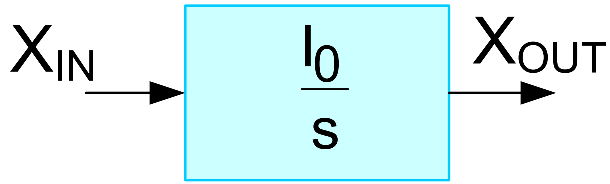
EE 508
Lecture 24

Integrator Design

TA-C Integrators
Other Integrator Structures

Review from last time

Integrator Characteristics of Interest



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

Properties of an ideal integrator:

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

Gain decreases with 1/ω

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

Phase is a constant -90^o

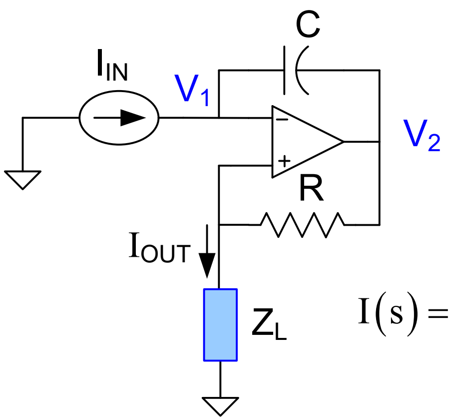
$$|I(jI_0)| = 1$$

Unity Gain Frequency = 1

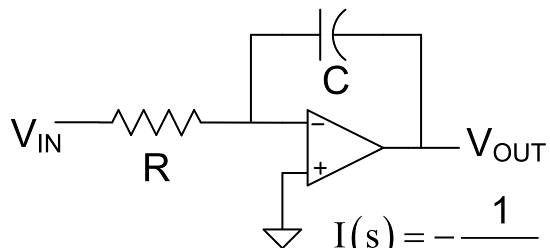
How important is it that an integrator have all 3 of these properties?

Review from last time

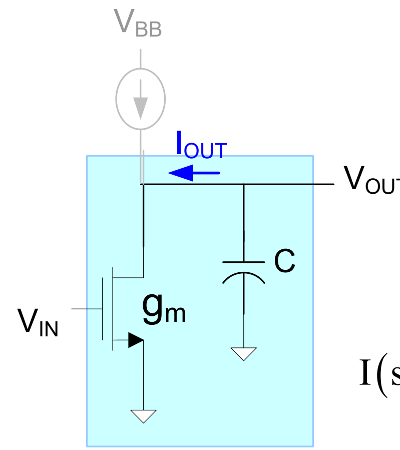
Some integrator structures



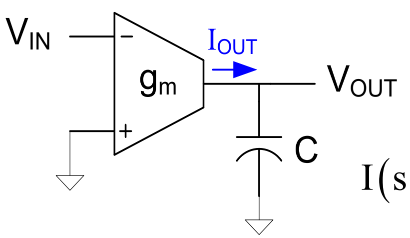
$$I(s) = -\frac{1}{sRC}$$



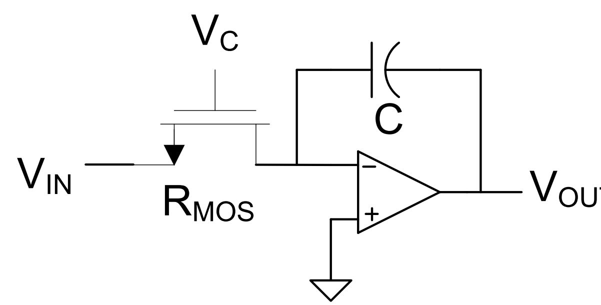
$$I(s) = -\frac{1}{sRC}$$



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



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



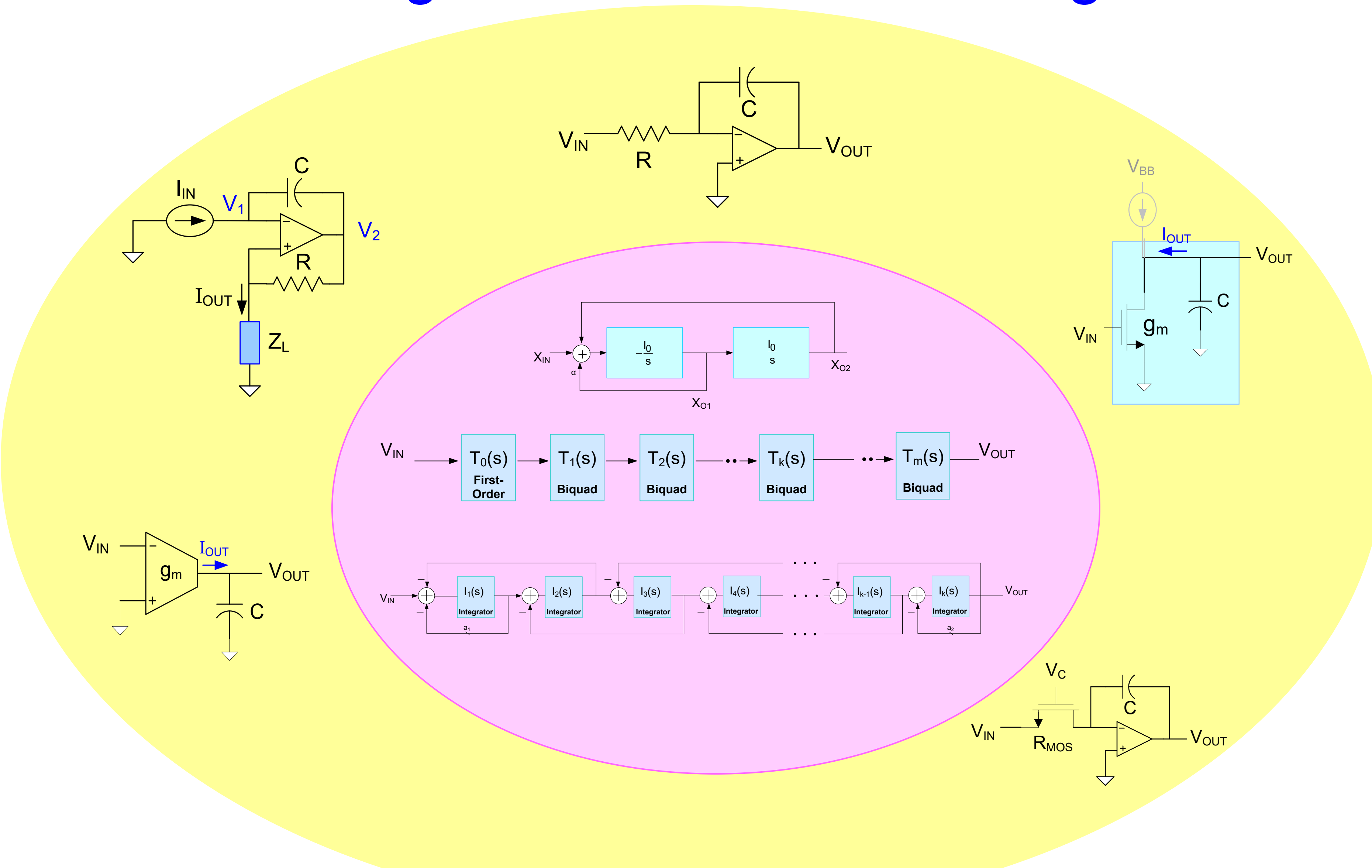
$$I(s) = -\frac{1}{sR_{MOS}C}$$

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

There are many different ways to build an inverting integrator

Review from last time

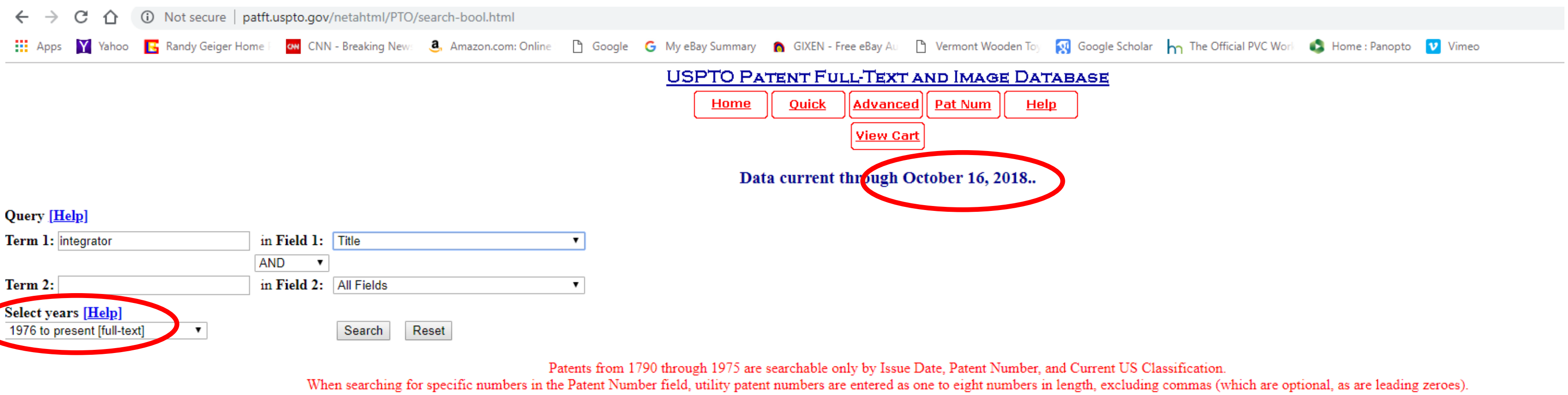
Integrator-Based Filter Design

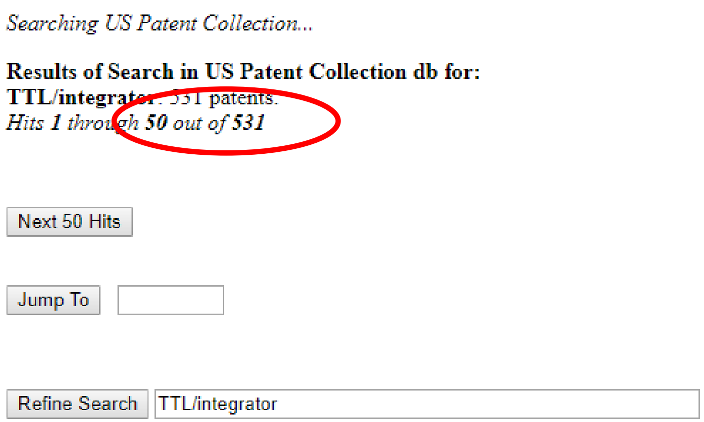


Any of these different types of integrators can be used to build integrator-based filters

Review from last time

Are new integrators still being invented?



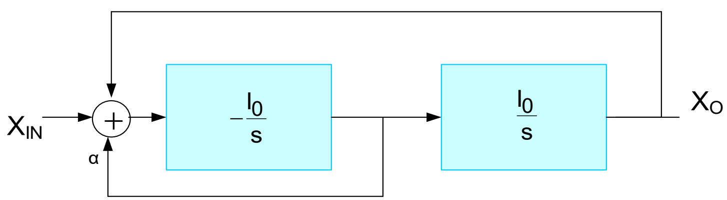


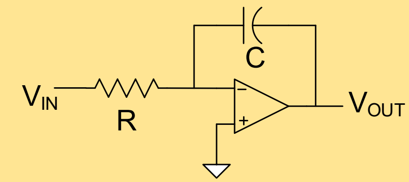
Oct 16 2018

Review from last time

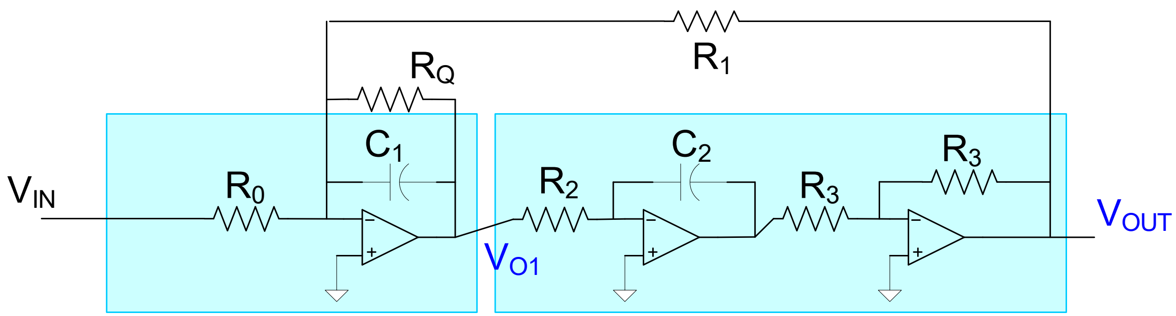
		PAT. NO.	Title
	1	10,082,922	T Increasing the dynamic range of an integrator based mutual-capacitance measurement circuit
	2	10,074,004	T Capacitive fingerprint sensor with integrator
	3	10,070,089	T Inverting amplifier, integrator, sample hold circuit, ad converter, image sensor, and imaging apparatus
	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

Example – Active RC Feedback Tow Thomas Biquad





Active RC Integrator Family



$$
\left.
\begin{aligned}
V_{OUT} &= \frac{1}{sR_2C_2} V_{O1} \\
V_{IN}G_0 + V_{O1}\left(sC_1 + G_Q\right) + G_1 V_{OUT} &= 0
\end{aligned}
\right\}
$$

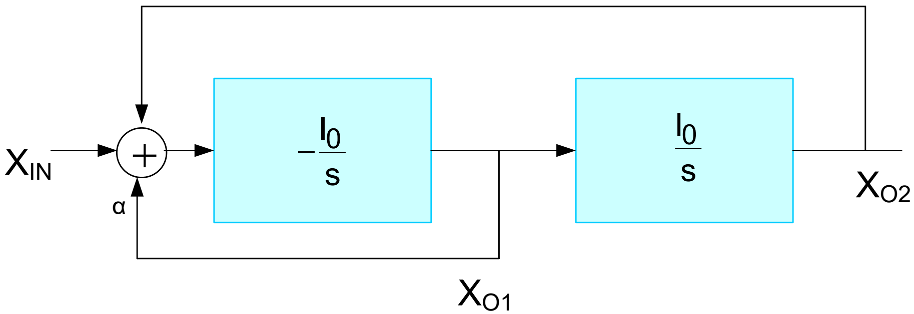
$$
\frac{V_{OUT}}{V_{IN}} = -\frac{\dfrac{1}{C_1R_0R_2C_2}}{s^2 + s\dfrac{1}{R_QC_1} + \dfrac{1}{C_1R_1R_2C_2}}
$$

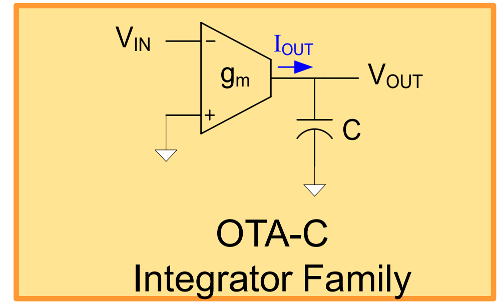
If $R_1=R_2=R$ and $C_1=C_2=C$

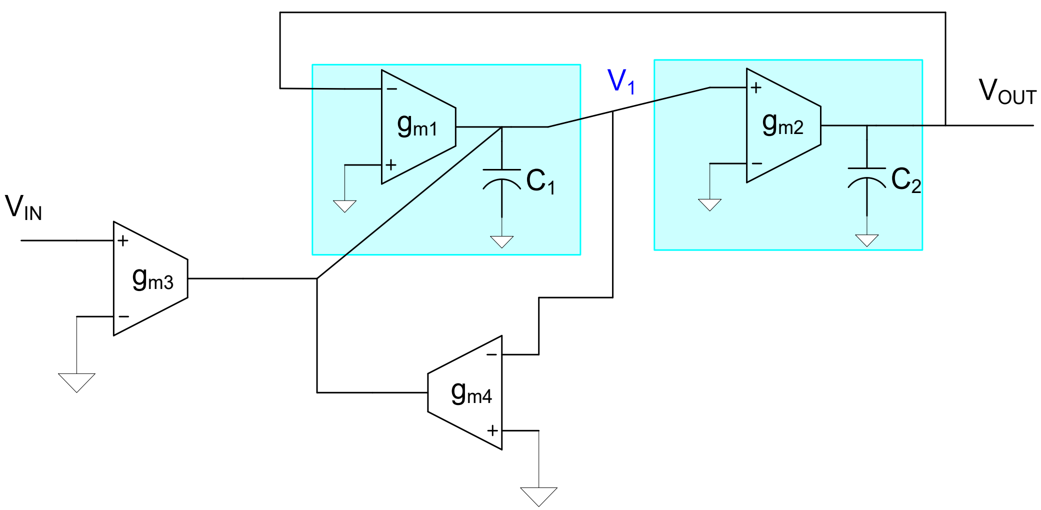
$$
\omega_0 = \frac{1}{RC}
$$

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

Example – OTA-C Tow Thomas Biquad







$$\left.\begin{aligned} V_{OUT}sC_2 &= g_{m2}V_1 \\ V_1sC_1 &= -g_{m1}V_{OUT} + g_{m3}V_{IN} - g_{m4}V_1 \end{aligned}\right\}$$

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

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

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

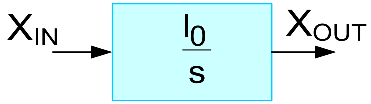
express as

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

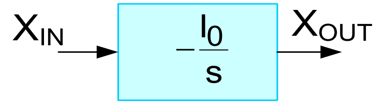
where

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

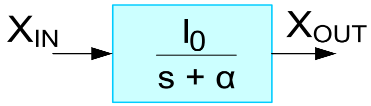
Basic Integrator Functionality (for all families)



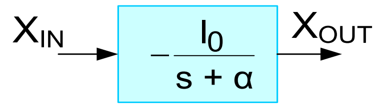
Noninverting



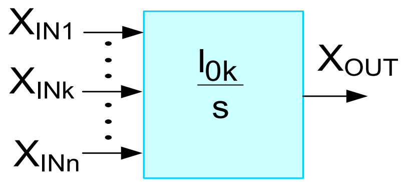
Inverting



Lossy Noninverting

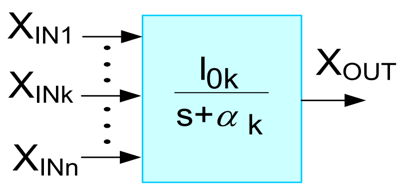


Lossy Inverting



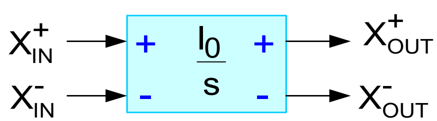
$$X_{OUT}=\sum_{k=1}^{n}\frac{\pm I_{0k}}{s}$$

Summing (Multiple-Input) Inverting/Noninverting



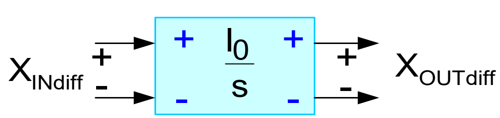
$$X_{OUT}=\sum_{k=1}^{n}\frac{\pm I_{0k}}{s+\alpha_k}$$

Summing (Multiple-Input) Lossy Inverting/Noninverting



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

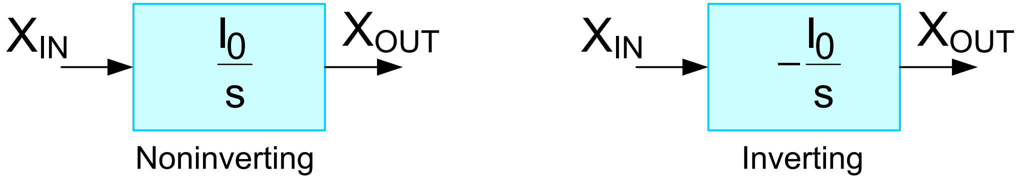
Balanced Differential



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

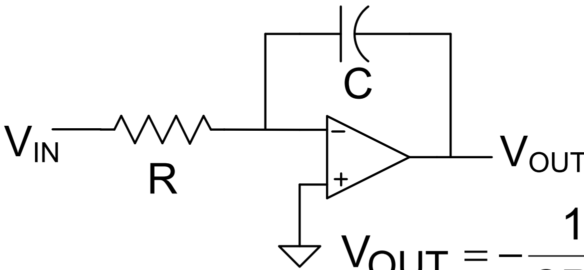
Fully Differential

Basic Integrator Functionality



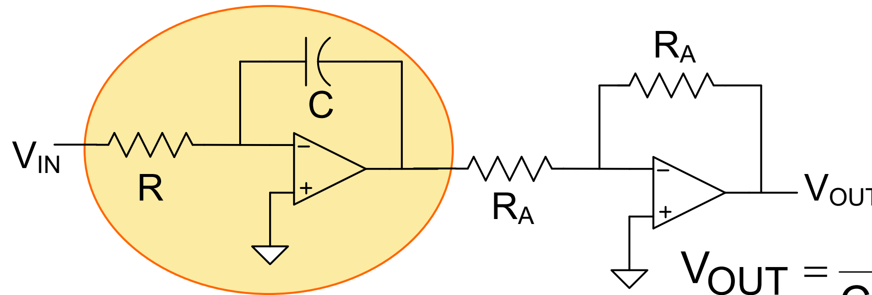
- An inverting/noninverting integrator pair define a family of integrators
- All integrator functional types can usually be obtained from the inverting/noninverting integrator pair
- Suffices to focus primarily on the design of the inverting/noninverting integrator pair since properties of class primarily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

Example – Basic Op-Amp Feedback Integrator Family



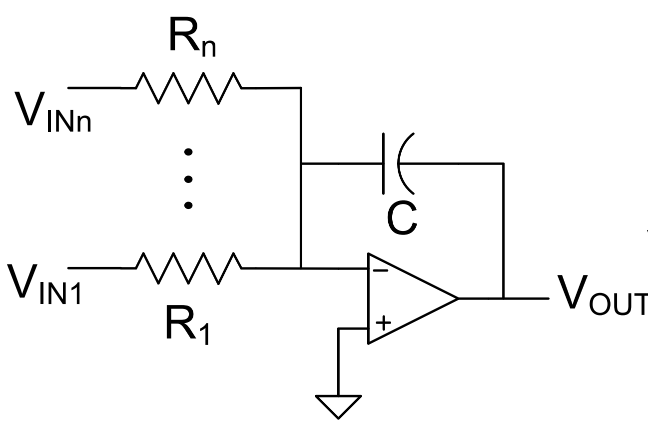
$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

Inverting Integrator of Family



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

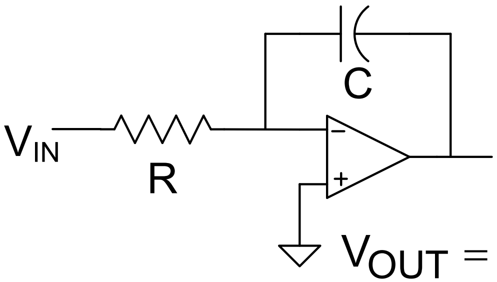
Noninverting Integrator



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

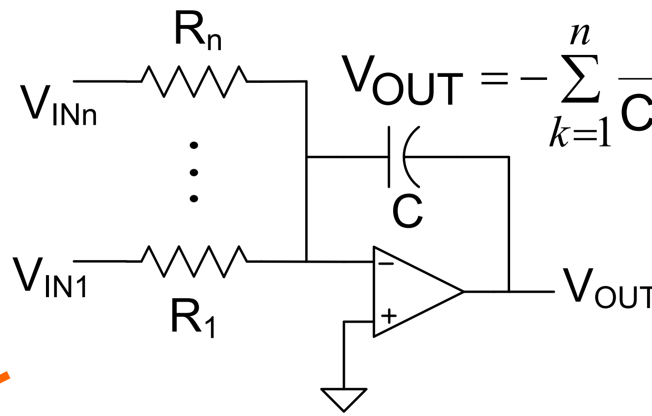
Summing Inverting Integrator

Example – Basic Op-Amp Feedback Integrator Family



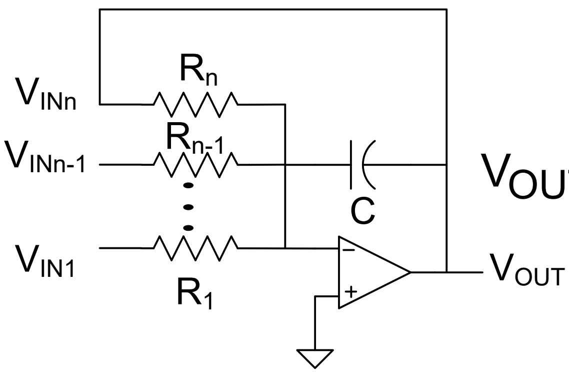
$$V_{OUT} = -\frac{1}{CRs} V_{IN}$$

Inverting Integrator of Family

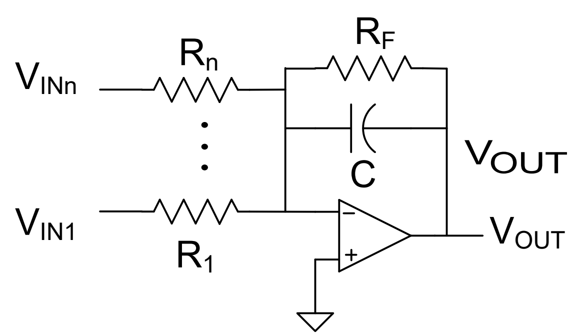


$$V_{OUT} = -\sum_{k=1}^{n} \frac{1}{CR_k s} V_{INk}$$

Summing Inverting Integrator



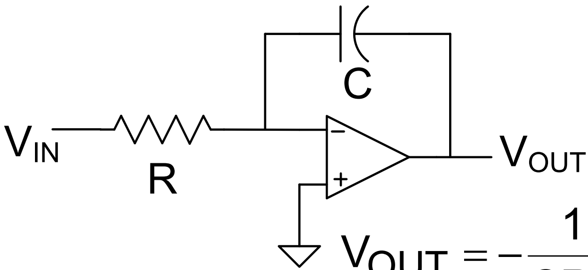
$$V_{OUT} = -\frac{\sum_{k=1}^{n-1} \frac{R_n}{R_k} V_{INk}}{1+CR_n s}$$



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

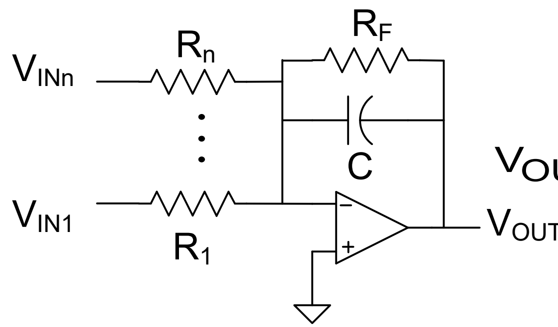
Lossy Summing Inverting Integrator

Example – Basic Op-Amp Feedback Integrator



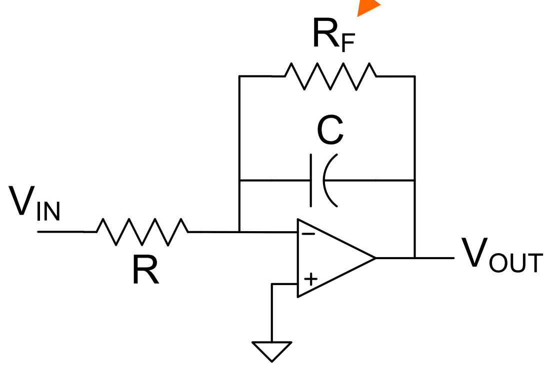
$$V_{OUT} = -\frac{1}{CRs}V_{IN}$$

Inverting Integrator of Family



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

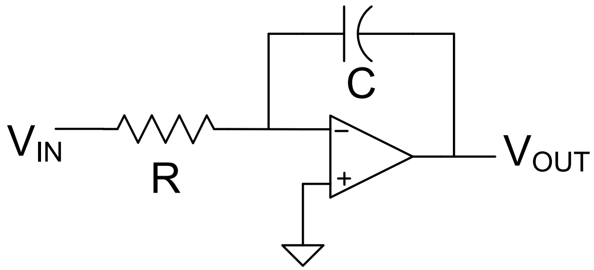
Lossy Summing Inverting Integrator



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

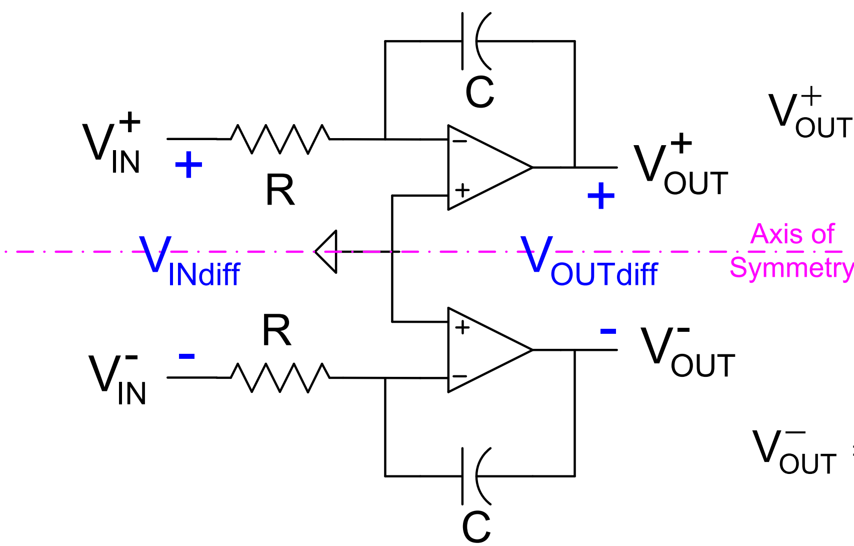
Lossy Inverting Integrator

Example – Basic Op-Amp Feedback Integrator Family



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

Inverting Integrator of Family



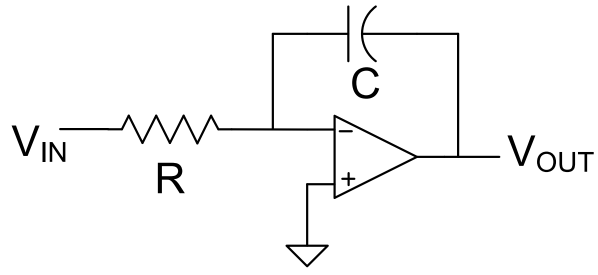
$$V_{OUT}^{+} = -\frac{1}{CRs} V_{IN}^{+}$$

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

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

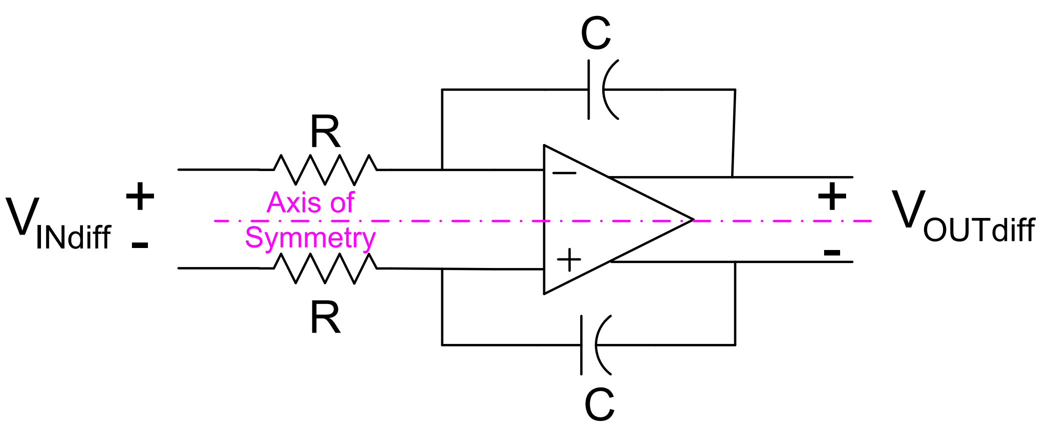
Balanced Differential Inverting Integrator

Example – Basic Op-Amp Feedback Integrator Family



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

Inverting Integrator of Family

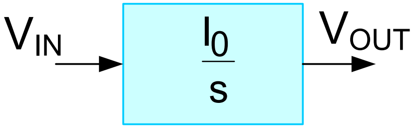


$$V_{OUTdiff} = -\frac{1}{CRs} V_{INdiff}$$

Fully Differential Inverting Integrator

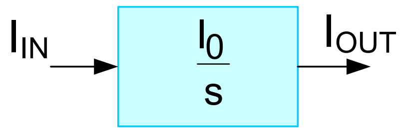
Note distinction between fully balanced and fully differential structures !

Integrator Types



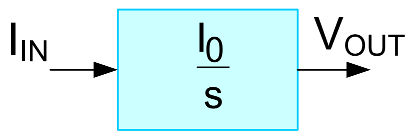
Voltage Mode

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



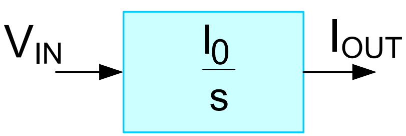
Current Mode

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



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

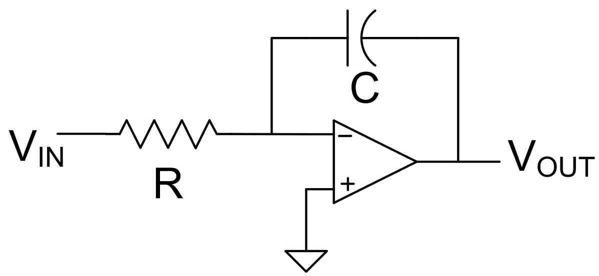
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed “current mode”

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

Discrete Time

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

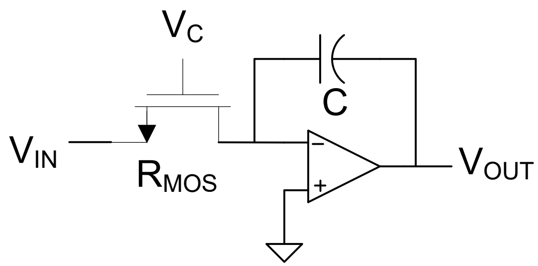
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed "current mode"

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

Discrete Time

MOSFET-C Voltage Mode Integrator

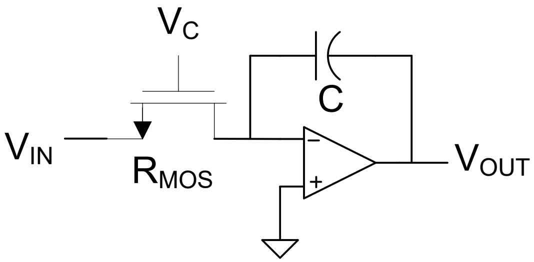


$$V_{OUT} = -\frac{1}{CR_{MOS}s} V_{IN}$$

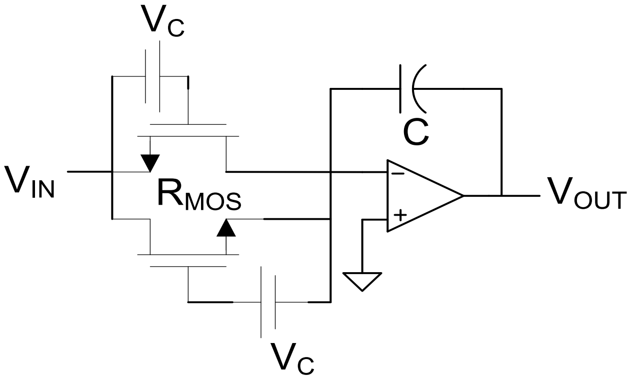
- Limited to low frequencies because of Op Amp limitations
- Area for R_{MOS} is manageable !
- Active devices are highly temperature dependent, process dependent
- Potential for tuning with V_C
- Highly Nonlinear (can be partially compensated with cross-coupled input

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

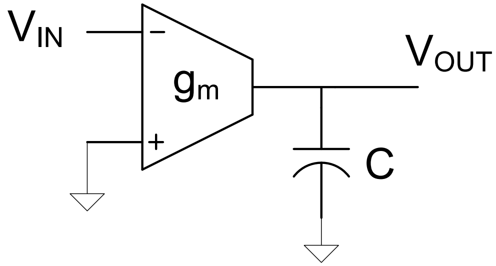
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

Sometimes termed "current mode"

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

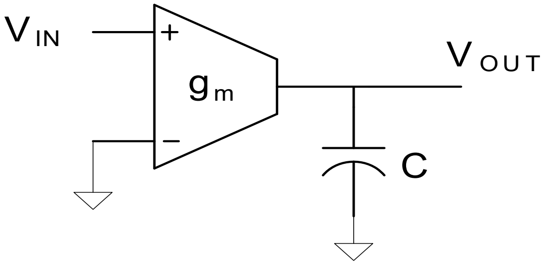
Discrete Time

OTA-C Voltage Mode Integrator



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

Inverting



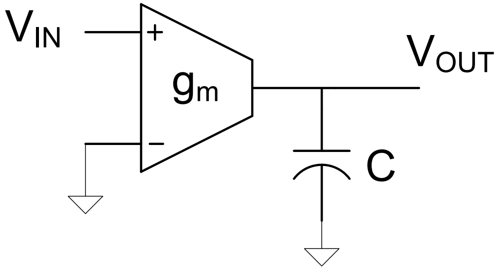
$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

Noninverting

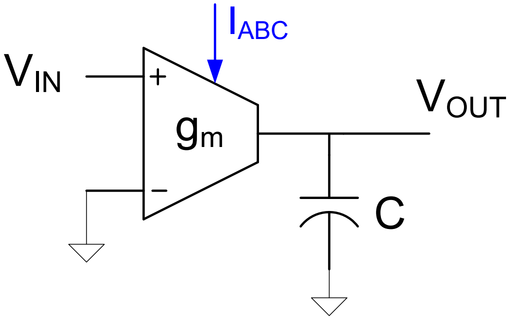
- Requires only two components
- Inverting and Noninverting structures of same complexity
- Good high-frequency performance
- Small area
- Linearity is limited (no feedback in integrator)
- Susceptible to process and temperature variations
- Tuning control can be readily added

Widely used in high frequency applications

OTA-C Voltage Mode Integrator



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

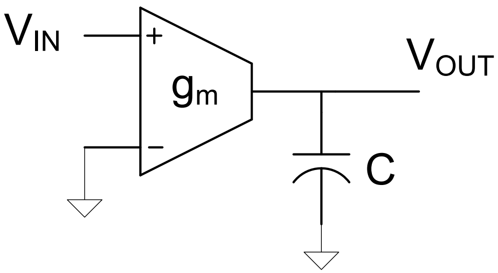


$$V_{OUT} = \frac{g_m}{sC} V_{IN}$$

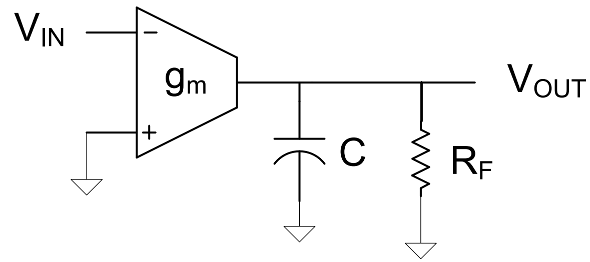
$$g_m = f(I_{ABC})$$

Programmable Integrator

OTA-C Voltage Mode Integrator



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

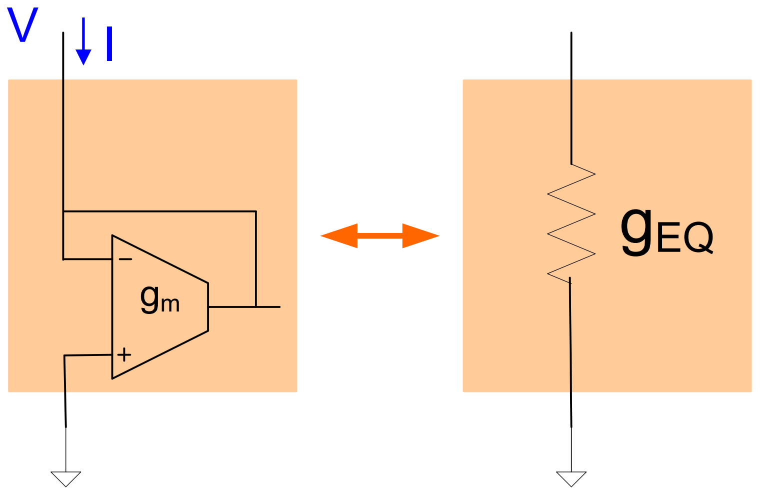


$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{g_m R_F}{1+s(R_F C)}$$

Lossy Integrator

But R_F is typically too large for integrated applications

OTA-C Voltage Mode Integrator



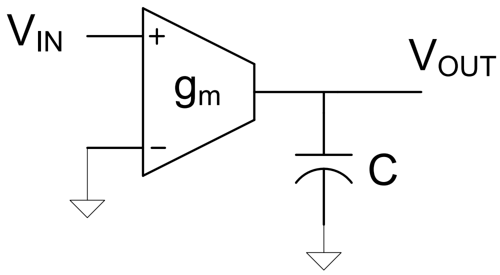
$$I = - -g_m V$$

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

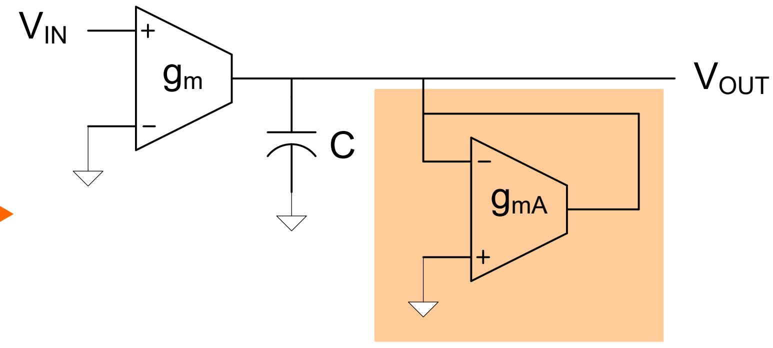
$$g_{EQ} = g_m$$

OTA is generally much smaller than a resistor

OTA-C Voltage Mode Integrator



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

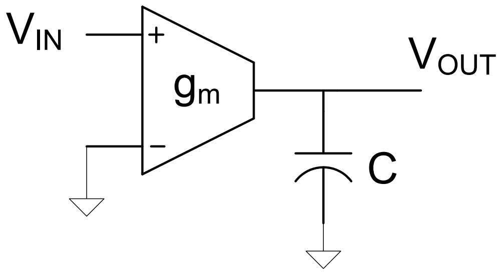


$$\frac{V_{OUT}(s)}{V_{IN}(s)} = \frac{g_m/g_{mA}}{1+s(C/g_{mA})}$$

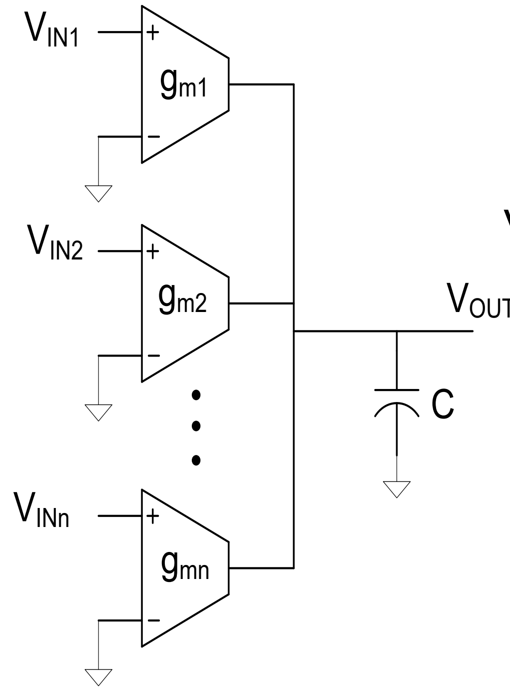
Lossy Integrator

- 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

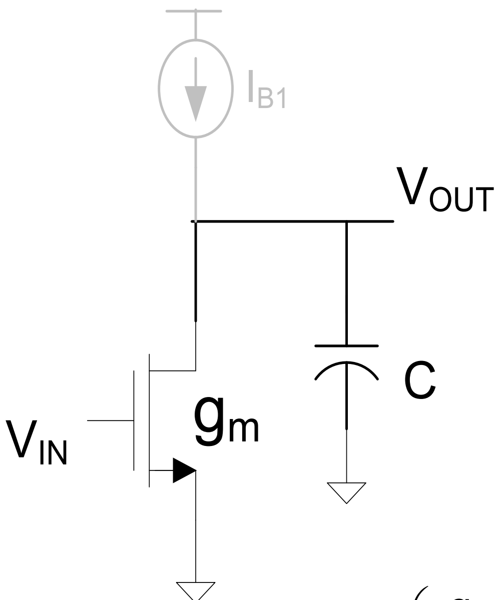
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

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

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

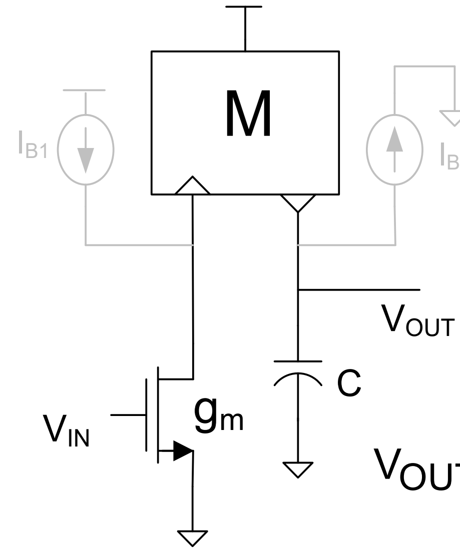
Discrete Time (Switched Capacitor, Switched Resistor)

TA-C Voltage Mode Integrator



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

Inverting Integrator



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

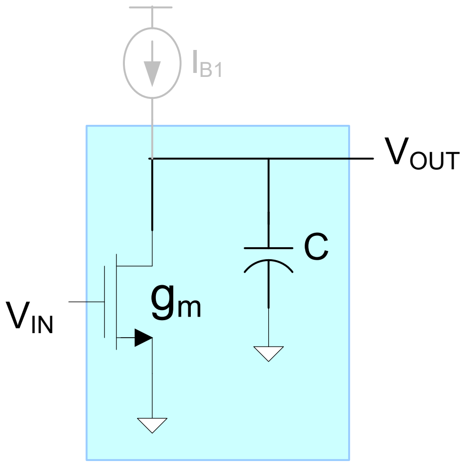
Typically M=1

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

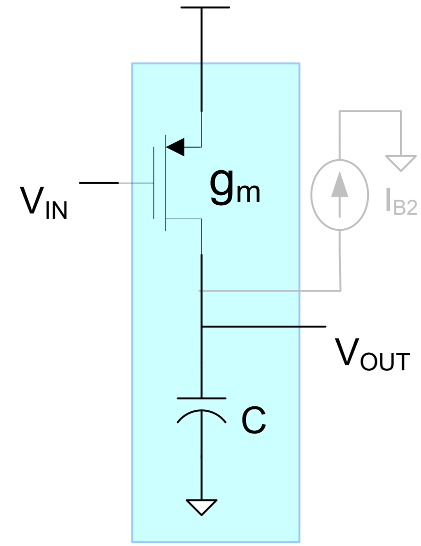
TA-C Voltage Mode Integrator

Some other perspectives



n-channel input

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

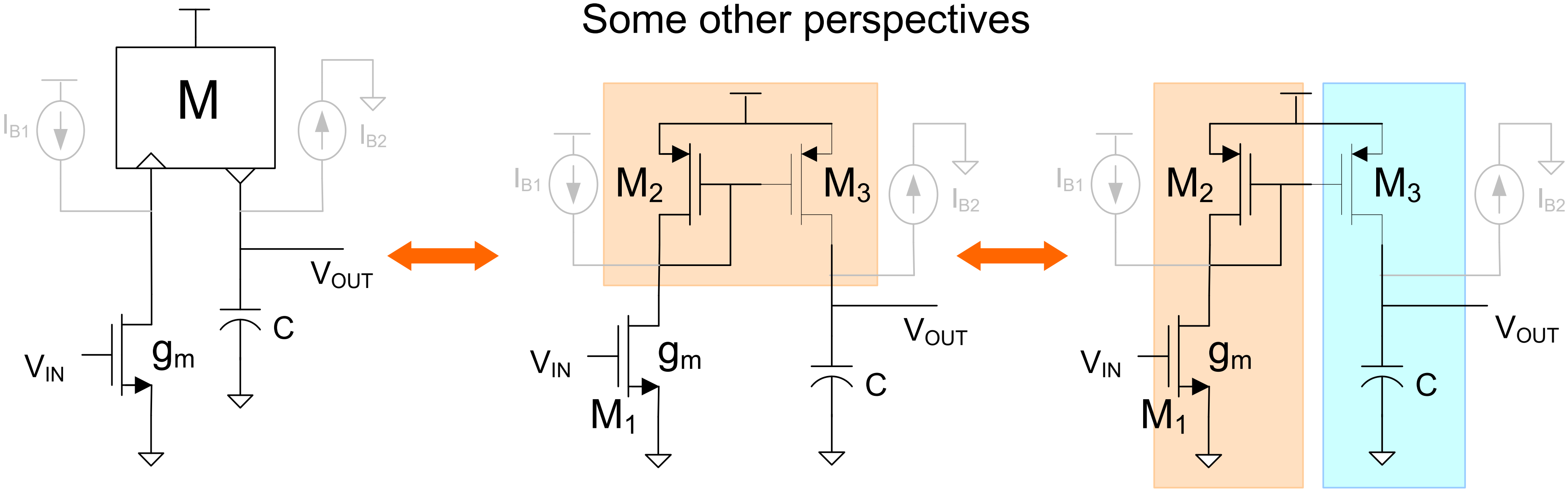


p-channel input

Inverting Integrators

TA-C Voltage Mode Integrator

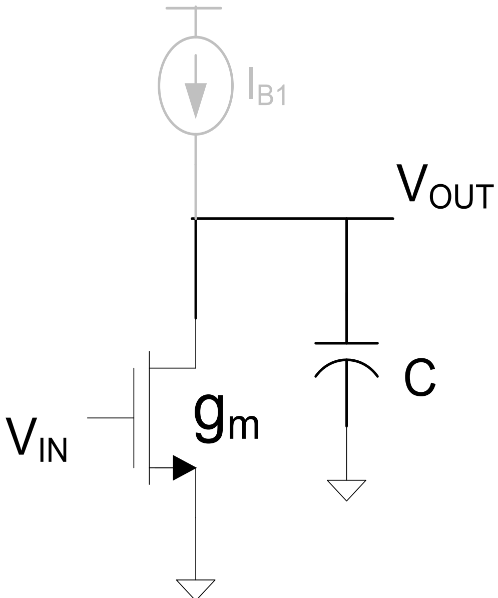
Some other perspectives



Noninverting Integrator

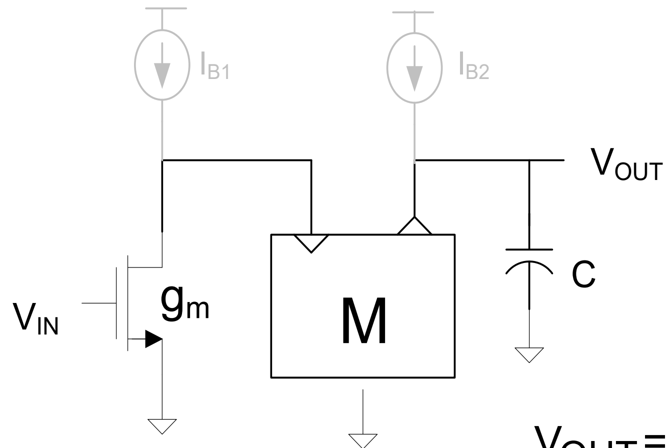
Can be viewed either as n-channel input with current mirror or as low-gain inverter driving a p-channel input inverting integrator

TA-C Voltage Mode Integrator



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

Inverting Integrator

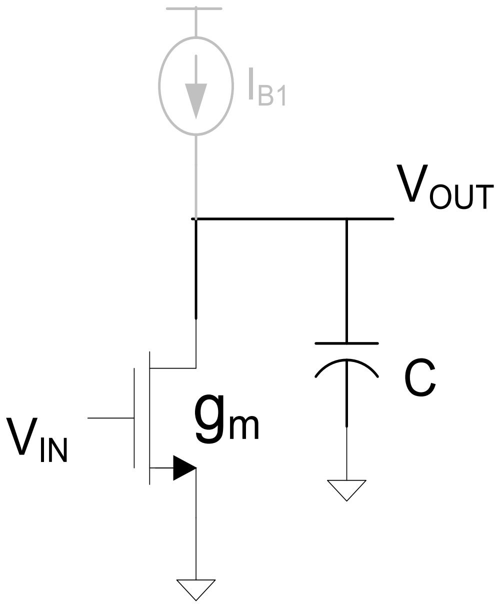


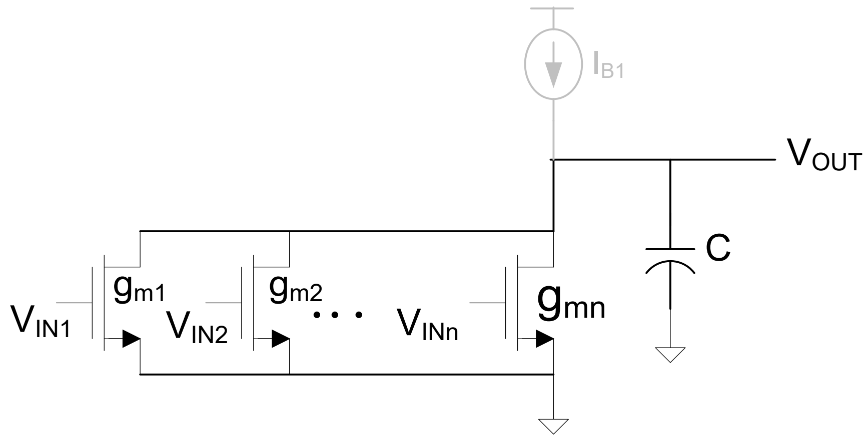
$$V_{OUT} = \left(\frac{g_m M}{sC} \right) V_{IN}$$

Typically M=1

Alternate noninverting Integrator

TA-C Voltage Mode Integrator





Summing Inverting Integrator

Voltage Mode Integrators

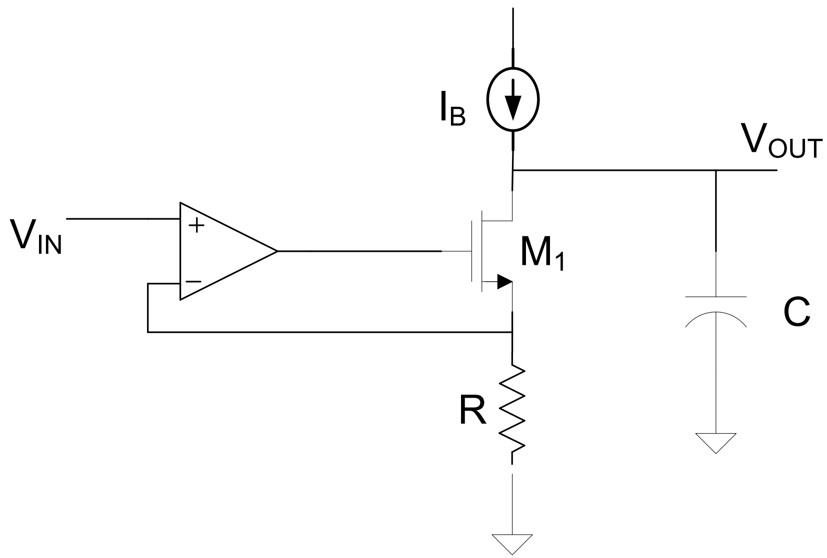
- Active RC (Feedback-based)
- MOSFET-C (Feedback-based)
- OTA-C
- TA-C

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

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

Discrete Time (Switched Capacitor, Switched Resistor)

Another Voltage Mode Integrator

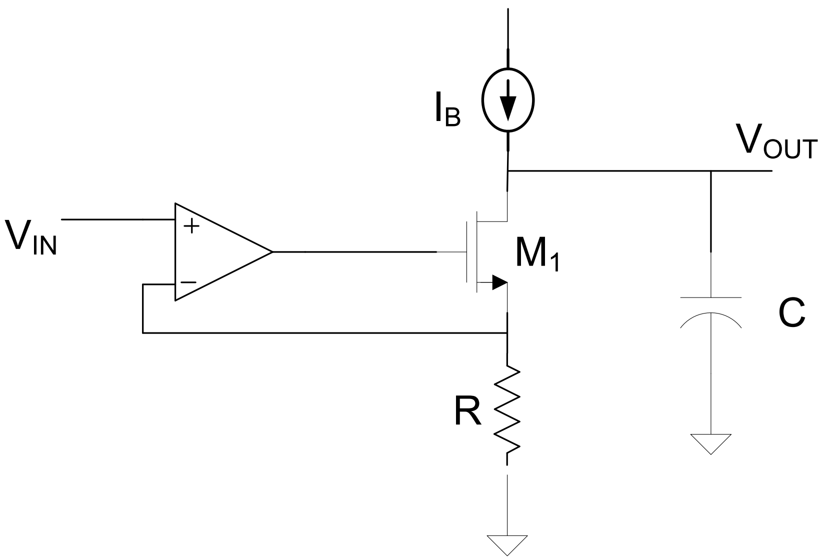


$$V_{OUT} = \left(\frac{-1}{sRC}\right) V_{IN}$$

Inverting Integrator

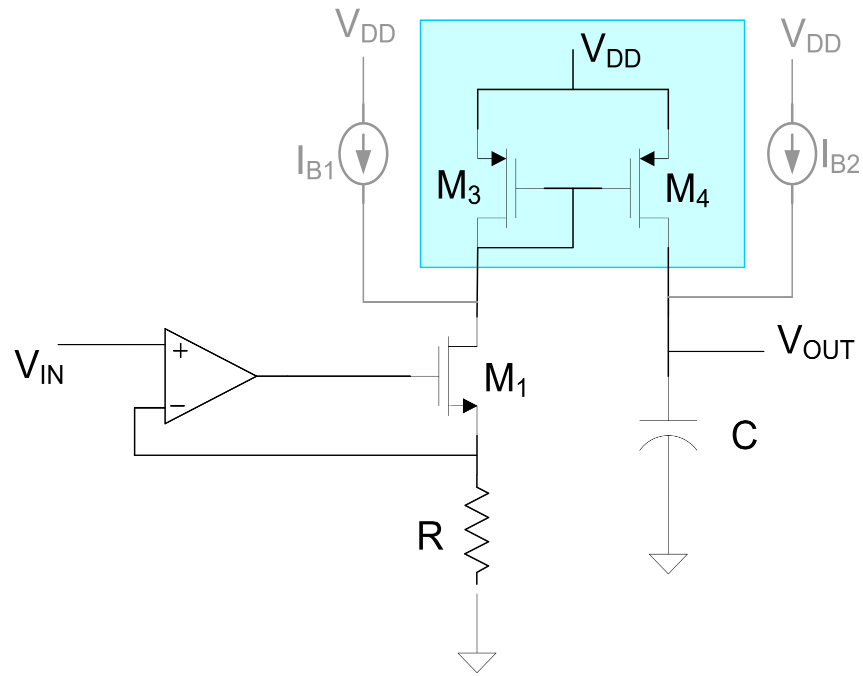
- **Infinite input impedance (in contrast to basic Active RC Integrator)**
- **Both R and C have one terminal grounded**
- **Requires integrated process**
- **Accuracy limited by process and temperature**
- **Size limitations same as basic Active RC Integrator**
- **Limited to lower frequencies because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

Another Voltage Mode Integrator



Inverting Integrator

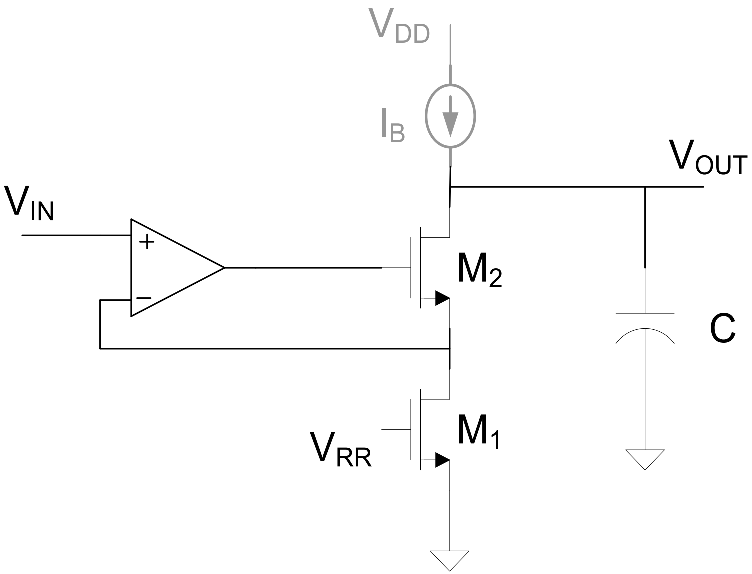
$$V_{OUT} = \left(\frac{-1}{sRC}\right) V_{IN}$$



Noninverting Integrator

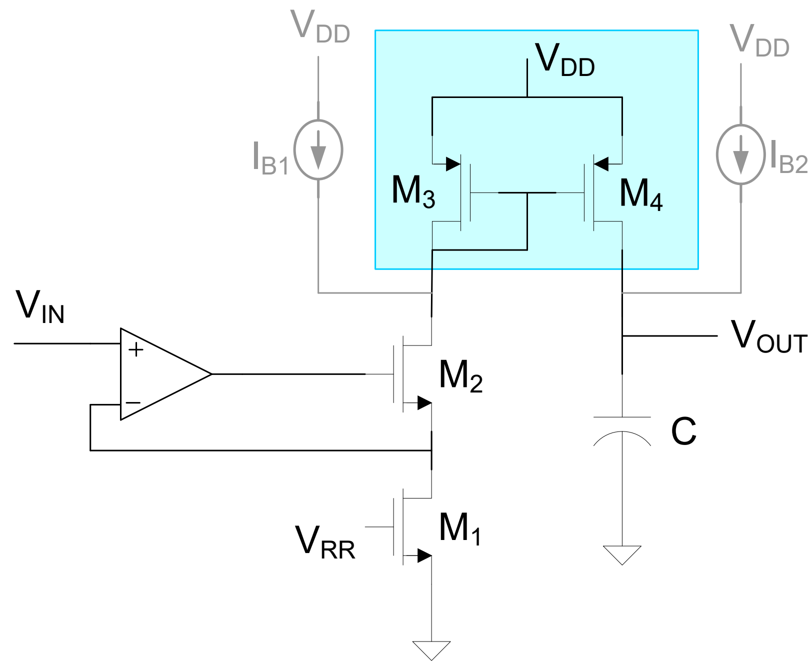
$$V_{OUT} = \left(\frac{1}{sRC}\right) V_{IN}$$

Another Voltage Mode Integrator



Inverting Integrator

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

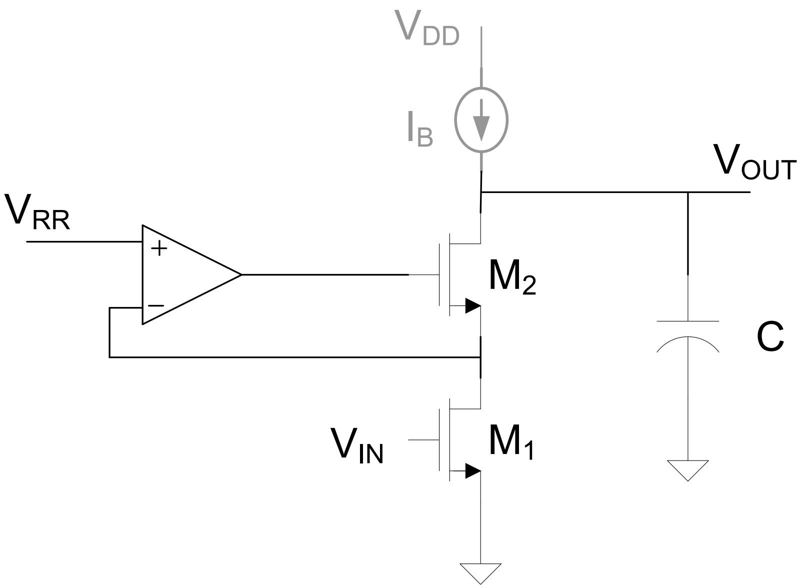


Noninverting Integrator

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

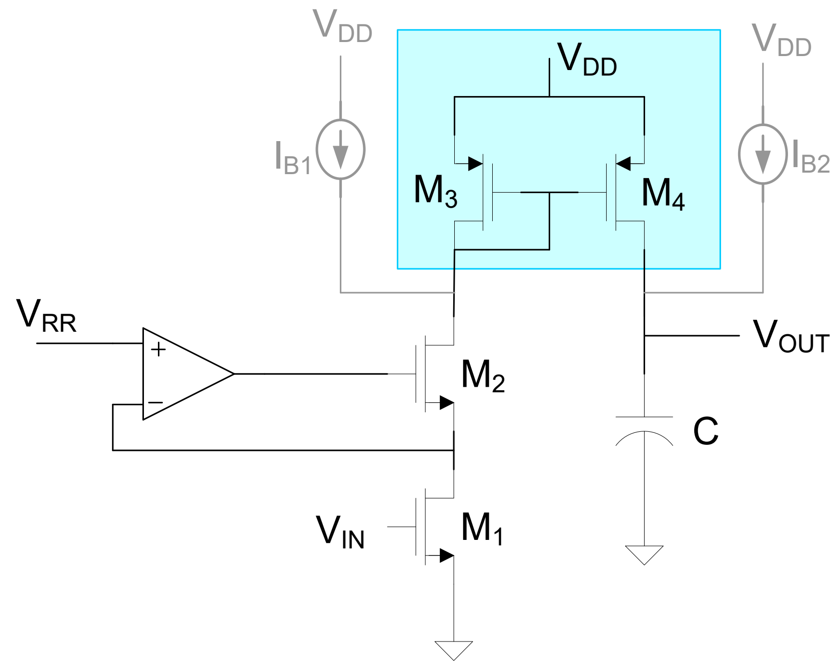
- M_1 in triode region
- Reduces Area Concerns but Loss of Linearity
- I_0 is programmable with V_{RR}
- Accurate control of I_B critical

Regulated Cascode Voltage Mode Integrator



Inverting Integrator

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



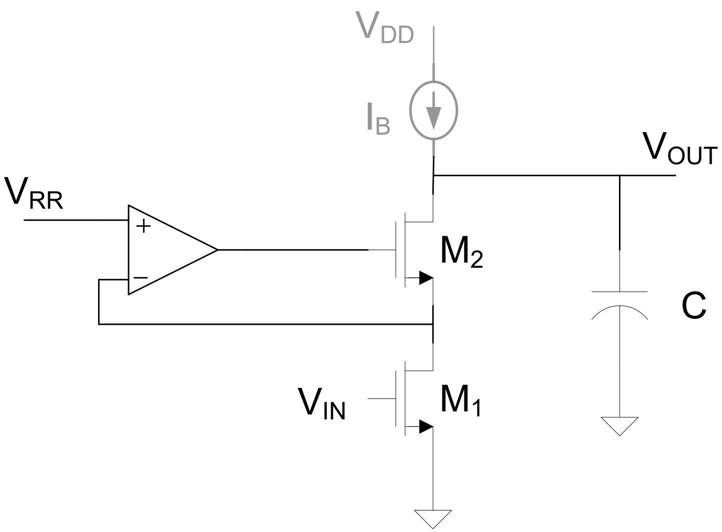
Noninverting Integrator

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

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

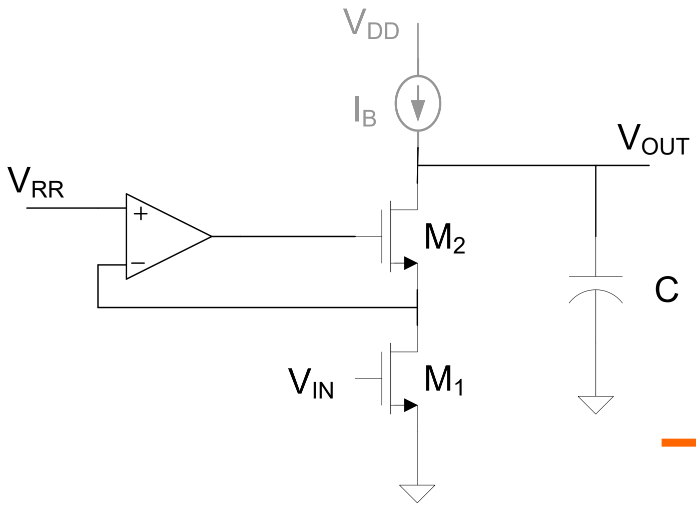
$$I_{D1} = \frac{\mu C_{OX} W}{L}\left(V_{GS} - V_T - \frac{V_{RR}}{2}\right) V_{RR}$$

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

Note linear dependence on V_{IN}

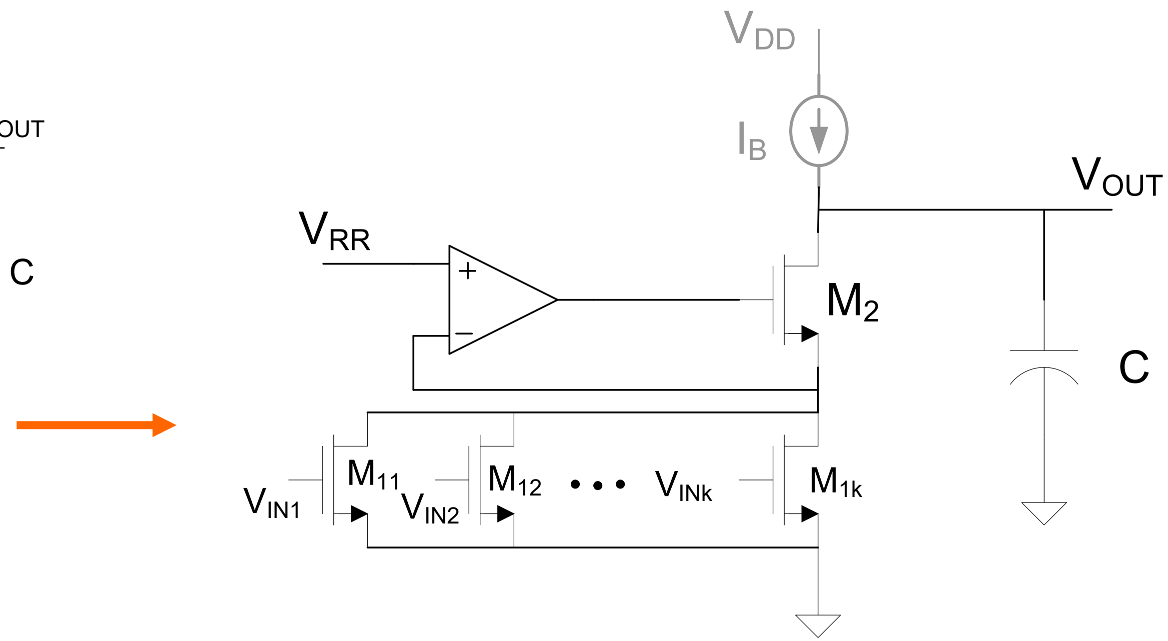
$$g_{mT} = \left[\frac{L}{\mu C_{OX} W\, V_{RR}}\right]$$

Regulated Cascode Voltage Mode Integrator



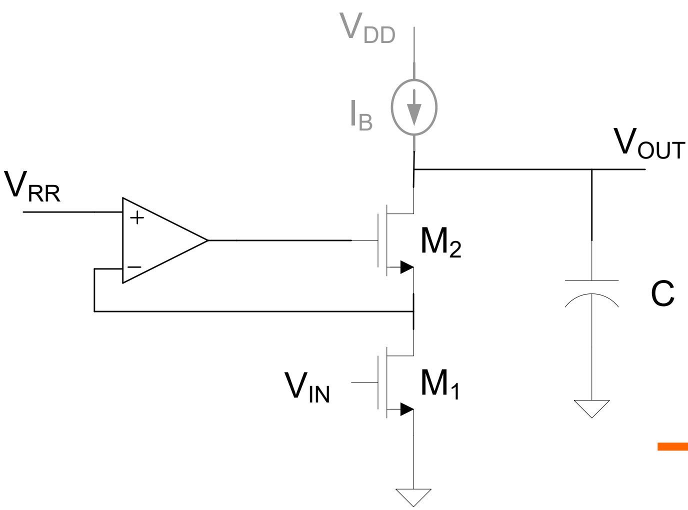
Inverting Integrator

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



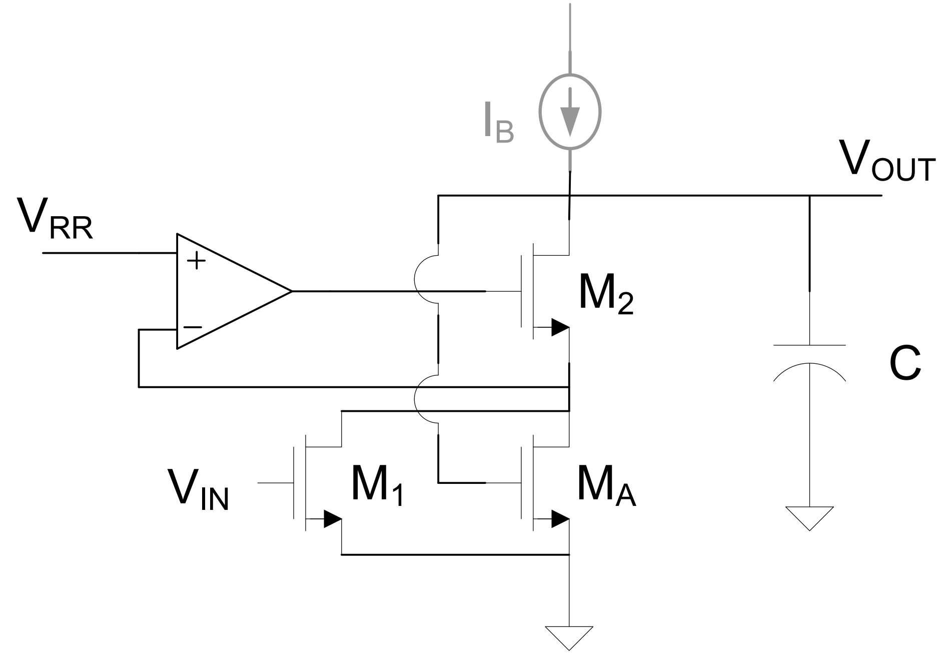
- **Multiple inputs require single additional transistor**
- **Accurate ratioing of gains practical**
- **Can also sum currents on C**

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