EE 508
Lecture 24

Integrator Design

TA-C Integrators
Other Integrator Structures

Review from last time

Summary of Sensitivity Observations

- Sensitivity varies substantially from one implementation to another

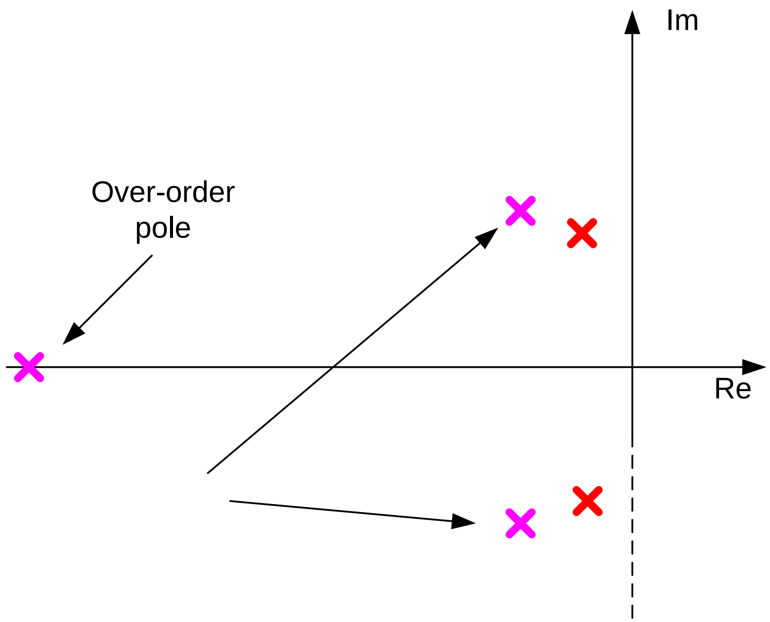
- Variability too high, even with low sensitivity, for more demanding applications

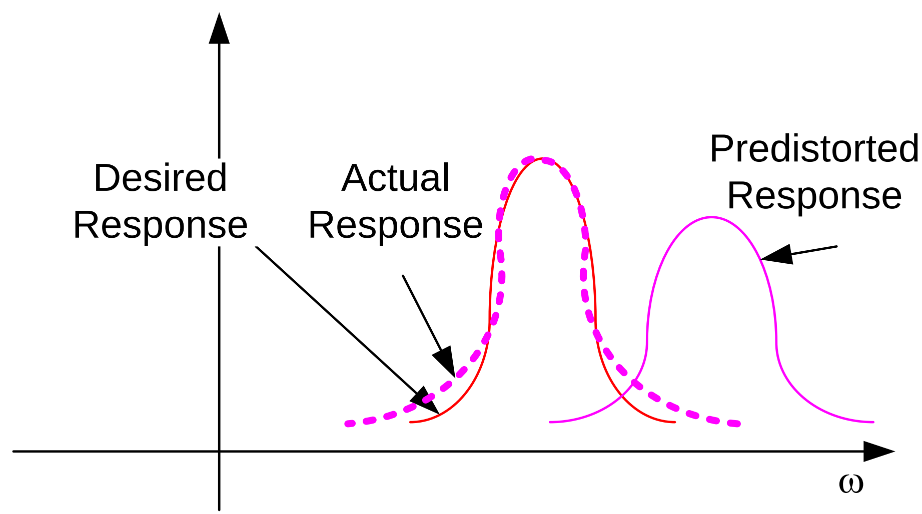
- Methods of managing high variability
  - Select good structures
  - Trimming
    - Functional
    - Deterministic
  - Predistortion
    - In particular, for active sensitivities
    - Useful but not a total solution
  - Frequency Referenced Techniques
    - Master-Slave Control
      - Depends upon matching
      - Can self-trim or self-compensate
    - Switched-Capacitor Filters
    - AD/digital filter/D/A
  - Alternate Design Approach
    - Other methods

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

Review from last time

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)

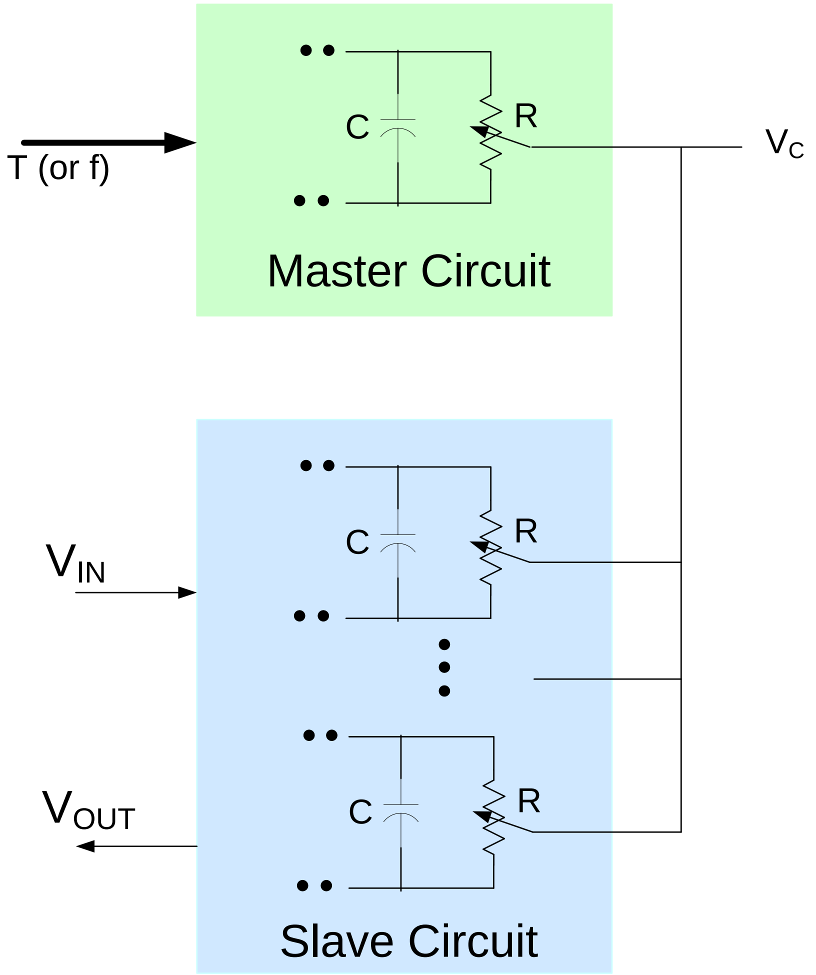
- Trim component values to their ideal value
  - Continuous-trims of resistors possible in some special processes
  - Continuous-trim of capacitors is more challenging
  - Link trimming of Rs or Cs is possible with either metal or switches
- If all components are ideal, the filter should also be ideal
  - 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

Review from last time

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

Filter Design Process

Establish Specifications

- possibly $T_D(s)$ or $H_D(z)$
- magnitude and phase characteristics or restrictions
- time domain requirements

↓

Approximation

- obtain acceptable transfer functions $T_A(s)$ or $H_A(z)$
- possibly acceptable realizable time-domain responses

↓

Where we are at →

Synthesis

- build circuit or implement algorithm that has response close to $T_A(s)$ or $H_A(z)$
- actually realize $T_R(s)$ or $H_R(z)$

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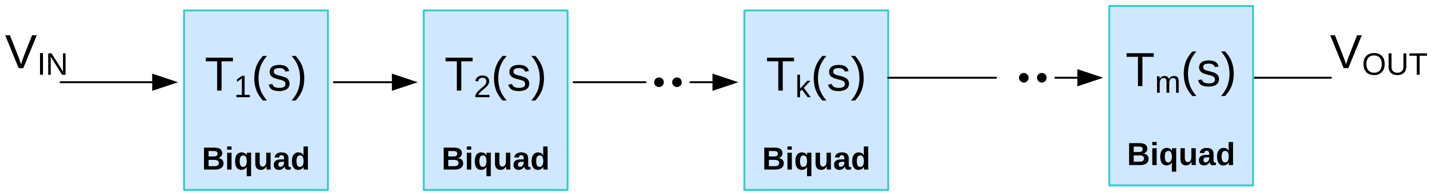
Filter

Filter Design/Synthesis Considerations

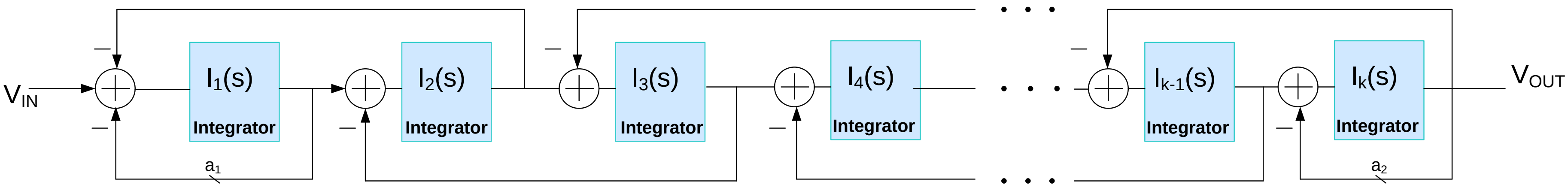
Most designs today use one of the following three basic architectures

Cascaded Biquads

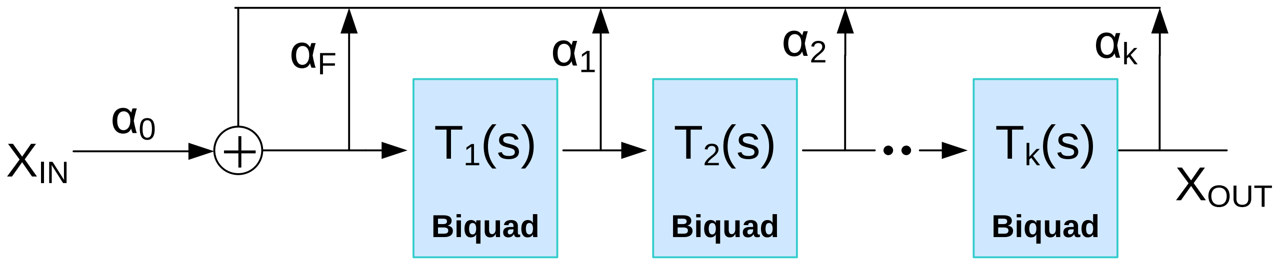


$$T(s) = T_1 T_2 \bullet\bullet T_m$$

Leapfrog

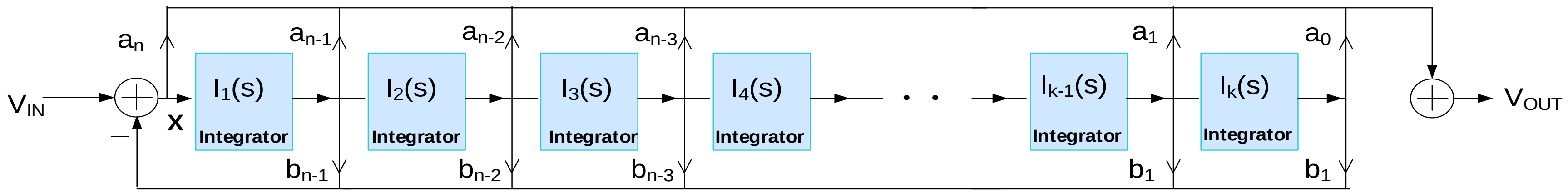


Multiple-loop Feedback – One type shown (less popular)



Filter Design/Synthesis Considerations

Multiple-loop Feedback – Another type



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

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

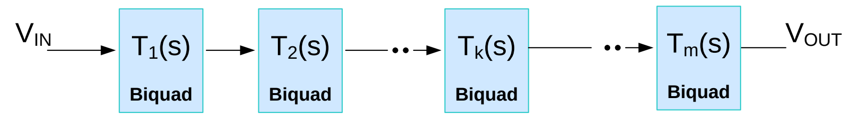
$$T(s) = \frac{\sum_{k=0}^{n} a_{n-k} \left(\frac{I_0}{s} \right)^k}{1 + \sum_{k=1}^{n} b_{n-k} \left(\frac{I_0}{s} \right)^k}$$

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

- 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



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

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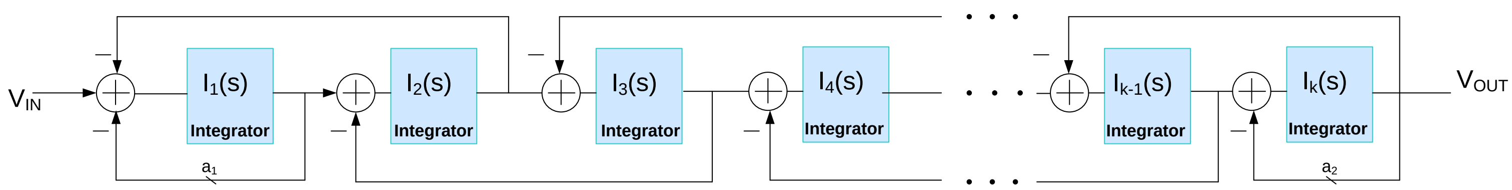
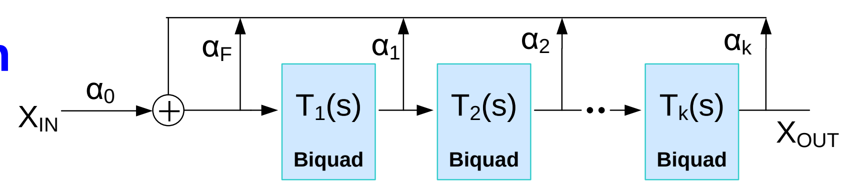


Multiple-loop Feedback – One type shown



Will study details of all three types of architectures later

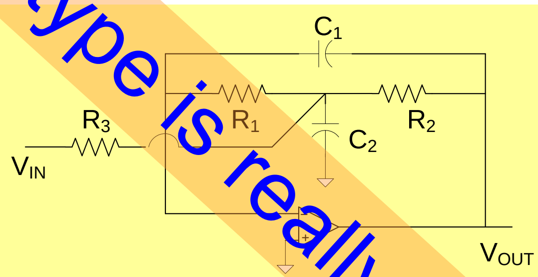
Observation: All filters are comprised of summers, biquads and integrators

Consider now the biquads

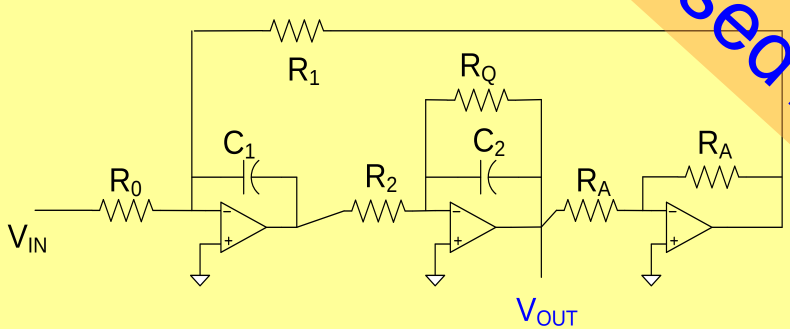
Biquad Filters Design Considerations

Several different Biquads were considered and other implementations exist

Sallen-Key Type (Dependent Sources)



Infinite Gain Amplifiers

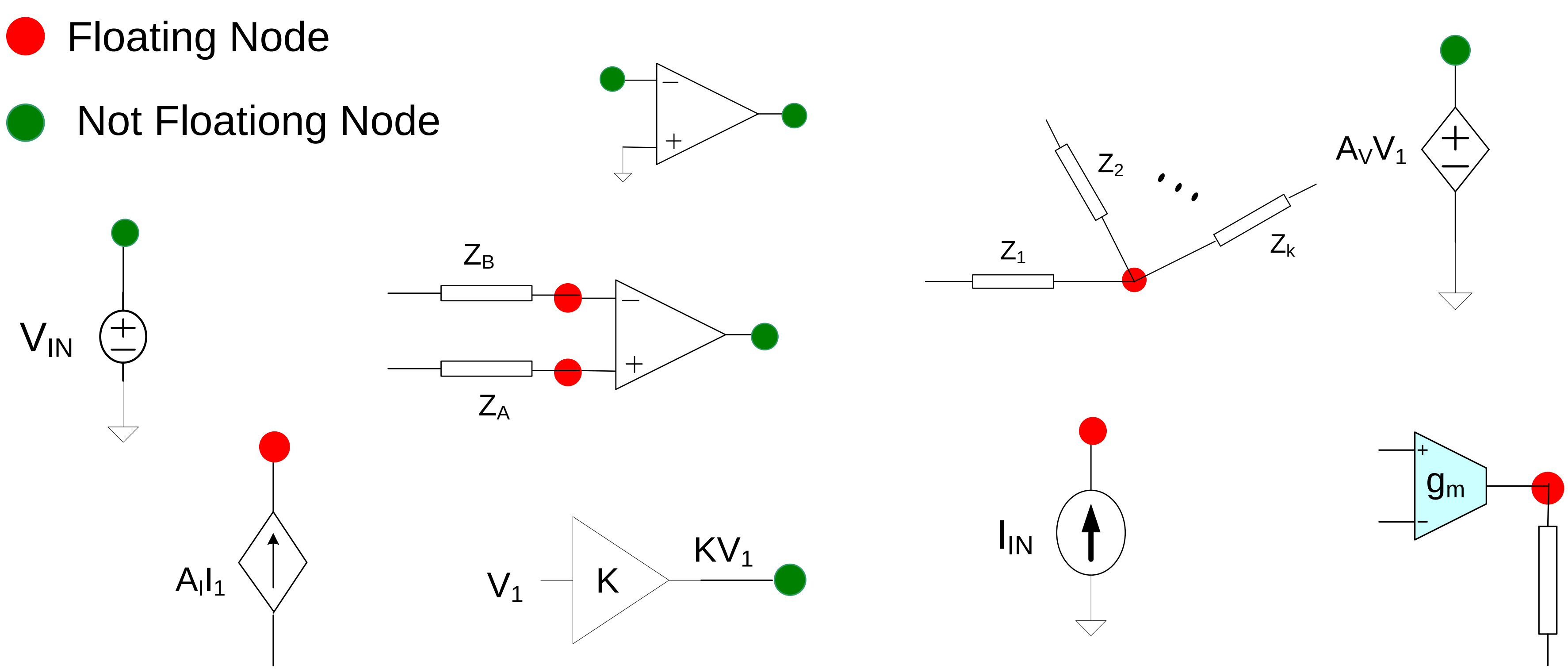


Integrator Based Structures

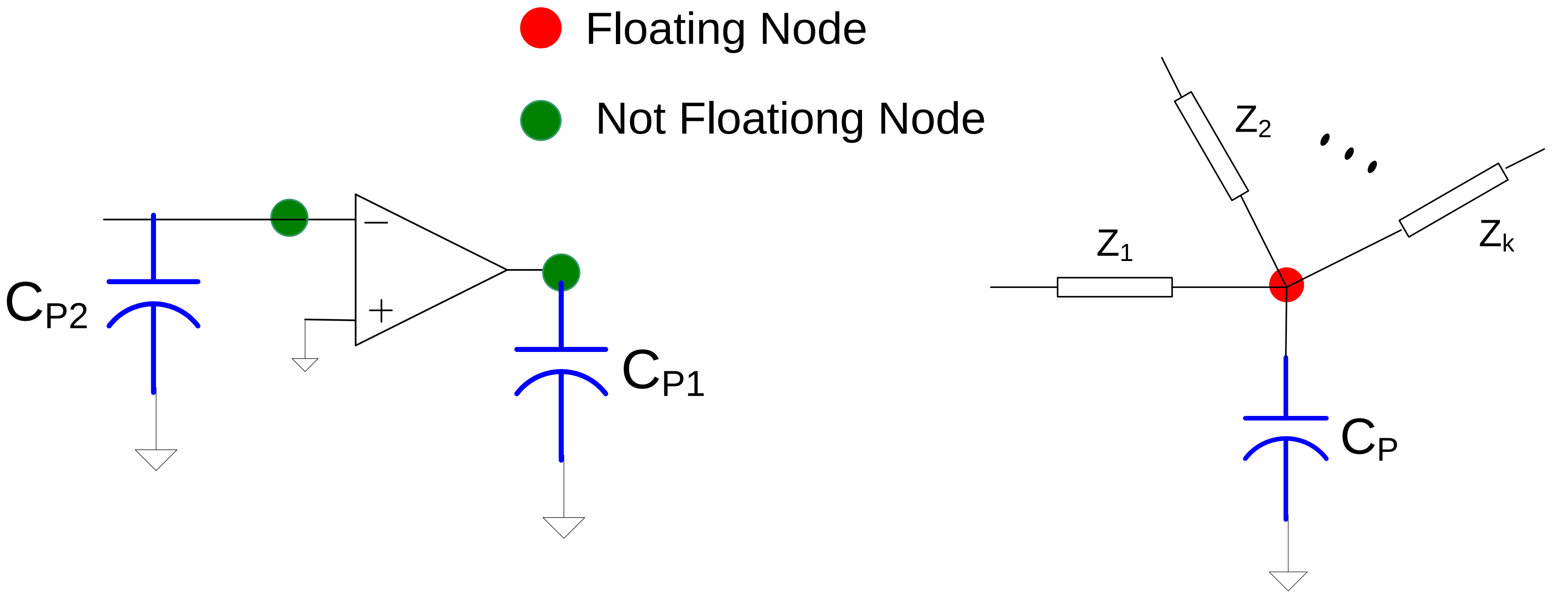
Which type is really used?

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

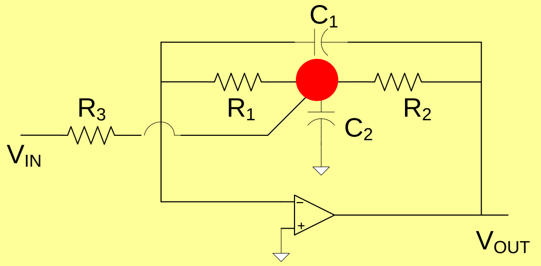
Parasitic capacitances are invariably large, nonlinear, and highly process dependent in integrated filters. Thus, it is difficult to build accurate integrated filters if floating nodes are present

Generally avoid floating nodes, if possible, in integrated filters

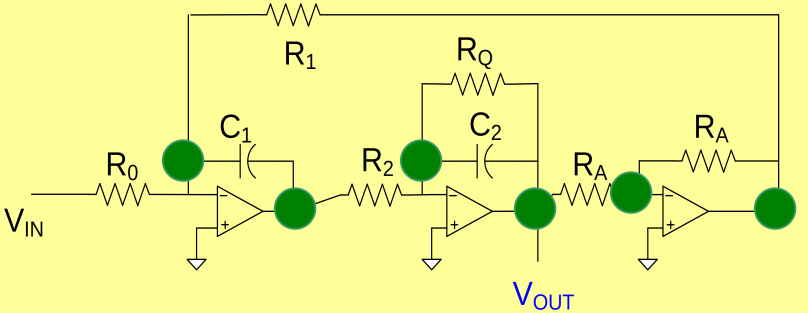
Which type of Biquad is really used?

Not Floationg Node   Floating Node

Sallen-Key Type (Dependent Sources)



Infinite Gain Amplifiers

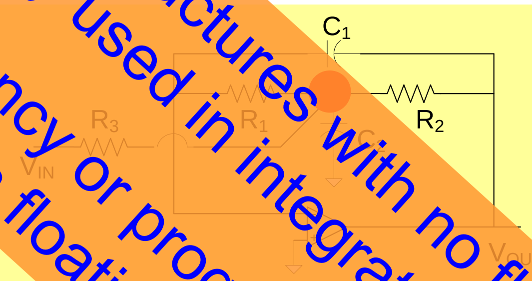


Integrator Based Structures

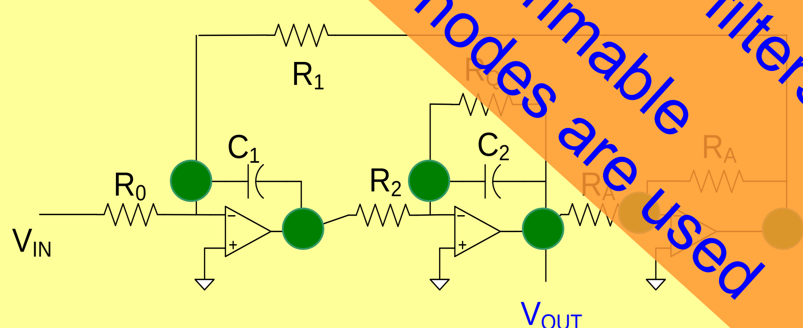
Which type of Biquad is really used?

Not Floatong Node   Floating Node

Sallen-Key type (Dependent Sources)



Infinite Gain Amplifiers

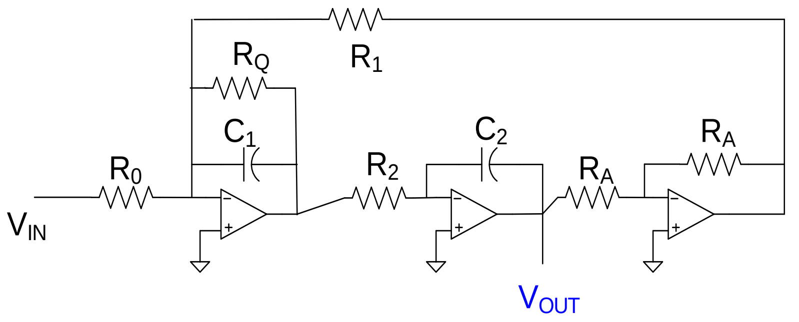


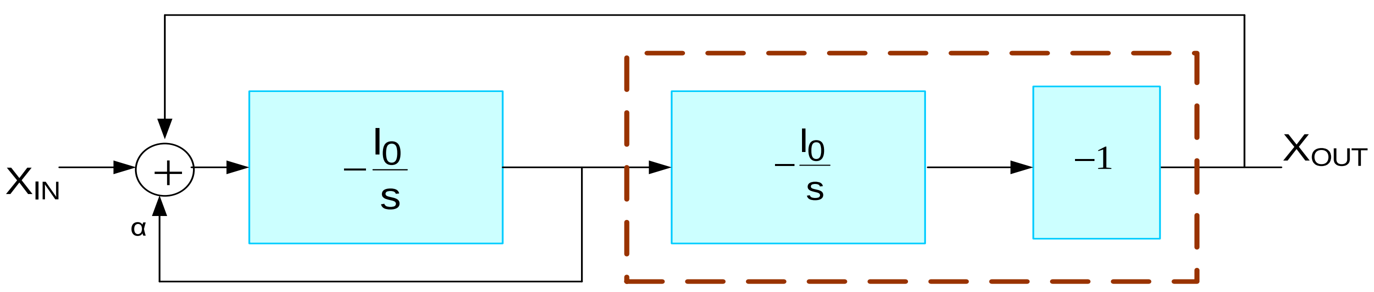
Integrator Based Structures

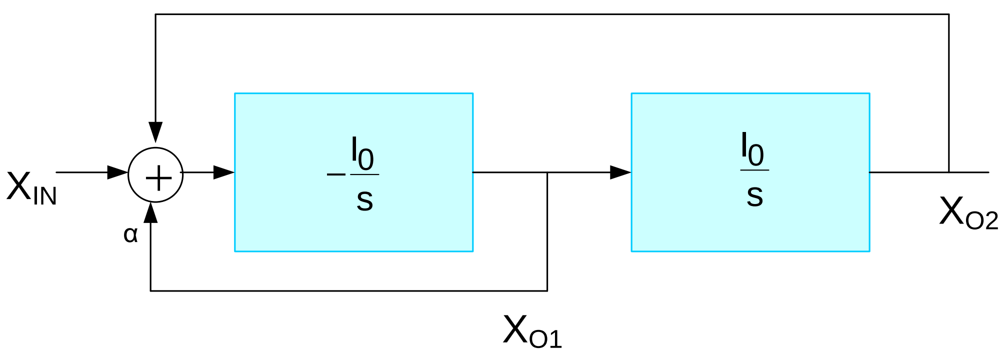
Integrator-based structures with no floating nodes dominantly used in integrated filters

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

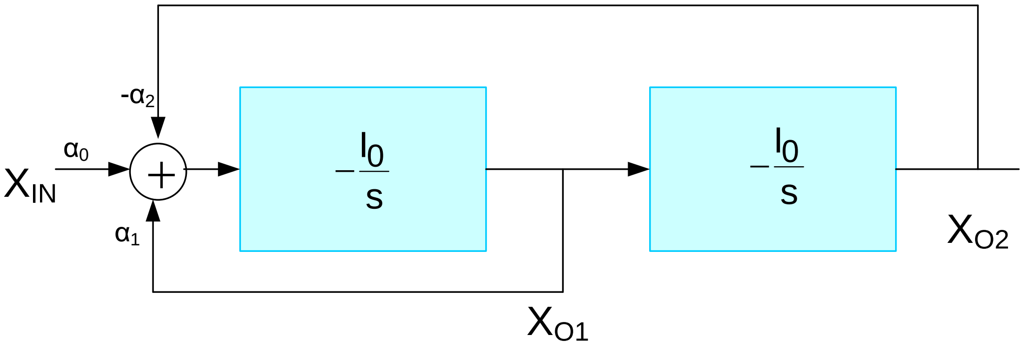
Integrator-based Biquads



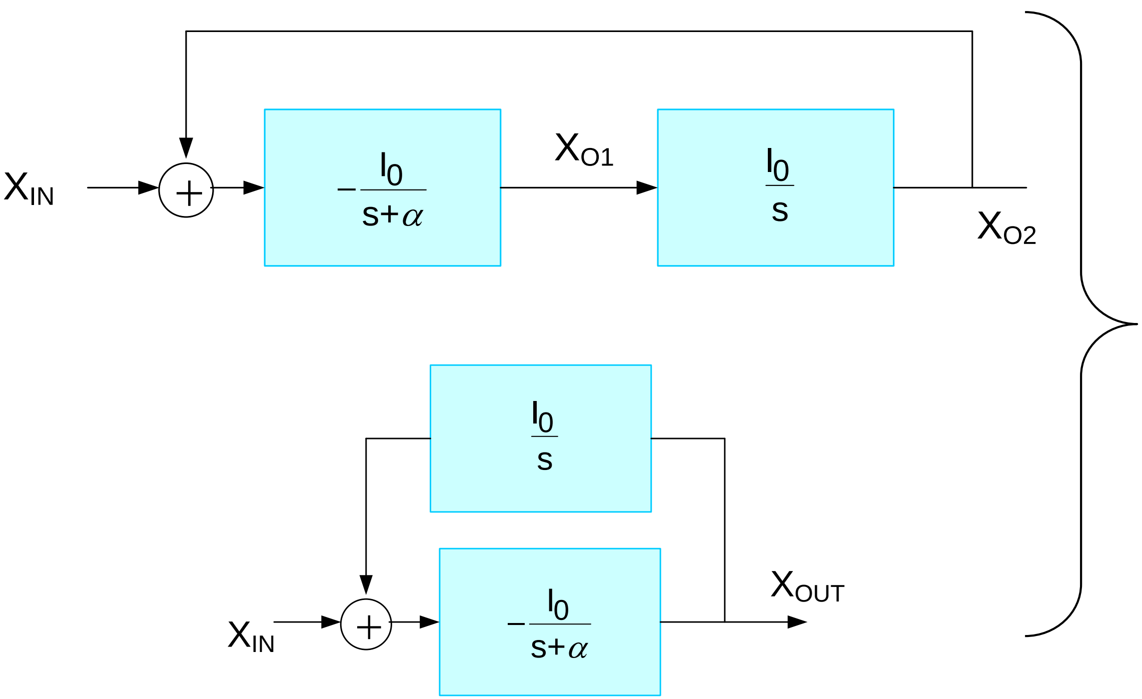




Integrator-based Biquads

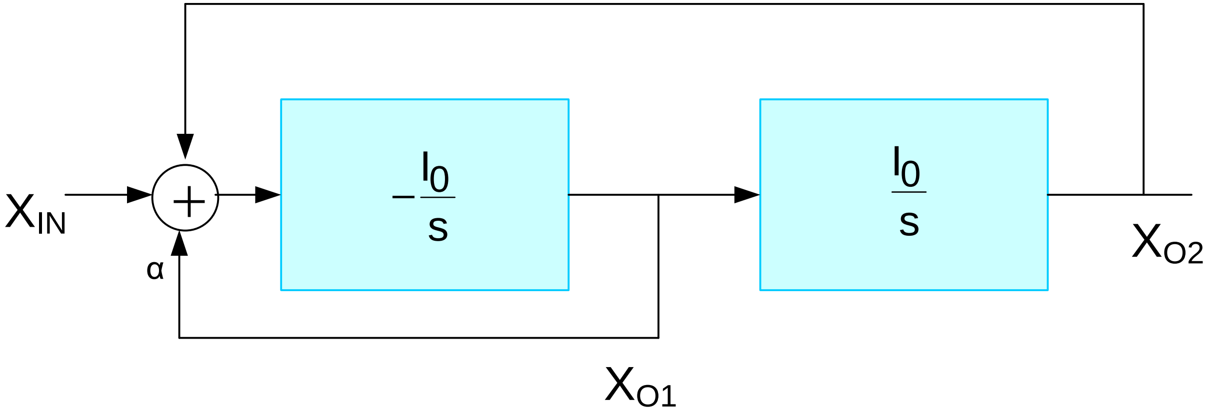


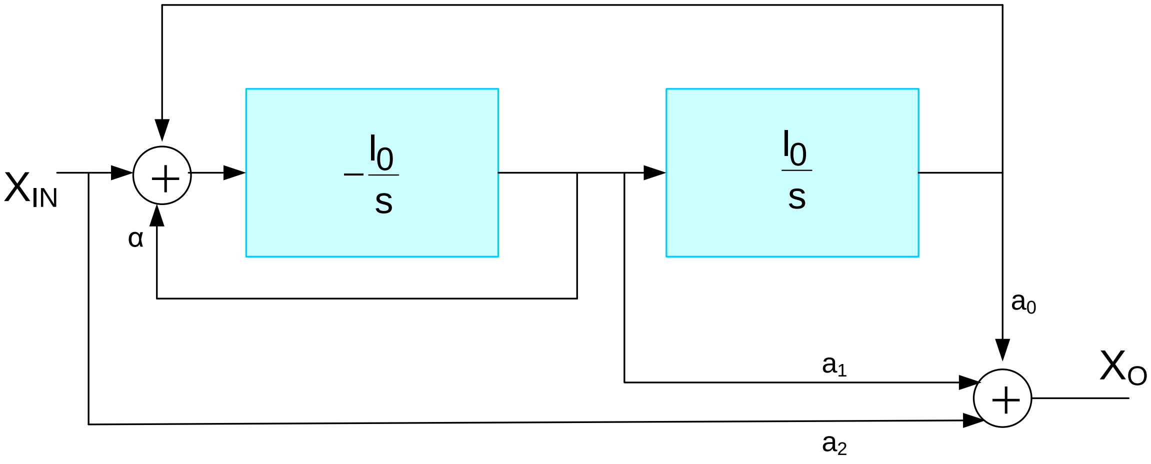
State Variable Biquad
(Alt KHN Biquad)



Integrator and lossy
integrator in a loop

Integrator-based Biquads

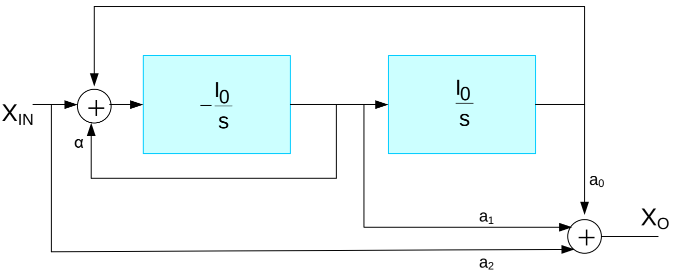


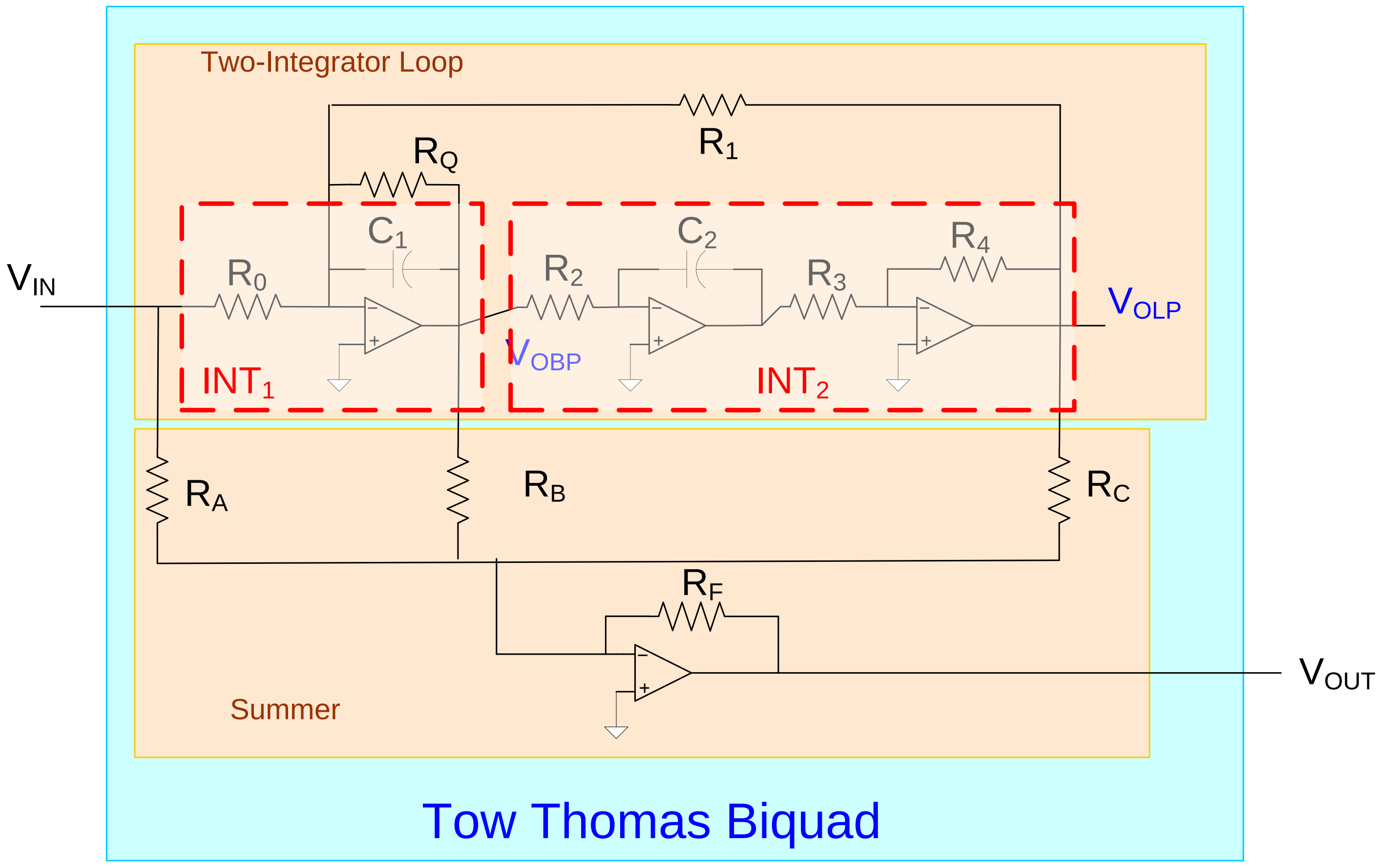


With arbitrary zero locations

Tow-Thomas Biquad

Integrator-based Biquads



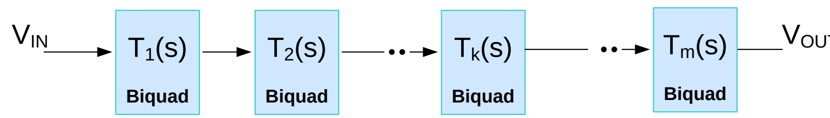


Integrator-based Biquads

- 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

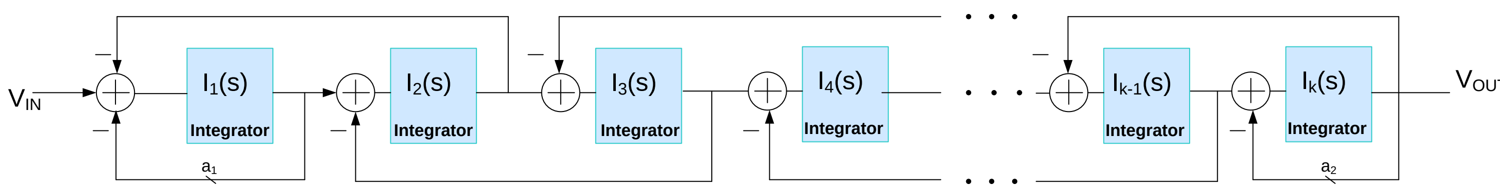
Filter Design/Synthesis Considerations

Cascaded Biquads

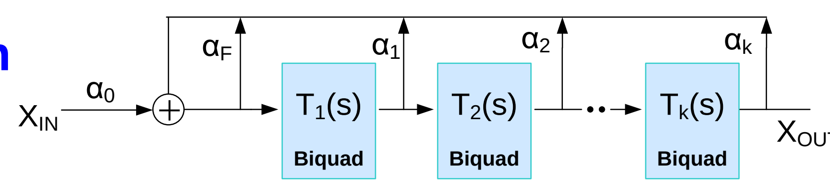


$$T(s) = T_1 T_2 \bullet\bullet T_m$$

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)

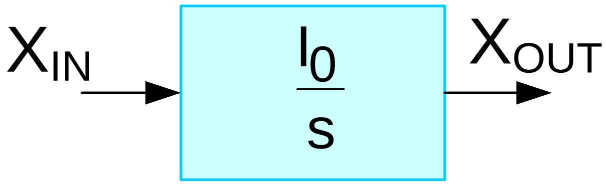
Will now focus on the design of integrators, summers, and op amps

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:

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

Gain decreases with 1/ω

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

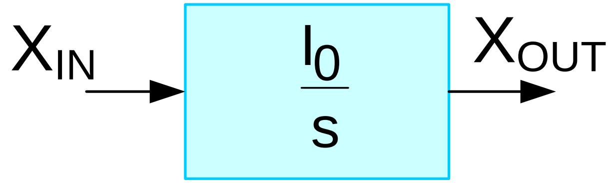
Phase is a constant -90^o

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

Unity Gain Frequency = I_0

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

Integrator Characteristics of Interest

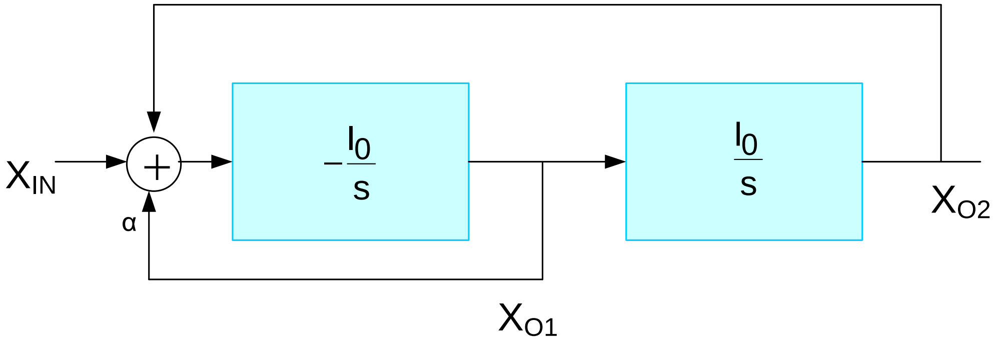


$$I(s) = \frac{I_0}{s}$$

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

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

Consider a filter example:



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

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

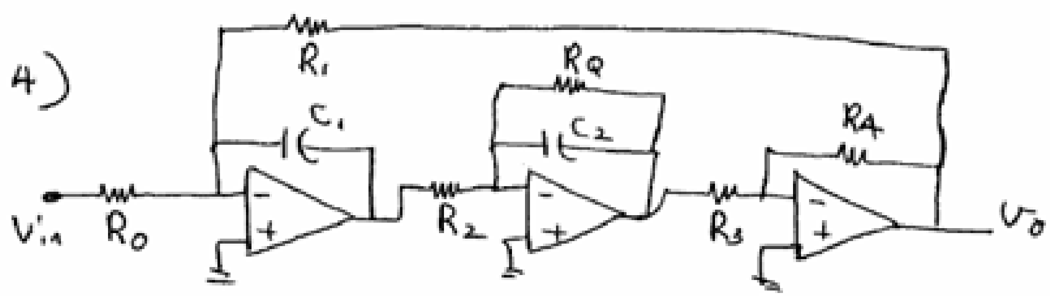
Band edges proportional to I_0

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)



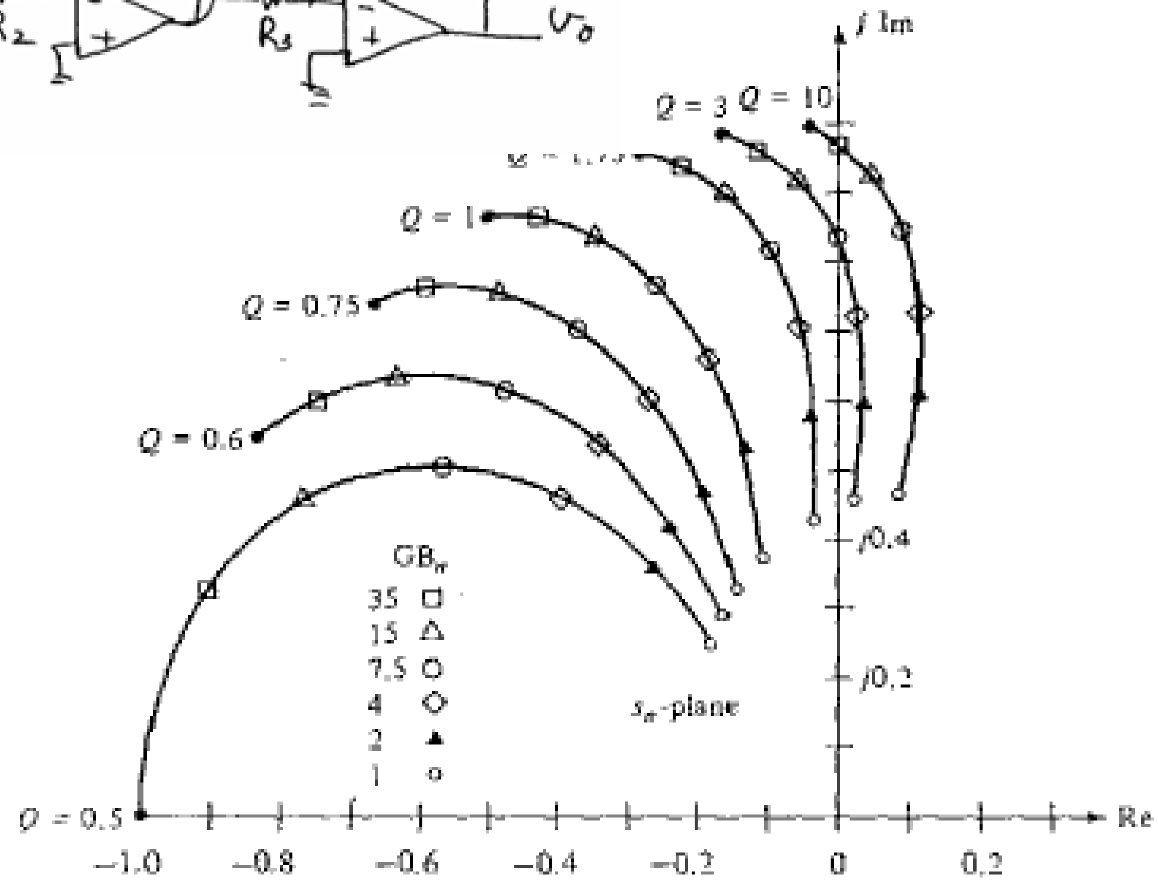
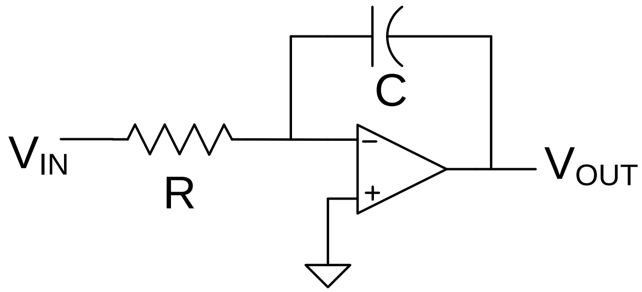


Fig. 10-17 Plot of upper half-plane root of

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

Some integrator structures

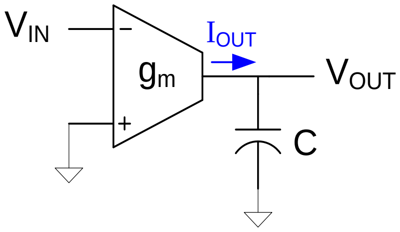


$$I(s) = -\frac{1}{RCs}$$

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

Inverting Active RC Integrator

Are there other integrator structures?

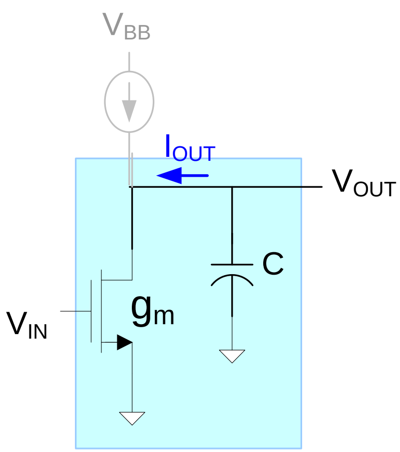


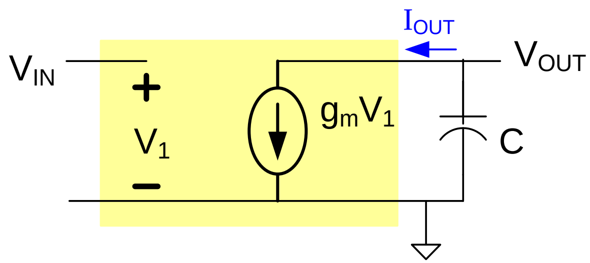
$$\left.\begin{aligned} I_{OUT} &= -g_m V_{IN} \\ V_{OUT} &= I_{OUT}\frac{1}{sC} \end{aligned}\right\} \quad I(s) = -\frac{g_m}{sC} \qquad I_0 = \frac{g_m}{C}$$

Termed an OTA-C or a gm-C integrator

Some integrator structures

Are there other integrator structures?





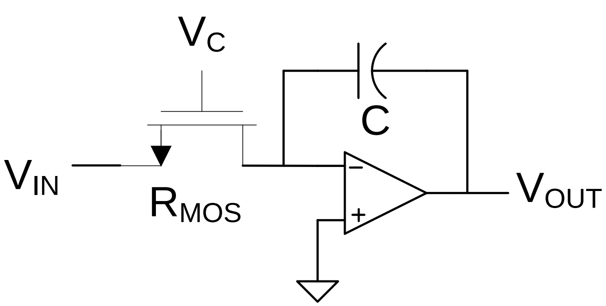
$$I_{OUT} = g_m V_{IN}$$

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

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

Termed a TA-C integrator

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



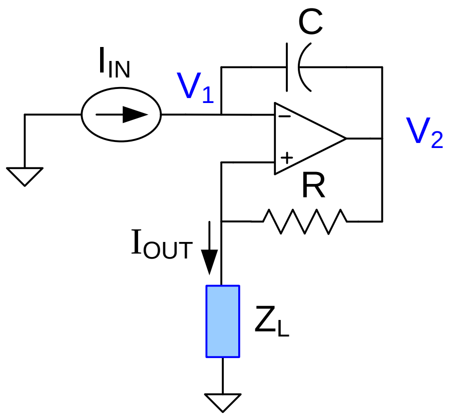
$$I(s) = -\frac{1}{sCR_{MOS}}$$

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

Termed MOSFET-C integrator

Some integrator structures

Are there other integrator structures?



$$\left.\begin{aligned} V_2 &= V_1 - I_{IN}\frac{1}{sC} \\ I_{OUT} &= \frac{V_2 - V_1}{R} \end{aligned}\right\}$$

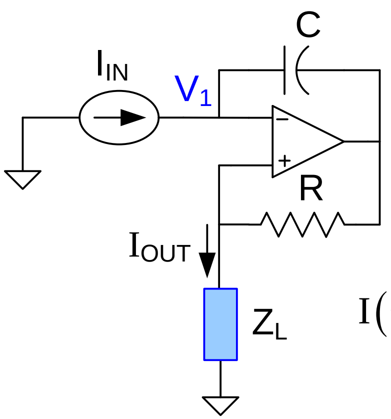
$$I(s) = \frac{I_{OUT}}{I_{IN}} = -\frac{1}{sRC}$$

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

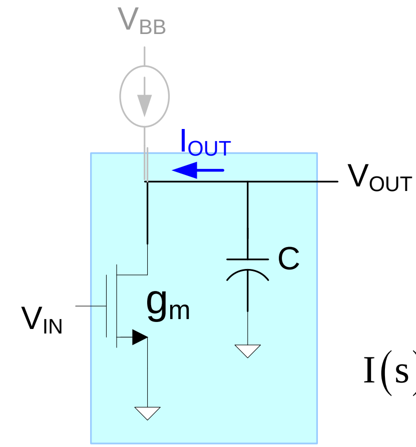
- Output current is independent of Z_L
- Thus output impedance is ∞ so provides current output

Termed active RC current-mode integrator

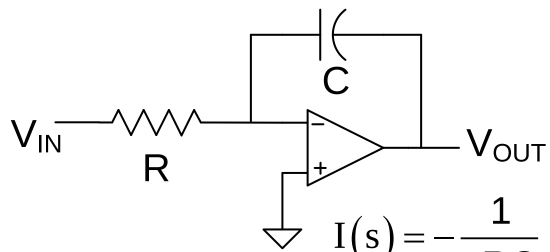
Some integrator structures



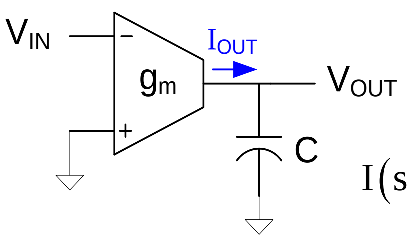
$$I(s) = -\frac{1}{sRC}$$



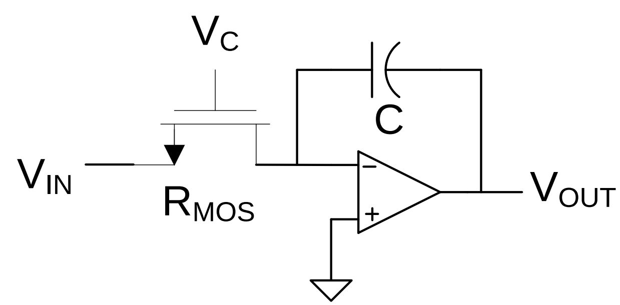
$$I(s) = -\frac{g_m}{sC}$$



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



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

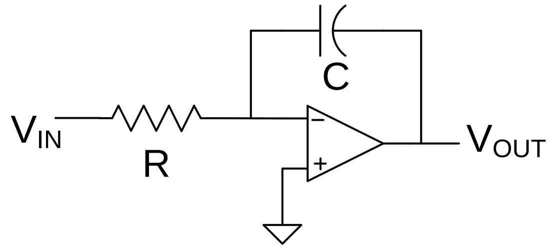


$$I(s) = -\frac{1}{sR_{MOS}C}$$

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

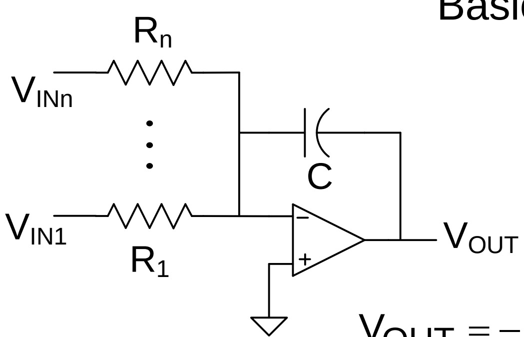
There are many different ways to build an inverting integrator

Integrator Functionality



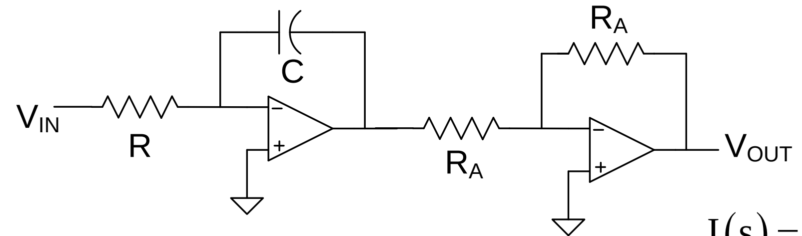
$$I(s) = -\frac{1}{sRC}$$

Basic Active RC Inverting Integrator



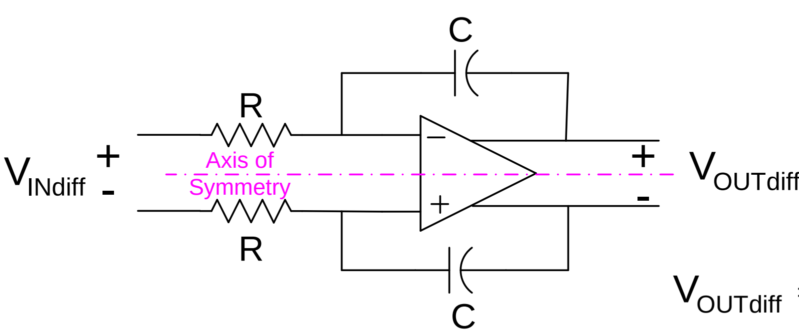
$$V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_k s} V_{INk}$$

Summing Integrator



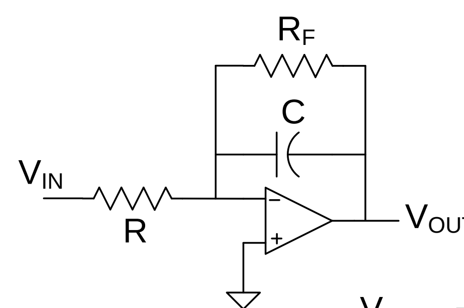
$$I(s) = \frac{1}{sRC}$$

Noninverting Integrator



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

Fully Differential Integrator



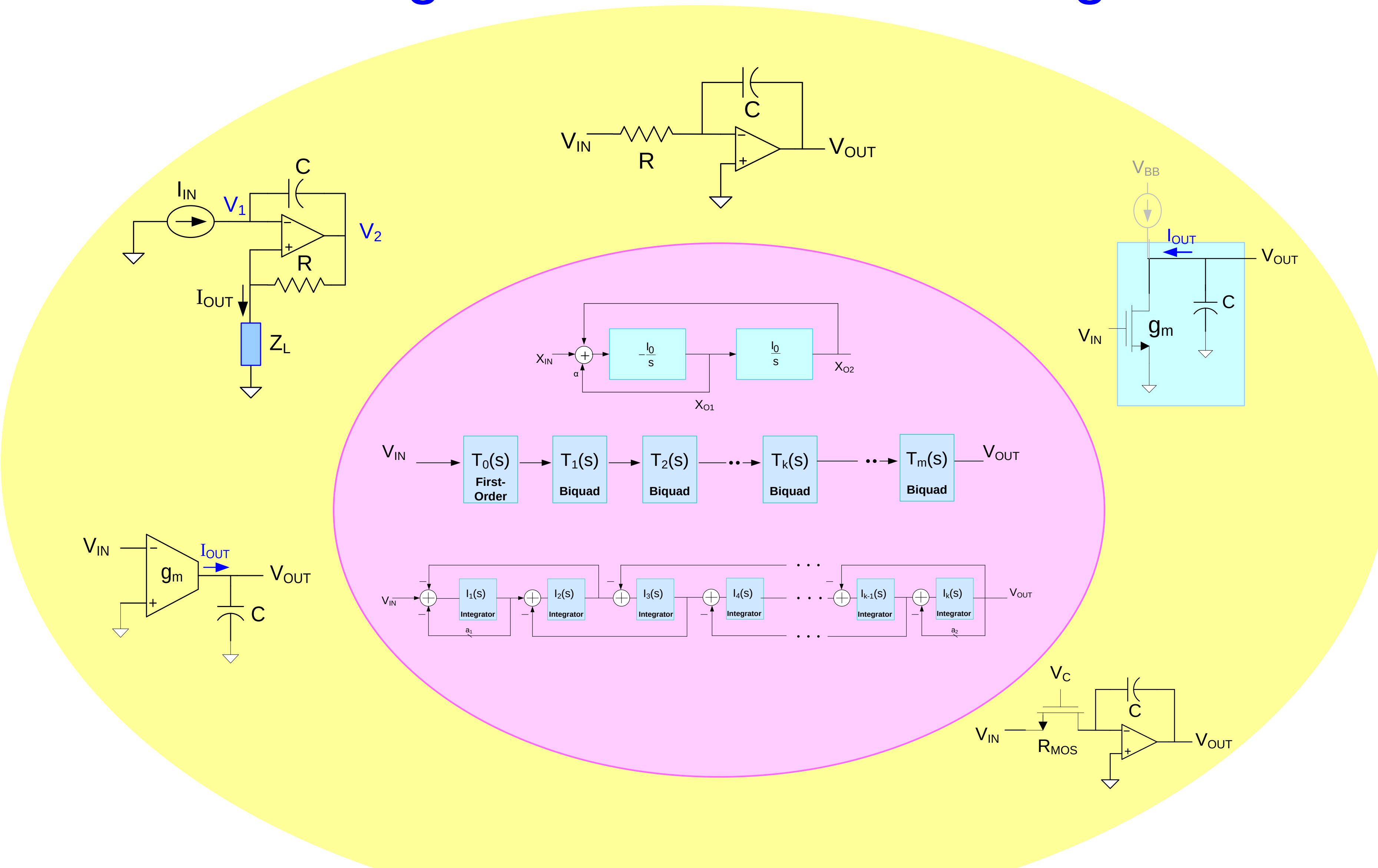
$$V_{OUT} = -\frac{R_F / R}{1 + CR_F s} V_{IN}$$

Lossy Integrator

Many different types of functionality from basic inverting integrator

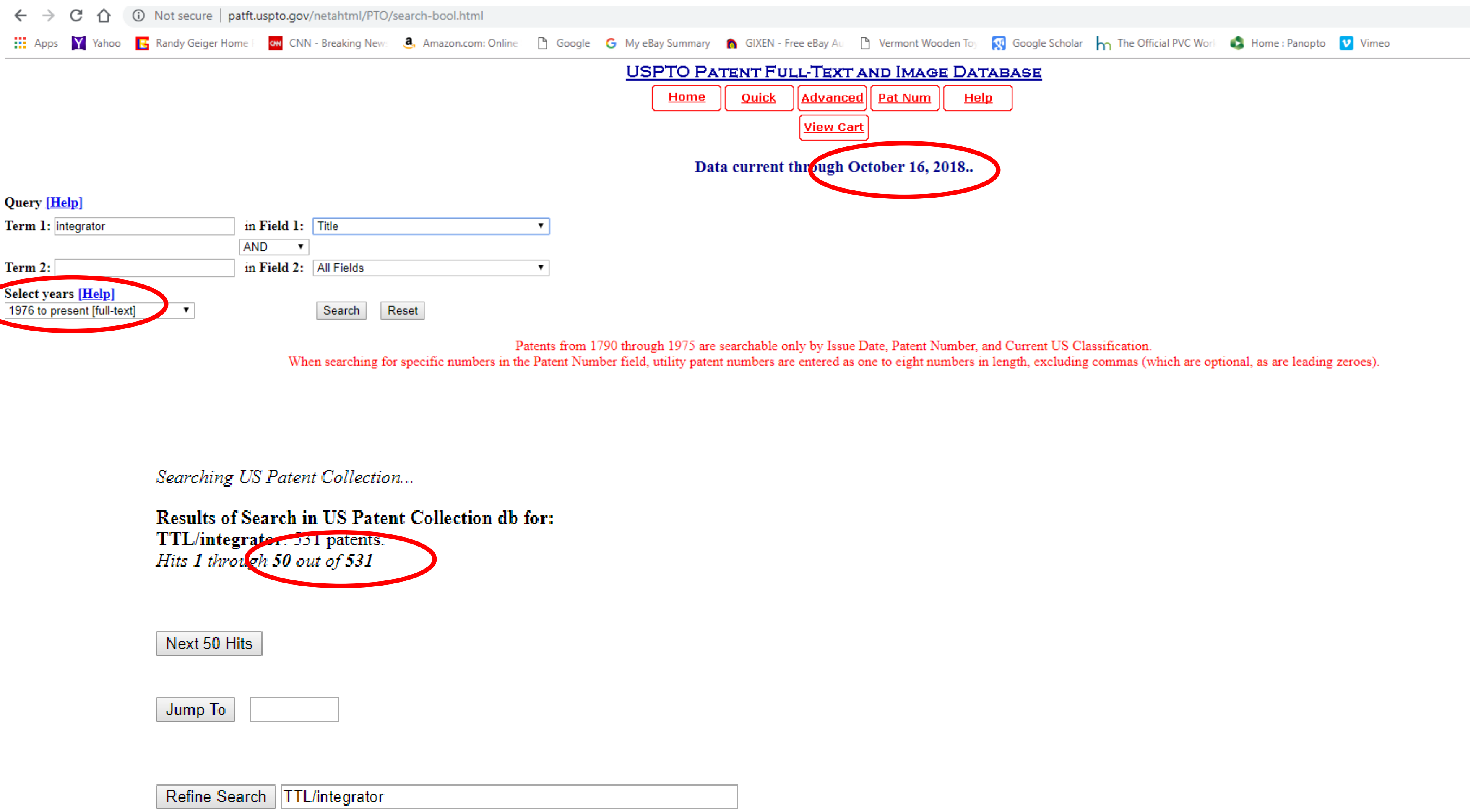
Same modifications exist for other integrator architectures

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	T	Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit
	2	10,074,004	T	Capacitive fingerprint sensor with integrator
	3	10,070,089	T	Inverting amplifier, integrator, sample hold circuit, ad converter, image sensor, and imaging apparatus
	4	9,985,594	T	Gated CDS integrator
	5	9,972,003	T	Pregame electronic commerce integrator
	6	9,954,514	T	Output range for interpolation architectures employing a cascaded integrator-comb (CIC) filter with a multiplier
	7	9,885,959	T	Illumination optical apparatus having deflecting member, lens, polarization member to set polarization in circumference direction, and optical integrator
	8	9,885,872	T	Illumination optical apparatus, exposure apparatus, and exposure method with optical integrator and polarization member that changes polarization state of light
	9	9,866,237	T	Low power switched capacitor integrator, analog-to-digital converter and switched capacitor amplifier
	10	9,852,283	T	Confirming the identity of integrator applications
Nov 2017	11	9,825,646	T	Integrator and A/D converter using the same
	12	9,817,917	T	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	T	Analog/digital converter with charge rebalanced integrator
	14	9,800,256	T	Semiconductor device including integrator and successive approximation register analog-to-digital converter and driving method of the same
	15	9,753,559	T	Feedback integrator current source, transistor, and resistor coupled to input
	16	9,726,521	T	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	T	Shell integrator
	18	9,703,178	T	Projector having a rod integrator with an entrance plane smaller than an area light source
	19	9,680,496	T	Apparatus for overload recovery of an integrator in a sigma-delta modulator
	20	9,671,916	T	Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit
	21	9,647,677	T	Integrator, AD converter, and radiation detection device
	22	9,634,688	T	Integrator, delta-sigma modulator, and communications device
	23	9,628,103	T	Multi-mode discrete-time delta-sigma modulator power optimization using split-integrator scheme
	24	9,608,598	T	Cascaded integrator-comb filter as a non-integer sample rate converter
	25	9,588,147	T	Electronic integrator for Rogowski coil sensors
	26	9,574,735	T	Shell integrator
	27	9,558,845	T	Sampling network and clocking scheme for a switched-capacitor integrator
	28	9,531,718	T	Confirming the identity of integrator applications
	29	9,524,054	T	Integrator and touch sensing system using the same
	30	9,519,462	T	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	T	Double integrator pulse wave shaper apparatus, system and method
Nov 2016	32	9,495,563	T	Analog integrator system and method
	33	9,473,075	T	Dynamic current source for amplifier integrator stages
	34	9,467,153	T	Low power and compact area digital integrator for a digital phase detector
	35	9,461,595	T	Integrator for class D audio amplifier
	36	9,454,069	T	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	T	Apparatuses, methods and systems for a universal payment integrator
	38	9,389,625	T	DC-DC converter controller apparatus with dual-counter digital integrator
	39	9,383,395	T	Charge balancing converter using a passive integrator circuit
	40	9,379,732	T	Delta-sigma modulator with reduced integrator requirements
	41	9,362,890	T	Compensation filter for cascaded-integrator-comb decimator
	42	9,354,953	T	System integrator and system integration method with reliability optimized integrated circuit chip selection
	43	9,314,389	T	Therapeutic integrator apparatus
	44	9,310,924	T	Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit
	45	9,268,441	T	Active integrator for a capacitive sense array
	46	9,225,351	T	Current amplifier circuit, integrator, and ad converter
	47	9,218,514	T	Apparatuses and method of switched-capacitor integrator
	48	9,171,189	T	Systems and methods for preventing saturation of analog integrator output
	49	9,152,387	T	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	T	One-sided detection and disabling of integrator wind up for speed control in a vehicle

51 9,063,789 T Hybrid cloud integrator plug-in components
52 9,061,592 T System and method for detecting power integrator malfunction
53 9,054,731 T Integrator output swing reduction
54 9,039,190 T Projector having integrator with greater illuminance in offset direction of projection lens and modulator
55 9,037,469 T Automated communication integrator
56 9,014,322 T Low power and compact area digital integrator for a digital phase detector
57 9,009,697 T Hybrid cloud integrator
58 8,995,061 T Speckle reduction using lenslet integrator
59 8,988,904 T Power supply with integrator for controlling current
60 8,957,363 T Differential photodiode integrator circuit for absorbance measurements
61 8,952,749 T Filter with combined resonator and integrator
62 8,941,526 T Time integrator and .DELTA..SIGMA. time-to-digital converter
63 8,937,567 T Delta-sigma modulator, integrator, and wireless communication device
64 8,922,290 T Pulse width modulator with two-way integrator
65 8,866,532 T Passive integrator and method
66 8,866,531 T Broadband analog radio-frequency integrator
67 8,860,491 T Integrator output swing reduction technique for sigma-delta analog-to-digital converters
68 8,854,107 T Integrator circuit with inverting integrator and non-inverting integrator
69 8,851,684 T Optical unit including an integrator optical system, and projection display device including the optical unit
70 8,835,827 T Current integrator with wide dynamic range
71 8,824,626 T Reduced-noise integrator, detector and CT circuits
72 8,816,763 T Integrator input error correction circuit and circuit method
July 2014
73 8,779,831 T Integrator
74 8,775,003 T Methods and systems for controlling a proportional integrator
75 8,767,343 T Disk drive increasing integrator output range to complete seek operation
76 8,724,080 T Optical raster element, optical integrator and illumination system of a microlithographic projection exposure apparatus
77 8,704,580 T Circuit sharing time delay integrator
78 8,674,864 T Integrator and oversampling A/D converter having the same
79 8,665,129 T Complex second-order integrator and oversampling A/D converter having the same
80 8,659,343 T Calibration for mixed-signal integrator architecture
81 8,653,867 T Pulse modulated neural integrator circuit and associated phase locked loop
82 8,639,513 T Automated communication integrator
83 8,638,420 T Optical integrator, illuminating optical device, exposure apparatus and device manufacturing method
84 8,614,639 T Integrator ramp generator with DAC and switched capacitors
85 8,611,013 T Optical integrator, illumination optical device, aligner, and method for fabricating device
86 8,587,764 T Optical integrator system, illumination optical apparatus, exposure apparatus, and device manufacturing method
87 8,575,988 T Mixed-signal integrator architecture
88 8,573,779 T Lighting device with plural light sources illuminating distinct regions of integrator
89 8,566,277 T 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 T Integrator circuit with multiple time window functions
91 8,558,610 T Integrator input error correction circuit and circuit method
92 8,536,923 T Integrator distortion correction circuit
93 8,526,487 T Differential energy difference integrator
94 8,520,307 T Optical integrator for an illumination system of a microlithographic projection exposure apparatus
95 8,504,503 T Pulse modulated neural integrator circuit
96 8,497,977 T Optical integrator, illumination optical system, exposure apparatus, and device manufacturing method
97 8,438,201 T Digital fractional integrator
98 8,432,150 T Methods for operating an array column integrator
99 8,432,149 T Array column integrator
100 8,422,018 T 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

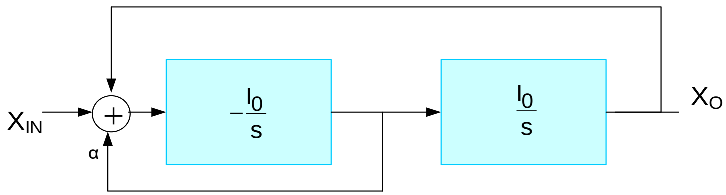
	PAT. NO.		Title
51	7,605,645	T	Transconductor, integrator, and filter circuit
52	7,599,631	T	Burst optical receiver with AC coupling and integrator feedback network
53	7,575,159	T	Point of sale integrator
54	7,570,032	T	Regulator with integrator in feedback signal
55	7,565,326	T	Dialect independent multi-dimensional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

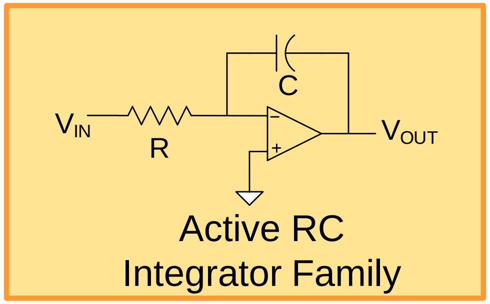
76 7,324,654 T Arbitrary coverage angle sound integrator
77 7,324,025 T Non-integer interpolation using cascaded integrator-comb filter
78 7,315,268 T Integrator current matching
79 7,304,592 T Method of adding a dither signal in output to the last integrator of a sigma-delta converter and relative sigma-delta 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

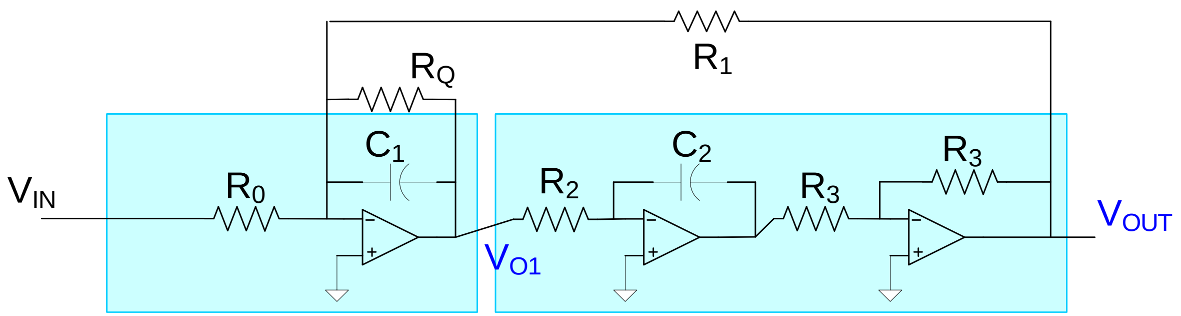
Aug 8 2006

	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

Example – Active RC Feedback Tow Thomas Biquad







$$\left.\begin{array}{l} V_{OUT}=\dfrac{1}{sR_2C_2}V_{O1} \\ V_{IN}G_0+V_{O1}\left(sC_1+G_Q\right)+G_1V_{OUT}=0 \end{array}\right\}$$

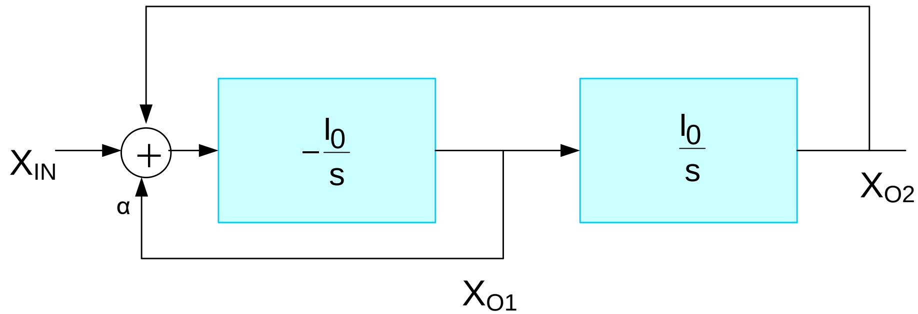
$$\frac{V_{OUT}}{V_{IN}}=-\frac{\dfrac{1}{C_1R_0R_2C_2}}{s^2+s\dfrac{1}{R_QC_1}+\dfrac{1}{C_1R_1R_2C_2}}$$

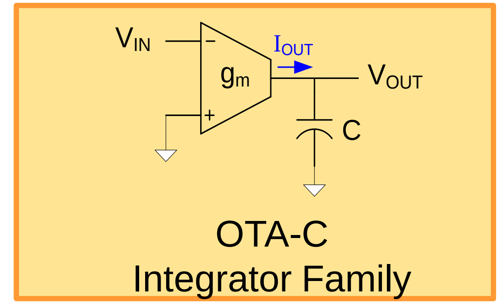
If $R_1=R_2=R$ and $C_1=C_2=C$

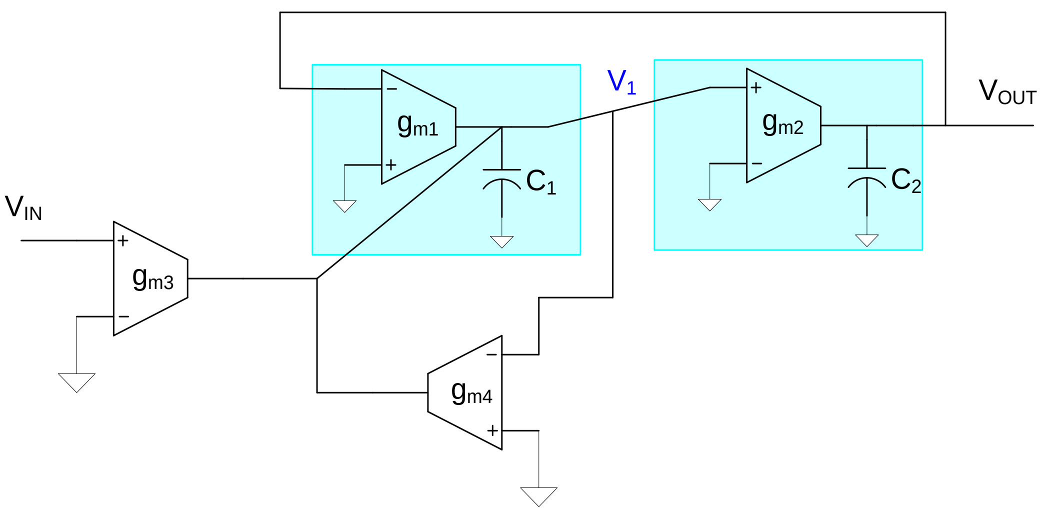
$$\omega_0=\frac{1}{RC}$$

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

Example – OTA-C Tow Thomas Biquad







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

$$V_1 sC_1 = -g_{m1} V_{OUT} + g_{m3} V_{IN} - g_{m4} V_1$$

$$\frac{V_{OUT}}{V_{IN}} = \frac{g_{m3} g_{m2}}{\left(s^2 C_1 C_2 + s g_{m4} C_2 + g_{m1} g_{m2}\right)}$$

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

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

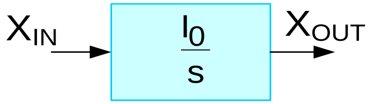
express as

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

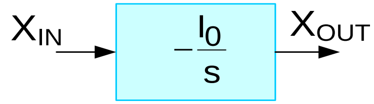
where

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

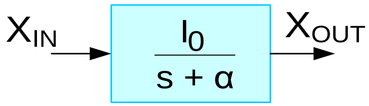
Basic Integrator Functionality (for all families)



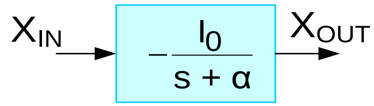
Noninverting



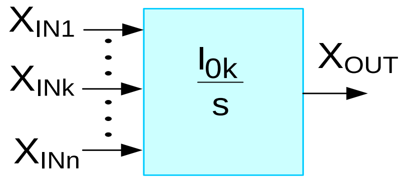
Inverting



Lossy Noninverting

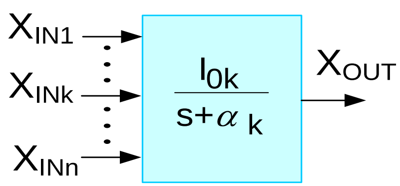


Lossy Inverting



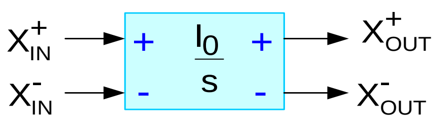
$$X_{OUT} = \sum_{k=1}^{n} \frac{\pm I_{0k}}{s}$$

Summing (Multiple-Input) Inverting/Noninverting



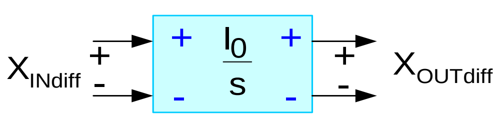
$$X_{OUT} = \sum_{k=1}^{n} \frac{\pm I_{0k}}{s+\alpha_k}$$

Summing (Multiple-Input) Lossy Inverting/Noninverting



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

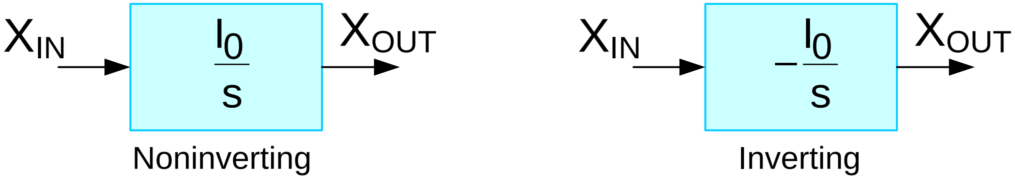
Balanced Differential



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

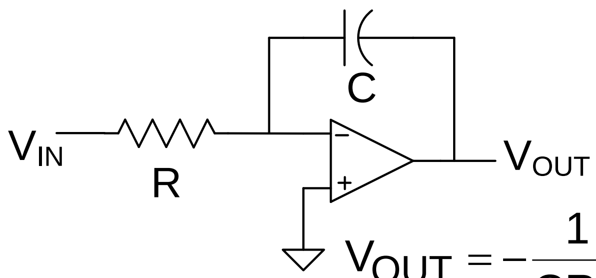
Fully Differential

Basic Integrator Functionality



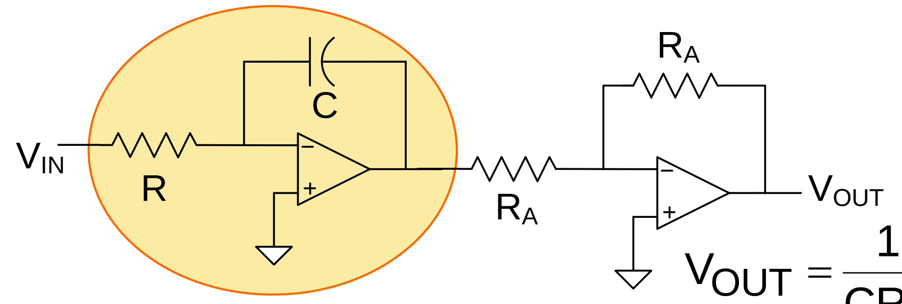
- An inverting/noninverting integrator pair define a family of integrators
- All integrator functional types can usually be obtained from the inverting/noninverting integrator pair
- Suffices to focus primarily on the design of the inverting/noninverting integrator pair since properties of class primarily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

Example – Basic Op-Amp Feedback Integrator Family



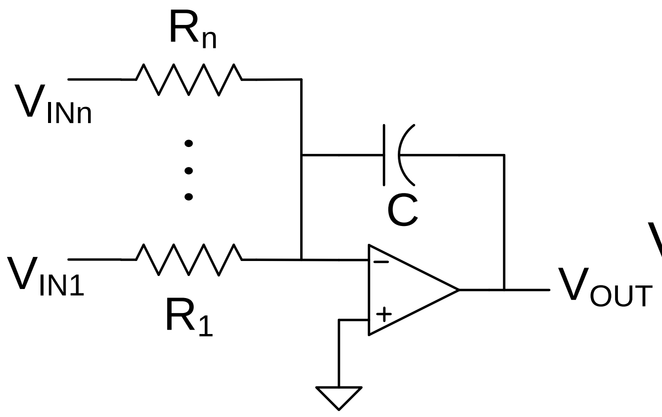
$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

Inverting Integrator of Family



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

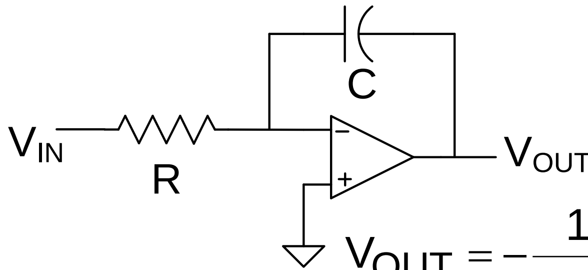
Noninverting Integrator



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

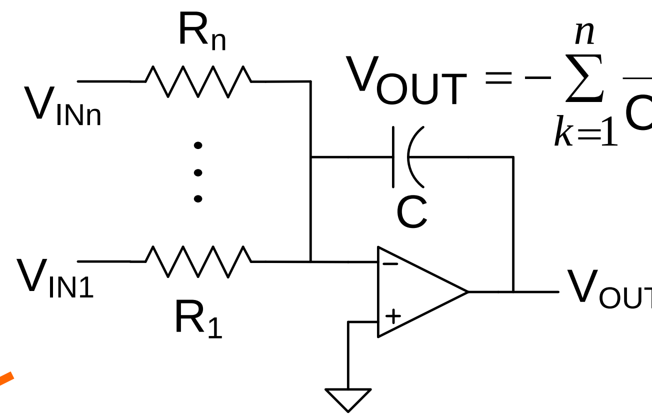
Summing Inverting Integrator

Example – Basic Op-Amp Feedback Integrator Family



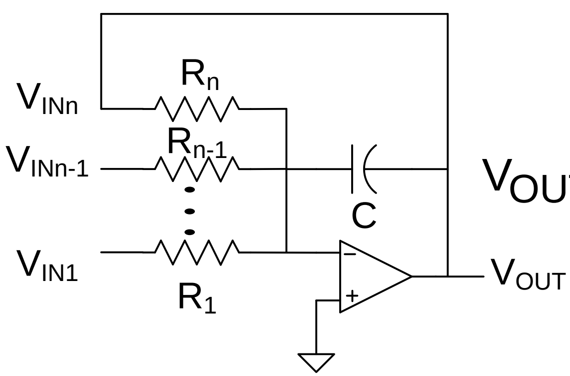
$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

Inverting Integrator of Family

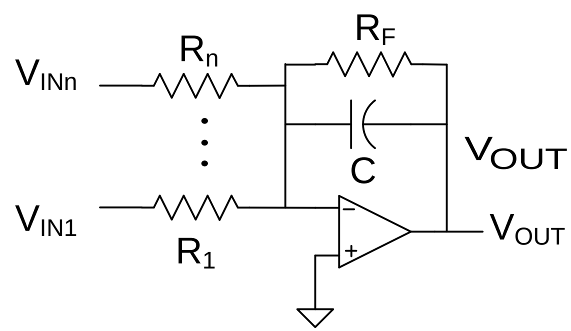


$$V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_k s} V_{INk}$$

Summing Inverting Integrator



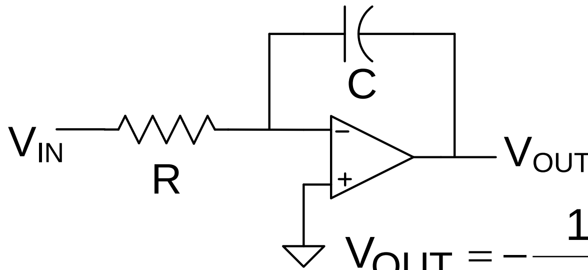
$$V_{OUT} = -\frac{\sum_{k=1}^{n-1} \frac{R_n}{R_k} V_{INk}}{1+CR_n s}$$



$$V_{OUT} = -\frac{\sum_{k=1}^{n} \frac{R_F}{R_k} V_{INk}}{1+CR_F s}$$

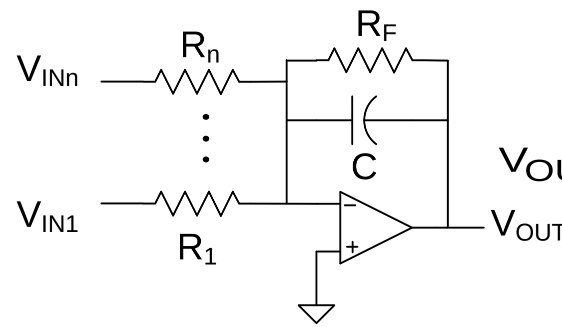
Lossy Summing Inverting Integrator

Example – Basic Op-Amp Feedback Integrator



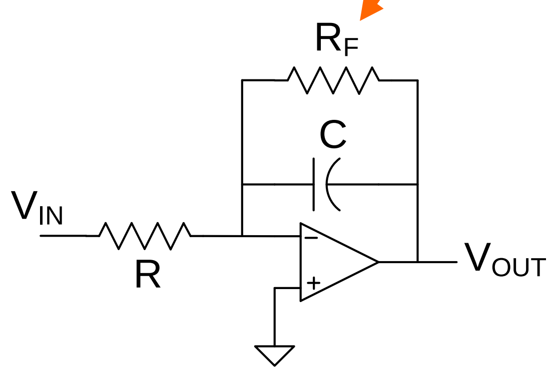
$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

Inverting Integrator of Family



$$V_{OUT} = -\frac{\sum_{k=1}^{n} \frac{R_F}{R_k} V_{INk}}{1+CR_F s}$$

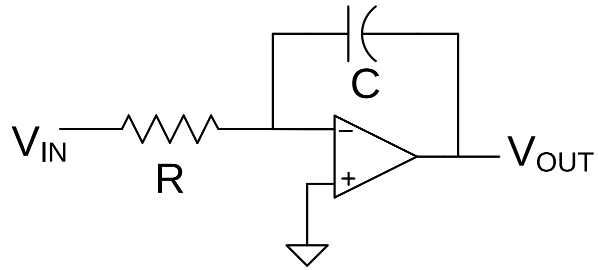
Lossy Summing Inverting Integrator



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

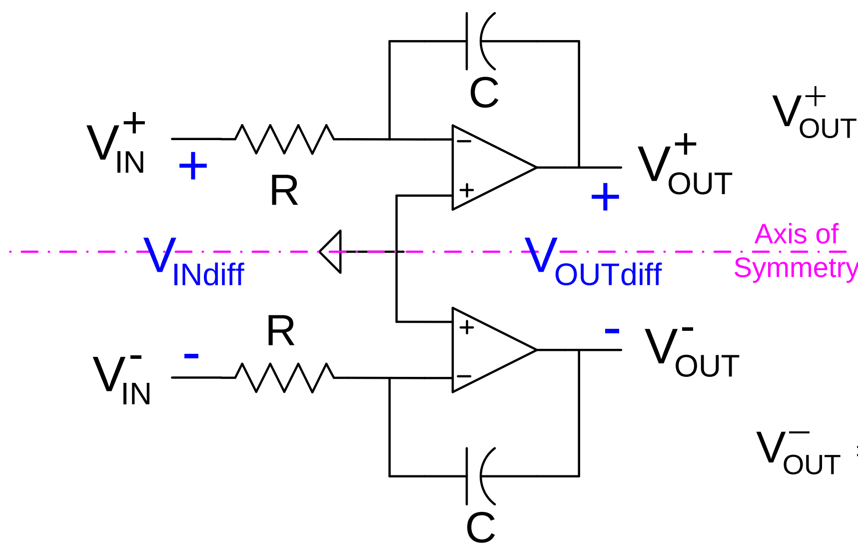
Lossy Inverting Integrator

Example – Basic Op-Amp Feedback Integrator Family



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

Inverting Integrator of Family



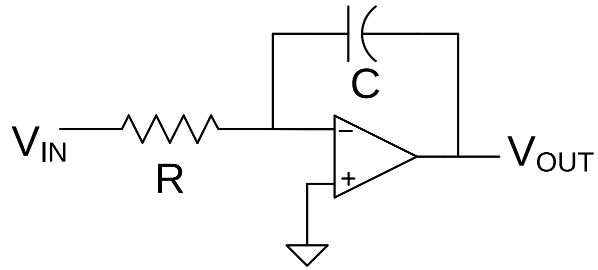
$$V_{OUT}^{+} = -\frac{1}{CRs} V_{IN}^{+}$$

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

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

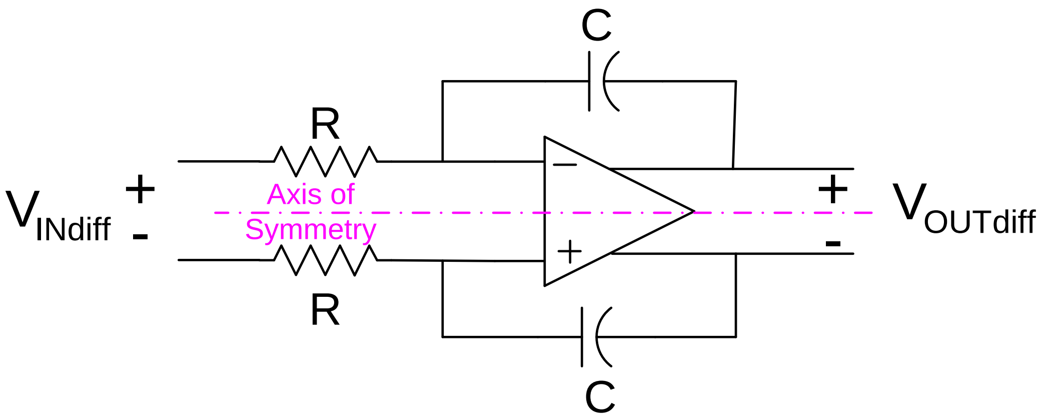
Balanced Differential Inverting Integrator

Example – Basic Op-Amp Feedback Integrator Family



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

Inverting Integrator of Family

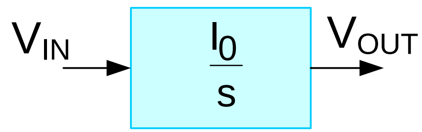


$$V_{OUTdiff} = -\frac{1}{CRs}V_{INdiff}$$

Fully Differential Inverting Integrator

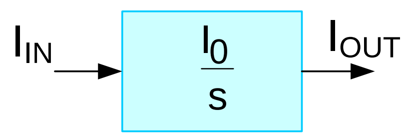
Note distinction between fully balanced and fully differential structures !

Integrator Types



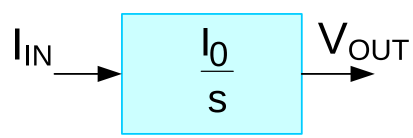
Voltage Mode

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



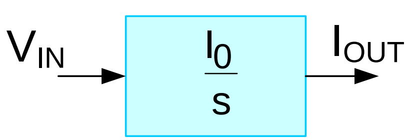
Current Mode

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



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

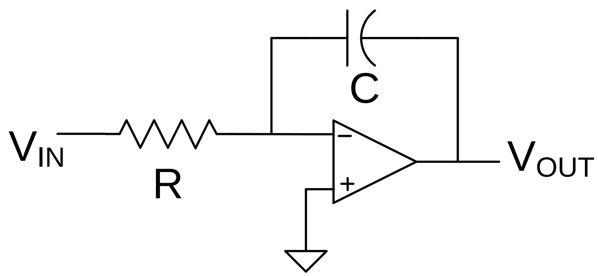
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed "current mode" (OTA-C and TA-C)

- Other Continuous-time Structures
- Switched Capacitor
- Switched Resistor

Discrete Time (Switched Capacitor and Switched Resistor)

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

Voltage Mode Integrators

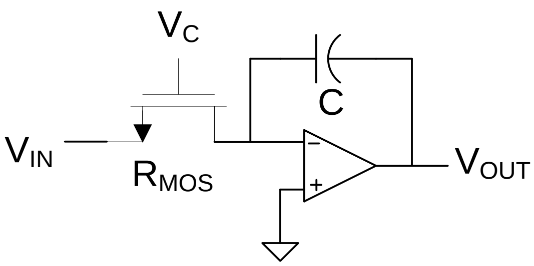
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed “current mode”

- Other Continuous-time Structures
- Switched Capacitor
- Switched Resistor

Discrete Time

MOSFET-C Voltage Mode Integrator

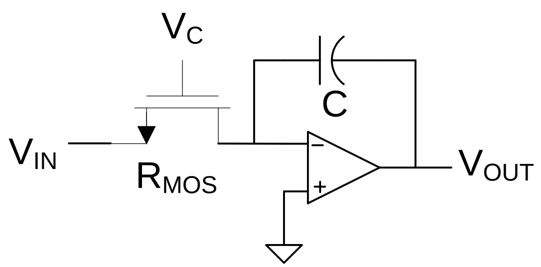


$$V_{OUT} = -\frac{1}{CR_{MOS}s} V_{IN}$$

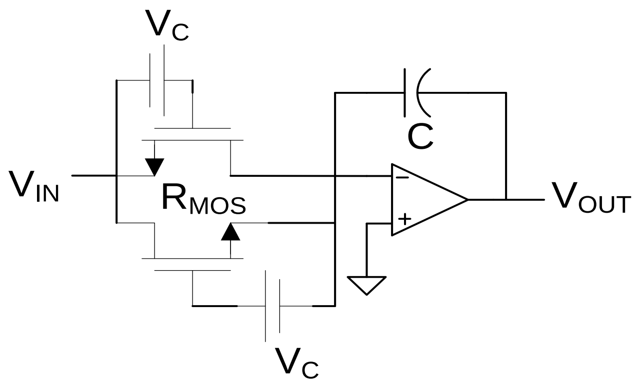
- Limited to low frequencies because of Op Amp limitations
- Area for R_{MOS} is manageable !
- Active devices are highly temperature dependent, process dependent
- Potential for tuning with V_C
- Highly Nonlinear (can be partially compensated with cross-coupled input

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

Voltage Mode Integrators

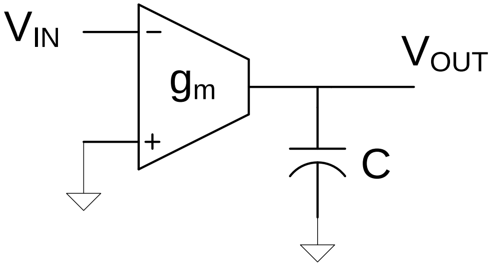
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed “current mode” (OTA-C, TA-C)

- Other Continuous-time Structures
- Switched Capacitor
- Switched Resistor

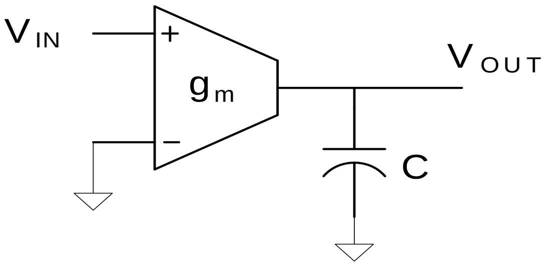
Discrete Time (Switched Capacitor, Switched Resistor)

OTA-C Voltage Mode Integrator



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

Inverting



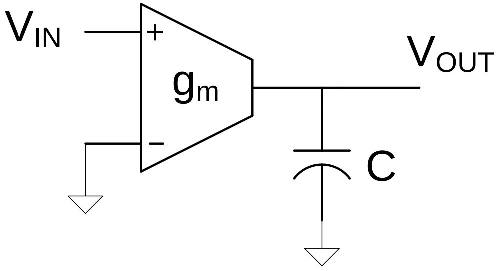
$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

Noninverting

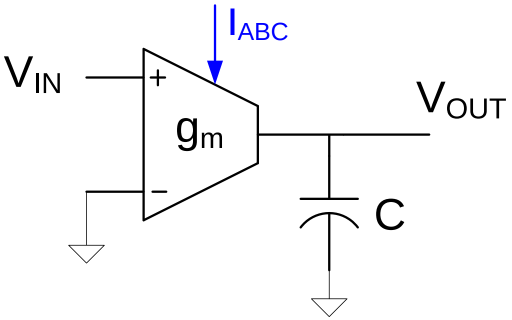
- Requires only two components
- Inverting and Noninverting structures of same complexity
- Good high-frequency performance
- Small area
- Linearity is limited (no feedback in integrator)
- Susceptible to process and temperature variations
- Tuning control can be readily added

Widely used in high frequency applications

OTA-C Voltage Mode Integrator



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

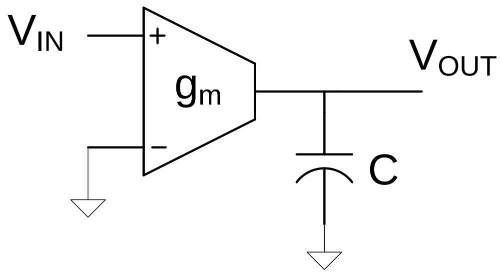


$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

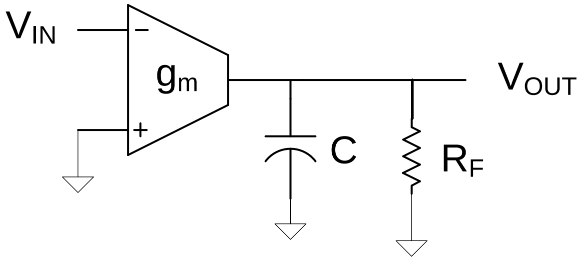
$$g_m = f(I_{ABC})$$

Programmable Integrator

OTA-C Voltage Mode Integrator



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

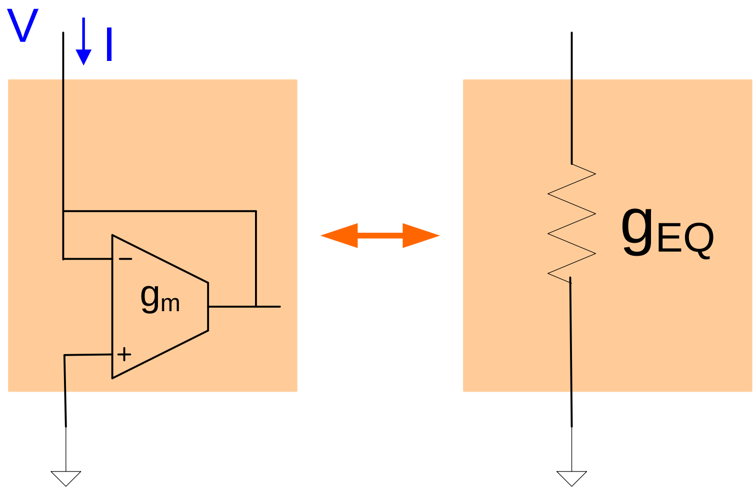


$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{g_m R_F}{1+s(R_F C)}$$

Lossy Integrator

But R_F is typically too large for integrated applications

OTA-C Voltage Mode Integrator



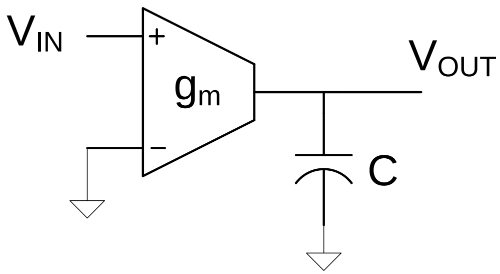
$$I = -\,{-g_m}V$$

$$g_{EQ} = \frac{I}{V}$$

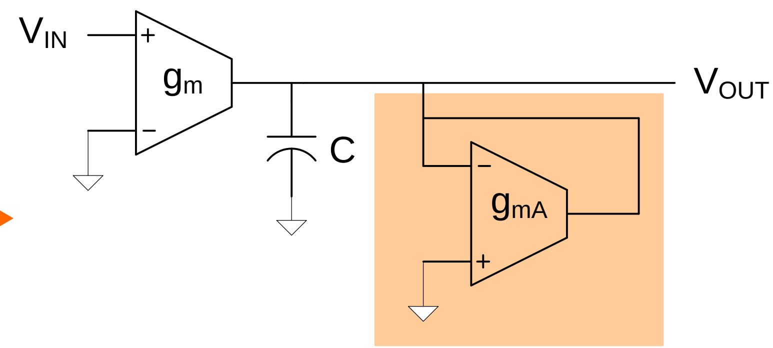
$$g_{EQ} = g_m$$

OTA is generally much smaller than a resistor

OTA-C Voltage Mode Integrator



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

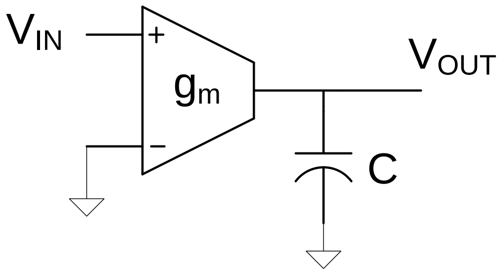


$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{g_m/g_{mA}}{1+s(C/g_{mA})}$$

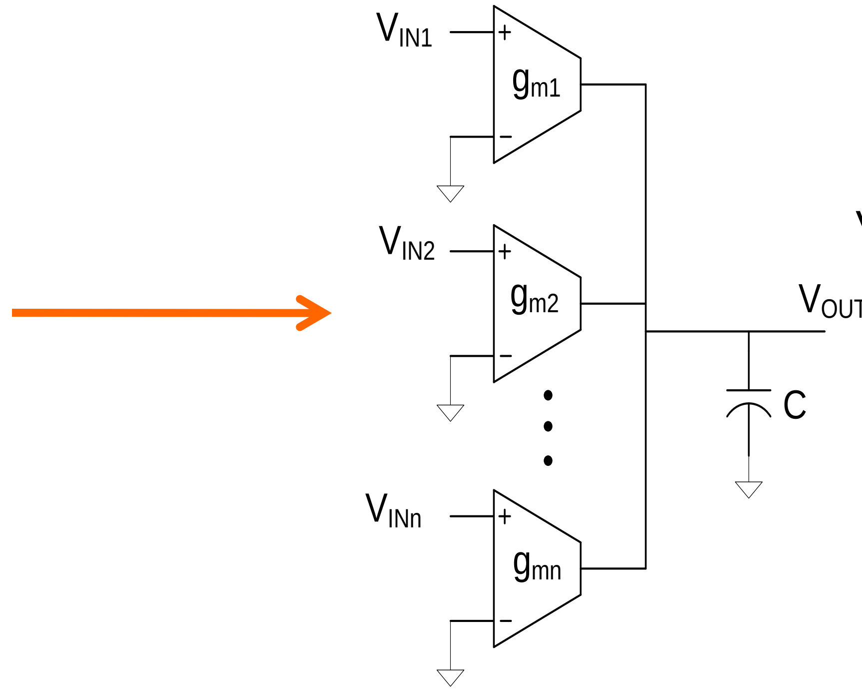
Lossy Integrator

- Practical implementation
- Both OTAs can be readily programmable

OTA-C Voltage Mode Integrator



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

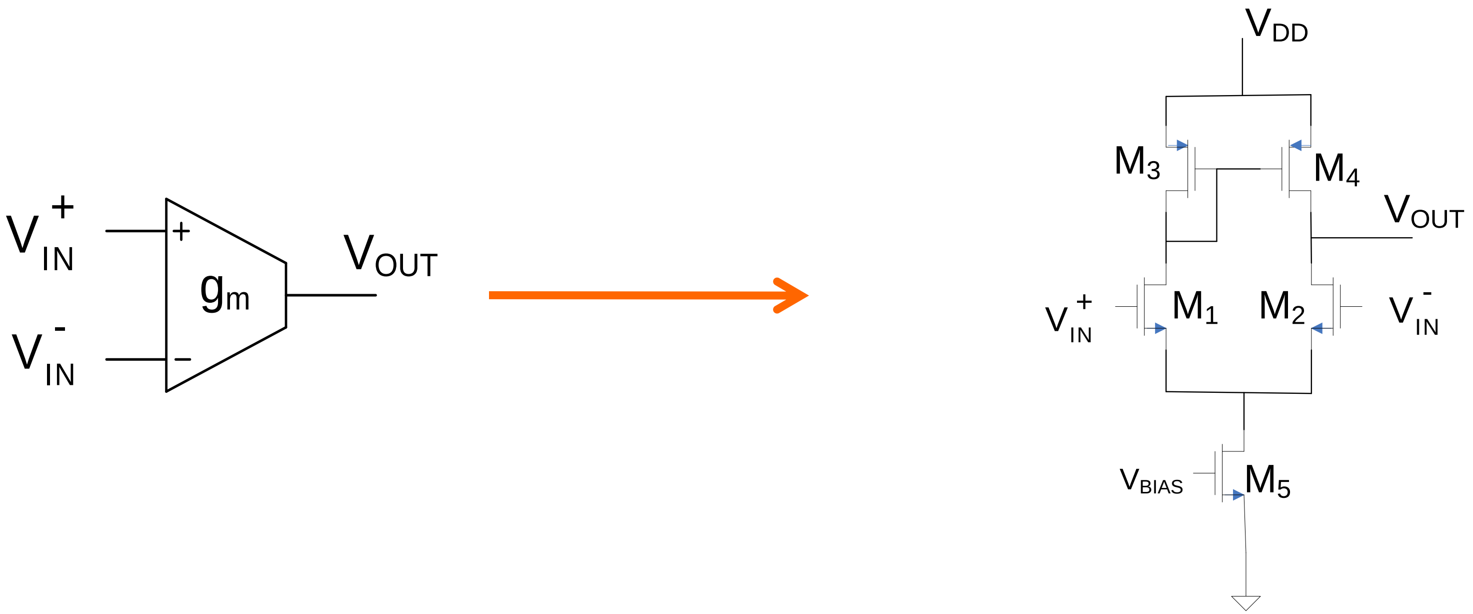


$$V_{OUT} = \frac{\sum_{k=1}^{n} g_{mk} V_{INk}}{sC}$$

Summing Integrator

- Inverting and noninverting functions can be combined in single summer
- All transconductance gains can be programmable

OTA Architecture



Mid-complexity OTA

- M_1 and M_2 matched
- M_2 and M_4 matched
- Define M to be the gain of the current mirror formed with M_2 and M_4
- g_m programmable with V_{BIAS}

$$g_m = \frac{g_{m1}}{2}(1+M)$$

Often M=1

$$g_m = g_{m1}$$

Other OTAs exist, considerable effort expended over past two decades on OTA design

Voltage Mode Integrators

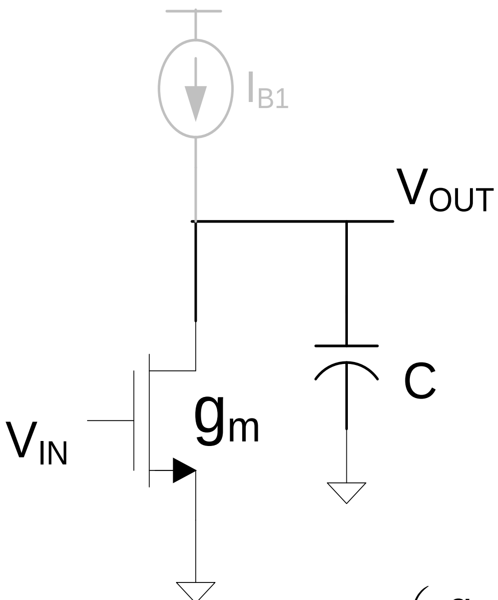
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed "current mode" (OTA-C, TA-C)

- Other Continuous-time Structures
- Switched Capacitor
- Switched Resistor

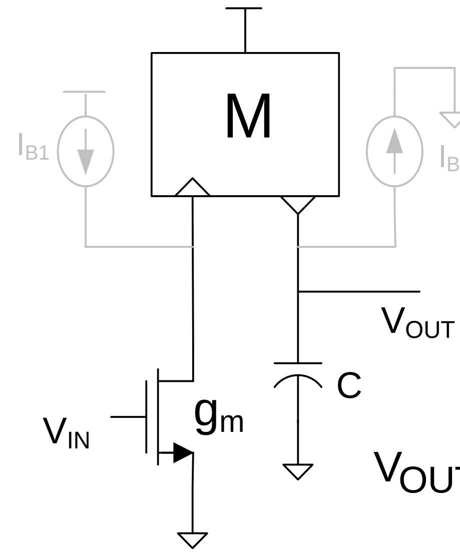
Discrete Time (Switched Capacitor, Switched Resistor)

TA-C Voltage Mode Integrator



$$V_{OUT} = \left(\frac{-g_m}{sC}\right) V_{IN}$$

Inverting Integrator



$$V_{OUT} = \left(\frac{g_m M}{sC}\right) V_{IN}$$

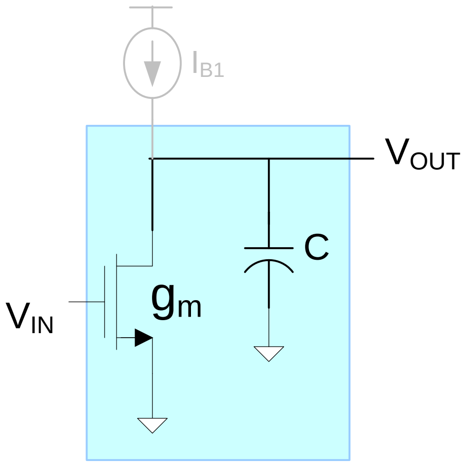
Typically M=1

Noninverting Integrator

- Can operate at very high frequencies
- Low device count circuit
- Simplicity is important for operating at very high frequencies
- I_0 is process and temperature dependent
- Linearity is limited

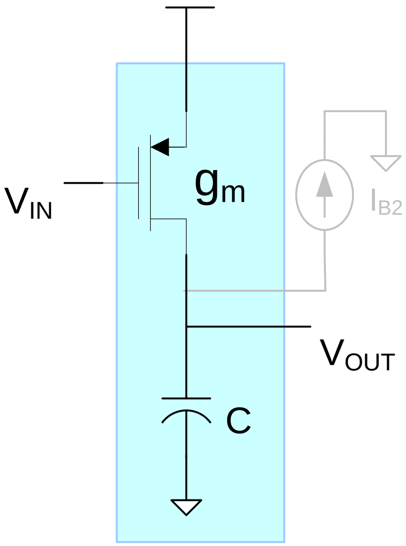
TA-C Voltage Mode Integrator

Some other perspectives



n-channel input

$$V_{OUT} = \left(\frac{-g_m}{sC}\right) V_{IN}$$

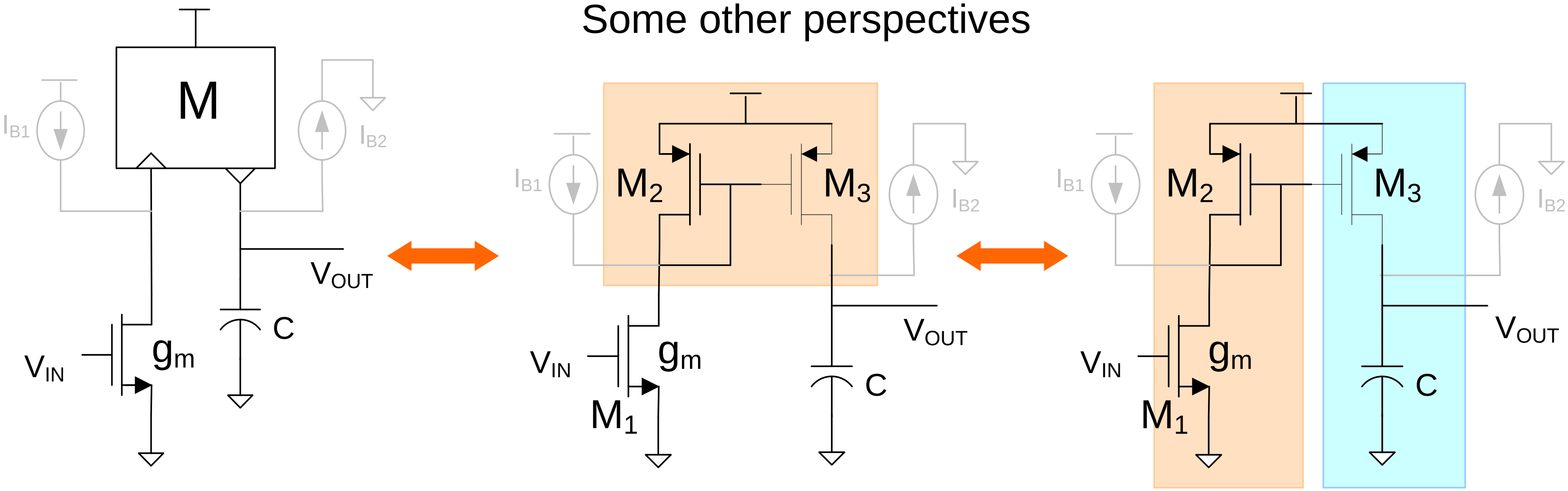


p-channel input

Inverting Integrators

TA-C Voltage Mode Integrator

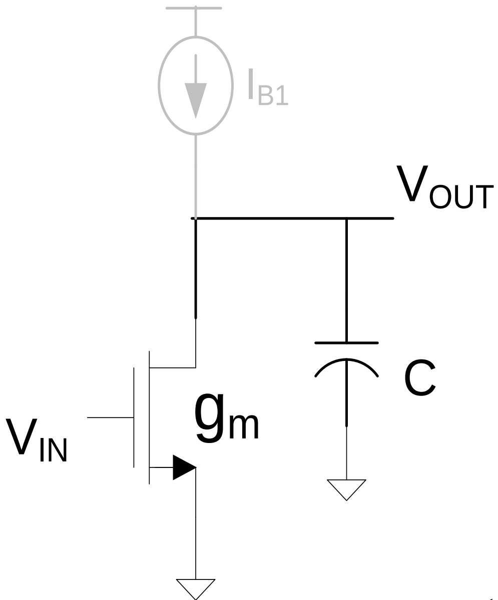
Some other perspectives



Noninverting Integrator

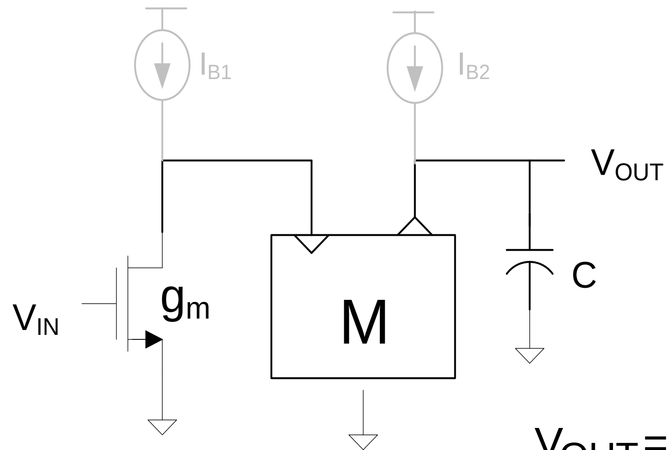
Can be viewed either as n-channel input with current mirror or as low-gain inverter driving a p-channel input inverting integrator

TA-C Voltage Mode Integrator



$$V_{OUT} = \left(\frac{-g_m}{sC}\right) V_{IN}$$

Inverting Integrator

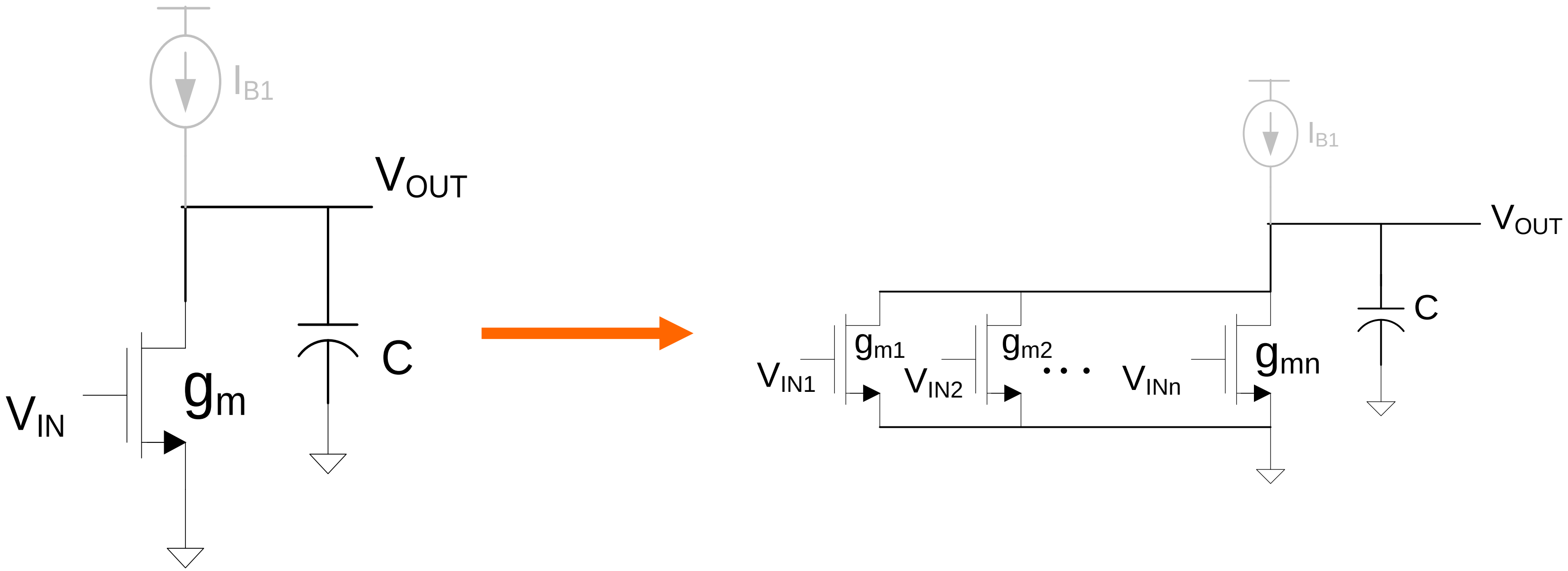


$$V_{OUT} = \left(\frac{g_m M}{sC}\right) V_{IN}$$

Typically M=1

Alternate noninverting Integrator

TA-C Voltage Mode Integrator



Summing Inverting Integrator

Voltage Mode Integrators

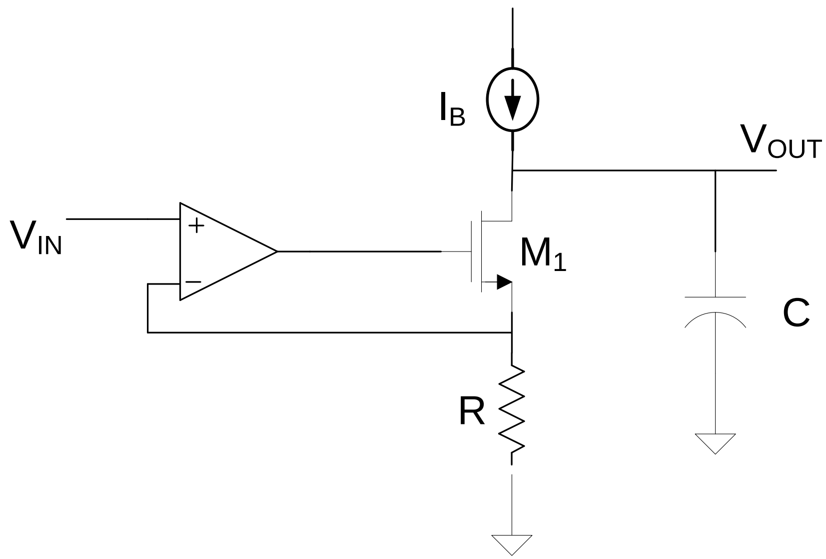
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed "current mode"

- Other Continuous-time Structures
- Switched Capacitor
- Switched Resistor

Discrete Time

Another Voltage Mode Integrator

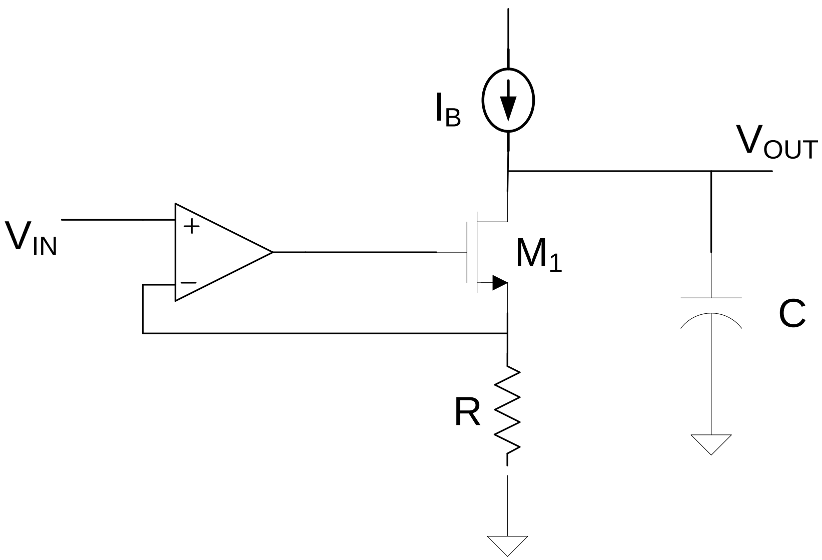


$$V_{OUT} = \left(\frac{-1}{sRC}\right) V_{IN}$$

Inverting Integrator

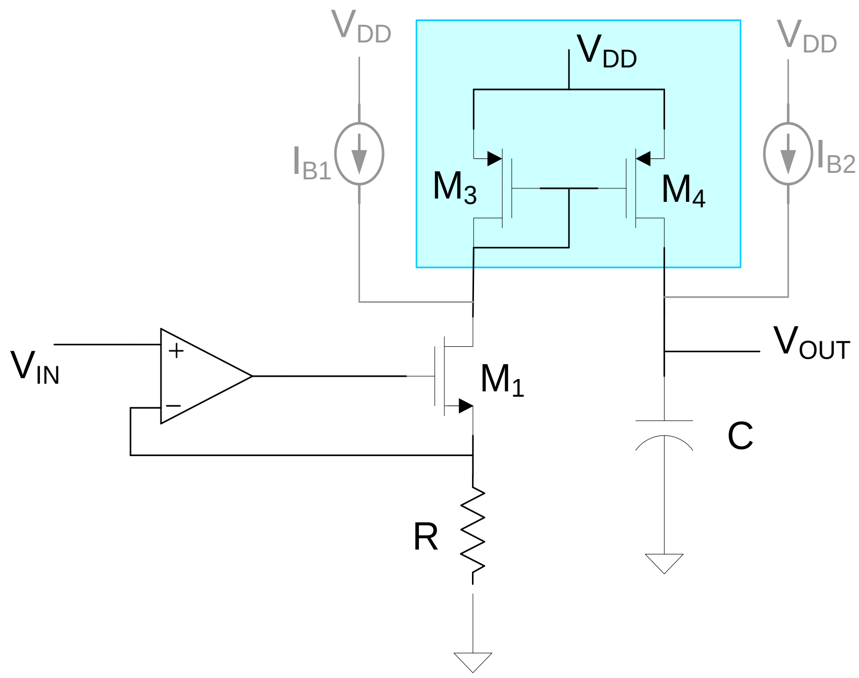
- **Infinite input impedance (in contrast to basic Active RC Integrator)**
- **Both R and C have one terminal grounded**
- **Requires integrated process**
- **Accuracy limited by process and temperature**
- **Size limitations same as basic Active RC Integrator**
- **Limited to lower frequencies because of Op Amp**
- **Good linearity**

Another Voltage Mode Integrator



Inverting Integrator

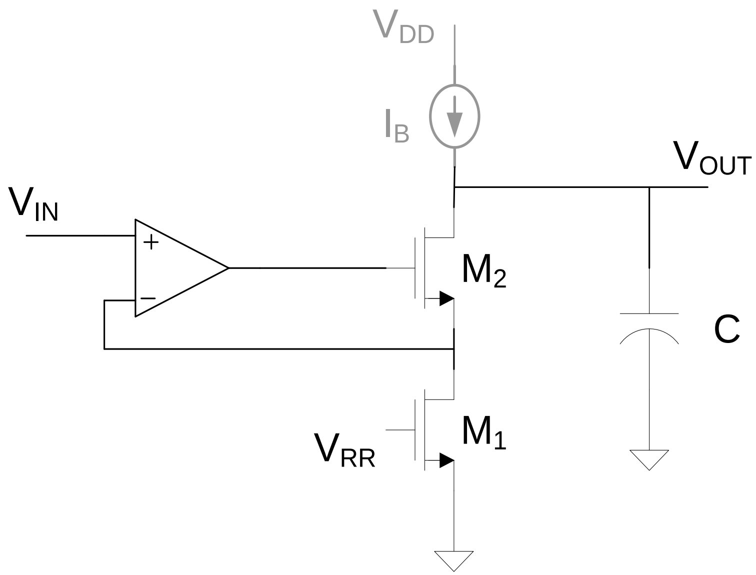
$$V_{OUT} = \left(\frac{-1}{sRC}\right) V_{IN}$$



Noninverting Integrator

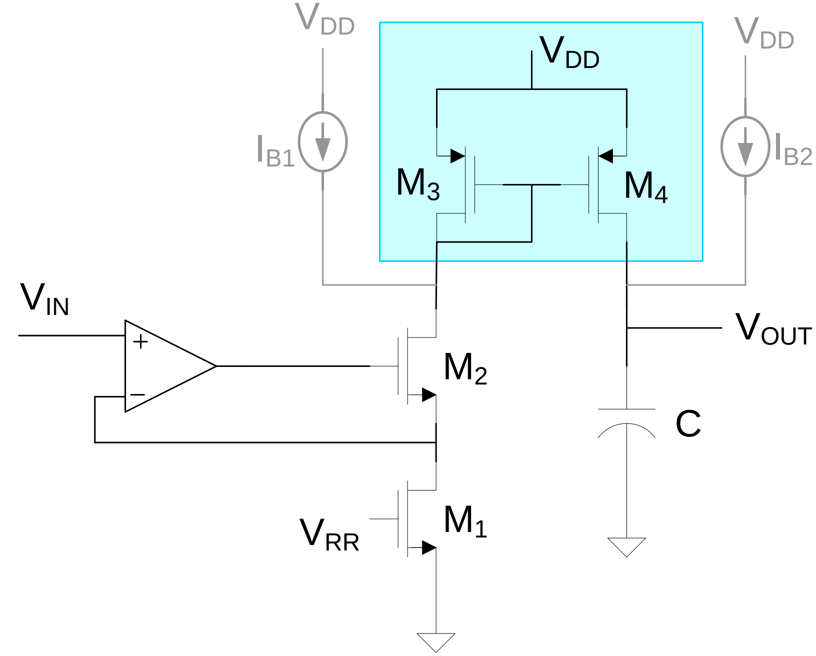
$$V_{OUT} = \left(\frac{1}{sRC}\right) V_{IN}$$

Another Voltage Mode Integrator



Inverting Integrator

$$V_{OUT} = \left(\frac{-1}{sR_{FET}C} \right) V_{IN}$$

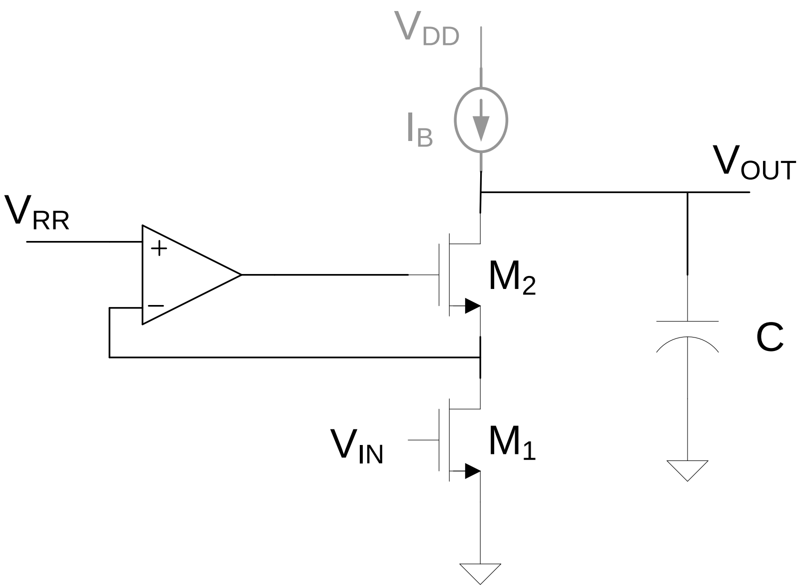


Noninverting Integrator

$$V_{OUT} = \left(\frac{1}{sR_{FET}C} \right) V_{IN}$$

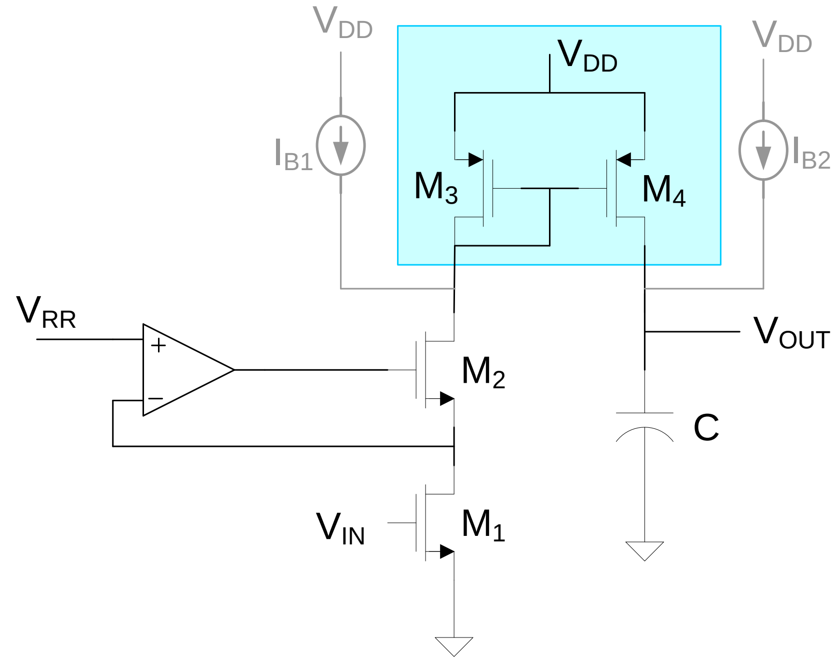
- M_1 in triode region
- Reduces Area Concerns but Loss of Linearity
- I_0 is programmable with V_{RR}
- Accurate control of I_B critical

Regulated Cascode Voltage Mode Integrator



Inverting Integrator

$$V_{OUT} = \left(\frac{-g_{mT}}{sC} \right) V_{IN}$$



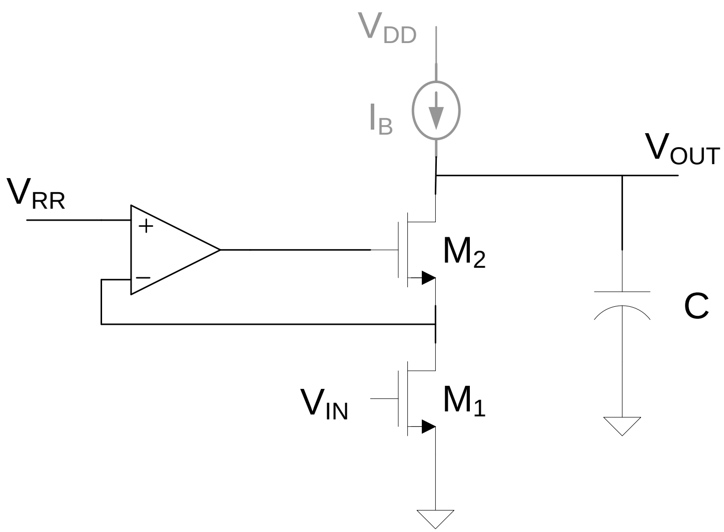
Noninverting Integrator

$$V_{OUT} = \left(\frac{g_{mT}}{sC} \right) V_{IN}$$

g_{MT} is triode region transconductance of M_1

- **M_1 operating in triode region**
- **R_{FET} programmable with V_{RR}**
- **Very good linearity properties**
- **Input impedance still infinite**

Regulated Cascode Voltage Mode Integrator



$$V_{OUT}=\left(\frac{-g_{mT}}{sC}\right)V_{IN}$$

Linearity Properties:

Assuming square-law triode model

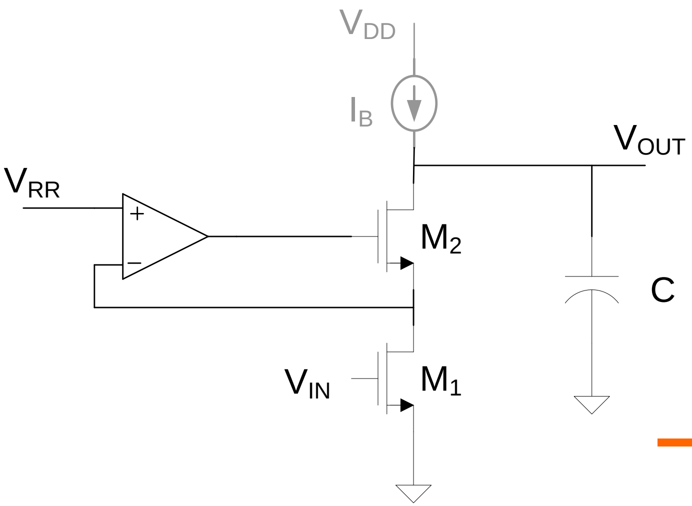
$$I_{D1}=\frac{\mu C_{OX}W}{L}\left(V_{GS}-V_T-\frac{V_{RR}}{2}\right)V_{RR}$$

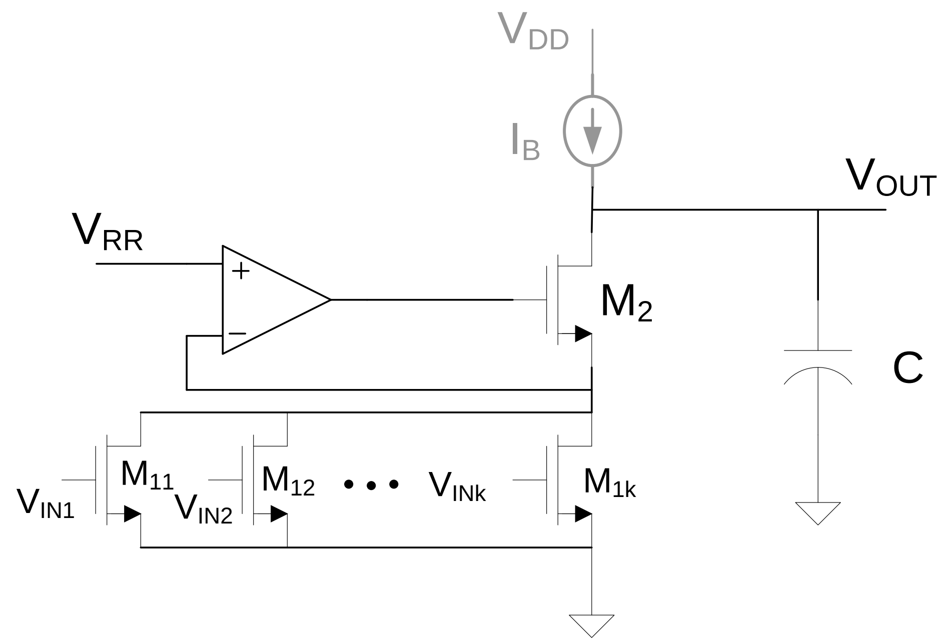
$$I_{D1}=\left[\frac{\mu C_{OX}W}{L}V_{RR}\right]V_{IN}+\left[\frac{\mu C_{OX}W}{L}\left(V_T+\frac{V_{RR}}{2}\right)V_{RR}\right]$$

Note linear dependence on V_{IN}

$$g_{mT}=\left[\frac{L}{\mu C_{OX}W\ V_{RR}}\right]$$

Regulated Cascode Voltage Mode Integrator



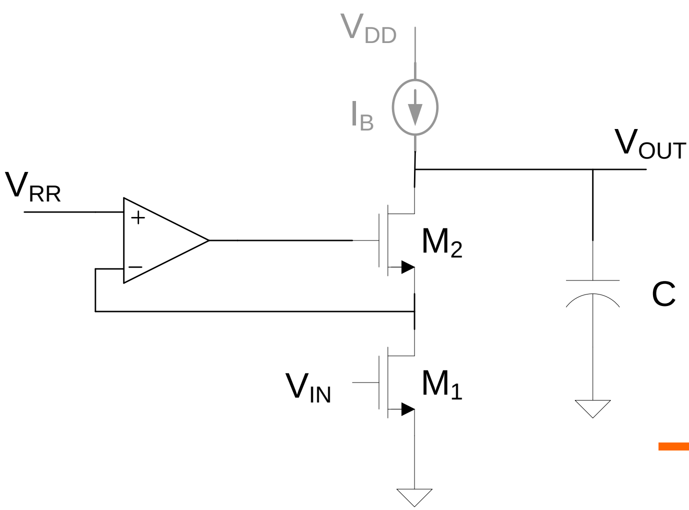


Inverting Integrator

$$V_{OUT} = \left(\frac{-1}{sR_{FET}C} \right) V_{IN}$$

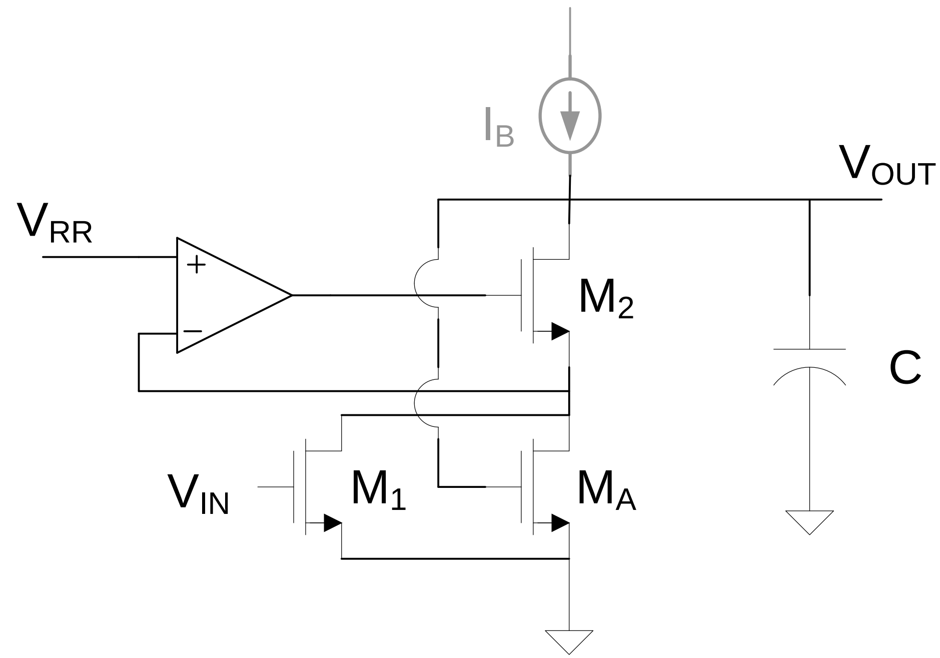
- **Multiple inputs require single additional transistor**
- **Accurate ratioing of gains practical**
- **Can also sum currents on C**

Regulated Cascode Voltage Mode Integrator



Inverting Integrator

$$V_{OUT} = \left(\frac{-1}{sR_{FET}C} \right) V_{IN}$$



Inverting Lossy Integrator

Stay Safe and Stay Healthy !

End of Lecture 24