\right) + s_n\left(1+\frac{GB_n}{3Q-1}\right) + \frac{QGB_n}{3Q-1} = 0$$

(Equal-R, equal-C)



◀Fig. 10-5b Plot of upper half plane root of

$$s_n^3 + s_n^2\left(2Q+\frac{1}{Q}+GB_n\right) + s_n\left(1+\frac{GB_n}{Q}\right) + GB_n = 0$$

(Unity-gain, equal-R)

Active Sensitivities

Bridged T Feedback

Table 10-3 Infinite-gain Realization
(see Fig. 10-10b)

Equal-R

$$\omega_o = \frac{1}{R\sqrt{C_1 C_2}}; \qquad Q = \frac{1}{3}\sqrt{\frac{C_1}{C_2}}$$

$$\frac{V_o}{V_i} = -\frac{\omega_o^2}{s^2 + s\frac{\omega_o}{Q} + \omega_o^2 + \frac{s}{\mathrm{GB}}\left[s^2 + s\omega_o\left(3Q + \frac{1}{Q}\right) + 2\omega_o^2\right]} \qquad \left(\omega_a \ll \frac{\omega_o}{2Q}\right)$$

$$-\frac{\Delta\alpha}{\omega_o} \simeq \frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta\beta}{\omega_o} \simeq -\frac{1}{2}\frac{3Q - \frac{1}{Q}}{\sqrt{1 - \frac{1}{4Q^2}}}\frac{\omega_o}{\mathrm{GB}}$$

$$\frac{\Delta\omega_o}{\omega_o} \simeq -\frac{3Q}{2}\frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta Q}{Q} \simeq \frac{Q}{2}\frac{\omega_o}{\mathrm{GB}}$$

Active Sensitivities

Bridged T Feedback

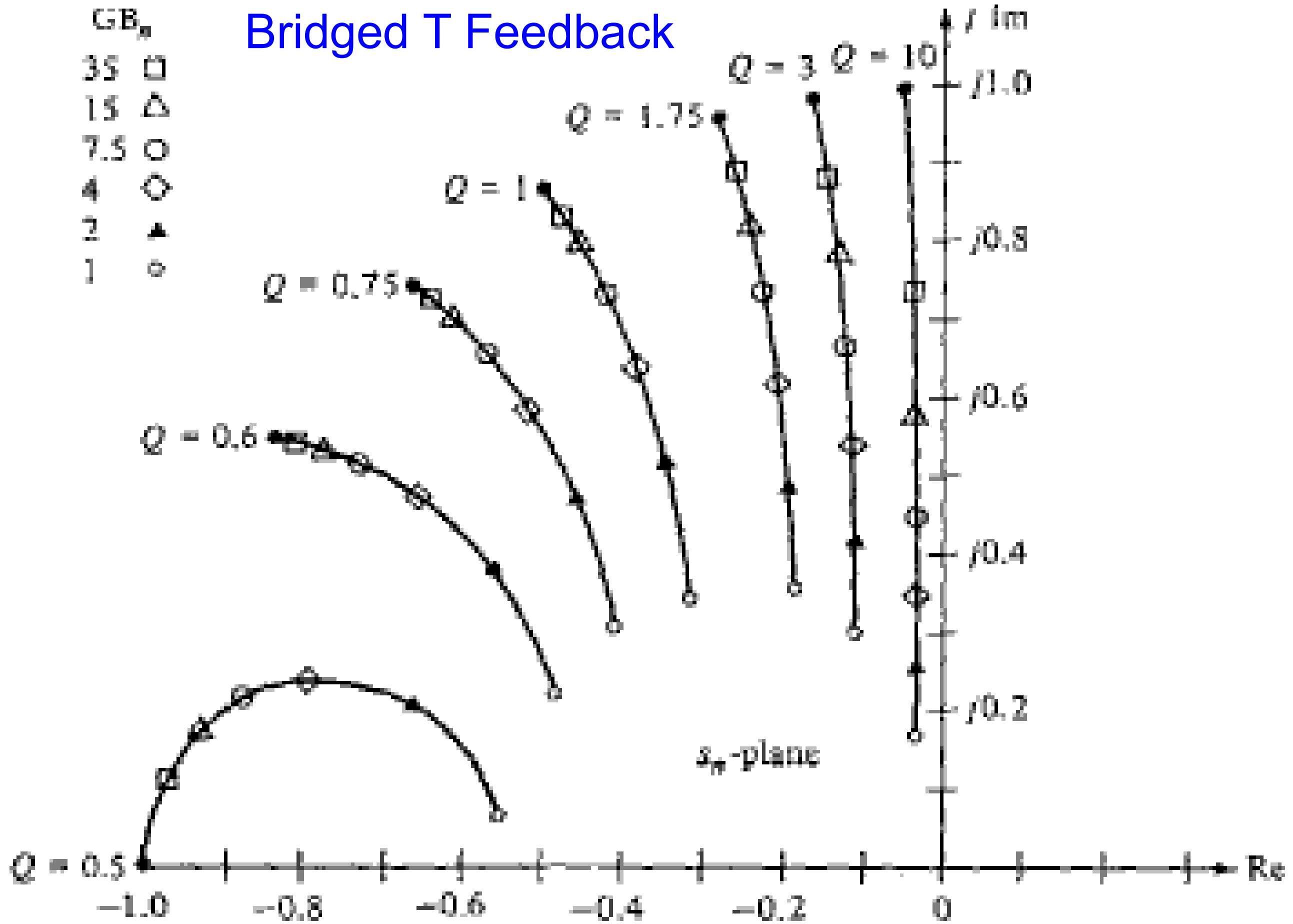


Fig. 10-12 Plot of upper half-plane root of

$$s_n^3 + s_n^2\left(3Q + \frac{1}{Q} + GB_n\right) + s_n\left(2 + \frac{GB_n}{Q}\right) + GB_n = 0$$

Active Sensitivities

Two integrator loop architecture

Equal-R (except R_Q) and Equal-C

$$\omega_o = \frac{1}{RC}, \qquad Q = \frac{R_Q}{R}$$

$$\frac{V_0}{V_i} \cong \frac{\omega_o^2\left(\frac{2}{\mathrm{GB}}s + 1\right)}{s^2 + s\frac{\omega_o}{Q} + \omega_o^2 + \frac{1}{\mathrm{GB}}\left\{4s\left[s^2 + s\omega_o\left(\frac{1}{2} + \frac{1}{Q}\right) + \frac{\omega_o^2}{4Q}\right]\right\}} \qquad \left(\omega_o \ll \frac{\omega_a}{2Q}\right)$$

$$-\frac{\Delta\alpha}{\omega_o} \simeq 2\left(1 + \frac{1}{4Q}\right)\frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta\beta}{\omega_o} \cong -\frac{\left(1 - \frac{1}{Q} - \frac{1}{4Q^2}\right)}{\sqrt{1 - \frac{1}{4Q^2}}}\frac{\omega_o}{\mathrm{GB}}$$

$$\frac{\Delta\omega_o}{\omega_o} \simeq -\frac{\omega_o}{\mathrm{GB}}, \qquad \frac{\Delta Q}{Q} \simeq 4Q\frac{\omega_o}{\mathrm{GB}}$$

Active Sensitivities

Two integrator loop architecture

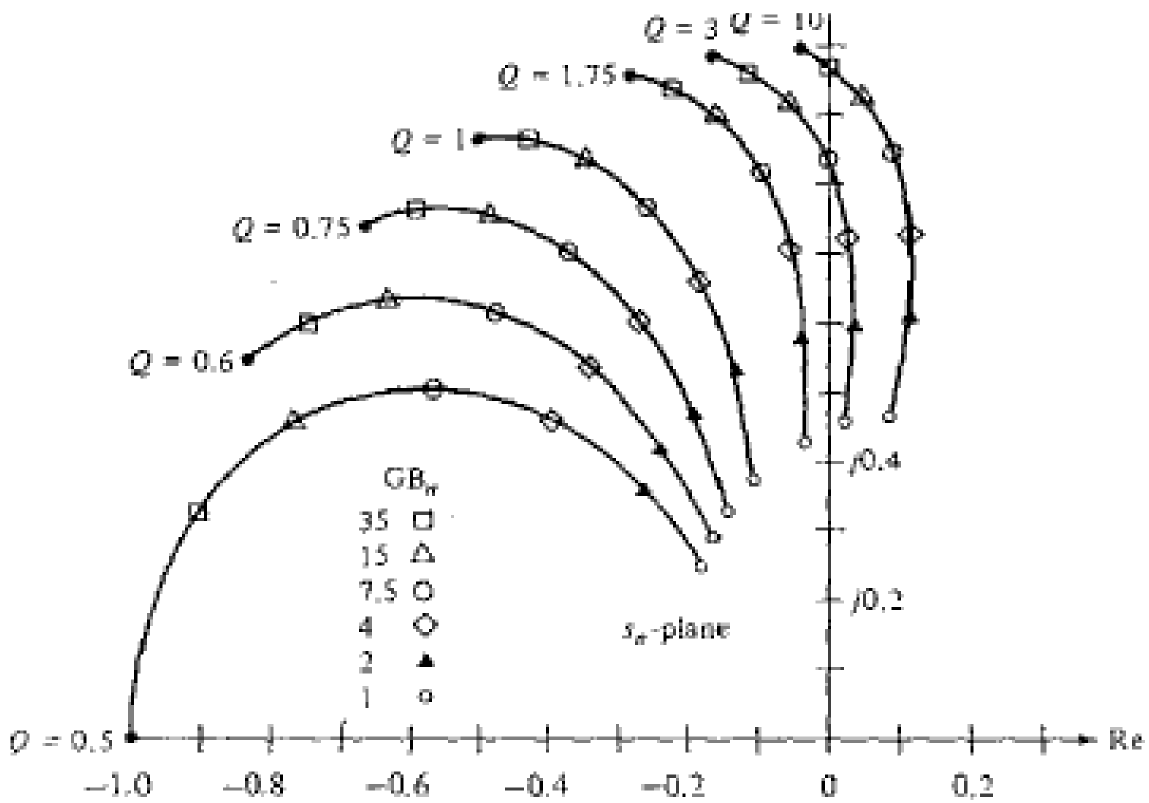


Fig. 10-17 Plot of upper half-plane root of

$$s_n^3 + s_n^2\left(\frac{1}{2} + \frac{1}{Q} + \frac{GB_n}{4}\right) + s_n \frac{1}{4Q}\left(1 + GB_n\right) + \frac{GB_n}{4} = 0$$

Active Sensitivities

- KRC

Equal-R, Equal-C

$$\omega_o = \frac{\sqrt{5+K_0}}{RC}, \qquad Q = \frac{\sqrt{5+K_0}}{5}$$

$$\frac{V_o}{V_i} = -\frac{\omega_o^2\left(1 - \frac{1}{5Q^2}\right)}{s^2 + s\frac{\omega_o}{Q} + \omega_o^2 + \frac{s}{GB}\left[s^2(25Q^2 - 4) + s\omega_o\left(20Q - \frac{3}{Q}\right) + \left(2 - \frac{1}{5Q^2}\right)\omega_o^2\right]}$$

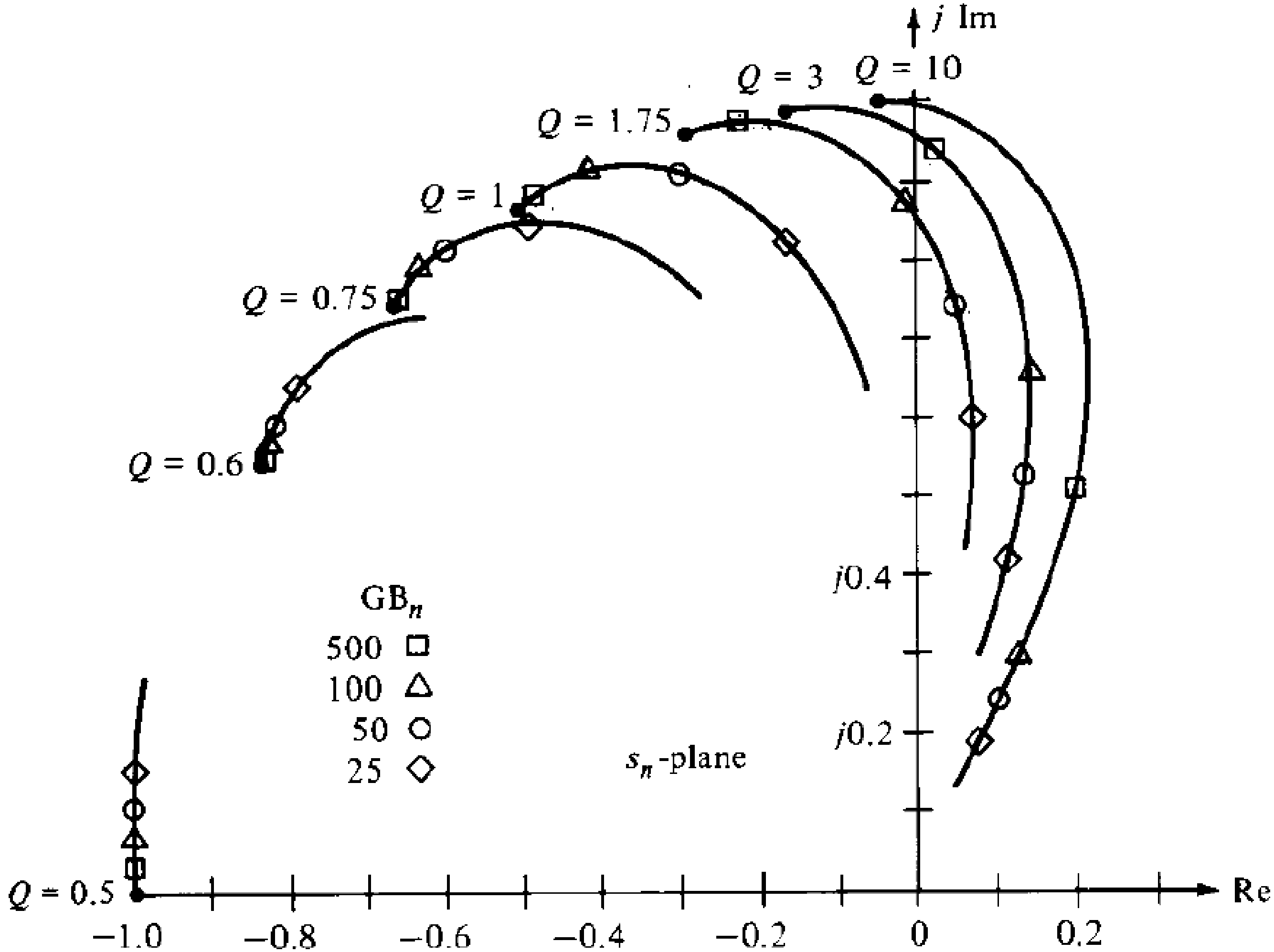
$$\left(\omega_a \ll \frac{\omega_o}{2Q}\right)$$

$$-\frac{\Delta\alpha}{\omega_o} \cong \frac{25Q^2}{2}\left(1 - \frac{1}{5Q^2}\right)\left(1 - \frac{6}{25Q^2}\right)\frac{\omega_o}{GB}, \qquad \frac{\Delta\beta}{\omega_o} \cong \frac{35Q}{4}\frac{\left(1 - \frac{1}{5Q^2}\right)\left(1 - \frac{6}{35Q^2}\right)}{\sqrt{1 - \frac{1}{4Q^2}}}\frac{\omega_o}{GB}$$

$$\frac{\Delta\omega_o}{\omega_o} \cong \frac{5Q}{2}\left(1 - \frac{1}{5Q^2}\right)\frac{\omega_o}{GB}, \qquad \frac{\Delta Q}{Q} \cong 25Q^3\left(1 - \frac{1}{5Q^2}\right)\left(1 - \frac{7}{5Q^2}\right)\frac{\omega_o}{GB}$$

Active Sensitivities

- KRC



Active Sensitivity Comparisons

	$\frac{\Delta\omega_0}{\omega_0}$	$\frac{\Delta Q}{Q}$
Passive RLC	NA	NA
+KRC		
Equal R, Equal C (K=3-1/Q)	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2 \tau\omega_0$	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2 \tau\omega_0$
Equal R, K=1 ($C_1=4Q^2C_2$)	$-Q\tau\omega_0$	$Q\tau\omega_0$
Bridged-T Feedback	$-\frac{3}{2}Q\tau\omega_0$	$\frac{1}{2}Q\tau\omega_0$
Two-Integrator Loop	$-\tau\omega_0$	$4Q\tau\omega_0$
-KRC	$\frac{5}{2}Q\tau\omega_0$	$25Q^3\tau\omega_0$

Substantial Differences Between Architectures

Are these passive sensitivities acceptable?

	$\left\lvert S_x^{\omega_0} \right\rvert$	$\left\lvert S_x^{Q} \right\rvert$
Passive RLC	$\leq \frac{1}{2}$	**1,1/2**
+KRC		
Equal R, Equal C (K=3-1/Q)	**0,1/2**	**Q, 2Q, 3Q**
Equal R, K=1 ($C_1=4Q^2C_2$)	**0,1/2**	**0,1/2, $2Q^2$**
Bridged-T Feedback	**0,1/2**	**1/3,1/2, 1/6**
Two-Integrator Loop	**0,1/2**	**1,1/2, 0**
-KRC	**less than or equal to 1/2**	**less than or equal to 1/2**

Are these active sensitivities acceptable?

Active Sensitivity Comparisons

	$\frac{\Delta\omega_0}{\omega_0}$	$\frac{\Delta Q}{Q}$
Passive RLC		
+KRC		
Equal R, Equal C (K=3-1/Q)	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2\tau\omega_0$	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2\tau\omega_0$
Equal R, K=1 ($C_1=4Q^2C_2$)	$-Q\tau\omega_0$	$Q\tau\omega_0$
Bridged-T Feedback	$-\frac{3}{2}Q\tau\omega_0$	$\frac{1}{2}Q\tau\omega_0$
Two-Integrator Loop	$-\tau\omega_0$	$4Q\tau\omega_0$
-KRC	$\frac{5}{2}Q\tau\omega_0$	$25Q^3\tau\omega_0$

Are these sensitivities acceptable?

Passive Sensitivities:

$$\frac{\Delta\omega_0}{\omega_0} \cong S_x^{\omega_0} \frac{\Delta x}{x}$$

In integrated circuits, Δ R/R and Δ C/C due to process variations can be $\pm$30% or larger due to process variations

Many applications require $\Delta\omega_0/\omega_0 < .001$ or smaller and similar requirements on $\Delta Q/Q$

Even if sensitivity is around ½ or 1, variability is often orders of magnitude too large

Active Sensitivities:

All are proportional to $\tau\omega_0$

Some architectures much more sensitive than others

Can reduce $\tau\omega_0$ by making GB large but this is at the expense of increased power and even if power is not of concern, process presents fundamental limits on how large GB can be made

Observe that for the +KRC circuit, the somewhat arbitrary use of the DOF has a major impact on performance

Similar observations can be made for other structures

	$\frac{\Delta\omega_0}{\omega_0}$	$\frac{\Delta Q}{Q}$
Equal R, Equal C (K=3-1/Q)	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2\tau\omega_0$	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2\tau\omega_0$
Equal R, K=1 ($C_1=4Q^2C_2$)	$-Q\tau\omega_0$	$Q\tau\omega_0$
Equal R, Equal C (K=3-1/Q)	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2\tau\omega_0$	$-\frac{1}{2}\left(3-\frac{1}{Q}\right)^2\tau\omega_0$
Equal R, K=1 ($C_1=4Q^2C_2$)	$-Q\tau\omega_0$	$Q\tau\omega_0$

Challenge: Can a major improvement in performance be obtained by a more judicious use of the two free DOF for the +KRC circuit?

What can be done to address these problems?

1. Predistortion

Design circuit so that after component shift, correct pole locations are obtained

Predistortion is generally used in integrated circuits to remove the bias associated with inadequate amplifier bandwidth

Predistortion does not help with process variations of passive components

Tedious process after fabrication since depends on individual components

Temperature dependence may not track

Difficult to maintain over time and temperature

Over-ordering will adversely affect performance

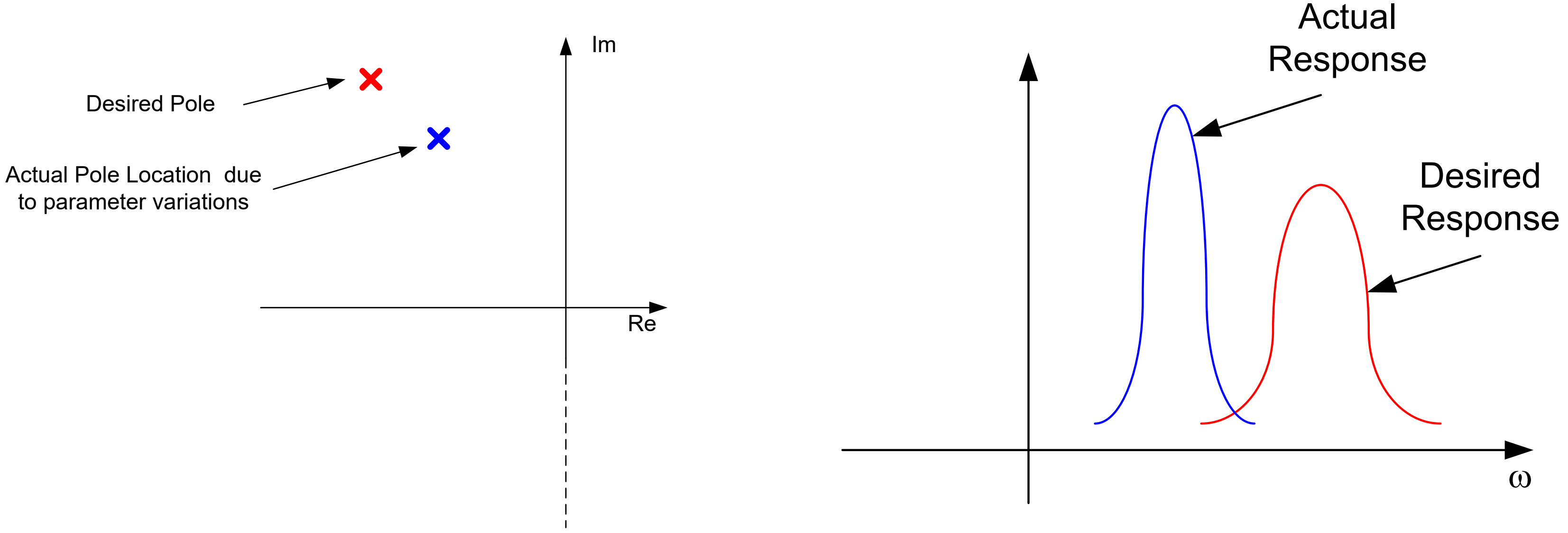
Seldom will predistortion alone be adequate to obtain acceptable performance

Bell Labs did to this in high-volume production (STAR Biquad)

What can be done to address these problems?

1. Predistortion

Design circuit so that after component shift, correct pole locations are obtained

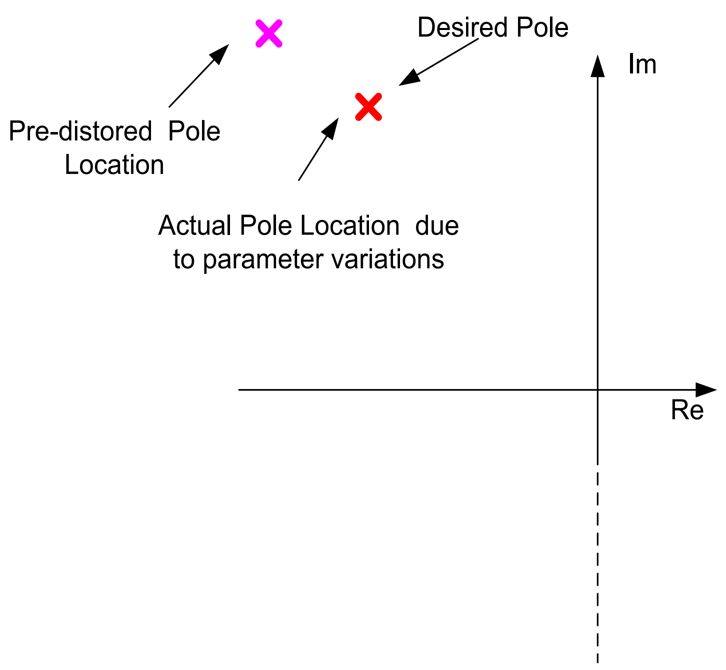


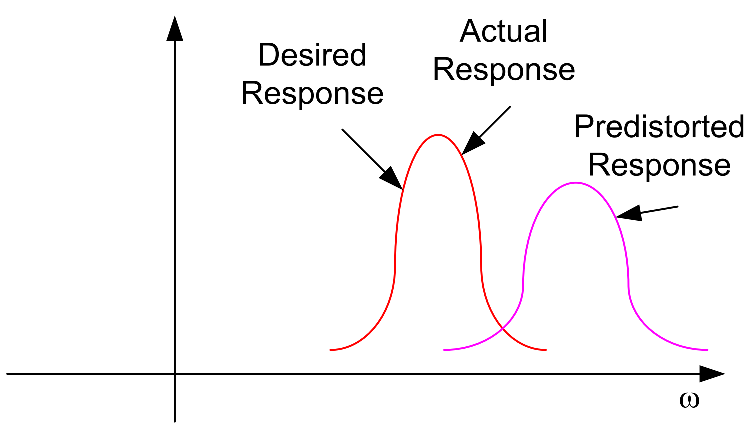
Pole shift due to parametric variations (e.g. inadequate GB)

What can be done to address these problems?

1. Predistortion

Design circuit so that after component shift, correct pole locations are obtained



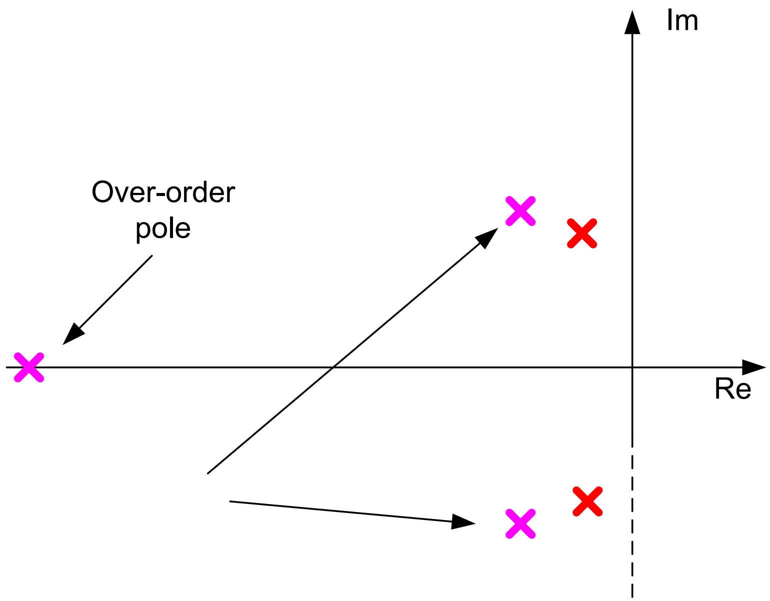


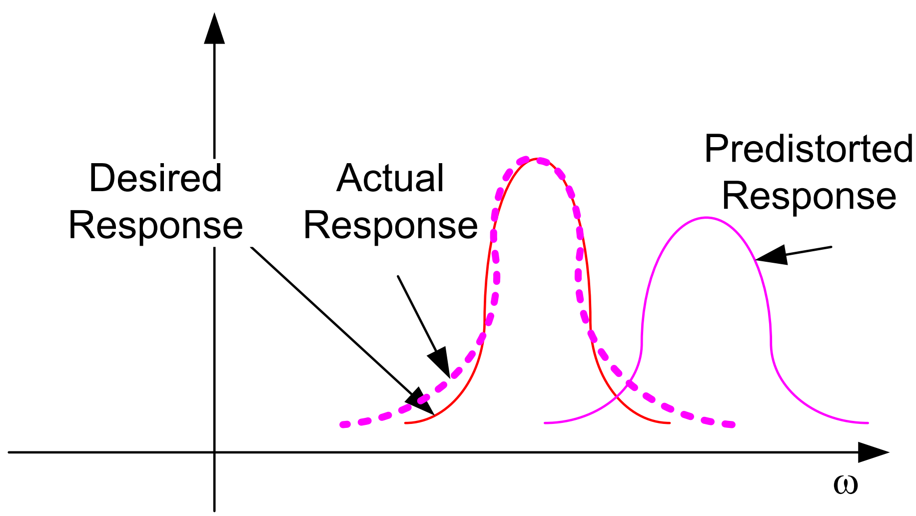
Pre-distortion concept

What can be done to address these problems?

1. Predistortion

Design circuit so that after component shift, correct pole locations are obtained





Over-ordering Limitations with Pre-distortion

Parasitic Pole Affects Response

Predistortion almost always done even if benefits only modest

Not effective if significant deviations exist before predistortion

What can be done to address these problems?

2. Trimming

a) Functional Trimming

- trim parameters of actual filter based upon measurements
- difficult to implement in many structures
- manageable for cascaded biquads

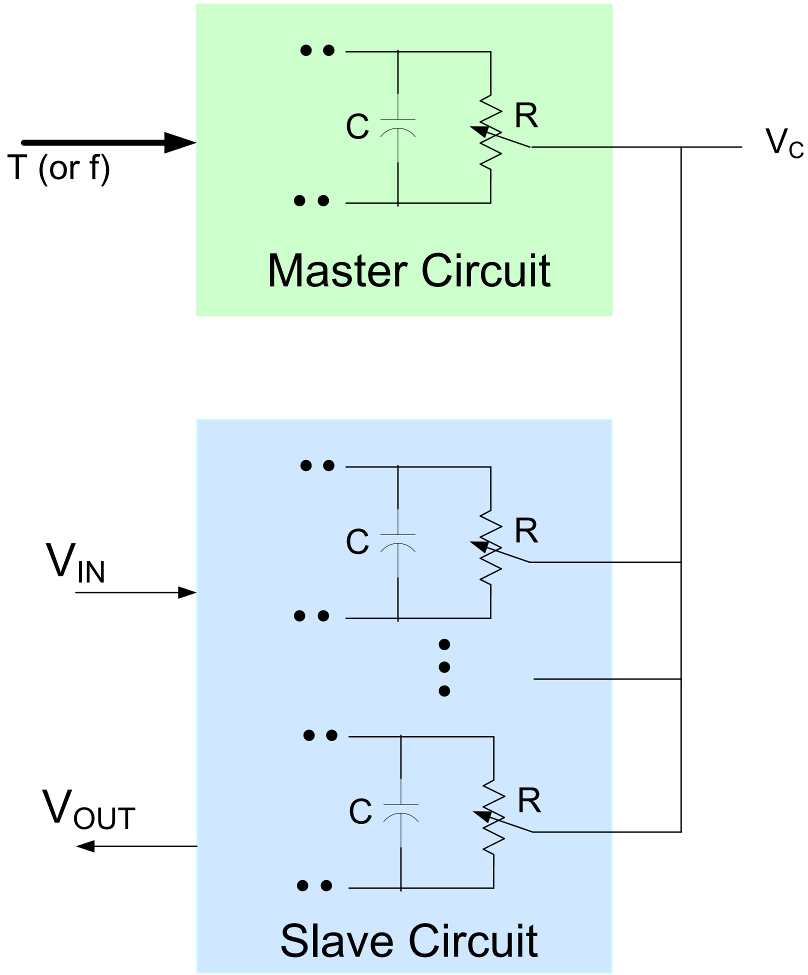
b) Deterministic Trimming (much preferred)

- Trim component values to their ideal value
  - Continuous-trims of resistors possible in some special processes
  - Continuous-trim of capacitors is more challenging
  - Link trimming of Rs or Cs is possible with either metal or switches
- If all components are ideal, the filter should also be ideal
  - R-trimming algorithms easy to implement
  - Limited to unidirectional trim
  - Trim generally done at wafer level for laser trimming, package for link trims
- Filter shifts occur due to stress in packaging and heat cycling

c) Master-slave reference control (depends upon matching in a process)

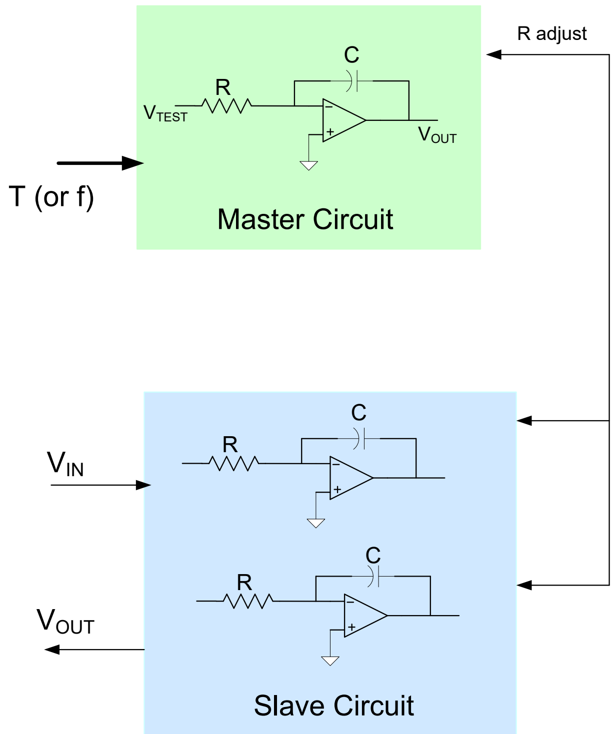
- Can be implemented in discrete or integrated structures
- Master typically frequency or period referenced
- Most effective in integrated form since good matching possible
- Widely used in integrated form

Master-slave Control (depends upon matching in a process)



- Automatically adjust R (or C) in the Master Circuit to match RC to T
- Rely on matching to match RC products in Slave Circuit to T
- Matching can be very good (1% or 0.1% or better)
- But does nothing to compensate for local random variations

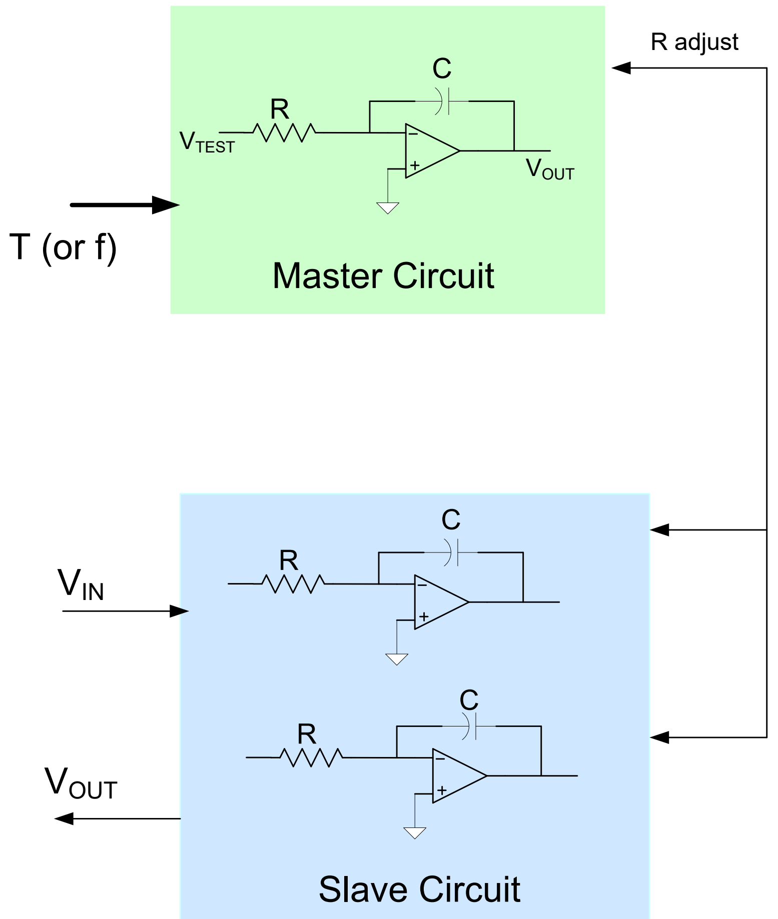
Master-slave Example:



$$T(s) = \frac{V_{OUT}}{V_{TEST}} = -\frac{1}{RCs}$$

- Key parameter of integrator is unity gain frequency I_0=1/RC
- Adjust R in Master Circuit so that I_0=1 at the input frequency f
- With matching, unity gain frequency of all integrators in Slave Circuit will also be 1
- May require considerable overhead to trim circuit elements
- Compensates for combined component variations and BW limitations

Master-slave Example:



$$T(s) = \frac{V_{OUT}}{V_{TEST}} = -\frac{1}{RCs}$$

$$T_{ACT}(s) = \frac{V_{OUT}}{V_{TEST}} = -\frac{1}{RCs + \tau\left(s + RCs^2\right)}$$

- Over-ordering will limit accuracy of master-slave approach even if unity gain frequency of master circuit is precisely obtained
- Technique is often used to maintain good control of effective RC products
- Power and area overhead but Master circuit may be off most of the time to reduce power overhead

What can be done to address these problems?

3. Select Appropriate Architecture

Helps a lot

Best architectures are not known

Performance of good architectures often not good enough

What can be done to address these problems?

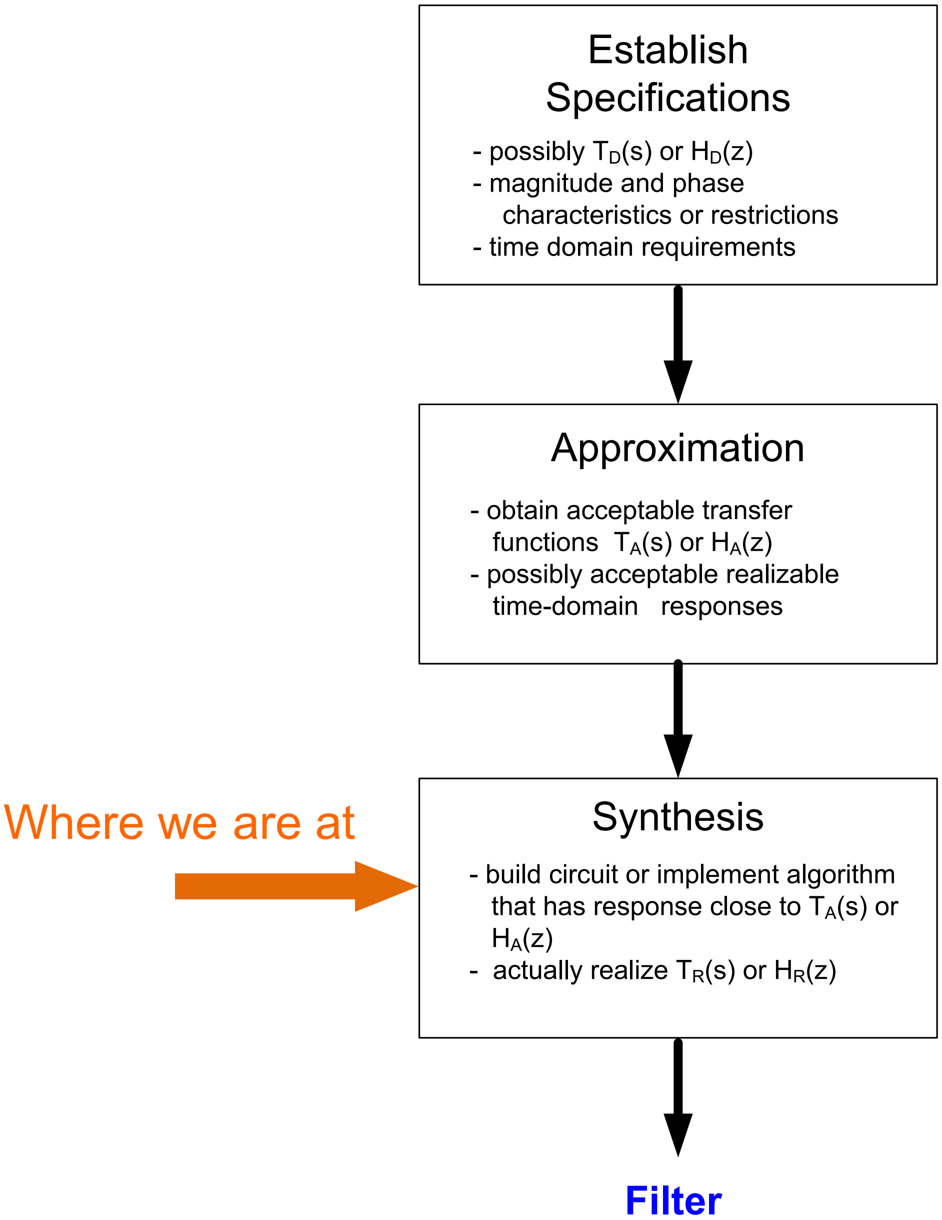
4. Different Approach for Filter Implementation

- **Frequency Referenced Filters**
  Switched-Capacitor Filters
- **DSP- Based Filter Implementation**
- **Other Niche Methods**

Summary of Sensitivity Observations

- Sensitivity varies substantially from one implementation to another
- Variability too high, even with low sensitivity, for more demanding applications
- Methods of managing high variability
  - Select good structures
  - Trimming
    - Functional
    - Deterministic
  - Predistortion
    - In particular, for active sensitivities
    - Useful but not a total solution
  - Frequency Referenced Techniques
    - Master-Slave Control
      - Depends upon matching
      - Can self-trim or self-compensate
    - Switched-Capacitor Filters
    - AD/digital filter/D/A
  - Alternate Design Approach
    - Other methods

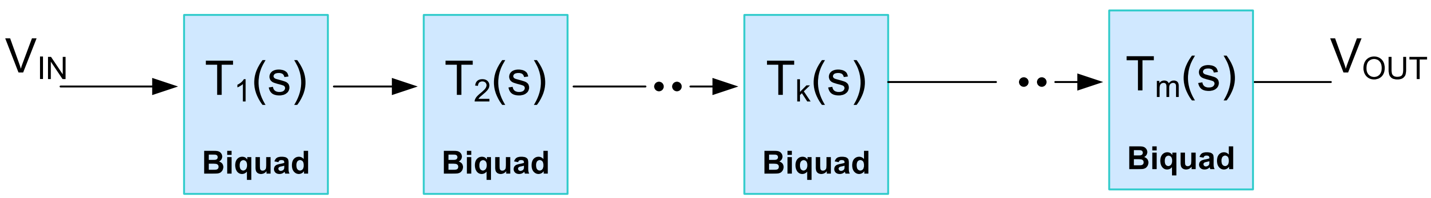
Filter Design Process



Filter Design/Synthesis Considerations

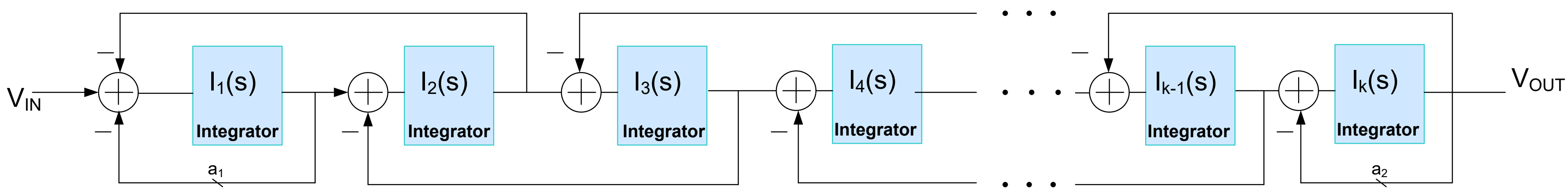
Most designs today use one of the following three basic architectures

Cascaded Biquads

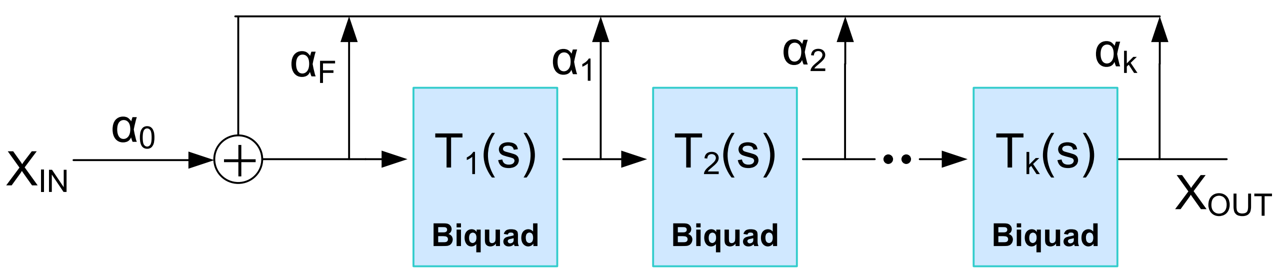


$$T(s) = T_1 T_2 \bullet\bullet T_m$$

Leapfrog

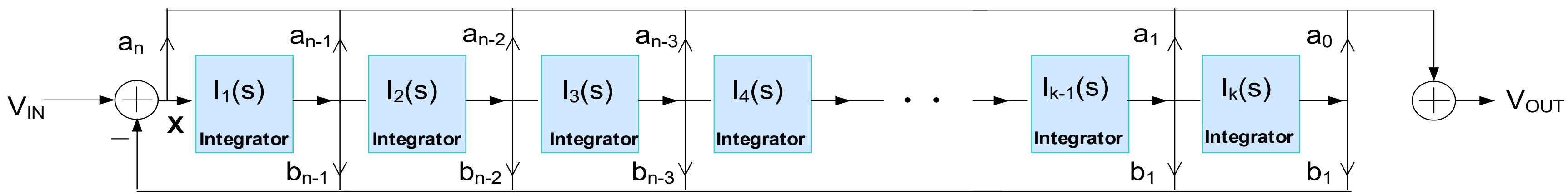


Multiple-loop Feedback – One type shown (less popular)



Filter Design/Synthesis Considerations

Multiple-loop Feedback – Another type



$$X = V_{IN} - X \bullet \sum_{k=1}^{n} b_{n-k} \left(\frac{I_0}{s} \right)^k$$

$$V_{OUT} = X \bullet \sum_{k=0}^{n} a_{n-k} \left(\frac{I_0}{s} \right)^k$$

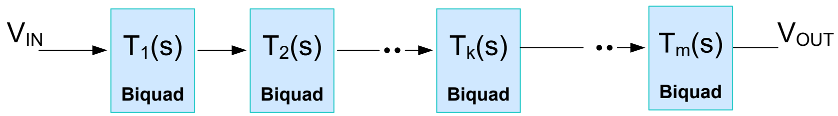
$$T(s) = \frac{\sum_{k=0}^{n} a_{n-k} \left(\frac{I_0}{s} \right)^k}{1 + \sum_{k=1}^{n} b_{n-k} \left(\frac{I_0}{s} \right)^k}$$

$$T(s) = \frac{\sum_{k=0}^{n} a_{n-k} I_0^k s^{n-k}}{s^n + \sum_{k=1}^{n} b_{n-k} I_0^k s^{n-k}}$$

- Termed the direct synthesis method
- Directly implements the coefficients in the numerator and denominator
- Approach followed in the Analog Computers
- Not particularly attractive from an overall performance viewpoint

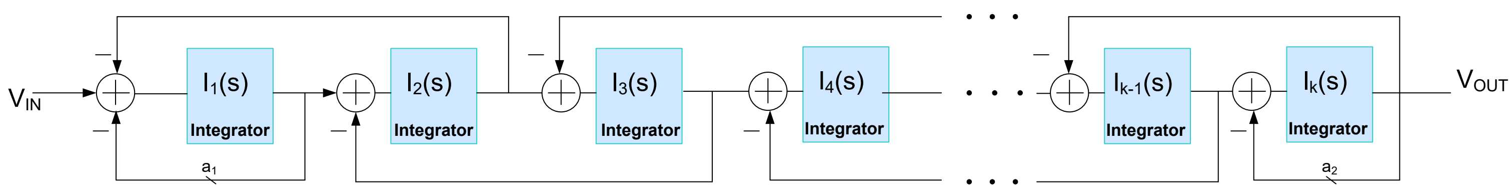
Filter Design/Synthesis Considerations

Cascaded Biquads

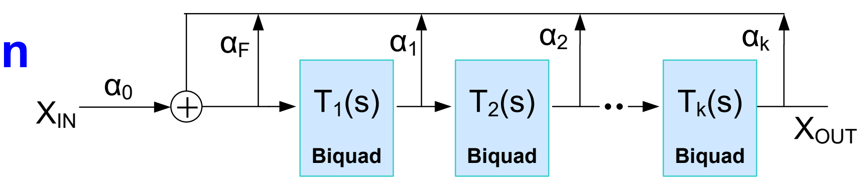


$$T(s) = T_1 T_2 \bullet\bullet T_m$$

Leapfrog



Multiple-loop Feedback – One type shown



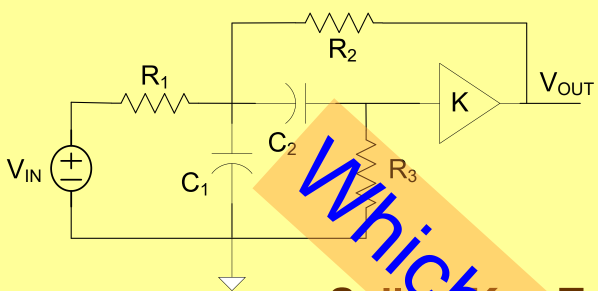
Will study details of all three types of architectures later

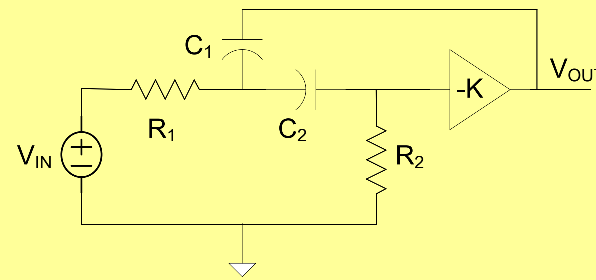
Observation: All filters are comprised of summers, biquads and integrators

Consider now the biquads

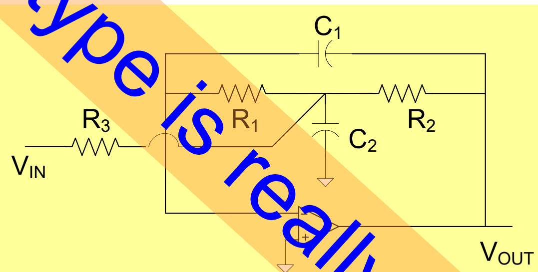
Biquad Filters Design Considerations

Several different Biquads were considered and other implementations exist

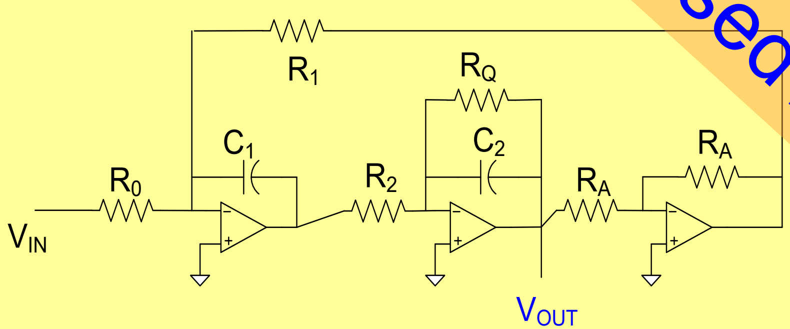




Sallen-Key Type (Dependent Sources)



Infinite Gain Amplifiers

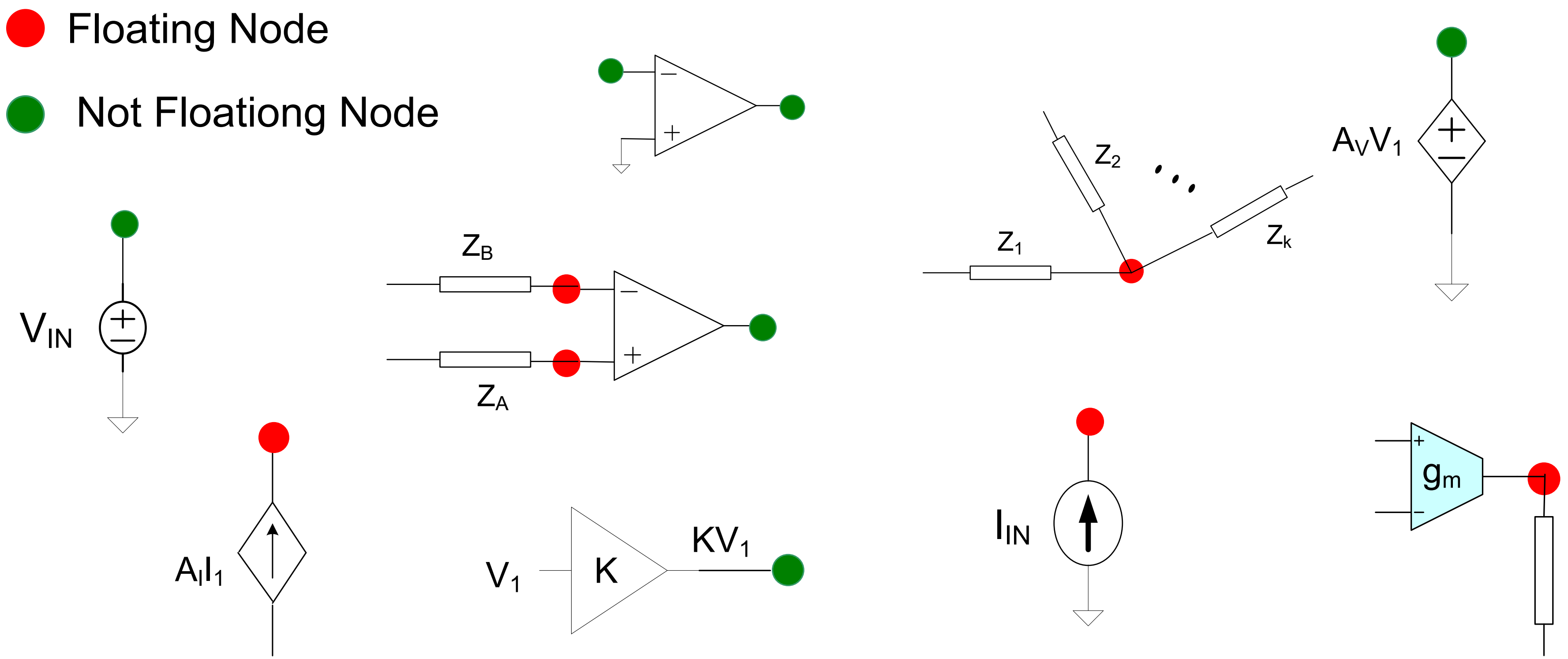


Integrator Based Structures

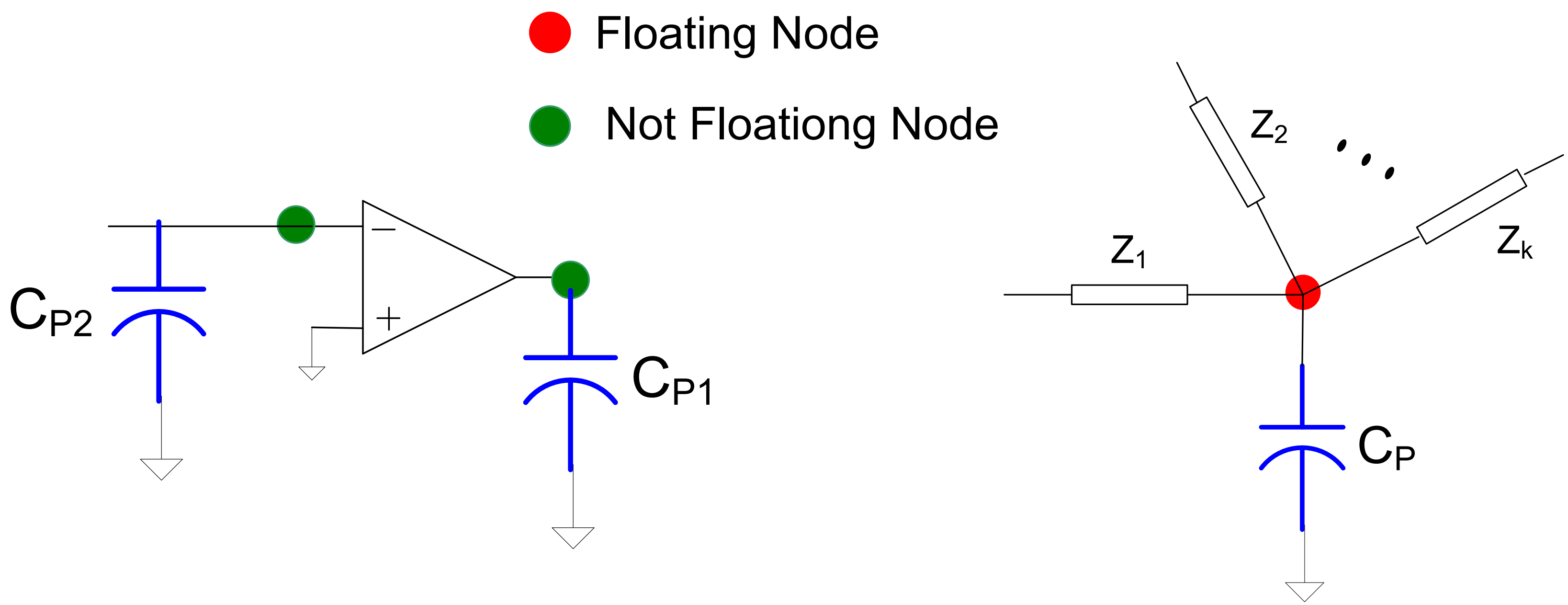
Which type is really used?

Floating Nodes

A node in a circuit is termed a floating node if it is not an output node of a ground-referenced voltage-output amplifier (dependent or independent), not connected to a ground-referenced voltage source, or not connected to a ground-referenced null-port



Parasitic Capacitances on Floating Nodes



Parasitic capacitances ideally have no affect on filter when on a non-floating node but directly affect transfer function when they appear on a floating node

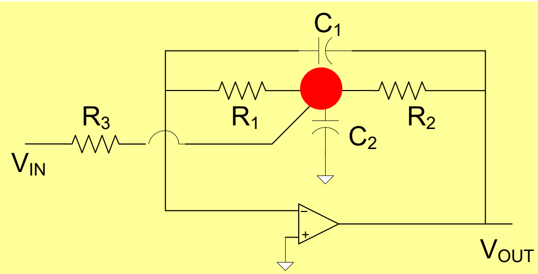
Parasitic capacitances are invariably large, nonlinear, and highly process dependent in integrated filters. Thus, it is difficult to build accurate integrated filters if floating nodes are present

Generally avoid floating nodes, if possible, in integrated filters

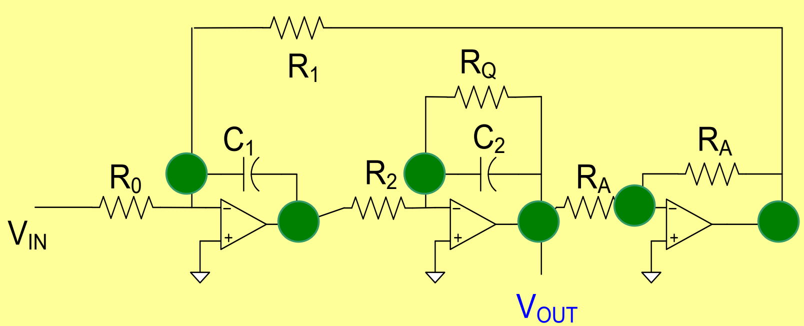
Which type of Biquad is really used?

Not Floatong Node   Floating Node

Sallen-Key Type (Dependent Sources)



Infinite Gain Amplifiers



Integrator Based Structures

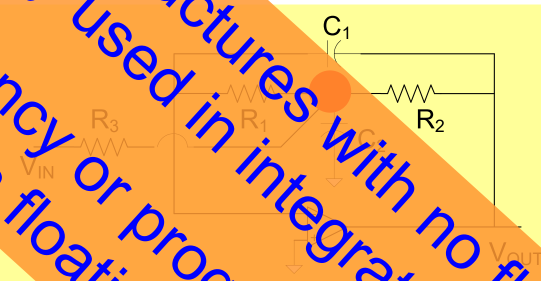
Which type of Biquad is really used?

Not Floationg Node   Floating Node

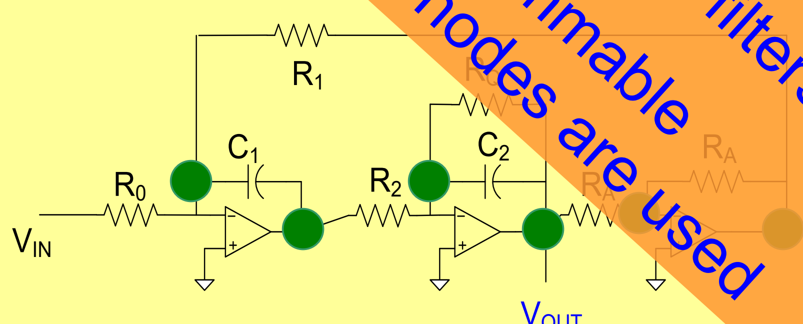
Integrator-based structures with no floating nodes dominantly used in integrated filters

Some high-frequency or programmable integrated filters with floating nodes are used

Sallen-Key type (Dependent Sources)

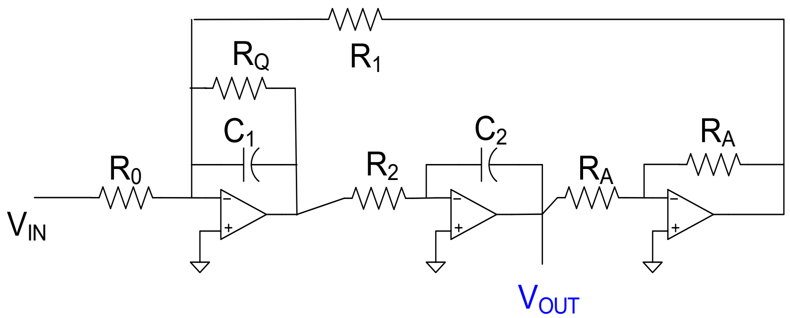


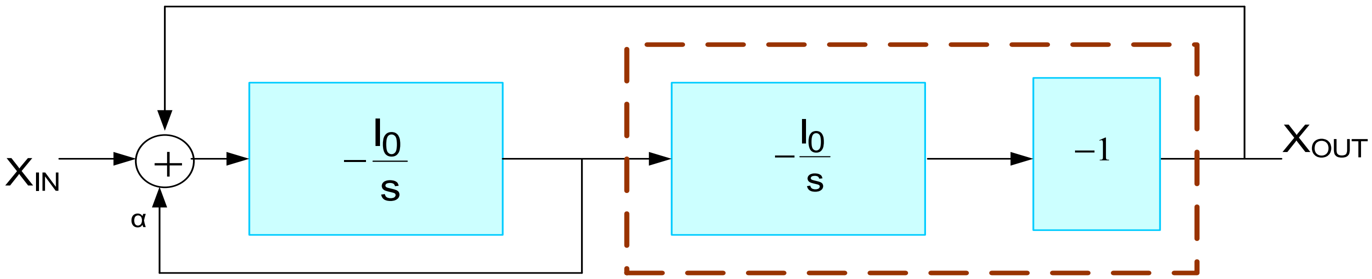
Infinite Gain Amplifiers

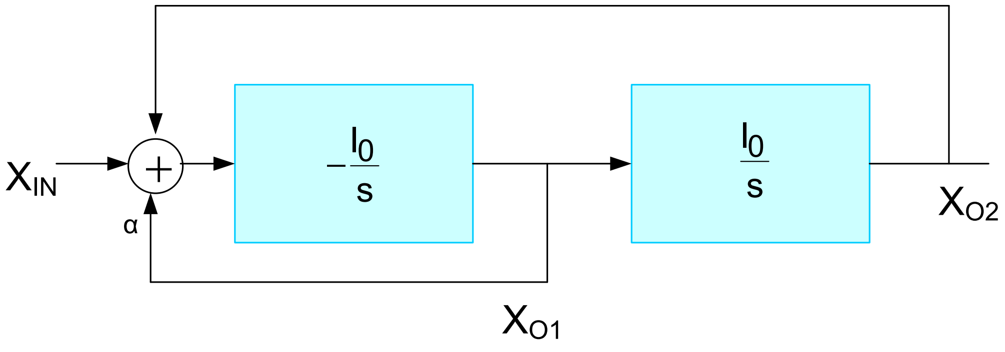


Integrator Based Structures

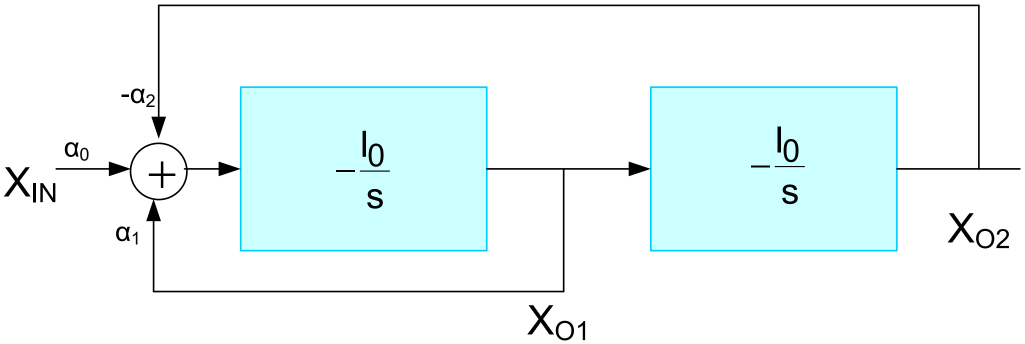
Integrator-based Biquads



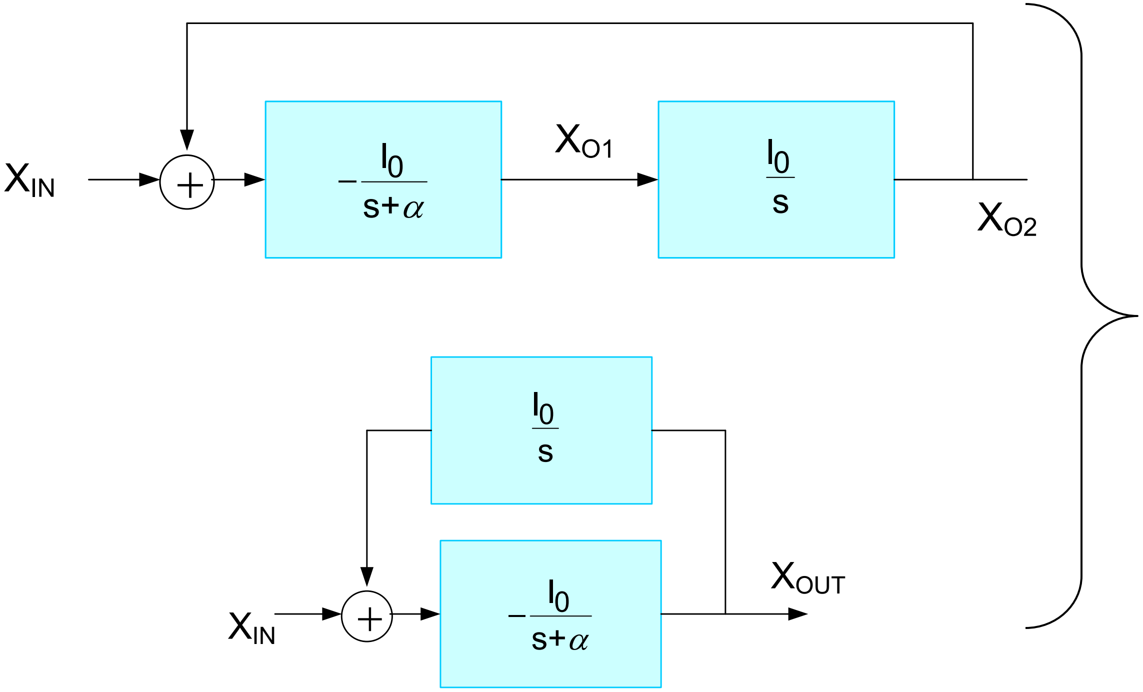




Integrator-based Biquads

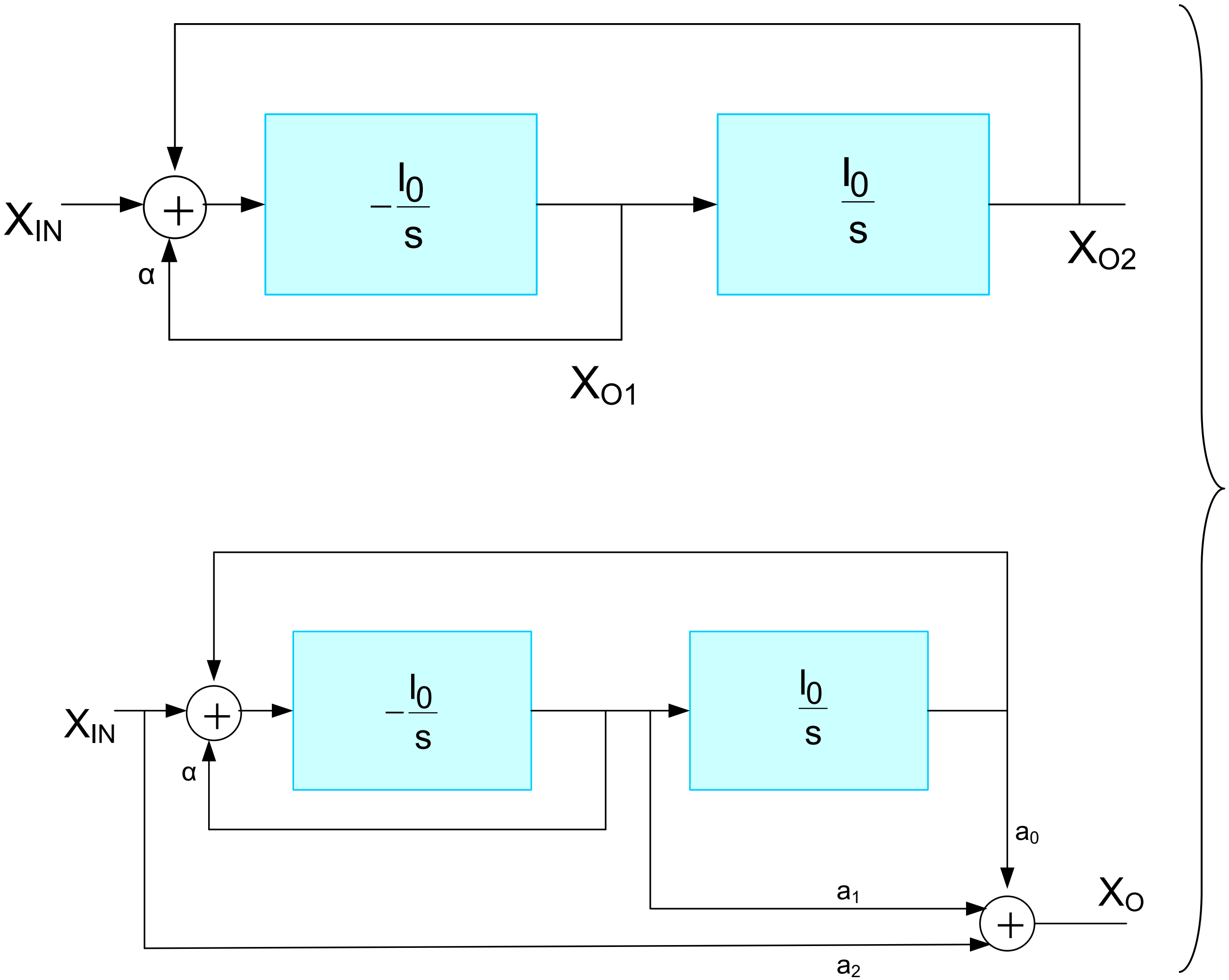


State Variable Biquad
(Alt KHN Biquad)



Integrator and lossy
integrator in a loop

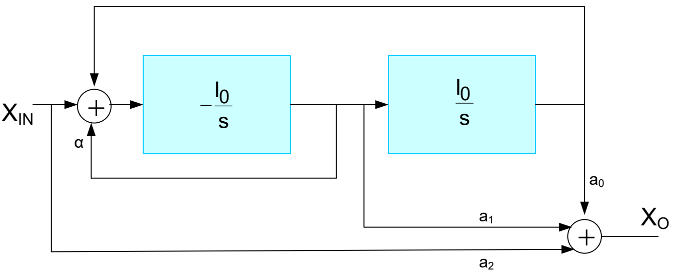
Integrator-based Biquads

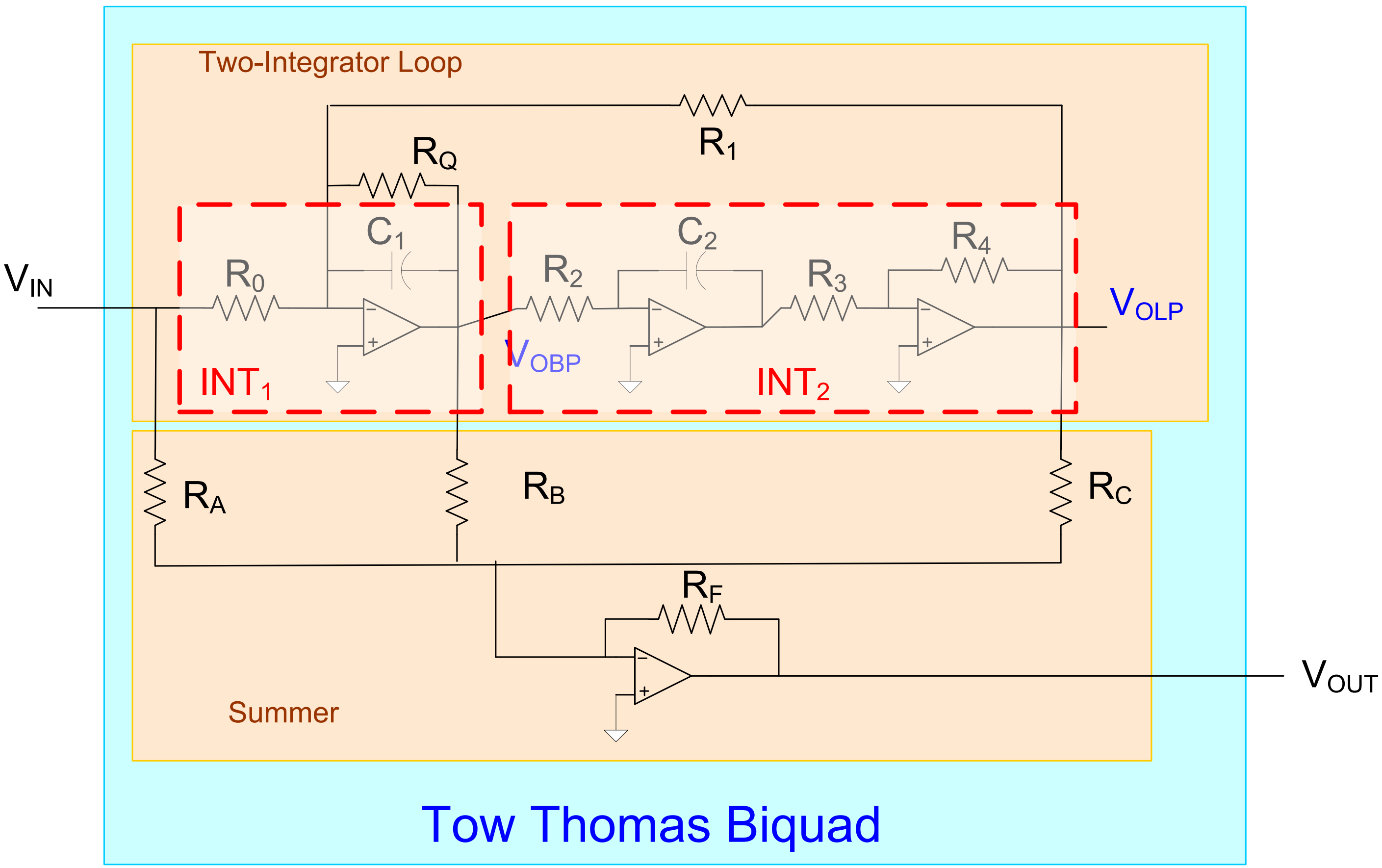


With arbitrary zero locations

Tow-Thomas Biquad

Integrator-based Biquads



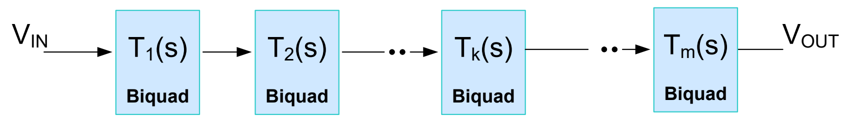


Integrator-based Biquads

- Integrator-based biquads all involve two integrators in a loop
- All integrator-based biquads discussed have no floating nodes
- Most biquads in integrated filters are based upon two integrator loop structures
- The summers are usually included as summing inputs on the integrators
- The loss can be combined with the integrator to form a lossy integrator
- Performance of the minor variants of the two integrator loop structures are comparable

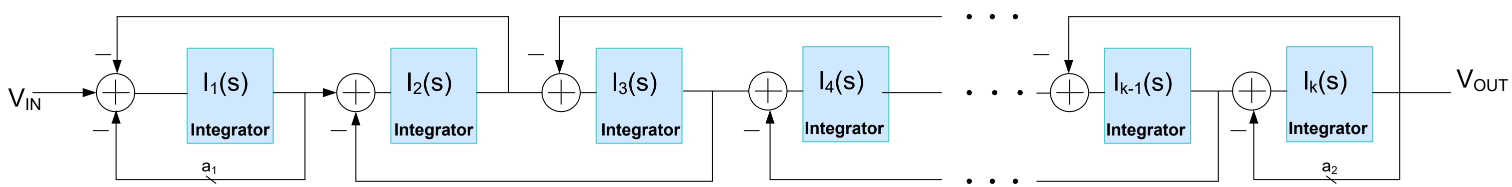
Filter Design/Synthesis Considerations

Cascaded Biquads

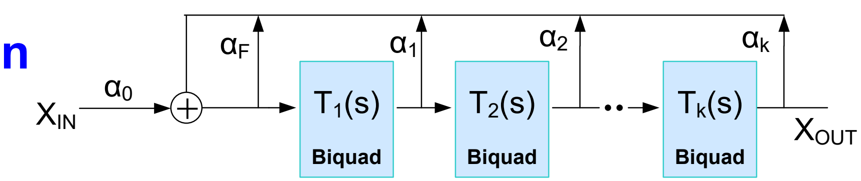


$$T(s) = T_1 T_2 \bullet\bullet T_m$$

Leapfrog



Multiple-loop Feedback – One type shown



Observation: All filters are comprised of summers, biquads and integrators

And biquads usually made with summers and integrators

Integrated filter design generally focused on design of integrators, summers, and amplifiers (Op Amps)

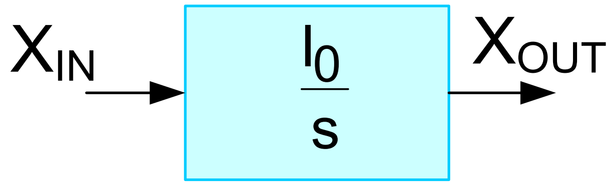
Will now focus on the design of integrators, summers, and op amps

Basic Filter Building Blocks

(particularly for integrated filters)

- Integrators
- Summers
- Operational Amplifiers

Integrator Characteristics of Interest



$$I(s) = \frac{I_0}{s}$$

Properties of an ideal integrator:

$$|I(j\omega)| = \frac{I_0}{\omega}$$

Gain decreases with $1/\omega$

$$\angle I(j\omega) = -90^0$$

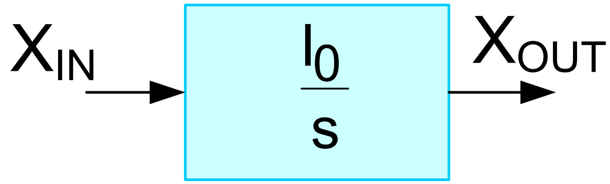
Phase is a constant -90^o

$$|I(jI_0)| = 1$$

Unity Gain Frequency = I_0

How important is it that an integrator have all 3 of these properties?

Integrator Characteristics of Interest

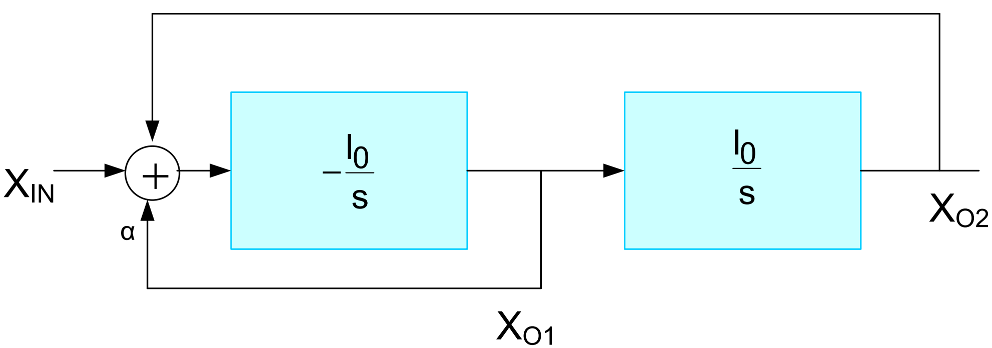


$$I(s) = \frac{I_0}{s}$$

$$|I(j\omega)| = \frac{I_0}{\omega} \qquad \angle I(j\omega) = -90^0 \qquad |I(jI_0)| = 1$$

How important is it that an integrator have all 3 of these properties?

Consider a filter example:



$$T(s) = \frac{-I_0^2}{s^2 + \alpha I_0 s + I_0^2}$$

$$Q = \frac{1}{\alpha} \qquad \omega_0 = I_0$$

Band edges proportional to I_0

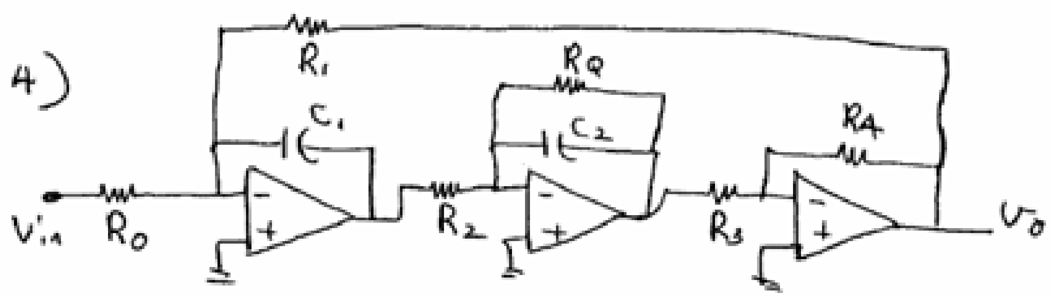
Phase critical to make Q expression valid

In many (most) applications it is critical that an integrator be very nearly ideal

(in the frequency range of interest)

)

4)



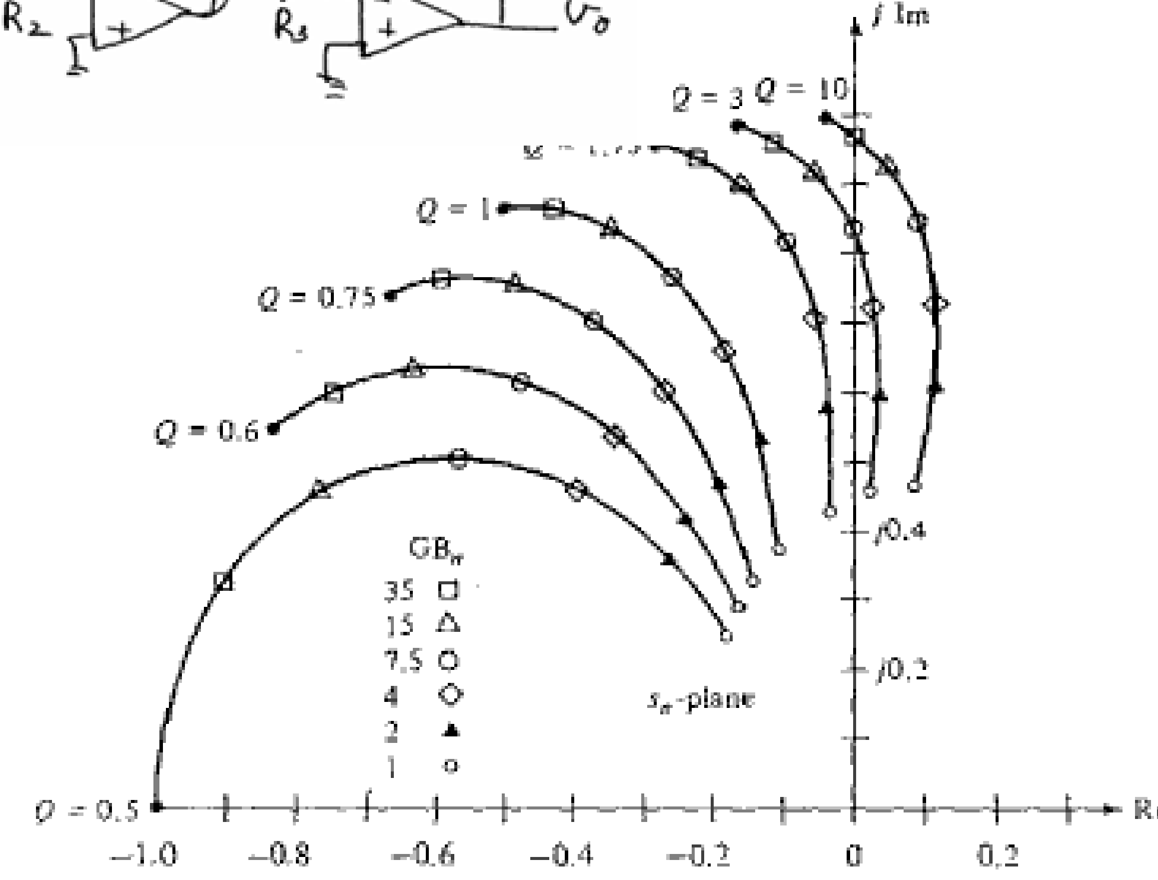
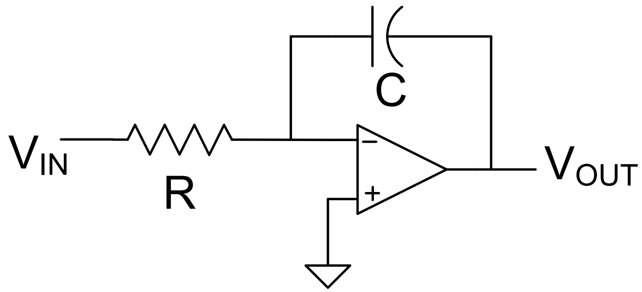


Fig. 10-17 Plot of upper half-plane root of

$$s_n^3 + s_n^2\left(\frac{1}{2} + \frac{1}{Q} + \frac{GB_n}{4}\right) + s_n\frac{1}{4Q}\left(1 + GB_n\right) + \frac{GB_n}{4} = 0$$

Some integrator structures

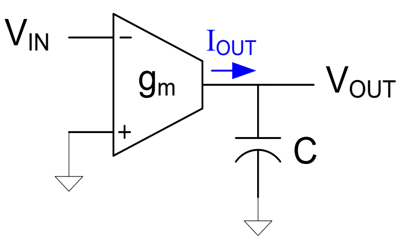


$$I(s) = -\frac{1}{RCs}$$

$$I_0 = \frac{1}{RC}$$

Inverting Active RC Integrator

Are there other integrator structures?



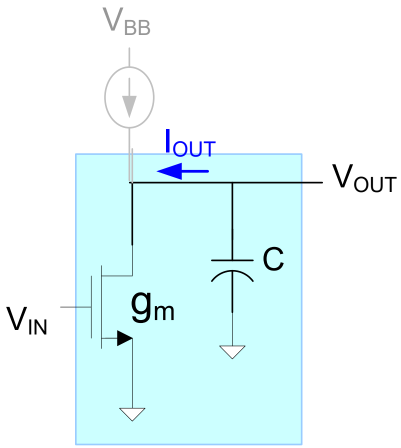
$$\left.\begin{aligned} I_{OUT} &= -g_m V_{IN} \\ V_{OUT} &= I_{OUT}\frac{1}{sC} \end{aligned}\right\} \quad I(s) = -\frac{g_m}{sC}$$

$$I_0 = \frac{g_m}{C}$$

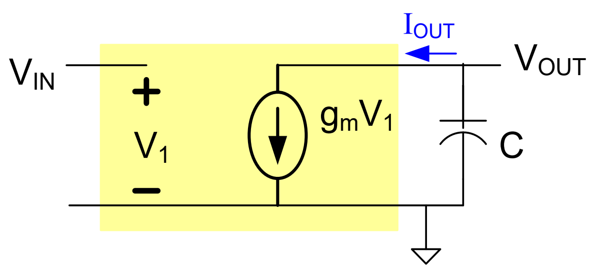
Termed an OTA-C or a gm-C integrator

Some integrator structures

Are there other integrator structures?



Termed a TA-C integrator

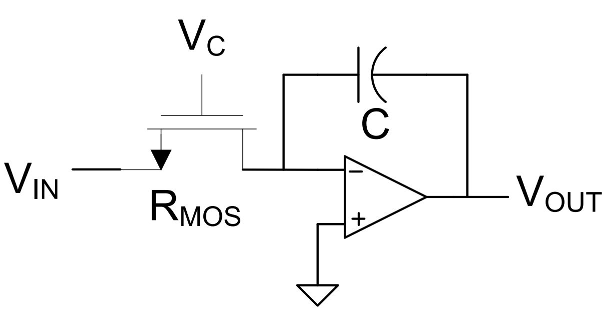


$$I_{OUT} = g_m V_{IN}$$

$$V_{OUT} = -I_{OUT}\frac{1}{sC}$$

$$I(s) = -\frac{g_m}{sC}$$

$$I_0 = \frac{g_m}{C}$$



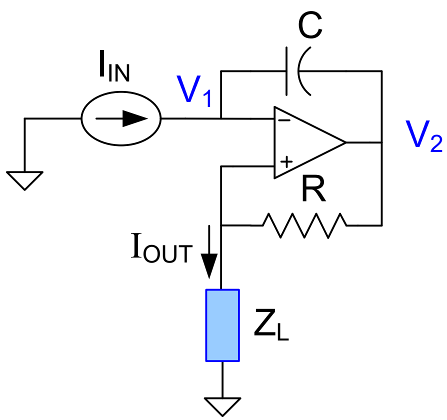
Termed MOSFET-C integrator

$$I(s) = -\frac{1}{sCR_{MOS}}$$

$$I_0 = -\frac{1}{R_{FET}C}$$

Some integrator structures

Are there other integrator structures?



$$V_2 = V_1 - I_{IN}\frac{1}{sC}$$

$$I_{OUT} = \frac{V_2 - V_1}{R}$$

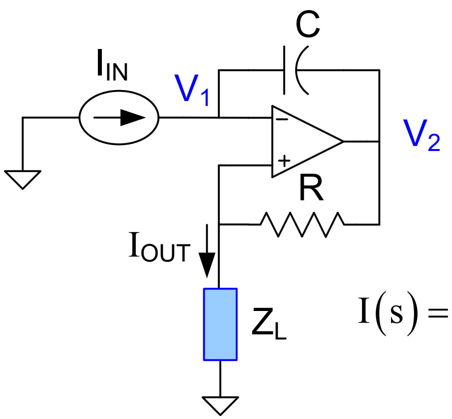
$$I(s) = \frac{I_{OUT}}{I_{IN}} = -\frac{1}{sRC}$$

$$I_0 = \frac{1}{RC}$$

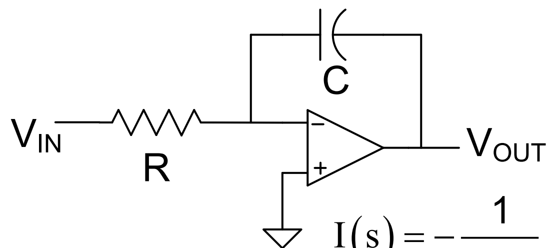
- Output current is independent of Z_L
- Thus output impedance is ∞ so provides current output

Termed active RC current-mode integrator

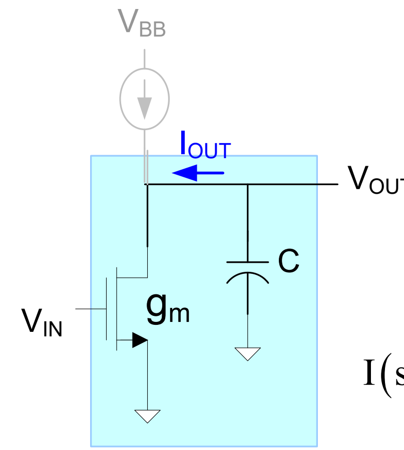
Some integrator structures



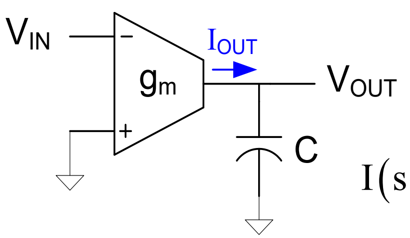
$$I(s) = -\frac{1}{sRC}$$



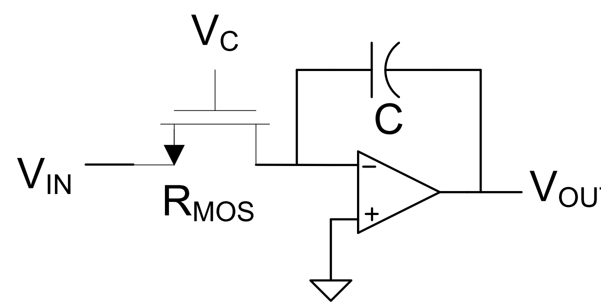
$$I(s) = -\frac{1}{sRC}$$



$$I(s) = -\frac{g_m}{sC}$$



$$I(s) = -\frac{g_m}{sC}$$

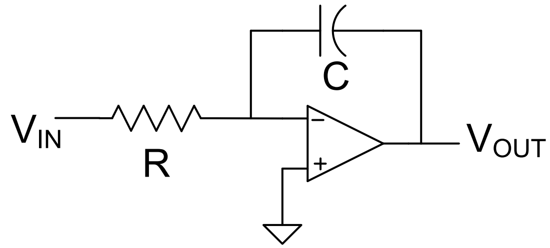


$$I(s) = -\frac{1}{sR_{MOS}C}$$

There are other useful integrator structures (some will be introduced later)

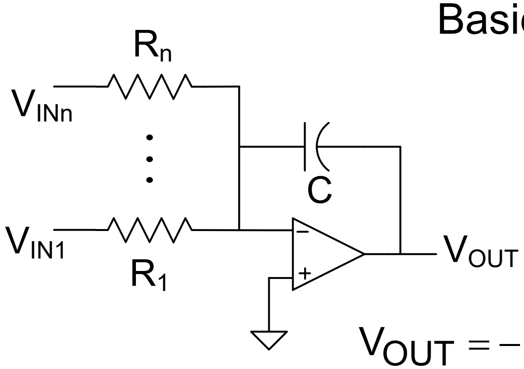
There are many different ways to build an inverting integrator

Integrator Functionality



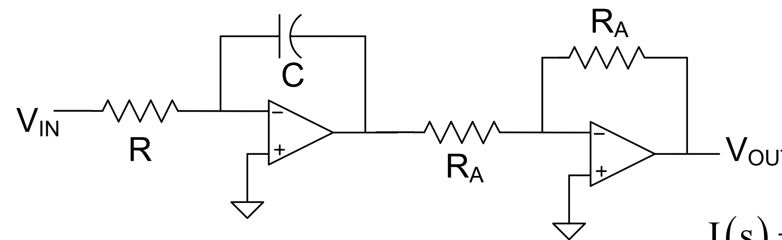
$$I(s) = -\frac{1}{sRC}$$

Basic Active RC Inverting Integrator



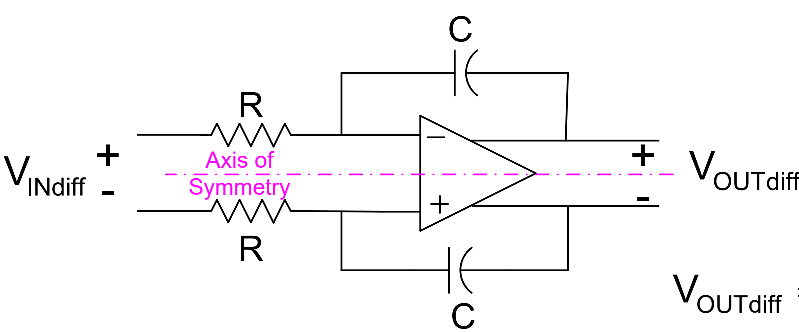
$$V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_k s} V_{INk}$$

Summing Integrator



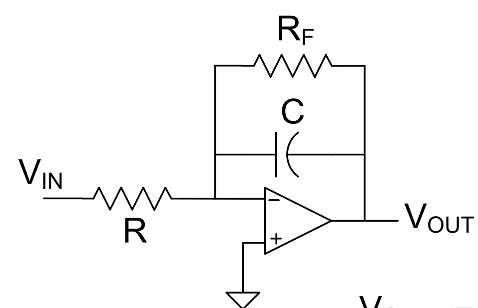
$$I(s) = \frac{1}{sRC}$$

Noninverting Integrator



$$V_{OUTdiff} = -\frac{1}{CRs} V_{INdiff}$$

Fully Differential Integrator



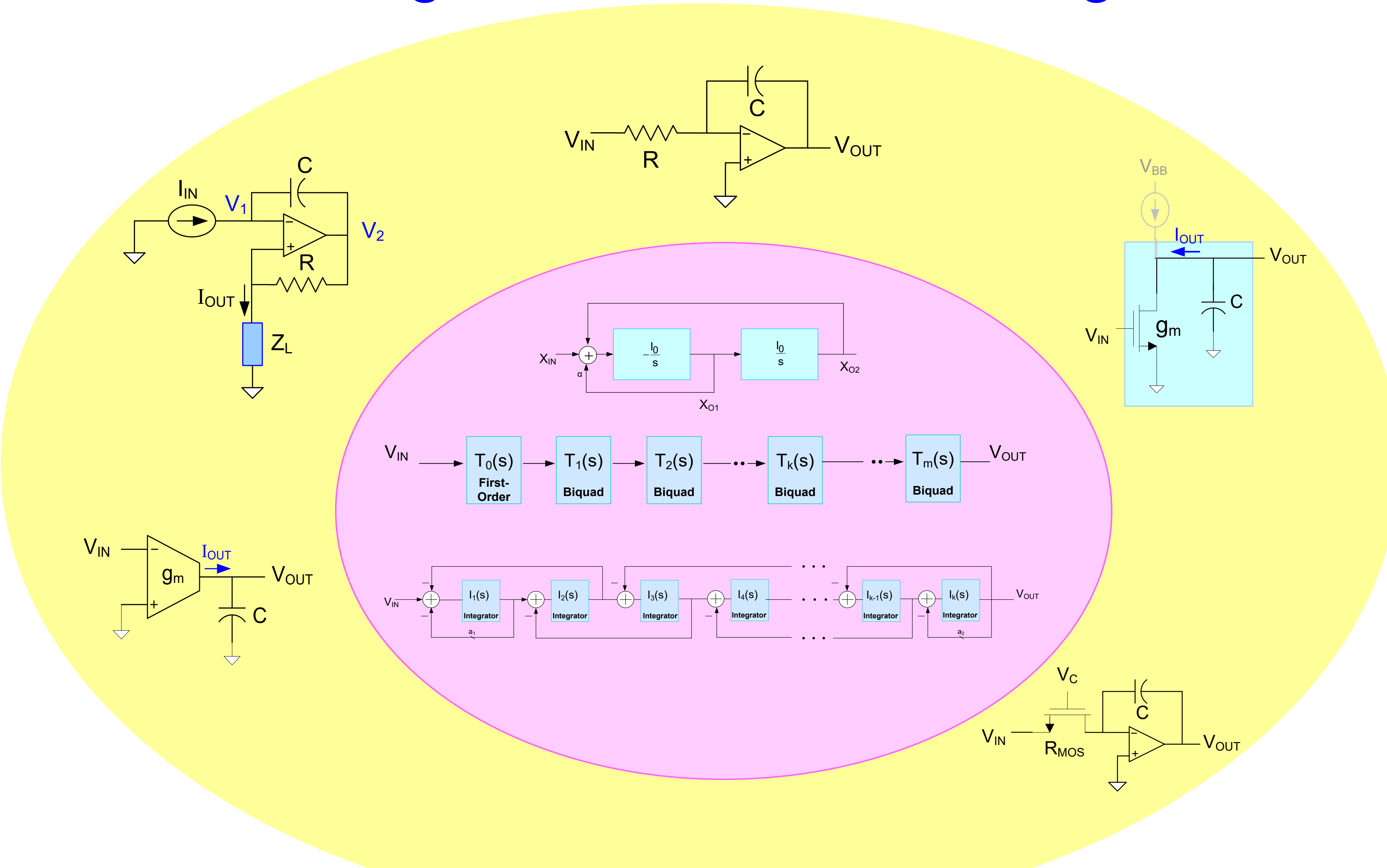
$$V_{OUT} = -\frac{R_F/R}{1+CR_F s} V_{IN}$$

Lossy Integrator

Many different types of functionality from basic inverting integrator

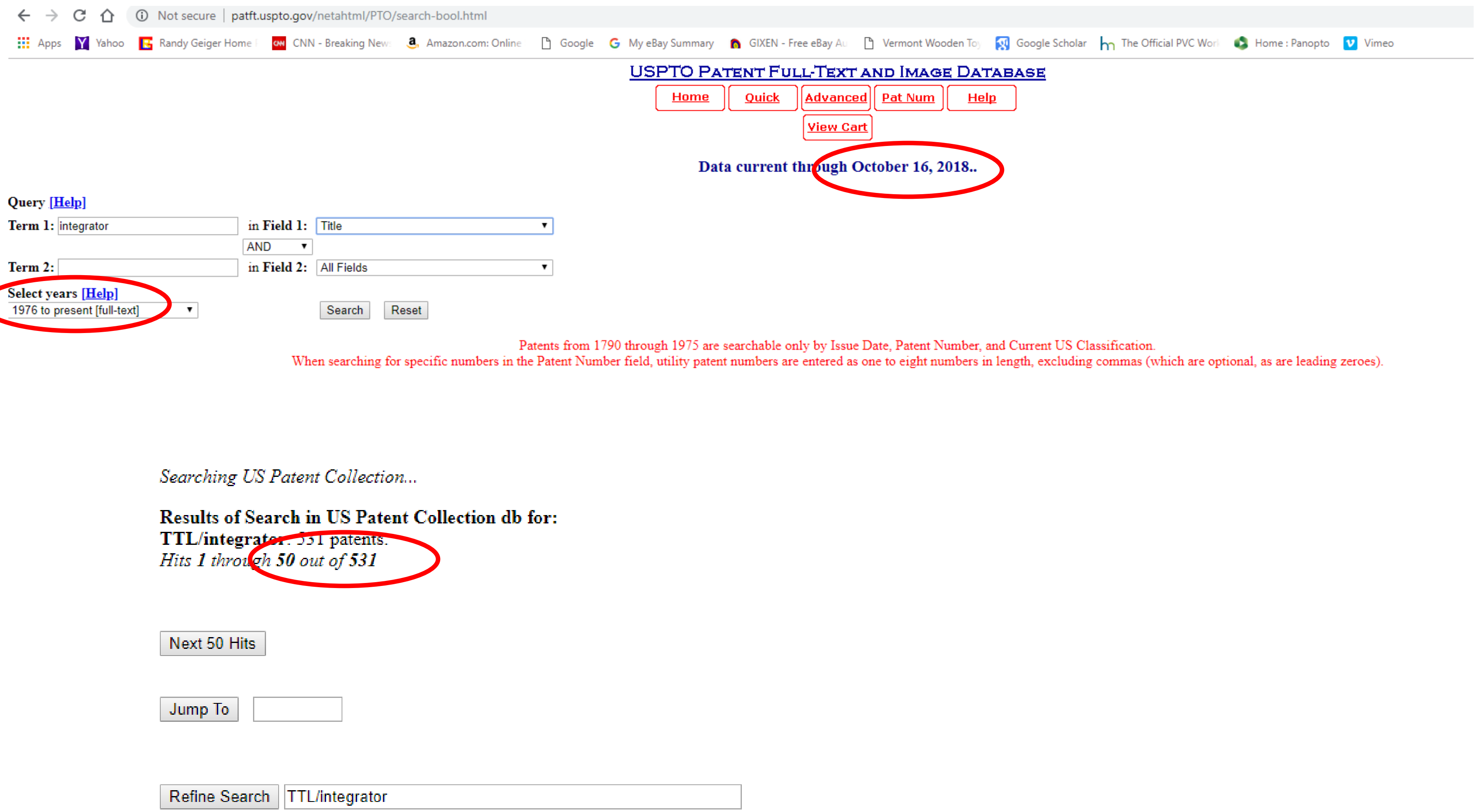
Same modifications exist for other integrator architectures

Integrator-Based Filter Design



Any of these different types of integrators can be used to build integrator-based filters

Are new integrators still being invented?



Oct 16 2018

		PAT. NO.	Title
	1	10,082,922	Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit
	2	10,074,004	Capacitive fingerprint sensor with integrator
	3	10,070,089	Inverting amplifier, integrator, sample hold circuit, ad converter, image sensor, and imaging apparatus
	4	9,985,594	Gated CDS integrator
	5	9,972,003	Pregame electronic commerce integrator
	6	9,954,514	Output range for interpolation architectures employing a cascaded integrator-comb (CIC) filter with a multiplier
	7	9,885,959	Illumination optical apparatus having deflecting member, lens, polarization member to set polarization in circumference direction, and optical integrator
	8	9,885,872	Illumination optical apparatus, exposure apparatus, and exposure method with optical integrator and polarization member that changes polarization state of light
	9	9,866,237	Low power switched capacitor integrator, analog-to-digital converter and switched capacitor amplifier
	10	9,852,283	Confirming the identity of integrator applications
Nov 2017	11	9,825,646	Integrator and A/D converter using the same
	12	9,817,917	System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems
	13	9,806,552	Analog/digital converter with charge rebalanced integrator
	14	9,800,256	Semiconductor device including integrator and successive approximation register analog-to-digital converter and driving method of the same
	15	9,753,559	Feedback integrator current source, transistor, and resistor coupled to input
	16	9,726,521	Signal processing apparatus for processing time variant signal with first and second input signals comprising a weighting integrator, a magnitude detector and a gain-adjustable amplifier
	17	9,709,242	Shell integrator
	18	9,703,178	Projector having a rod integrator with an entrance plane smaller than an area light source
	19	9,680,496	Apparatus for overload recovery of an integrator in a sigma-delta modulator
	20	9,671,916	Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit
	21	9,647,677	Integrator, AD converter, and radiation detection device
	22	9,634,688	Integrator, delta-sigma modulator, and communications device
	23	9,628,103	Multi-mode discrete-time delta-sigma modulator power optimization using split-integrator scheme
	24	9,608,598	Cascaded integrator-comb filter as a non-integer sample rate converter
	25	9,588,147	Electronic integrator for Rogowski coil sensors
	26	9,574,735	Shell integrator
	27	9,558,845	Sampling network and clocking scheme for a switched-capacitor integrator
	28	9,531,718	Confirming the identity of integrator applications
	29	9,524,054	Integrator and touch sensing system using the same
	30	9,519,462	System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems
	31	9,496,969	Double integrator pulse wave shaper apparatus, system and method
Nov 2016	32	9,495,563	Analog integrator system and method
	33	9,473,075	Dynamic current source for amplifier integrator stages
	34	9,467,153	Low power and compact area digital integrator for a digital phase detector
	35	9,461,595	Integrator for class D audio amplifier
	36	9,454,069	Illumination system having first and second lens arrays including plano-convex lenses wherein some lenses in the second array include a first and a second lens element, projection-type display apparatus, and optical integrator
	37	9,405,800	Apparatuses, methods and systems for a universal payment integrator
	38	9,389,625	DC-DC converter controller apparatus with dual-counter digital integrator
	39	9,383,395	Charge balancing converter using a passive integrator circuit
	40	9,379,732	Delta-sigma modulator with reduced integrator requirements
	41	9,362,890	Compensation filter for cascaded-integrator-comb decimator
	42	9,354,953	System integrator and system integration method with reliability optimized integrated circuit chip selection
	43	9,314,389	Therapeutic integrator apparatus
	44	9,310,924	Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit
	45	9,268,441	Active integrator for a capacitive sense array
	46	9,225,351	Current amplifier circuit, integrator, and ad converter
	47	9,218,514	Apparatuses and method of switched-capacitor integrator
	48	9,171,189	Systems and methods for preventing saturation of analog integrator output
	49	9,152,387	System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems
	50	9,139,096	One-sided detection and disabling of integrator wind up for speed control in a vehicle

51 9,063,789 Hybrid cloud integrator plug-in components
52 9,061,592 System and method for detecting power integrator malfunction
53 9,054,731 Integrator output swing reduction
54 9,039,190 Projector having integrator with greater illuminance in offset direction of projection lens and modulator
55 9,037,469 Automated communication integrator
56 9,014,322 Low power and compact area digital integrator for a digital phase detector
57 9,009,697 Hybrid cloud integrator
58 8,995,061 Speckle reduction using lenslet integrator
59 8,988,904 Power supply with integrator for controlling current
60 8,957,363 Differential photodiode integrator circuit for absorbance measurements
61 8,952,749 Filter with combined resonator and integrator
62 8,941,526 Time integrator and .DELTA..SIGMA. time-to-digital converter
63 8,937,567 Delta-sigma modulator, integrator, and wireless communication device
64 8,922,290 Pulse width modulator with two-way integrator
65 8,866,532 Passive integrator and method
66 8,866,531 Broadband analog radio-frequency integrator
67 8,860,491 Integrator output swing reduction technique for sigma-delta analog-to-digital converters
68 8,854,107 Integrator circuit with inverting integrator and non-inverting integrator
69 8,851,684 Optical unit including an integrator optical system, and projection display device including the optical unit
70 8,835,827 Current integrator with wide dynamic range
71 8,824,626 Reduced-noise integrator, detector and CT circuits
72 8,816,763 Integrator input error correction circuit and circuit method

July 2014

73 8,779,831 Integrator
74 8,775,003 Methods and systems for controlling a proportional integrator
75 8,767,343 Disk drive increasing integrator output range to complete seek operation
76 8,724,080 Optical raster element, optical integrator and illumination system of a microlithographic projection exposure apparatus
77 8,704,580 Circuit sharing time delay integrator
78 8,674,864 Integrator and oversampling A/D converter having the same
79 8,665,129 Complex second-order integrator and oversampling A/D converter having the same
80 8,659,343 Calibration for mixed-signal integrator architecture
81 8,653,867 Pulse modulated neural integrator circuit and associated phase locked loop
82 8,639,513 Automated communication integrator
83 8,638,420 Optical integrator, illuminating optical device, exposure apparatus and device manufacturing method
84 8,614,639 Integrator ramp generator with DAC and switched capacitors
85 8,611,013 Optical integrator, illumination optical device, aligner, and method for fabricating device
86 8,587,764 Optical integrator system, illumination optical apparatus, exposure apparatus, and device manufacturing method
87 8,575,988 Mixed-signal integrator architecture
88 8,573,779 Lighting device with plural light sources illuminating distinct regions of integrator
89 8,566,277 System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems
90 8,564,358 Integrator circuit with multiple time window functions
91 8,558,610 Integrator input error correction circuit and circuit method
92 8,536,923 Integrator distortion correction circuit
93 8,526,487 Differential energy difference integrator
94 8,520,307 Optical integrator for an illumination system of a microlithographic projection exposure apparatus
95 8,504,503 Pulse modulated neural integrator circuit
96 8,497,977 Optical integrator, illumination optical system, exposure apparatus, and device manufacturing method
97 8,438,201 Digital fractional integrator
98 8,432,150 Methods for operating an array column integrator
99 8,432,149 Array column integrator
100 8,422,018 Optical measurement apparatus including hemispherical optical integrator

Oct 16 2012

	PAT. NO.		Title
1	8,290,897	T	System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems
2	8,283,966	T	Integrator circuit
3	8,275,307	T	Vehicle audio integrator
4	8,264,388	T	Frequency integrator with digital phase error message for phase-locked loop applications
5	8,258,990	T	Integrator, resonator, and oversampling A/D converter
6	8,253,473	T	Integrated circuit of an integrator with enhanced stability and related stabilization method
7	8,199,038	T	Active resistance-capacitor integrator and continuous-time sigma-delta modulator with gain control function
8	8,164,873	T	Integrator and circuit-breaker having an integrator
9	8,145,597	T	System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems
10	8,129,972	T	Single integrator sensorless current mode control for a switching power converter
11	8,125,262	T	Low power and low noise switched capacitor integrator with flexible input common mode range
12	8,098,377	T	Electric gated integrator detection method and device thereof
13	8,081,098	T	Integrator, delta-sigma modulator, analog-to-digital converter and applications thereof
14	8,035,439	T	Multi-channel integrator
15	8,031,404	T	Fly's eye integrator, illuminator, lithographic apparatus and method
16	8,029,144	T	Color mixing rod integrator in a laser-based projector
17	8,028,304	T	Component integrator
18	8,013,657	T	Temperature compensated integrator
19	8,011,810	T	Light integrator for more than one lamp
20	7,997,740	T	Integrator unit
21	7,965,795	T	Prevention of integrator wind-up in PI type controllers
22	7,965,151	T	Pulse width modulator with two-way integrator
23	7,954,962	T	Laser image display, and optical integrator and laser light source package used in such laser image display
24	7,943,893	T	Illumination optical system and image projection device having a rod integrator uniformizing spatial energy distribution of diffused illumination beam
25	7,933,812	T	System integrator and commodity roll-up

Apr 26 2011

26 7,932,960 T Integrator array for HUD backlighting
27 7,911,256 T Dual integrator circuit for analog front end (AFE)
28 7,907,115 T Digitally synchronized integrator for noise rejection in system using PWM dimming signals to control brightness of cold cathode fluorescent lamp for backlighting liquid crystal display
29 7,905,631 T Illumination system having coherent light source and integrator rotatable transverse the illumination axis
30 7,884,662 T Multi-channel integrator
31 7,880,969 T Optical integrator for an illumination system of a microlithographic projection exposure apparatus
32 7,873,223 T Cognition integrator and language
33 7,834,963 T Optical integrator
34 7,830,197 T Adjustable integrator using a single capacitance
35 RE41,792 T Controllable integrator
36 7,788,309 T Interleaved comb and integrator filter structures
37 7,773,730 T Voice record integrator
38 7,729,577 T Waveguide-optical Kohler integrator utilizing geodesic lenses
39 7,726,819 T Structure for protecting a rod integrator having a light shield plate with an opening
40 7,724,063 T Integrator-based common-mode stabilization technique for pseudo-differential switched-capacitor circuits
41 7,714,634 T Pseudo-differential active RC integrator
42 7,706,072 T Optical integrator, illumination optical device, photolithograph, photolithography, and method for fabricating device
43 7,696,913 T Signal processing system using delta-sigma modulation having an internal stabilizer path with direct output-to-integrator connection
44 7,693,430 T Burst optical receiver with AC coupling and integrator feedback network
45 7,679,540 T Double sampling DAC and integrator
46 7,671,774 T Analog-to-digital converter with integrator circuit for overload recovery
47 7,658,497 T Rod integrator holder and projection type video display
48 7,629,917 T Integrator and cyclic AD converter using the same
49 7,619,550 T Delta-sigma AD converter apparatus using delta-sigma modulator circuit provided with reset circuit resetting integrator
50 7,611,246 T Projection display and optical integrator

Nov 3 2009

	PAT. NO.	Title
51	7,605,645	Transconductor, integrator, and filter circuit
52	7,599,631	Burst optical receiver with AC coupling and integrator feedback network
53	7,575,159	Point of sale integrator
54	7,570,032	Regulator with integrator in feedback signal
55	7,565,326	Dialect independent multi-dimensional integrator using a normalized language platform and secure controlled access
56	7,554,400	Integrator and error amplifier
57	7,543,945	Integrator module with a collimator and a compact light source and projection display having the same
58	7,532,145	High resolution and wide dynamic range integrator
59	7,528,818	Digitally synchronized integrator for noise rejection in system using PWM dimming signals to control brightness of light source
60	7,511,648	Integrating/SAR ADC and method with low integrator swing and low complexity
61	7,474,241	Delta-sigma modulator provided with a charge sharing integrator
62	7,471,456	Optical integrator, illumination optical device, exposure device, and exposure method
63	7,454,750	Integrator adaptor and proxy based composite application provisioning method and apparatus
64	7,447,049	Single ended flyback power supply controllers with integrator to integrate the difference between feedback signal a reference signal
65	7,423,729	Method of monitoring the light integrator of a photolithography system
66	7,417,485	Differential energy difference integrator
67	7,415,716	Component integrator
68	7,411,534	Analog-to-digital converter (ADC) having integrator dither injection and quantizer output compensation
69	7,411,198	Integrator circuitry for single channel radiation detector
70	7,395,090	Personal portable integrator for music player and mobile phone
71	7,385,426	Low current offset integrator with signal independent low input capacitance buffer circuit
72	7,379,160	Optical integrator, illumination optical device, exposure apparatus, and exposure method
73	7,352,510	Light-pipe integrator for uniform irradiance and intensity
74	7,345,285	Spectra acquisition system with threshold adaptation integrator
75	7,333,626	Arbitrary coverage angle sound integrator

76 7,324,654 T Arbitrary coverage angle sound integrator
77 7,324,025 T Non-integer interpolation using cascaded integrator-comb filter
78 7,315,268 T Integrator current matching
79 7,304,592 T Method of adding a dither signal in output to the last integrator of a sigma-delta converter and relative sigma-delta converter
80 7,280,405 T Integrator-based current sensing circuit for reading memory cells
81 7,262,056 T Enhancing intermolecular integration of nucleic acids using integrator complexes
82 7,243,844 T Point of sale integrator
83 7,242,333 T Alternate sampling integrator
84 7,205,849 T Phase locked loop including an integrator-free loop filter
85 7,187,948 T Personal portable integrator for music player and mobile phone
86 7,182,468 T Dual lamp illumination system using multiple integrator rods
87 7,180,357 T Operational amplifier integrator
88 7,170,959 T Tailored response cascaded integrator comb digital filter and methodology for parallel integrator processing
89 7,155,470 T Variable gain integrator
90 7,152,981 T Projection illumination system with tunnel integrator and field lens
91 7,152,084 T Parallelized infinite impulse response (IIR) and integrator filters
92 7,150,968 T Bridging INtegrator-2 (Bin2) nucleic acid molecules and proteins and uses therefor
93 7,138,848 T Switched capacitor integrator system
94 7,130,764 T Robust DSP integrator for accelerometer signals
95 7,102,844 T Dual direction integrator for constant velocity control for an actuator using sampled back EMF control
96 7,102,548 T Cascaded integrator comb filter with arbitrary integer decimation value and scaling for unity gain
97 7,098,845 T Apparatus for generating an integrator timing reference from a local oscillator signal
98 7,098,827 T Integrator circuit
99 7,098,718 T Tunable current-mode integrator for low-frequency filters
100 7,087,881 T Solid state image pickup device including an integrator with a variable reference potential

Aug 8 2006

	PAT. NO.		Title
501	4,161,658	T	Wind turbine generator having integrator tracking
502	4,160,954	T	Multiple rate discharge circuit for integrator, especially for use in computerized axial tomography
503	4,154,102	T	Continuous integrator control linkage
504	4,140,062	T	Differential integrator
505	4,132,923	T	Circuit for light-integrator-controlled electronic flash unit
506	4,122,528	T	Integrator circuits for a constant velocity vector generator
507	4,083,365	T	Dual integrator EEG analyzer
508	4,081,733	T	Automatic control system with integrator offset
509	4,061,033	T	Temperature function integrator
510	4,059,751	T	Logic controlled integrator
511	4,053,746	T	System and method for operating a steam turbine with digital computer control having integrator limit
512	4,042,842	T	Multiple-time-constant integrator or differentiator
513	4,035,809	T	Electronic integrator for chart recorder
514	4,030,038	T	Multiple dumping integrator
515	4,023,019	T	Automatic scaled digital integrator
516	4,012,730	T	Doppler detection device with integrator sampling means to inhibit false alarms
517	4,006,415	T	Fast reset integrator
518	4,006,317	T	Electrostatic transducer and acoustic and electric signal integrator
519	4,002,067	T	Low friction absolute pressure continuous integrator
520	4,001,721	T	Field effect transistor Miller integrator oscillator with temperature compensating impedance
521	3,991,730	T	Noise immune reset circuit for resetting the integrator of an electronic engine spark timing controller
522	3,990,073	T	Digital signal processing arrangement using a cascaded integrator function generator
523	3,989,961	T	Bidirectional reset integrator converter
524	3,980,865	T	Electronic integrator for gas volume calculations
525	3,975,682	T	Watt/watthour transducer and integrator and current sources therefor
526	3,971,993	T	High capacity recirculating delay loop integrator
527	3,961,173	T	Heat unit integrator for X-ray tubes
528	3,946,609	T	Barometrically compensated pressure index continuous integrator for measuring throughput fluid flow of meters
529	3,943,456	T	Signal generator for electronic musical instrument, employing variable rate integrator
530	3,942,131	T	Low frequency two phase oscillator including variable feedback integrator circuits
Jan 1976 531	3,931,619	T	Overtemperature monitor and integrator apparatus

Stay Safe and Stay Healthy !

End of Lecture 23