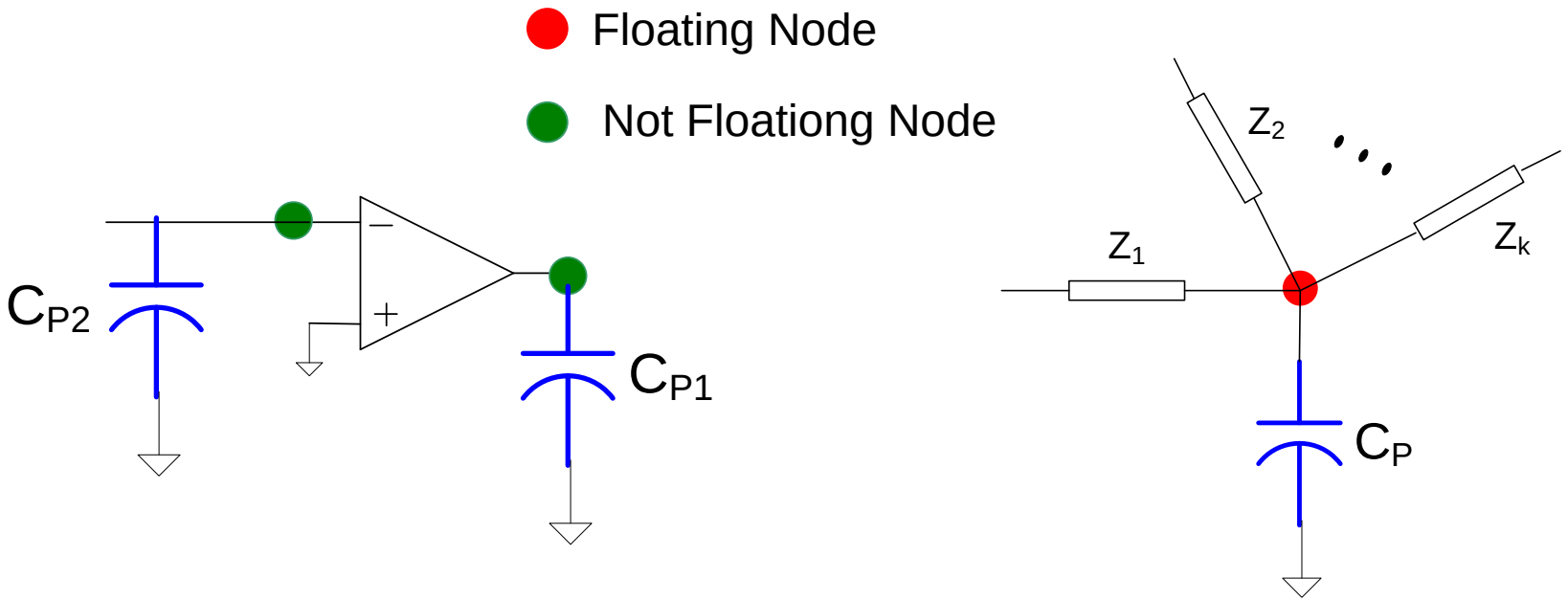
EE 508
Lecture 25

Integrator Design

Parasitic Capacitances on Floating Nodes



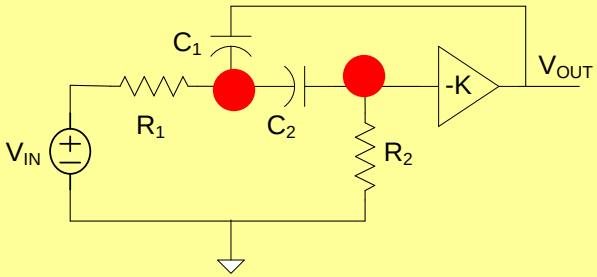
Parasitic capacitances ideally have no affect on filter when on a non-floating node but directly affect transfer function when they appear on a floating node

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

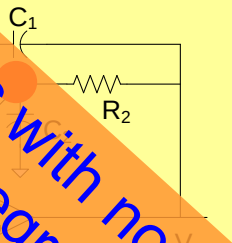
Generally avoid floating nodes, if possible, in integrated filters

Which type of Biquad is really used?

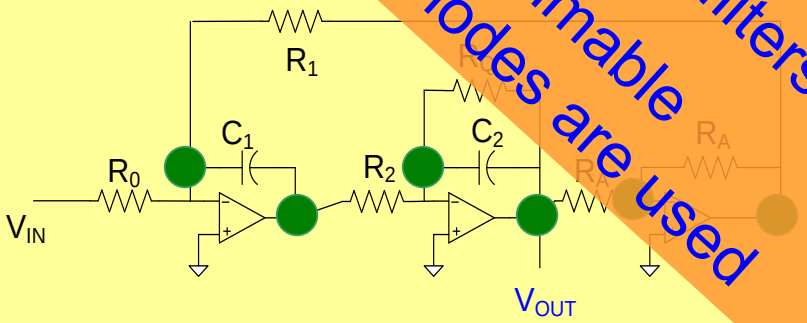
Not Floationg Node Floating Node



(Dependent Sources)



Integrator Based Structures



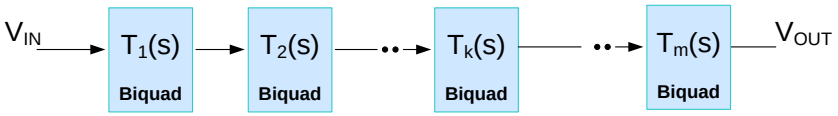
Integrator-based structures with no floating nodes dominantly used in integrated filters

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

Review from last time

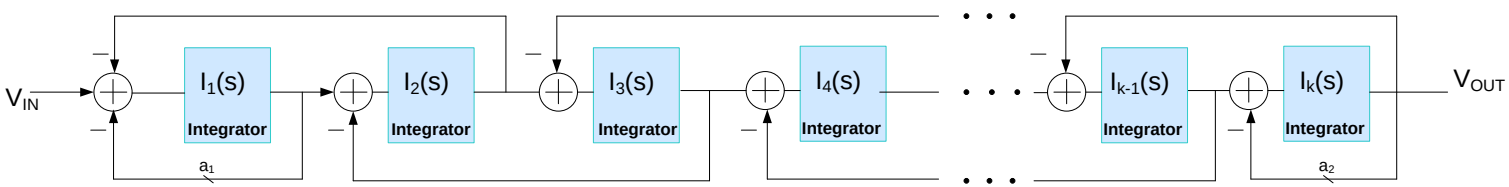
Filter Design/Synthesis Considerations

Cascaded Biquads

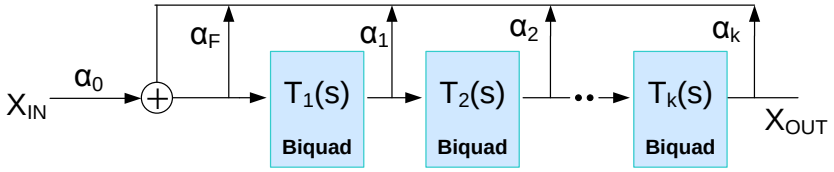


$$T(s) = T_1 T_2 \bullet\bullet T_m$$

Leapfrog



Multiple-loop Feedback – One type shown



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

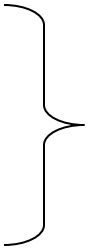
And biquads usually made with summers and integrators

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

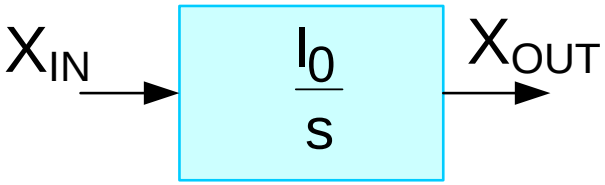
Basic Filter Building Blocks
(particularly for integrated filters)

- Integrators
- Summers



- Operational Amplifiers

Integrator Characteristics of Interest



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

Properties of an ideal integrator:

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

Gain decreases with 1/ω

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

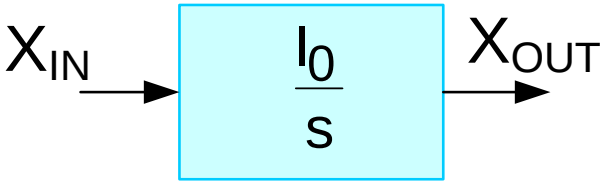
Phase is a constant -90º

$$\left|I(jI_0)\right| = 1$$

Unity Gain Frequency = 1

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

Integrator Characteristics of Interest

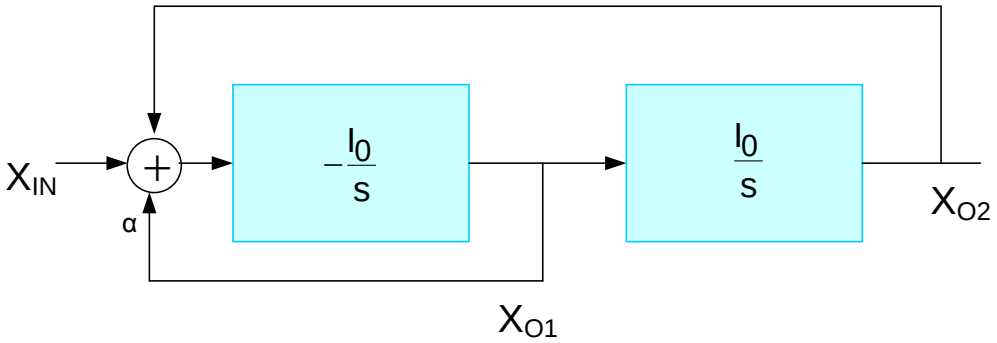


$$I(s) = \frac{I_0}{s}$$

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

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

Consider a filter example:



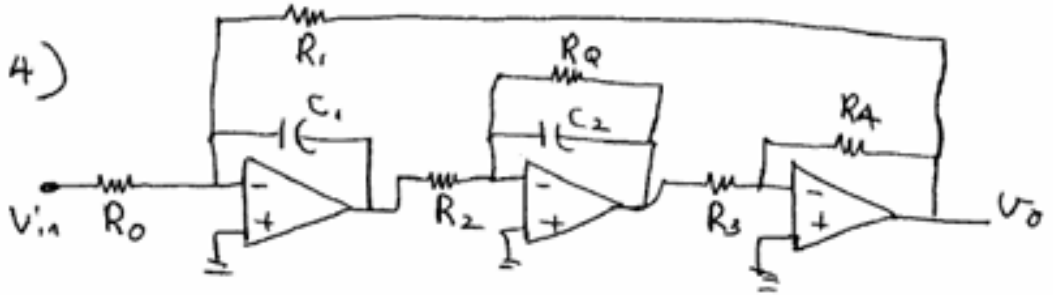
$$T(s) = \frac{-I_0^2}{s^2 + \alpha I_0 s + I_0^2}$$

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

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)



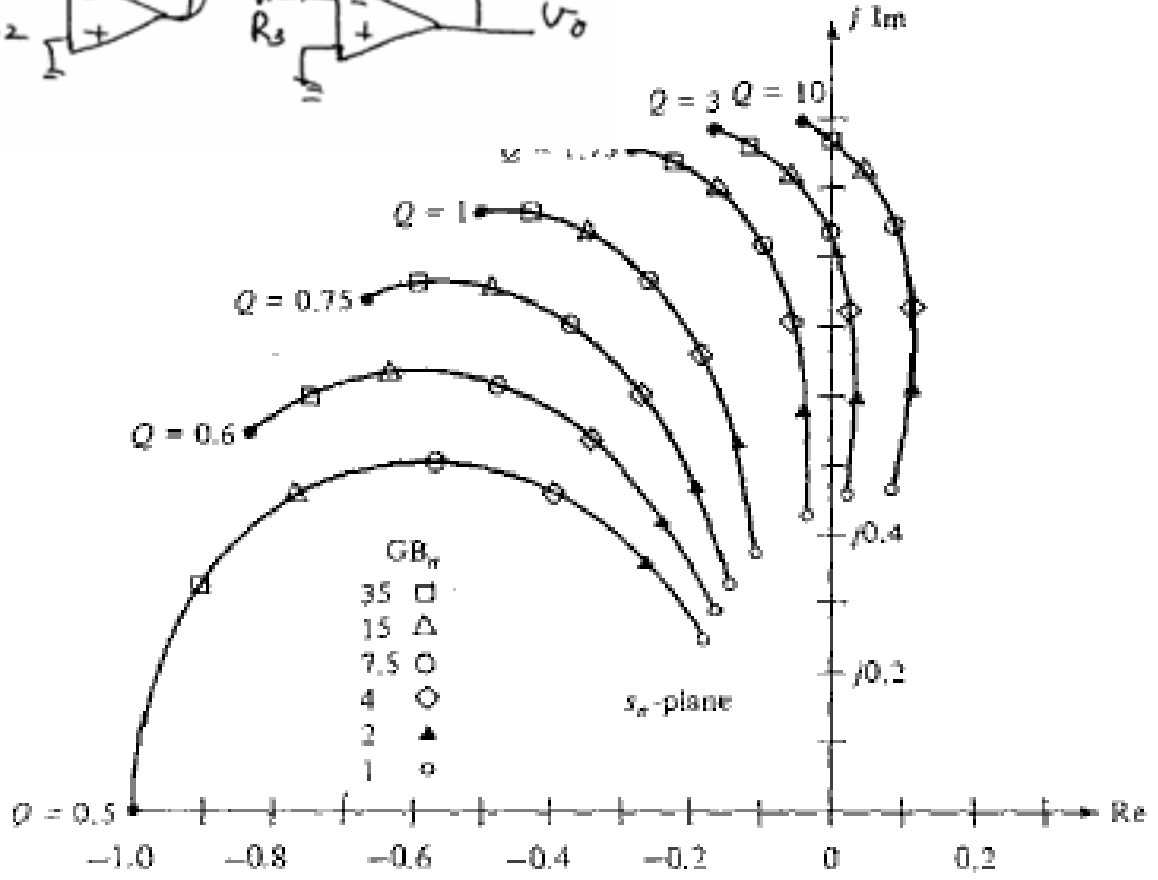
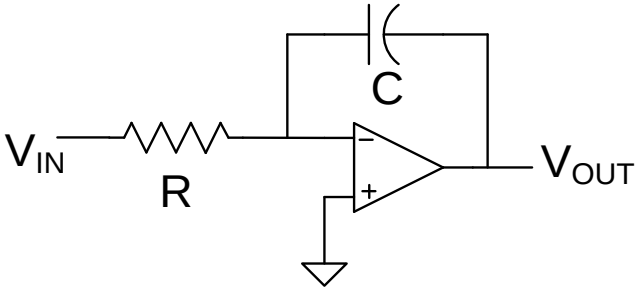


Fig. 10-17 Plot of upper half-plane root of

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

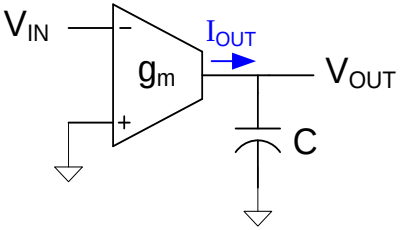
Some integrator structures



$$I(s) = -\frac{1}{RCs} \qquad I_0 = \frac{1}{RC}$$

Inverting Active RC Integrator

Are there other integrator structures?



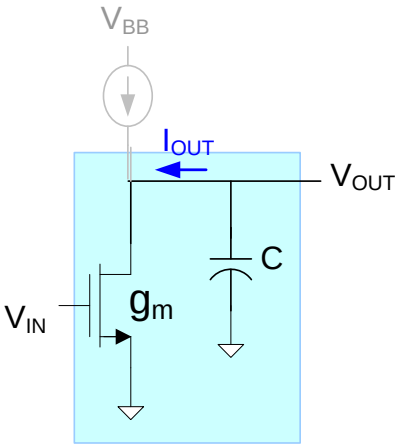
$$I_{OUT} = -g_m V_{IN}$$
$$V_{OUT} = I_{OUT}\frac{1}{sC}$$

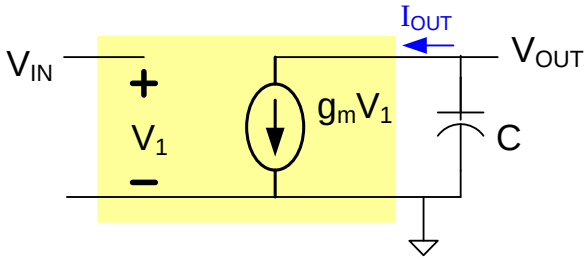
$$I(s) = -\frac{g_m}{sC} \qquad I_0 = \frac{g_m}{C}$$

Termed an OTA-C or a gm-C integrator

Some integrator structures

Are there other integrator structures?





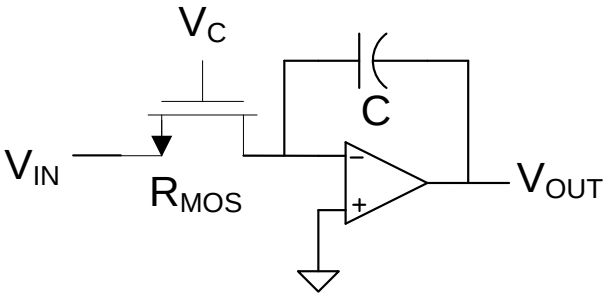
$$I_{OUT} = g_m V_{IN}$$

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

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

Termed a TA-C integrator

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



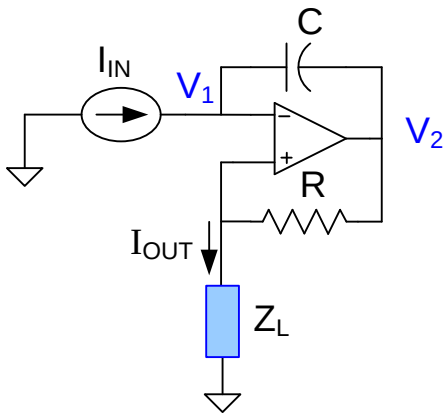
$$I(s) = -\frac{1}{sCR_{MOS}}$$

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

Termed MOSFET-C integrator

Some integrator structures

Are there other integrator structures?



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

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

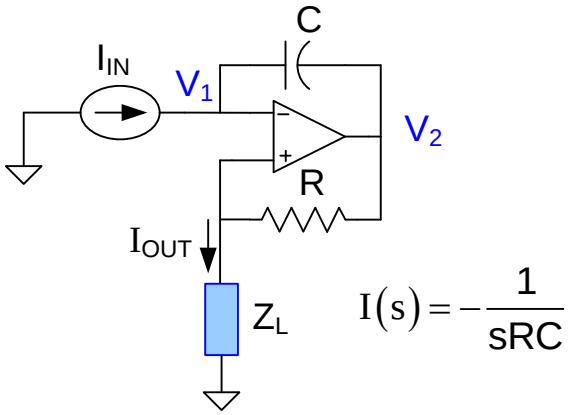
$$I(s) = \frac{I_{OUT}}{I_{IN}} = -\frac{1}{sRC}$$

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

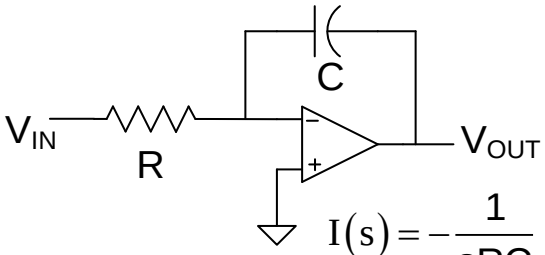
- Output current is independent of Z_L
- Thus output impedance is ∞ so provides current output

Termed active RC current-mode integrator

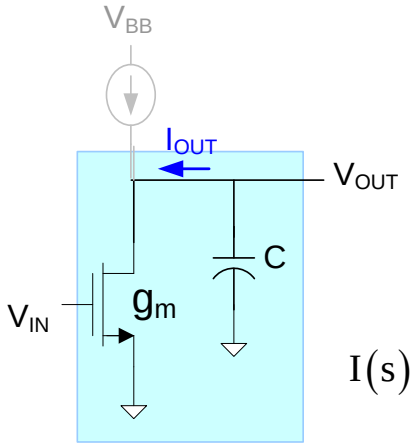
Some integrator structures



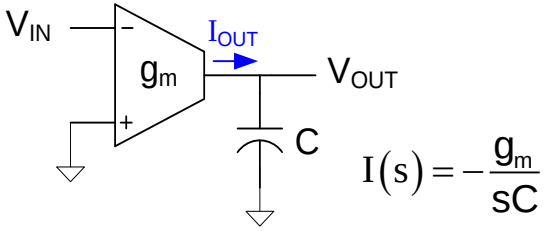
$$I(s) = -\frac{1}{sRC}$$



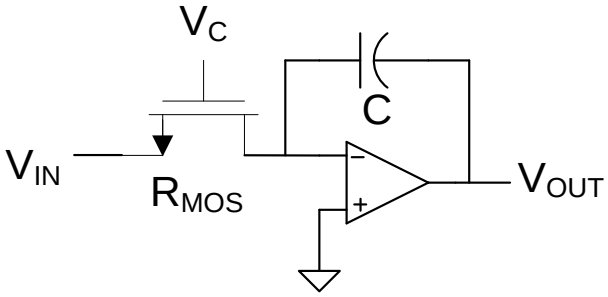
$$I(s) = -\frac{1}{sRC}$$



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



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

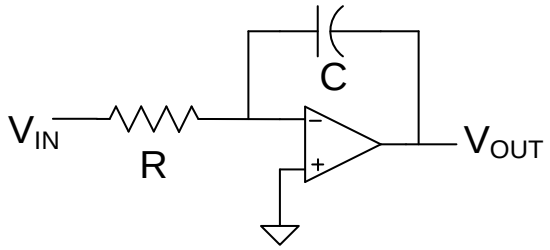


$$I(s) = -\frac{1}{sR_{MOS}C}$$

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

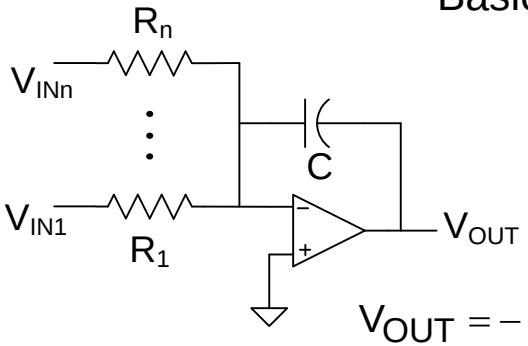
There are many different ways to build an inverting integrator

Integrator Functionality



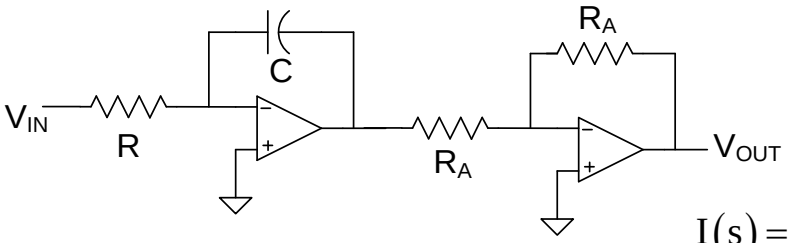
$$I(s) = -\frac{1}{sRC}$$

Basic Active RC Inverting Integrator



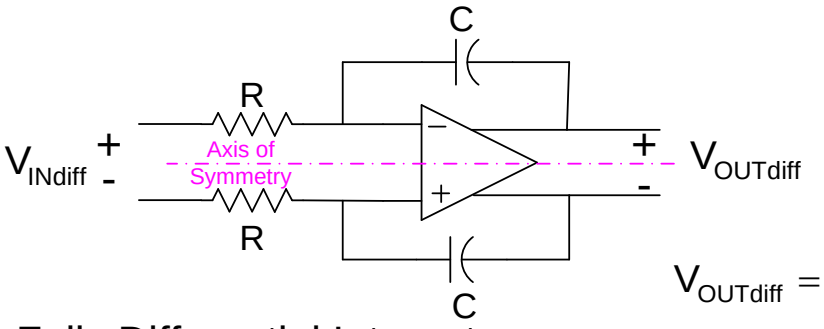
$$V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_k s} V_{INk}$$

Summing Integrator



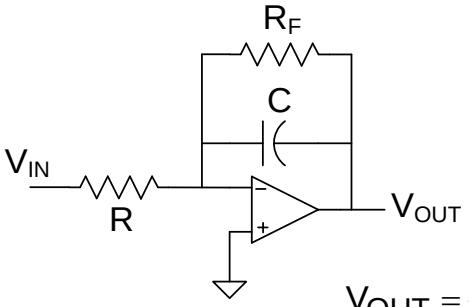
$$I(s) = \frac{1}{sRC}$$

Noninverting Integrator



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

Fully Differential Integrator

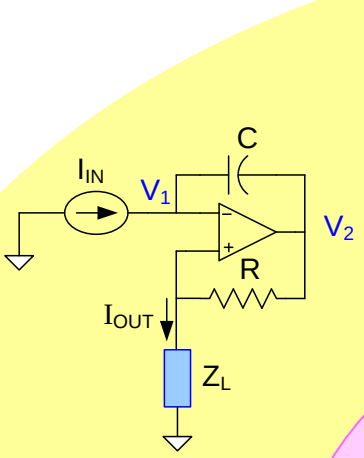


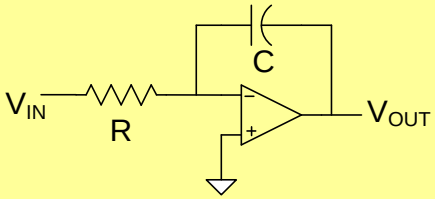
$$V_{OUT} = -\frac{R_F \,/\!/\, R}{1+CR_F s} V_{IN}$$

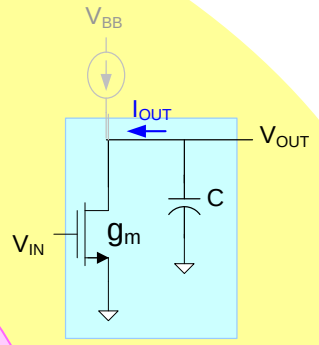
Lossy Integrator

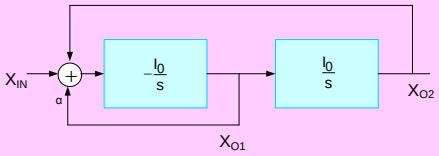
Many different types of functionality from basic inverting integrator
Same modifications exist for other integrator architectures

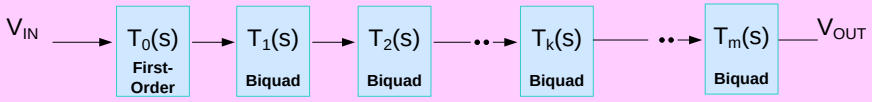
Integrator-Based Filter Design

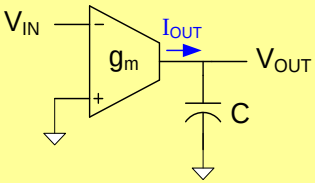


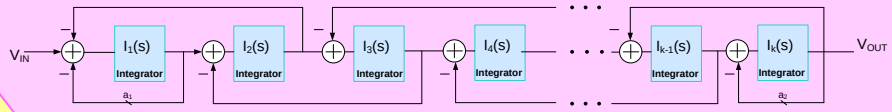


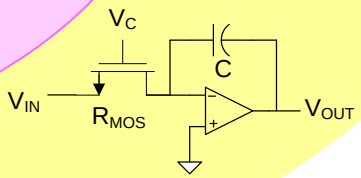












Any of these different types of integrators can be used to build integrator-based filters

Are new integrators still being invented?

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Searching US Patent Collection...

Results of Search in US Patent Collection db for:
TTL/integrator: 419 patents.
*Hits **1** through **50** out of **419***

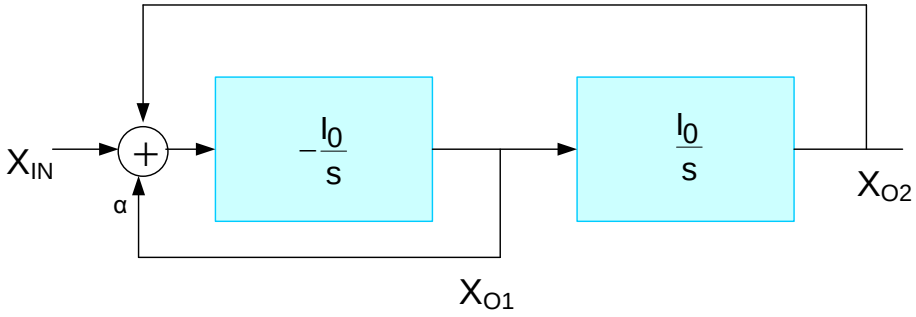
	PAT. NO.	Title
1	8,290,897	System integrator and method for mapping dynamic COBOL constructs to object instances for the automatic integration to object-oriented computing systems
2	8,283,966	Integrator circuit
3	8,275,307	Vehicle audio integrator
4	8,264,388	Frequency integrator with digital phase error message for phase-locked loop applications
5	8,258,990	Integrator, resonator, and oversampling A/D converter
6	8,253,473	Integrated circuit of an integrator with enhanced stability and related stabilization method
7	8,199,038	Active resistance-capacitor integrator and continuous-time sigma-delta modulator with gain control function
8	8,164,873	Integrator and circuit-breaker having an integrator
9	8,145,597	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	Single integrator sensorless current mode control for a switching power converter
11	8,125,262	Low power and low noise switched capacitor integrator with flexible input common mode range
12	8,098,377	Electric gated integrator detection method and device thereof
13	8,081,098	Integrator, delta-sigma modulator, analog-to-digital converter and applications thereof
14	8,035,439	Multi-channel integrator
15	8,031,404	Fly's eye integrator, illuminator, lithographic apparatus and method
16	8,029,144	Color mixing rod integrator in a laser-based projector
17	8,028,304	Component integrator
18	8,013,657	Temperature compensated integrator
19	8,011,810	Light integrator for more than one lamp
20	7,997,740	Integrator unit
21	7,965,795	Prevention of integrator wind-up in PI type controllers
22	7,965,151	Pulse width modulator with two-way integrator
23	7,954,962	Laser image display, and optical integrator and laser light source package used in such laser image display
24	7,943,893	Illumination optical system and image projection device having a rod integrator uniformizing spatial energy distribution of diffused illumination beam
25	7,933,812	System integrator and commodity roll-up

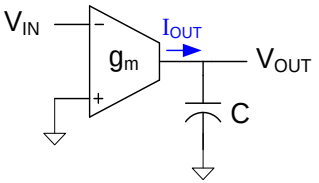
26 7,932,960 T Integrator array for HUD backlighting
27 7,911,256 T Dual integrator circuit for analog front end (AFE)
28 7,907,115 T Digitally synchronized integrator for noise rejection in system using PWM dimming signals to control brightness of cold cathode fluorescent lamp for backlighting liquid 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

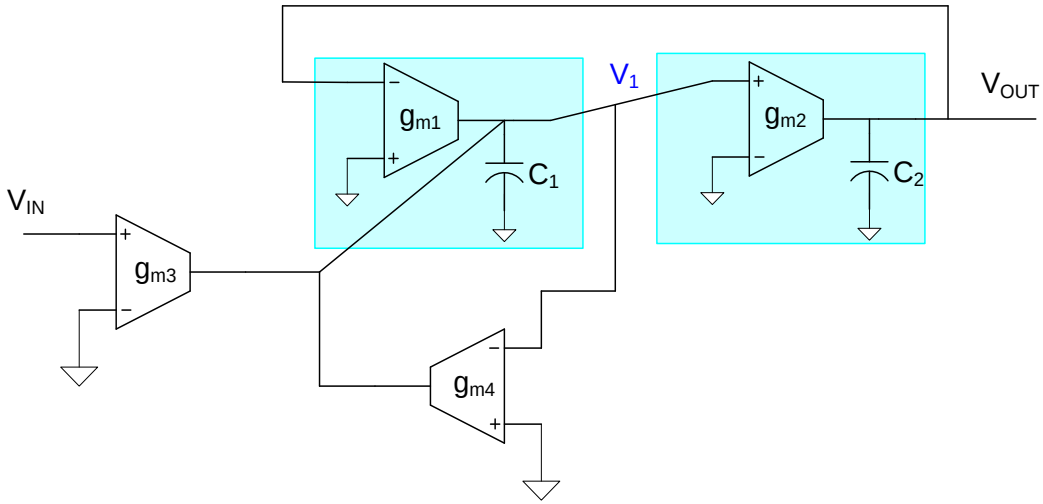
	PAT. NO.	Title
51	7,605,645	Transconductor, integrator, and filter circuit
52	7,599,631	Burst optical receiver with AC coupling and integrator feedback network
53	7,575,159	Point of sale integrator
54	7,570,032	Regulator with integrator in feedback signal
55	7,565,326	Dialect independent multi-dimensional 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

Example – OTA-C Tow Thomas Biquad







$$V_{OUT}sC_2 = g_{m2}V_1$$

$$V_1sC_1 = -g_{m1}V_{OUT} + g_{m3}V_{IN} - g_{m4}V_1$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{g_{m3}g_{m2}}{\left(s^2C_1C_2 + sg_{m4}C_2 + g_{m1}g_{m2}\right)}$$

Assume $g_{m1}=g_{m2}=g_m$, $C_1=C_2=C$

$$\frac{V_{OUT}}{V_{IN}} = \frac{\left(\frac{g_{m3}}{g_m}\right)\frac{g_m^2}{C^2}}{\left(s^2 + s\left(\frac{g_{m4}}{g_m}\right)\frac{g_m}{C} + \frac{g_m^2}{C^2}\right)}$$

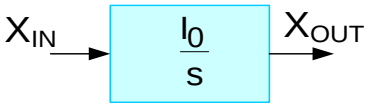
express as

$$\frac{V_{OUT}}{V_{IN}} = \frac{\left(\frac{g_{m3}}{g_m}\right)\omega_0^2}{\left(s^2 + s\frac{\omega_0}{Q} + \omega_0^2\right)}$$

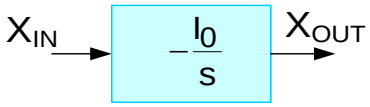
where

$$\omega_0 = \frac{g_m}{C} \qquad Q = \frac{g_m}{g_{m4}}$$

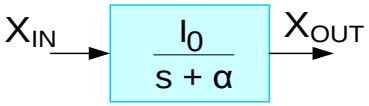
Basic Integrator Functionality



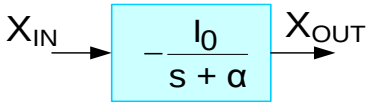
Noninverting



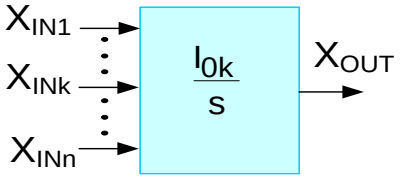
Inverting



Lossy Noninverting

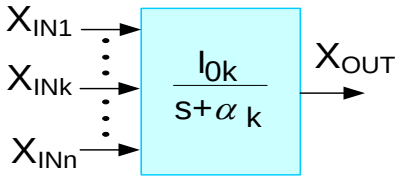


Lossy Inverting



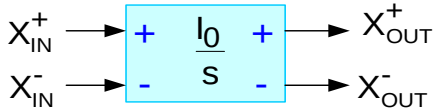
$$X_{OUT} = \sum_{k=1}^{n} \frac{\pm I_{Ok}}{s}$$

Summing (Multiple-Input) Inverting/Noninverting



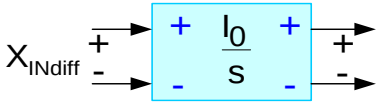
$$X_{OUT} = \sum_{k=1}^{n} \frac{\pm I_{Ok}}{s+\alpha_k}$$

Summing (Multiple-Input) Lossy Inverting/Noninverting



$$X_{OUT}^{+} - X_{OUT}^{+} = \frac{I_0}{s}\left(X_{IN}^{+} - X_{IN}^{+}\right)$$

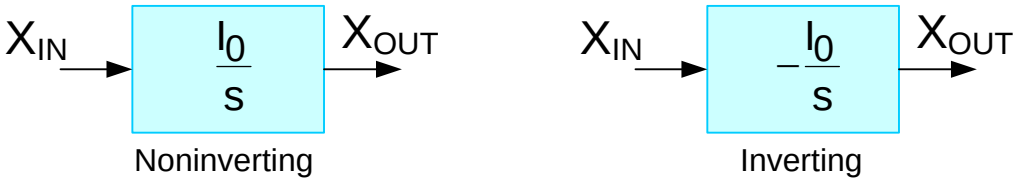
Balanced Differential



$$X_{OUTdiff} = \frac{I_0}{s} X_{INdiff}$$

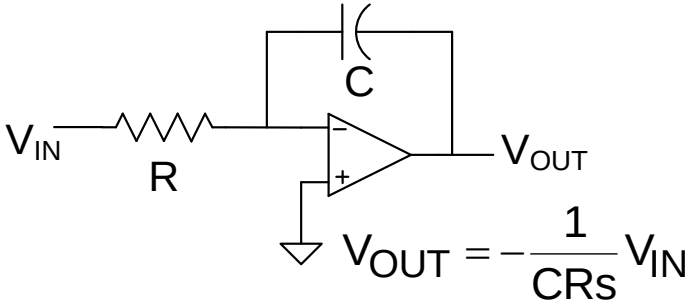
Fully Differential

Basic Integrator Functionality

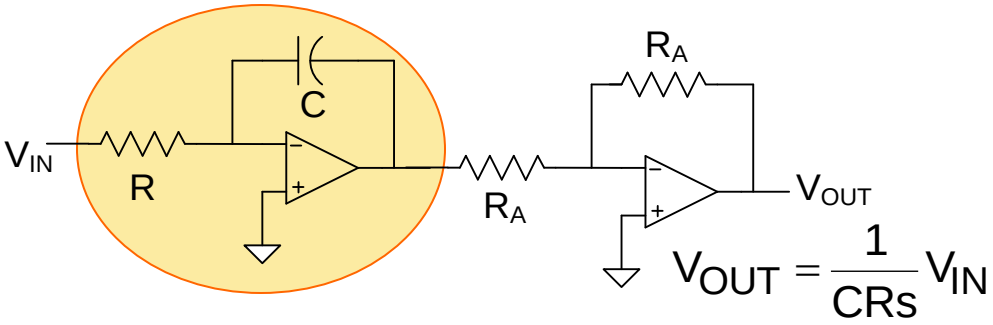


- An inverting/noninverting integrator pair define a family of integrators
- All integrator functional types can usually be obtained from the inverting/noninverting integrator pair
- Suffices to focus primarily on the design of the inverting/noninverting integrator pair since properties of class primarily determined by properties of integrator pair

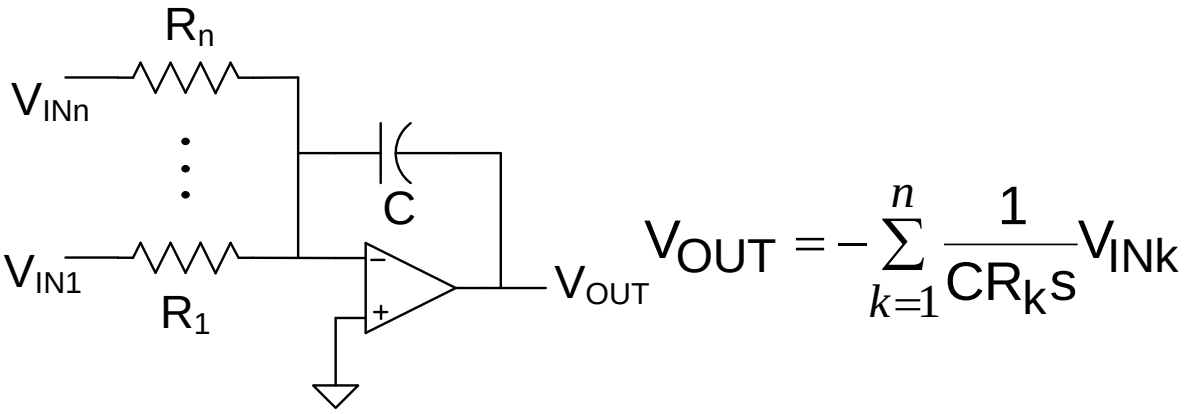
Example – Basic Op-Amp Feedback Integrator



Inverting Integrator of Family

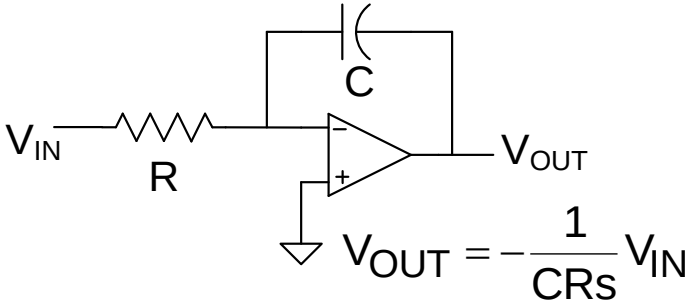


Noninverting Integrator

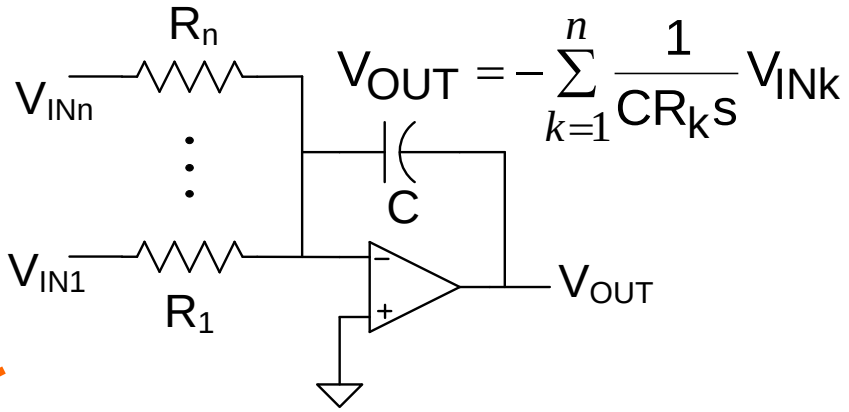


Summing Inverting Integrator

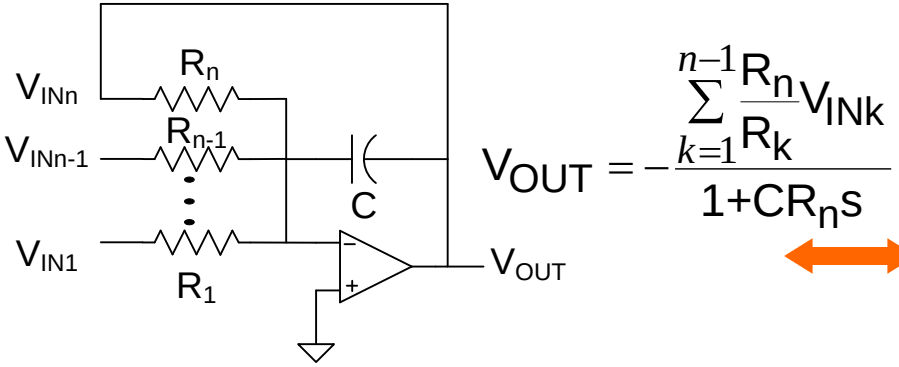
Example – Basic Op-Amp Feedback Integrator

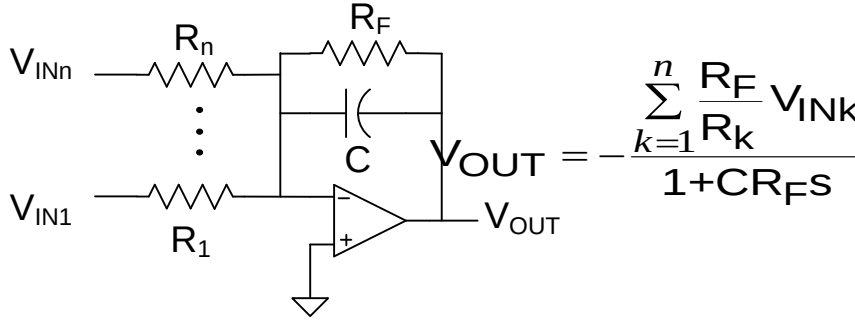


Inverting Integrator of Family



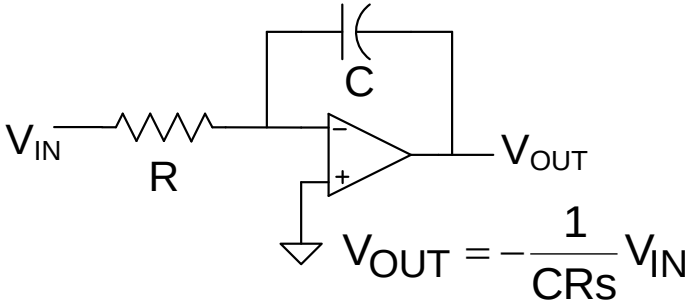
Summing Inverting Integrator



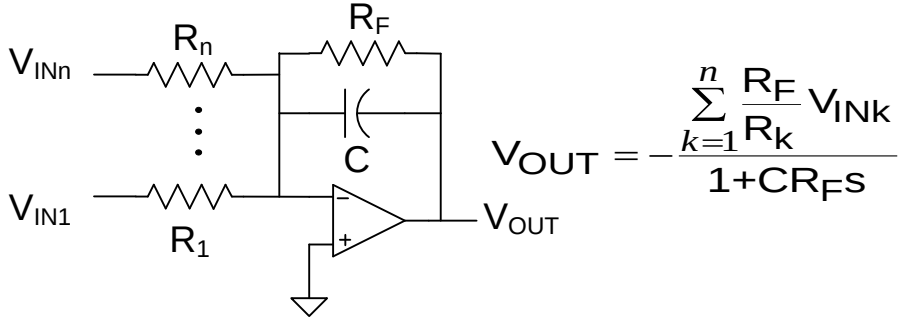


Lossy Summing Inverting Integrator

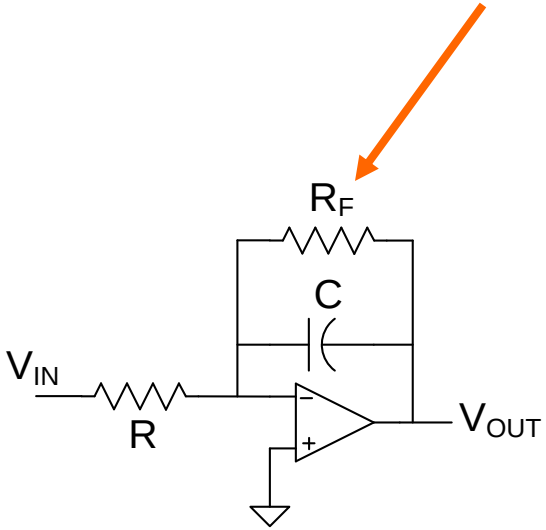
Example – Basic Op-Amp Feedback Integrator



Inverting Integrator of Family



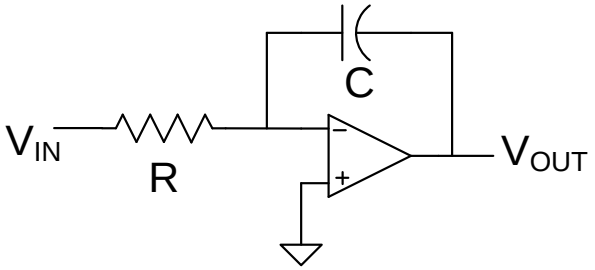
Lossy Summing Inverting Integrator



$$V_{OUT} = -\frac{R_F \,/\!/\, R}{1+CR_Fs} V_{IN}$$

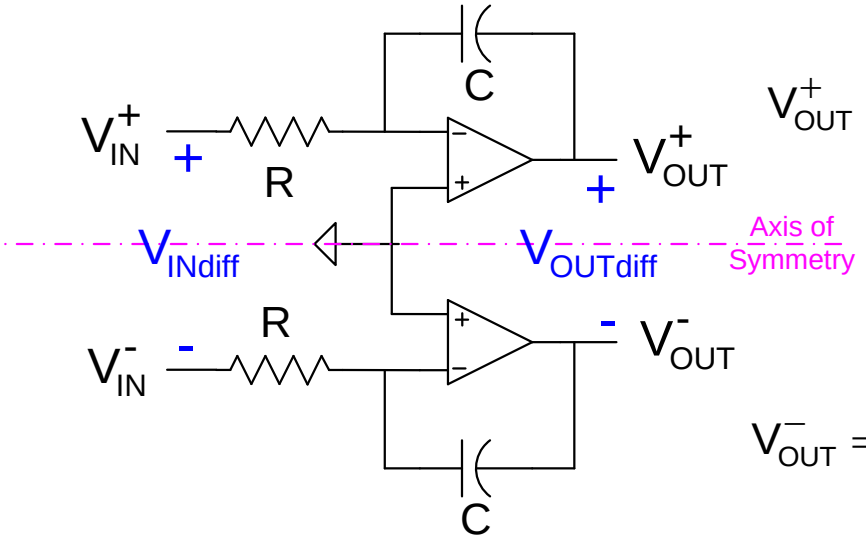
Lossy Inverting Integrator

Example – Basic Op-Amp Feedback Integrator



$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

Inverting Integrator of Family



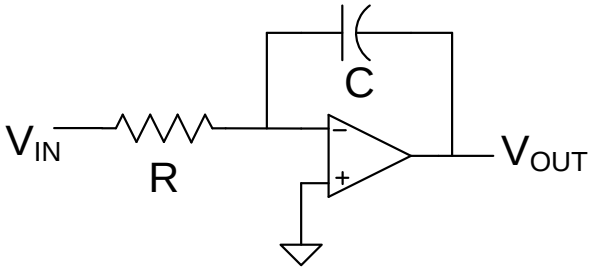
$$V_{OUT}^{+} = -\frac{1}{CRs} V_{IN}^{+}$$

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

$$V_{OUT}^{-} = -\frac{1}{CRs} V_{IN}^{-}$$

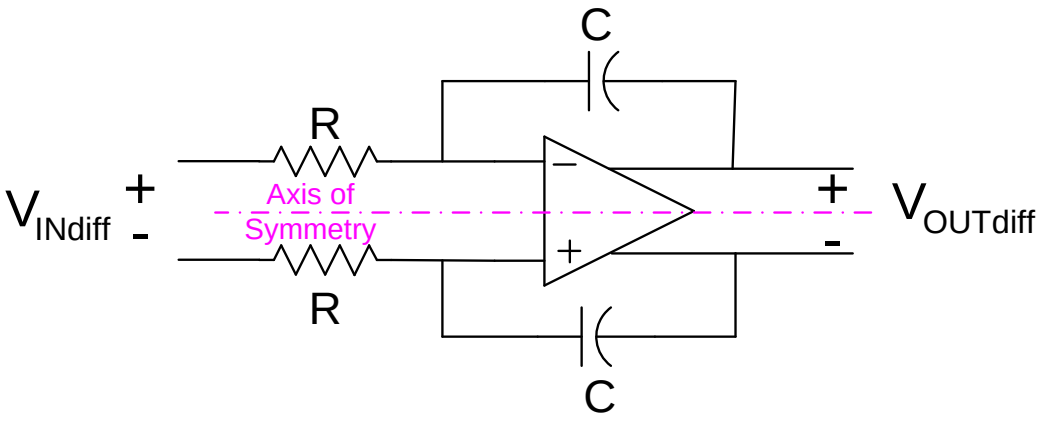
Balanced Differential Inverting Integrator

Example – Basic Op-Amp Feedback Integrator



$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

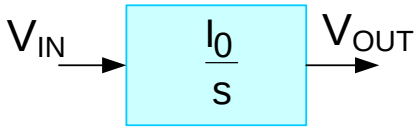
Inverting Integrator of Family



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

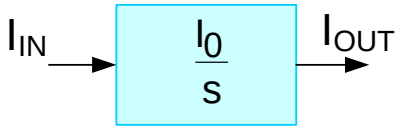
Fully Differential Inverting Integrator

Integrator Types



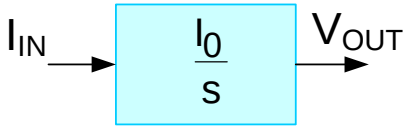
Voltage Mode

$$V_{OUT} = \frac{I_o}{s} V_{IN}$$



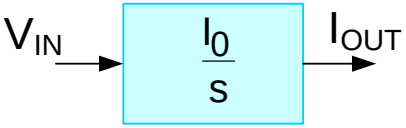
Current Mode

$$I_{OUT} = \frac{I_o}{s} I_{IN}$$



Transresistance Mode

$$V_{OUT} = \frac{I_o}{s} I_{IN}$$



Transconductance Mode

$$I_{OUT} = \frac{I_o}{s} V_{IN}$$

Will consider first the Voltage Mode type of integrators

Voltage Mode Integrators

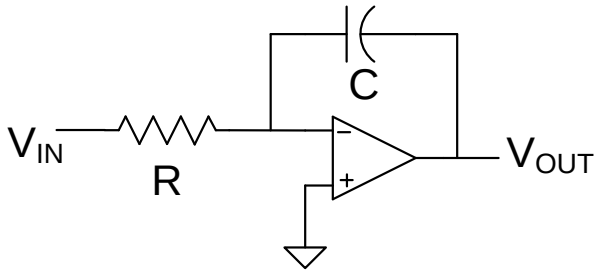
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed “current mode”

- Switched Capacitor
- Switched Resistor

Will discuss later

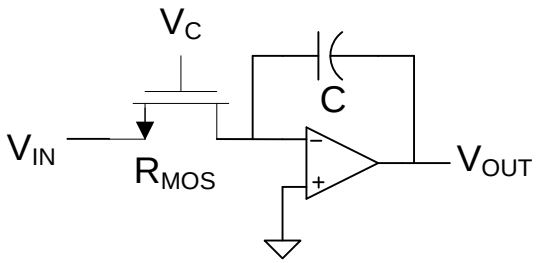
Active RC Voltage Mode Integrator



$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

- Limited to low frequencies because of Op Amp limitations
- No good resistors for monolithic implementations
  - Area for passive resistors is too large at low frequencies
    - Some recent work by Haibo Fei shows promise for some audio frequency applications
- Capacitor area too large at low frequencies for monolithic implementatins
- Active devices are highly temperature dependent, proc. dependent, and nonlinear
- No practical tuning or trimming scheme for integrated applications with passive resistors

MOSFET-C Voltage Mode Integrator

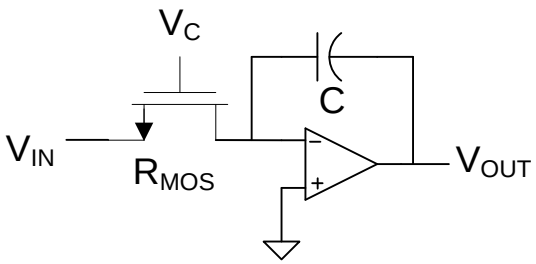


$$V_{OUT} = -\frac{1}{CR_{MOS}s} V_{IN}$$

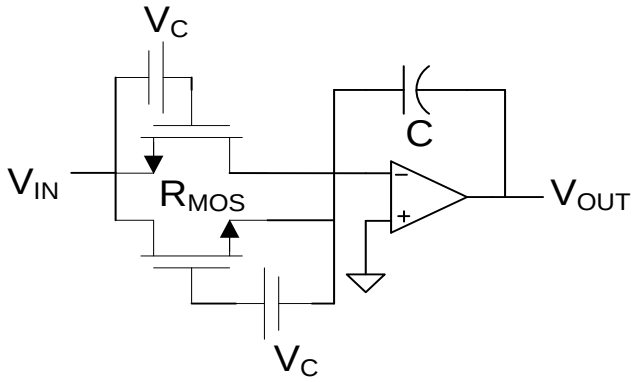
- Limited to low frequencies because of Op Amp limitations
- Area for R_{MOS} is manageable !
- Active devices are highly temperature dependent, process dependent
- Potential for tuning with V_C
- Highly Nonlinear (can be partially compensated with cross-coupled input

A Solution without a Problem

MOSFET-C Voltage Mode Integrator



$$V_{OUT} = -\frac{1}{C\,R_{MOS}s}V_{IN}$$

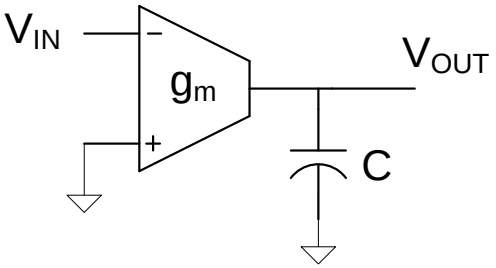


$$V_{OUT} = -\frac{1}{C\,R_{MOS}s}V_{IN}$$

- Improved Linearity
- Some challenges for implementing V_C

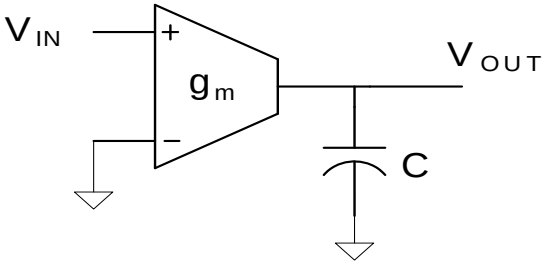
Still A Solution without a Problem

OTA-C Voltage Mode Integrator



$$V_{OUT} = -\frac{g_m}{sC} V_{IN}$$

Inverting



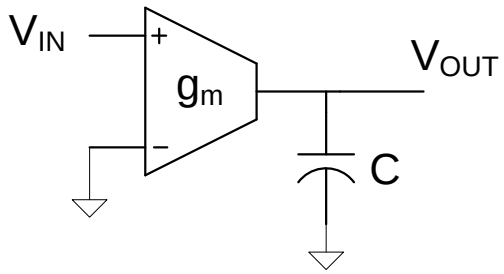
$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

Noninverting

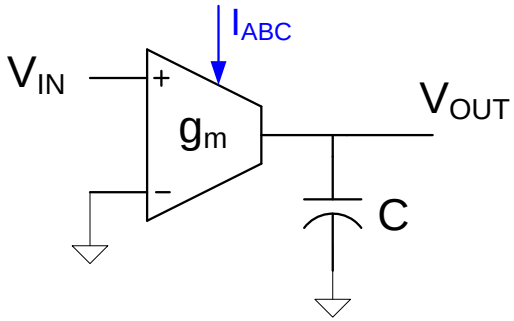
- Requires only two components
- Inverting and Noninverting structures of same complexity
- Good high-frequency performance
- Small area
- Linearity is limited (no feedback in integrator)
- Susceptible to process and temperature variations
- Tuning control can be readily added

Widely used in high frequency applications

OTA-C Voltage Mode Integrator



$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

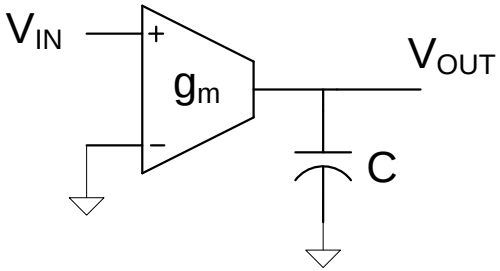


$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

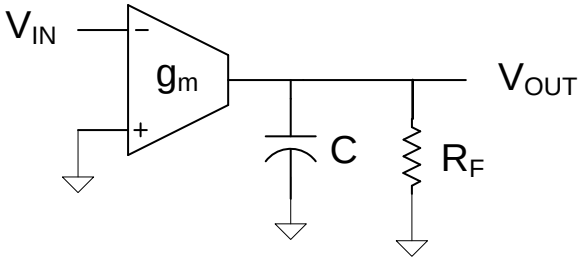
$$g_m = f(I_{ABC})$$

Programmable Integrator

OTA-C Voltage Mode Integrator



$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$



$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{g_m R_F}{1+s(R_F C)}$$

Lossy Integrator

But R_F is typically too large for integrated applications

End of Lecture 25